Subir Sachdev
Top 5 articles

1. *Non-zero temperature transport near quantum critical points*, K. Damle and S. Sachdev, Physical Review B **56**, 8714 (1997).
   Building on ideas in *Universal quantum critical dynamics of two-dimensional antiferromagnets*, S. Sachdev and J. Ye, Physical Review Letters **69**, 2411 (1992), this paper 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, Physical Review B **78**, 085416 (2008) interpreted the transport properties of pure graphene along quantum-critical lines, to the surprise of many in the field. This led to predictions for microwave conductivity which were experimentally observed in Gallagher *et al.* Science **364**, 158 (2019).
   - *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, Physical Review B **76**, 144502 (2007) and *Collective cyclotron motion of the relativistic plasma in graphene*, M. Müller and S. Sachdev, Physical Review B **78**, 115419 (2008) were the first to propose that graphene should display hydrodynamic transport near charge neutrality. Predictions on novel thermoelectric transport were observed in *Observation of the Dirac fluid and the breakdown of the Wiedemann-Franz law in graphene*, J. Crossno, Jing K. Shi, Ke Wang, Xiaomeng Liu, A. Harzheim, A. Lucas, S. Sachdev, Philip Kim, Takashi Taniguchi, Kenji Watanabe, T. A. Ohki, and Kin Chung Fong, Science **351**, 1058 (2016). 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) and Palm *et al.*, Science **384**, 465 (2024).
   - The hydrodynamic analyses also led to the realization that transport in *clean* quantum critical systems is in the strong drag limit, and so *cannot* explain the ubiquitous strange metal phase of correlated electron materials with a finite density Fermi surface, as discussed in *Transport near the Ising-nematic quantum critical point of metals in two dimensions*, S. A. Hartnoll, R. Mahajan, M. Punk, and S. Sachdev, Physical Review B **89**, 155130 (2014), DC resistivity at the onset of spin density wave order in two-dimensional metals, A. A. Patel and S. Sachdev, Physical Review B 90, 165146 (2014), and *Large N theory of critical Fermi surfaces II: conductivity*, Haoyu Guo, A. A. Patel, I. Esterlis, and S. Sachdev, Physical Review B **106**, 115151 (2022).
   - The Damle-Sachdev paper motivated holographic models of transport in quantum-critical matter in *Quantum critical transport, duality, and M theory*, C. P. Herzog, P. Kovtun. S. Sachdev, and D. T. Son, Physical Review D **75**, 085020 (2007). 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.

2. *Gapless spin-fluid ground state in a random quantum Heisenberg magnet*, S. Sachdev and J. Ye, Physical Review Letters **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.

This model has since had an extensive influence on the quantum theory of charged black holes (described in item 5), and on the theory of quantum phase transitions in metals with a Fermi surface, as summarized in 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).

Already in the 1993 SY paper, an explanation of the "marginal Fermi liquid" behavior in cuprates was noted. Subsequent developments led to:

- *Universal theory of strange metals from spatially random interactions*, A. A. Patel, Haoyu Guo, I. Esterlis, and S. Sachdev, Science **381**, 790 (2023) develops a theory of quantum phase transitions of two-dimensional metallic systems in the presence of random impurities. Surprisingly, the various clean Hertz-Millis classes, and also the topological transitions involving without broken symmetries all fall into essentially the same universality class. Complete results for the optical conductivity in both the normal and superconducting phases were obtained in *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, Physical Review Letters **133**, 186502 (2024). There is a wide intermediate temperature regime over which the solution of this two-dimensional generalization of the Sachdev-Ye-Kitaev model applies. At lower temperatures, there are strong disorder 'Griffiths' effects discussed in *Localization of overdamped bosonic modes and transport in strange metals*, A. A. Patel, P. Lunts, and S. Sachdev, Proceedings of National Academy of Sciences **121**, e2402052121 (2024). These results connect to a variety of experiments:
  (a) *Reconciling scaling of the optical conductivity of cuprate superconductors with Planckian resistivity and specific heat*, B. Michon *et al.*, Nature Communications **14**, 3033 (2023).
  (b) *A unified form of low-energy nodal electronic interactions in hole-doped cuprate superconductors*, T. J. Reber *et al.*, Nature Communications **10**, 3447 (2019).
  (c) *Impact of low-energy spin fluctuations on the strange metal in a cuprate superconductor*, D. J. Campbell *et al.* Nature Physics **21**, 1759 (2025).
  (d) *Critical spin fluctuations across the superconducting dome in* $La_{2-x}Sr_xCuO_4$, J. Radaelli *et al.*, Nature Communications **17**, 4564 (2026).
  (e) *Singular spin fluctuations in the strange-metal phase of* $La_{2-x}Sr_xCuO_4$, B. Costarella *et al.*, arXiv:2605.13573.
  (f) Decoupling momentum and energy relaxation rates in cuprate strange metals via giant THz nonlinearities, D. Chaudhuri *et al.*, arXiv:2503.15646.

- *Thermopower across Fermi-volume-changing quantum phase transitions without translational symmetry breaking*, P. Lunts, A. A. Patel, and S. Sachdev, Physical Review B **111**, 245151 (2025) explains thermopower observations across the strange metal region in the cuprates and other compounds.
- *Superlinear Hall angle and carrier mobility from non-Boltzmann magnetotransport in the spatially disordered Yukawa-SYK model on a square lattice*, D. Valentinis, J. Schmalian, S. Sachdev, and A. A. Patel, Physical Review Research **8**, 013299 (2026) addresses the long-standing 'Hall angle' puzzle of strange metal phases in correlated electron compounds.
- Another extensive set of developments began with the extension of the 1993 SY work by A. M. Sengupta (arXiv:9707316, Physical Review B **61**, 4041 (2000)) to Kondo models. This was developed by Qimiao Si and others into what is now known as "extended dynamical mean field theory", and has been used as a theory of local criticality of Kondo breakdown transitions in heavy fermion compounds.

3. *Fractionalized Fermi liquids* (FL*), T. Senthil, S. Sachdev, and M. Vojta, Physical Review Letters **90**, 216403 (2003).
Conventional metals have Fermi surfaces that enclose the same volume as that of free electrons with the same density and the same symmetry–this is the classic result of Luttinger (1960). Oshikawa related this result to a mixed anomaly between translations and the global U(1) symmetry related to fermion number conservation (Physical Review Letters **84**, 3370, (2000)). Our paper introduced a new metallic state, FL*, which satisfied the Oshikawa anomaly in a different manner: part of the anomaly is satisfied by a spin liquid state (usually quantized to a density of one particle per site), and the remainder by a Fermi surface enclosing a quantized non-Luttinger volume. Such a FL* state has been observed in the intermetallic 'heavy fermion' compound $CeCoIn_5$ by Maksimovic *et al.*, Science **375**, 76 (2021)).

Explicit constructions of the FL* state in single-band Hubbard-type models, appropriate for the cuprates, were described in:

- *Hole dynamics in an antiferromagnet across a deconfined quantum critical point*, R. K. Kaul, A. Kolezhuk, M. Levin, S. Sachdev, and T. Senthil, Physical Review B **75** , 235122 (2007).
- *Algebraic charge liquids*, R. K. Kaul, Y. B. Kim, S. Sachdev, and T. Senthil, Nature Physics **4**, 28 (2008).
- *Effective theory of Fermi pockets in fluctuating antiferromagnets*, Y. Qi and S. Sachdev, Physical Review B **81**, 115129 (2010).
- *A quantum dimer model for the pseudogap metal*, M. Punk, A. Allais, and S. Sachdev, Proceedings of the National Academy of Sciences **112**, 9552 (2015).
- *From the pseudogap metal to the Fermi liquid using ancilla qubits*, Ya-Hui Zhang and S. Sachdev, Physical Review Research **2**, 023172 (2020).

Experiments on the pseudogap metal phase of the cuprates observe a Yamaji effect (Chan *et al.* Nature Physics **21**, 1753 (2025)) with hole pocket areas close to the FL* value of $p/8$, where p is the hole doping (in contrast, spin density wave theory predicts area $p/4$). Computations of the electronic spectrum in the pseudogap metal in *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, Physical Review B **105**, 075146 (2022) were successfully compared to photoemission experiments of He *et al.*, Science **331**, 1579 (2011) and Chen *et al.*, Science **366**, 1099 (2019). Ultracold atom simulations of the square lattice Hubbard model have observed multipoint correlation functions (Koepsell *et al.*, Science 374, 82 (2021)) which agree with numerical studies of the transition from FL* to a Fermi liquid (*Polaronic correlations from optimized ancilla wave functions for the Fermi-Hubbard model*, T. Müller, R. Thomale, S. Sachdev, and Y. Iqbal, Proceedings of the National Academy of Sciences **122**, e2504261122 (2025); L. Shackleton and Shiwei Zhang, arXiv:2408.02190).

4. *Valence bond and spin-Peierls ground states of low dimensional quantum antiferromagnets*, N. Read and S. Sachdev, Physical Review Letters **62**, 1694 (1989).
This paper was the first complete emergent gauge theory of two-dimensional quantum antiferromagnets with time-reversal symmetry, introducing numerous key ideas which have since played important roles in the development of the theory of entangled states of quantum matter. It predicted the existence of a valence bond solid (VBS) state across a quantum phase transition from a Néel state in which the spins are ordered collinearly.

- The transition from the Néel state to the VBS applies also to the Shastry-Sutherland lattice, as was discussed in *Quantum phases of the Shastry-Sutherland antiferromagnet: Application to $SrCu_2(BO_3)_2$*, C.H. Chung, J.B. Marston, and S. Sachdev, Physical Review B **64**, 134407 (2001), and has been observed in $SrCu_2(BO_3)_2$ by Zayed *et al.*, Nature Physics **13**, 962 (2017). On the honeycomb lattice, the predicted VBS order was of the Kekulé type. Such order has been observed in undoped graphene in a magnetic field by Liu *et al.*, Science **375**, 321 (2021) and Coissard *et al.*, Nature **605**, 51 (2022).
- The importance of the analog of Lieb-Schultz-Mattias anomalies (realized here as monopole Berry phases) was pointed out. Such anomalies have since played a central role in the theory of gapped and gapless quantum spin liquids, and of quantum phase transitions out of them, including those realized by 'deconfined critiality' (*Deconfined Quantum Critical Points*, T. Senthil, A. Vishwanath, L. Balents, S. Sachdev, and M. P. A. Fisher, Science **303**, 1490 (2004)). Evidence for deconfined criticality is present in $SrCu_2(BO_3)_2$ (Cui *et al.*, Science **380**, 6650 (2023)).
- *Spin-Peierls, valence bond solid, and Néel ground states of low dimensional quantum antiferromagnets*, N. Read and S. Sachdev, Physical Review B **42**, 4568 (1990) also established an equivalence between the U(1) gauge theory of monopoles with Berry phases and the quantum dimer model on the square lattice.
- By considering Higgs transitions of the emergent gauge field, *Large-N expansion for frustrated quantum antiferromagnets*, N. Read and S. Sachdev, Physical Review Letters **66**, 1773 (1991) introduced the first example of a gapped fractionalized state of matter with time-reversal symmetry—the $\mathbb{Z}_2$ spin liquid.
- The importance of Lieb-Schultz-Mattis anomalies in the $\mathbb{Z}_2$ spin liquid was pointed out by *Spontaneous alignment of frustrated bonds in an anisotropic, three-dimensional Ising model*, R. Jalabert and S. Sachdev, Physical Review B **44**, 686 (1991) and *Translational symmetry breaking in two-dimensional antiferromagnets and superconductors*, S. Sachdev and M. Vojta, Journal of the Physical Society of Japan **69** Supplement B, 1 (2000), and this showed that Anderson's resonating valence bond state was an 'odd' $\mathbb{Z}_2$ spin liquid.
- Doping the nearly-critical quantum spin liquid at the Néel-VBS transition leads to a theory of the confinement transition from the pseudogap to high temperature d-wave superconductivity in the cuprates, and for the associated competing charge order:
  - *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, Proceedings of the National Academy of Sciences **121**, e2418633121 (2024)).
- *Thermal SU(2) lattice gauge theory for intertwined orders and hole pockets in the cuprates*, H. Pandey, M. Christos, P. M. Bonetti, R. Shanker, A. Nikolaenko, S. Sharma, and S. Sachdev, Proceedings of the National Academy of Sciences **123**, e2606117123 (2026).

5. *Holographic Metals and the Fractionalized Fermi Liquid*, S. Sachdev, Physical Review Letters **105**, 151602 (2010).
There has been 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 *Quantum fluctuations of a nearly critical Heisenberg spin glass*, A. Georges, O. Parcollet, and S. Sachdev, Physical Review B **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 *Quantum statistical mechanics of the Sachdev-Ye-Kitaev model and charged black holes*, International Journal of Modern Physics B **38**, 2430003 (2024)). 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.