Subir Sachdev Research Highlights

I. QUANTUM CRITICALITY

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), and in Majumdar *et al.*, Nature Physics **21**, 1374 (2025). 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: the 2D-Yukawa-Sachdev-Ye-Kitaev model. 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 paper 4 below. 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. *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 quantum matter states without quasiparticle excitations realize the low energy quantum physics of charged black holes. It noted in its abstract:

> ...certain mean-field gapless spin liquids are states of matter at non-zero density realizing the near-horizon, $AdS_2 \times R^2$ physics of Reissner-Nordström 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.

4. *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).
There is a wide intermediate temperature regime over which the self-averaged solution of the 2D-YSYK model in A. A. Patel, Haoyu Guo, I. Esterlis, and S. Sachdev, Science **381**, 790 (2023) 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, Physical Review Letters **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 in (i) transport measurements by R.A. Cooper *et al.* Science **323**, 603 (2009). Other connections to observation are noted under paper 2.

II. QUANTUM MAGNETISM

5. *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-Mattis 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.

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, Physical Review Letters, **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.
   - *Universal magnetic properties of frustrated quantum antiferromagnets in two dimensions*, A. V. Chubukov, T. Senthil, and S. Sachdev, Physical Review Letters **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.

8. *Spontaneous alignment of frustrated bonds in an anisotropic, three dimensional Ising model*, R. Jalabert and S. Sachdev, Physical Review B **44**, 686 (1991).
   Using the analog of Lieb-Schultz-Mattis anomalies, 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. *Low temperature relaxational dynamics of the Ising chain in a transverse field*, S. Sachdev and A. P. Young, Physical Review Letters **78**, 2220 (1997).
Low temperature spin diffusion in the one-dimensional quantum O(3) nonlinear σ-model S. Sachdev and K. Damle, Physical Review Letters **78**, 943 (1997).
Spin dynamics and transport in gapped one-dimensional Heisenberg antiferromagnets at nonzero temperatures, K. Damle and S. Sachdev, Physical Review B **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.*, Physical Review Letters **76**, 2173 (1996), G. Xu *et al.*, Science **317**, 1049 (2007), and A. W. Kinross *et al.*, Physical Review X **4**, 031008 (2014).

10. *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, Physical Review B **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.

11. *Landau theory of quantum spin glasses of rotors and Ising spins*, N. Read, S. Sachdev, and J. Ye, Physical Review B, **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.

12. *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). This paper introduced a new metallic state, FL*, and stated (ρ_a is the total electron density, $\mathcal{K}_d = (2\pi)^d/(2v_0)$, v_0 is the volume of the unit cell of the ground state):

> The primary purpose of this paper is to show that there exist non-magnetic, metallic states (FL*) in dimensions $d \geq 2$ with a Fermi surface of ordinary $S = 1/2$, charge $-e$, sharp quasiparticles, enclosing a volume
>
> $$\mathcal{V}_{FL^*} = \mathcal{K}_d[(\rho_a - 1)(\text{mod } 2)]\,.$$

The Luttinger result does not have the -1 subtraction from the density: this subtraction is *quantized*, and is associated an anomaly of a fractionalized quantum spin liquid. 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 coherent interlayer transport and a Yamaji effect (Yawen Fang *et al.*, Nature Physics **18**, 558 (2022), Chan *et al.* Nature Physics **21**, 1753 (2025)), both characteristics of the FL* state. The hole pocket areas measured by the Yamaji angle are close to the FL* value of $p/8$, where p is the hole doping, in contrast the spin density wave theory predicts area $p/4$ (*Yamaji effect in models of underdoped cuprates*, Jing-Yu Zhao, S. Chatterjee, S. Sachdev, and Ya-Hui Zhang, Physical Review B **113**, 245150 (2026)). 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).

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. *Resonant thermal Hall effect of phonons coupled to dynamical defects*, Haoyu Guo, D. G. Joshi, and S. Sachdev, Proceedings of the National Academy of Sciences **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).

15. *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).
These papers describe the low temperature fate of the FL* pseudogap metal of the cuprates. The calculations are enabled by the Ancilla Layer Model of *From the pseudogap metal to the Fermi liquid using ancilla qubits*, Ya-Hui Zhang and S. Sachdev, Physical Review Research **2**, 023172 (2020). 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, Physical Review B **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 6 and M. Vojta and S. Sachdev, Physical Review Letters **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.

16. *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).
The cuprate pseudogap phase displays Fermi arc spectral weight in photoemission and scanning tunneling microscopy, while recent magnetotransport observations yield evidence for the existence of hole pockets of fractional area $p/8$, where p is the doping density. This paper reconciles these observations by a Monte Carlo study of a SU(2) lattice gauge theory of the background spin liquid of a fractionalized Fermi liquid of hole pockets.

IV. ULTRACOLD ATOMS

17. *Mott insulators in strong electric fields*, by S. Sachdev, K. Sengupta, and S. M. Girvin, Physical Review B **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.* Physical Review Letters **111**, 053003 (2013).

18. *Competing density-wave orders in a one-dimensional hard-boson model*, P. Fendley, K. Sengupta, and S. Sachdev, Physical Review B **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, Physical Review Letters **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).

Quantum coarsening and collective dynamics on a programmable quantum simulator, T. Manovitz, S. H. Li, S. Ebadi, R. Samajdar, A. A. Geim, S. J. Evered, D. Bluvstein, H. Zhou, N. U. Köylüoğlu, J. Feldmeier, P. E. Dolgirev, N. Maskara, M. Kalinowski, S. Sachdev, D. A. Huse, M. Greiner, V. Vuletić, M. D. Lukin, Nature **638**, 86 (2025).

Prediction and observation of the phase diagram and dynamics 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).

    Probing the Kitaev honeycomb model on a neutral-atom quantum computer, S. J. Evered, M. Kalinowski, A. A. Geim, T. Manovitz, D. Bluvstein, Sophie H. Li, N. Maskara, Hengyun Zhou, S. Ebadi, Muqing Xu, J. Campo, M. Cain, S. Ostermann, S. F. Yelin, S. Sachdev, M. Greiner, V. Vuletić, M. D. Lukin, Nature **645**, 341 (2025).

    The first 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). The second paper reports signatures of anyons in the Kitaev model on the honeycomb lattice.