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Advanced quantum materials – a new frontier for ultracold atoms

Ketterle, Wolfgang
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 MASSACHUSETTS AVE
CAMBRIDGE, MA, 02139
USA

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14. ABSTRACT The central goal of this project has been to study theoretically and realize experimentally new quantum phases of matter that go beyond this simple paradigm of symmetry breaking, order parameters, and mean-field description. The key ingredients necessary for these states are topology, frustration, and a high degree of degeneracy. Recent experimental progress with ultracold atoms gives us the tools necessary for realizing such novel states of matter. Band structures can be designed to offer nontrivial topology and to contain numerous degeneracies, thereby amplifying interactions. Frustration in spin systems can be enhanced by selecting the lattice geometry, going to higher SU(N) symmetry, or by having longer range interactions. Systems that we have realized can be broadly divided into two broad categories. The first one will be systems that are completely new and do not have counterparts in Nature, and the second one will be realizations of idealized states that provide paradigms for our understanding of fundamental nontrivial states of matter.					
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Universities involved:

MIT, Harvard, UMass Amherst, University of Colorado, University of Maryland, University of California at Berkeley

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The central goal of this project has been to study theoretically and realize experimentally new quantum phases of matter that go beyond this simple paradigm of symmetry breaking, order parameters, and mean-field description. The key ingredients necessary for these states are topology, frustration, and a high degree of degeneracy. Recent experimental progress with ultracold atoms gives us the tools necessary for realizing such novel states of matter. Band structures can be designed to offer nontrivial topology and to contain numerous degeneracies, thereby amplifying interactions. Frustration in spin systems can be enhanced by selecting the lattice geometry, going to higher $SU(N)$ symmetry, or by having longer range interactions. Systems that we have realized can be broadly divided into two broad categories. The first one will be systems that are completely new and do not have counterparts in Nature, and the second one will be realizations of idealized states that provide paradigms for our understanding of fundamental nontrivial states of matter.

Here is a list of publications of projects which were at least partially funded by the MURI grant, and a short summary from each participating group.

Harvard – Ashvin Vishwanath

Title: Advanced quantum materials – a new frontier for ultracold atoms

The main achievements in this theoretical thrust of the MURI were proposals to realize topological ground states of bosons and theoretical investigation of entirely new phases of matter in coherently driven (Floquet) many body systems, and their realization in ultracold atoms and related platforms.

Specifically, we made proposal to create the related phases of bosonic Quantum Hall states in optical lattices and Chiral Spin liquids in dipolar atom arrays. The former, in conjunction with Greiner's group showed a path to realizing $\nu=1/2$ Laughlin states of bosons and the latter, with Stamper-Kurn and Yao's group predict a chiral spin liquid with dipolar spins on the Kagome lattice. One of the major breakthroughs during this MURI was a close collaboration with the Monroe group along with Norman Yao, which proposed a theoretical blueprint for realizing and probing discrete time crystals, and an experiment-theory collaboration that saw the first signs of time crystalline order in a Floquet driven ion chain. New chiral Floquet phases for bosons were also predicted including a radical chiral phase, with underlying connections to Kitaev models on the honeycomb.

Eight graduate students worked on this project.

PUBLICATIONS:

1. Observation of a discrete time crystal

J. Zhang, P. W. Hess, A. Kyprianidis, P. Becker, A. Lee, J. Smith, G. Pagano, I.-D. Potirniche, A. C. Potter, A. Vishwanath, N. Y. Yao & C. Monroe

Nature volume 543, pages 217–220 (2017)



2. Realizing and Adiabatically Preparing Bosonic Integer and Fractional Quantum Hall states in Optical Lattices

Yin-Chen He, Fabian Grusdt, Adam Kaufman, Markus Greiner, Ashvin Vishwanath

Phys. Rev. B 96, 201103 (2017)

3. An infinite family of 3d Floquet topological paramagnets

Authors: Andrew C. Potter, Ashvin Vishwanath, Lukasz Fidkowski

Phys. Rev. B 97, 245106 (2018)

4. Interacting invariants for Floquet phases of fermions in two dimensions

Authors: Lukasz Fidkowski, Hoi Chun Po, Andrew C. Potter, Ashvin Vishwanath

Phys. Rev. B 99, 085115 (2019)

5. A quantum dipolar spin liquid

NY Yao, MP Zaletel, DM Stamper-Kurn, A Vishwanath

Nature Physics, 14, 405–410 (2018).

6. Discrete time crystals: rigidity, criticality, and realizations

Norman Y. Yao, Andrew C. Potter, Ionut-Dragos Potirniche, Ashvin Vishwanath

Phys. Rev. Lett. 118, 030401 (2017).

7. Chiral Floquet Phases of Many-body Localized Bosons

Authors: Hoi Chun Po, Lukasz Fidkowski, Takahiro Morimoto, Andrew C. Potter, Ashvin Vishwanath

Phys. Rev. X 6, 041070 (2016)

8. Floquet symmetry-protected topological phases in cold atomic systems

Ionut-Dragos Potirniche, Andrew C. Potter, Monika Schleier-Smith, Ashvin Vishwanath, Norman Y. Yao

Phys. Rev. B 96, 245116 (2017).

9. Radical chiral Floquet phases in a periodically driven Kitaev model and beyond

Hoi Chun Po, Lukasz Fidkowski, Ashvin Vishwanath, Andrew C. Potter

Phys. Rev. B 96, 245116 (2017)

10. arXiv:1903.09179

Stable Luttinger liquids and emergent U(1) symmetry in constrained quantum chains

Authors: Ruben Verresen, Ashvin Vishwanath, Frank Pollmann

Harvard – Eugene Demler

An important result of Demler's group was theoretical analysis of a mobile hole moving in an Mott insulating phase of fermions with antiferromagnetic order. Dynamics of a hole distorts the Neel order and leads to the formation of magnetic polaron. This phenomenon is believed to be at the heart of high-temperature superconductivity in cuprates. They studied a single hole described by the t-J model at strong couplings, where hole hopping is much larger than couplings between the spins. In this regime they found strong theoretical evidence that magnetic polarons can be understood as bound states of two partons, a spinon and a holon carrying spin and charge quantum numbers, respectively. Starting from first principles, they introduced a microscopic parton description which was benchmarked by comparison with results from advanced numerical simulations. Using this parton theory, they predicted a series of excited states that are invisible in the spectral function and correspond to rotational excitations of the spinon-holon pair. This is reminiscent of mesonic resonances observed in high-energy physics, which can be understood as rotating quark-antiquark pairs carrying orbital angular momentum. They applied the strong-coupling parton theory to study far-from-equilibrium dynamics of magnetic polarons observable in current experiments with ultracold atoms. This work supports earlier ideas that partons in a confining phase of matter represent a useful paradigm in condensed-matter physics and in the context of high-temperature superconductivity in particular. While direct observations of spinons and holons in real space are impossible in traditional solid-state experiments, quantum gas microscopes provide a new experimental toolbox. The work of Demler's group showed that, using this platform, direct observations of partons in and out of equilibrium are now possible.

Demler's group collaborated with the experimental group of Immanuel Bloch at the Max Planck Institute in Garching, Germany to analyze equilibrium properties of weakly doped Mott insulating states in the 2d Fermi Hubbard model. This work revealed strong modifications of magnetic correlations in the vicinity of charge carriers, as expected from the picture of magnetic polarons. Demler's group collaborated with Greiner's group to analyze dynamics of a single hole in the Fermi Hubbard model. Theoretical analysis showed that experimental results support essential features of magnetic polarons: long time (low frequency) dynamics on the scale of superexchange J and short time (high frequency) dynamics on the scale of fermion tunneling t . Together, these two theory-experiment collaborations established the physical picture of charge carriers in weakly doped Mott insulators being magnetic polarons. Such magnetic polarons can be efficiently described using the geometric string model of spinon-holon bound states, that utilizes analogy to QCD, where mesons are quark pairs held together by gluon strings. This approach was suggested theoretically in the early years of the studies of high T_c but experimental evidence for its validity was lacking. Demler's group extended this approach and demonstrated that predictions from this model are in excellent agreement with the experimentally measured snapshots of the doped Fermi Hubbard model.

Demler's group developed a new class of variational wavefunctions based on applying entangling transformations on top of the direct product of fermionic and bosonic states. This approach is based on constructing variational wavefunctions which extend Gaussian states by including generalized canonical transformations between the fields. The key advantage of such states compared to simple Gaussian states is presence of non-factorizable correlations and the possibility of describing states with strong entanglement between particles. In contrast to the commonly used canonical transformations, such as the polaron or Lang-Firsov transformations, the new method allows parameters of the transformations to be time dependent, which extends their regions of applicability. Demler's group derived equations of motion for the parameters characterizing the states both in real and imaginary time using the differential structure of the variational manifold. The ground state can be found by following the imaginary time evolution until it converges to a steady state. Collective excitations in the system can be obtained by linearizing the real-time equations of motion in the vicinity of the imaginary time steady-state solution. This formalism allows not only to determine the energy spectrum of quasiparticles and their lifetime, but to obtain the complete spectral functions and to explore far out of equilibrium dynamics such as coherent evolution following a quantum quench. The unitary entangling transformations greatly extends the subspace of variational states and makes them more suitable for describing both equilibrium and dynamical states. Results of Demler's group demonstrate both the viability of this approach and the capability of tackling complex systems and a broad range of experimental protocols. They benchmarked time-dependent non-Gaussian method in several

systems where numerically exact solutions for dynamics were known. For instance, they studied the nonequilibrium dynamics of the anisotropic Kondo model with either ferromagnetic and antiferromagnetic states. They further analyzed the evolution of impurity spin magnetization as well as the spatially dependent correlation function between the impurity spin and the bath fermions.

Results were shown to be in excellent agreement with simulations based on the Matrix Product State ansatz up to relatively long times. This approach was applied to analyze dynamics of concrete experimental systems, including spin dynamics of Kondo-impurity systems realized with ultracold atoms, transport through quantum dots in the Coulomb blockade regime, and dynamics of the Quantum Rydberg Central Spin Model. The non-Gaussian method was used to investigate static and dynamic properties of the Abelian U(1) (Schwinger model) and the non-Abelian SU(2) lattice gauge models in 1+1 dimensions. Both static and dynamic properties of strong breaking have been explored and benchmarked against tensor network simulations.

M. Serbyn, M. Knap, S. Gopalakrishnan, Z. Papić, N. Y. Yao, C. R. Laumann, D. A. Abanin, M. D. Lukin, E. Demler, Interferometric probes of many-body localization, [Phys. Rev. Lett. 113:147204 \(2014\)](#)

F. Grusdt, A. Shashi, D. Abanin, E. Demler, Bloch oscillations of bosonic lattice polarons, [Phys. Rev. A 90:063610 \(2014\)](#)

F. Grusdt, E. Demler, New theoretical approaches to Bose polarons, Proceedings of International School of Physics Enrico Fermi, Varenna, Italy 2014 [arXiv:1510.04934](#)

M. Kanasz-Nagy, E. Demler, G. Zarand, Confinement-induced interlayer molecules: A route to strong interatomic interactions, [Phys. Rev. A 91, 032704 \(2015\)](#)

D. Benjamin, I. Klich, E. Demler, Probing Competing and Intertwined Orders with Resonant Inelastic x-ray Scattering in the Hole-Doped Cuprates, [Phys. Rev. B 92:035151 \(2015\)](#)

F. Grusdt, Y. Shchadilova, A. Rubtsov, E. Demler, Renormalization group approach to the Froehlich polaron model: application to impurity-BEC problem, [Scientific Reports 5:12124 \(2015\)](#)

J. Bauer, M. Babadi, E. Demler, Dynamical instabilities and transient short-range order in the fermionic Hubbard model, [Phys. Rev. B 92:024305 \(2015\)](#)

S. Gopalakrishnan, C. Parker, and E. Demler, Mobile Magnetic Impurities in a Fermi Superfluid: A Route to Designer Molecules, [Phys. Rev. Lett. 114:045301 \(2015\)](#)

M. Babadi, E. Demler, M. Knap, Far-from-equilibrium field theory of many-body quantum spin systems: Prethermalization and relaxation of spin spiral states in three dimensions, [Phys. Rev. X 5:041005 \(2015\)](#)

M. Bukov, S. Gopalakrishnan, M. Knap, E. Demler, Prethermal Floquet steady-states and instabilities in the periodically-driven, weakly-interacting Bose-Hubbard model, [Phys. Rev. Lett. 115:205301 \(2015\)](#)

M. Kanasz-Nagy, Y. Shi, I. Klich, E. Demler, Resonant inelastic x-ray scattering as a band structure probe, [Phys. Rev. B 94:165127 \(2016\)](#)

Y. Shi, D. Benjamin, E. Demler, I. Klich, Superconducting pairing in resonant inelastic X-ray scattering, [Phys. Rev. B 94:094516 \(2016\)](#)

S. Gopalakrishnan, M. Knap, E. Demler, Regimes of heating and dynamical response in driven many-body localized systems, [Phys. Rev. B 94:094201 \(2016\)](#)

M. Kanasz-Nagy, L. Glazman, T. Esslinger, E. Demler, Anomalous conductances in an ultracold quantum wire, [Phys. Rev. Lett. 117:255302 \(2016\)](#).

E. Dalla Torre, Y. Shchadilova, E. Wilner, M. Lukin, E. Demler, Dicke phase transition without total spin conservation, [Phys. Rev. A 94: 061802\(R\) \(2016\)](#)

K. Agarwal, R. Schmidt, B. Halperin, V. Oganesyan, G. Zaránd, M. Lukin, E. Demler, Magnetic noise spectroscopy as a probe of local electronic correlations in two-dimensional systems [Phys. Rev. B 95:155107 \(2017\)](#)

K. Agarwal, E. Dalla Torre, J. Schmiedmayer, E. Demler, Quantum heat waves in a one-dimensional condensate, [Phys. Rev. B 95:195157 \(2017\)](#)

K. Agarwal, E. Altman, E. Demler, S. Gopalakrishnan, D. Huse, M. Knap, Rare region effects and dynamics near the many-body localization transition, [Annalen der Physik 1600326 \(2017\)](#)

K. Agarwal, R. Schmidt, B. Halperin, V. Oganesyan, G. Zaránd, M. Lukin, E. Demler, Magnetic noise spectroscopy as a probe of local electronic correlations in two-dimensional systems [Phys. Rev. B 95:155107 \(2017\)](#)

T. Shi, E. Demler, I. Cirac, Variational Study of Fermionic and Bosonic Systems with Non-Gaussian States: Theory and Applications, [Annals of Physics 390:245 \(2018\)](#)

T. Langen, T. Schweigler, E. Demler, J. Schmiedmayer, Double light-cone dynamics establish thermal states in integrable 1D Bose gases, [New J. Phys. 20:023034 \(2018\)](#)

F. Camargo, R. Schmidt, J. D. Whalen, R. Ding, G. Woehl Jr., S. Yoshida, J. Burgdorfer, F. B. Dunning, H. R. Sadeghpour, E. Demler, T. C. Killian, Creation of Rydberg Polarons in a Bose Gas, [Phys. Rev. Lett. 120:083401 \(2018\)](#)

A. Bohrdt, D. Greif, E. Demler, M. Knap, F. Grusdt, Angle-resolved photoemission spectroscopy with quantum gas microscopes, [Phys. Rev. B 97:125117 \(2018\)](#)

M. Pigneur, T. Berrada, M. Bonneau, T. Schumm, E. Demler, J. Schmiedmayer, Relaxation to a Phase-locked Equilibrium State in a One-dimensional Bosonic Josephson Junction, [Phys. Rev. Lett. 120:173601 \(2018\)](#)

F. Grusdt, M. Kanasz-Nagy, A. Bohrdt, C. Chiu, G. Ji, M. Greiner, D. Greif, E. Demler, Parton theory of magnetic polarons: Mesonic resonances and signatures in dynamics, [Phys. Rev. X 8:011046 \(2018\)](#)

Y. Ashida, T. Shi, M. C. Banuls, I. Cirac, E. Demler, Solving quantum impurity problems in and out of equilibrium with variational approach, [Phys. Rev. Lett. 121:026805 \(2018\)](#)

Y. Ashida, T. Shi, M. C. Banuls, I. Cirac, E. Demler, Variational principle for quantum impurity systems in and out of equilibrium: application to Kondo problems, [Phys. Rev. B 98:024103 \(2018\)](#)

R. Schmidt, J. D. Whalen, R. Ding, F. Camargo, G. Woehl Jr., S. Yoshida, J. Burgdorfer, F. B. Dunning, E. Demler, H. R. Sadeghpour, T. C. Killian, Theory of excitation of Rydberg polarons in an atomic quantum gas, [Phys. Rev. A 97:02270](#)

P. Sala, T. Shi, S. Kuhn, M. C. Banuls, E. Demler, J. I. Cirac, Variational study of U(1) and SU(2) lattice gauge theories with Gaussian states in 1+1 dimensions, [Phys. Rev. D 98:034505 \(2018\)](#)

- F. Grusdt, Z. Zhu, T. Shi, E. Demler, Meson formation in mixed-dimensional t-J models, [SciPost Phys 5:057 \(2018\)](#)
- K. Wintersperger, M. Bukov, J. Nager, S. Lellouch, E. Demler, U. Schneider, I. Bloch, N. Goldman, and M. Aidelsburger Parametric instabilities of interacting bosons in periodically-driven 1D optical lattices, [Phys. Rev. X 10:011030 \(2020\)](#),
- F. Grusdt, A. Bohrdt, E. Demler, Microscopic spinon-charge theory of magnetic polarons in the t-J model, [Phys. Rev. B 99:224422 \(2019\)](#)
- S. You, R. Schmidt, D. Ivanov, M. Knap, E. Demler, Atomtronics with a spin: statistics of spin transport and non-equilibrium orthogonality catastrophe in cold quantum gases, [Phys. Rev. B 99:214505 \(2019\)](#)
- T. Boulier, J. Maslek, M. Bukov, C. Bracamontes, E. Magnan, S. Lellouch, E. Demler, N. Goldman, J. V. Porto, Parametric instabilities in a 2D periodically-driven bosonic system: Beyond the weakly-interacting regime, [Phys. Rev. X 9:011047 \(2019\)](#)
- L. Barbiero, C. Schweizer, M. Aidelsburger, E. Demler, N. Goldman, F. Grusdt, Coupling ultracold matter to dynamical gauge fields in optical lattices: From flux-attachment to Z₂ lattice gauge theories, [Sci Adv 5 \(10\), eaav7444 \(2019\)](#)
- J. Koepsell, J. Vijayan, P. Sompet, F. Grusdt, T. Hilker, E. Demler, G. Salomon, I. Bloch, C. Gross, Imaging magnetic polarons in the doped Fermi-Hubbard model, [Nature 572:358 \(2019\)](#)
- A. Bohrdt, C. Chiu, G. Ji, M. Xu, D. Greif, M. Greiner, E. Demler, F. Grusdt, M. Knap, Classifying Snapshots of the Doped Hubbard Model with Machine Learning, [Nature Physics 15:921 \(2019\)](#)
- M. Michael, J. Schmiedmayer, E. Demler, From the moving piston to the dynamical Casimir effect: explorations with shaken condensates, [Phys. Rev. A 99:053615 \(2019\)](#)
- C. Schweizer, F. Grusdt, M. Berngruber, L. Barbiero, E. Demler, N. Goldman, I. Bloch, M. Aidelsburger, Floquet approach to Z₂ lattice gauge theories with ultracold atoms in optical lattices, [Nature Physics 15:1168 \(2019\)](#)
- J. P. Dehollain, U. Mukhopadhyay, V. P. Michal, Y. Wang, B. Wunsch, C. Reichl, W. Wegscheider, M. S. Rudner, E. Demler, L. M. K. Vandersypen, Nagaoka ferromagnetism observed in a quantum dot plaquette, [Nature 579:528 \(2020\)](#),
- Y. Ashida, T. Shi, R. Schmidt, H. R. Sadeghpour, J. I. Cirac, E. Demler, Efficient variational approach to dynamics of a spatially extended bosonic Kondo model, [Phys. Rev. A 100:043618 \(2019\)](#)

A. Bohrdt, A. Omran, E. Demler, S. Gazit, F. Grusdt, Multiparticle interactions for ultracold atoms in optical tweezers: Cyclic ring-exchange terms,
[Phys. Rev. Lett. 124:073601 \(2020\)](#)

Harvard – Markus Greiner

Extension period:

Quantum gas microscopes for ultracold atoms provides high-resolution real-space snapshots of complex many-body systems. We implemented machine learning to analyze and classify such snapshots of ultracold atoms. We compared the data from an experimental realization of the two-dimensional Fermi-Hubbard model to two theoretical approaches: a doped quantum spin liquid state of resonating valence bond type, and the geometric string theory, describing a state with hidden spin order. This approach considered all available information without a potential bias towards one particular theory by the choice of an observable and can therefore select the theory which is more predictive in general. In follow-up work we investigated the interplay between charge and spin and its effects on transport is a ubiquitous challenge in quantum many-body systems. In the Fermi-Hubbard model, this interplay is thought to give rise to magnetic polarons, whose dynamics may explain emergent properties of quantum materials such as high-temperature superconductivity. We directly observed the formation dynamics and subsequent spreading of individual magnetic polarons. Measuring the density- and spin-resolved evolution of a single hole in a 2D Hubbard insulator with short-range antiferromagnetic correlations reveals fast initial delocalization and a dressing of the spin background, indicating polaron formation. At long times, we find that dynamics are slowed down by the spin exchange time, and they are compatible with a polaronic model with strong density and spin coupling.

Full period:

The Greiner group developed quantum simulation and quantum gas microscopy to provide control on and manipulations on a single site level. They demonstrated multi-particle quantum walks and Bloch oscillations, and developed a scheme to directly measure entanglement entropy. They then used this scheme to measure the entanglement growth in quantum thermalization. Next, they carried out the first measurement of the logarithmic entanglement growth in many-body localization (MBL), measured critical phenomena at the MBL transition and for the first time demonstrated the onset of quantum avalanches, an effect that is believed to destroy the robustness of MBL in the thermodynamic limit. In a new experiment they demonstrated the fast creation of a Bose-Einstein condensate in highly magnetic Erbium atoms. In their Fermi-Hubbard simulator they realized the first Hubbard antiferromagnet and upon doping found evidence for the emergence of string pattern. They studied the doped Hubbard model with machine learning techniques and observed the formation and propagation of polarons in the doped Hubbard model.

The grant supported ~12 graduate students.

1. Cole Miles, Annabelle Bohrdt, Ruihan Wu, Christie Chiu, Muqing Xu, Geoffrey Ji, Markus Greiner, Kilian Q. Weinberger, Eugene Demler, Eun-Ah Kim, **Correlator Convolutional Neural Networks: An Interpretable Architecture for Image-like Quantum Matter Data**, *Nature Communications* **12**, 3905, doi:10.1038/s41467-021-23952-w (Jun 23 2021).
2. Geoffrey Ji, Muqing Xu, Lev Kendrick, Christie S. Chiu, Justus C. Bruggenjürgen, Daniel Greif, Annabelle Bohrdt, Fabian Grusdt, Eugene Demler, Martin Lebrat, Markus Greiner, **Coupling a Mobile Hole to an Antiferromagnetic Spin Background: Transient Dynamics of a Magnetic Polaron**, *Physical Review X* **11**, 021022, doi:10.1103/PhysRevX.11.021022 (Apr 27, 2021).

3. Julian Léonard, Matthew Rispoli, Alexander Lukin, Robert Schittko, Sooshin Kim, Joyce Kwan, Dries Sels, Eugene Demler, Markus Greiner, **Signatures of bath-induced quantum avalanches in a many-body--localized system**, arXiv:2012.15270 (Dec 30 2020).
4. Gregory A. Phelps, Anne Hebert, Aaron Krahn, Susannah Dickerson, Furkan Ozturk, Sepehr Ebadi, Lin Su, Markus Greiner, **Sub-second production of a quantum degenerate gas**, arXiv:2007.10807 (Jul 21 2020).
5. Matthew Rispoli, Alexander Lukin, Robert Schittko, Sooshin Kim, M. Eric Tai, Julian Leonard, Markus Greiner, **Quantum critical behavior at the many-body localization transition**, *Nature* 573: 385-389, doi:10.1038/s41586-019-1527-2 (Sep 4 2019).
6. Jordan Cotler, Soonwon Choi, Alexander Lukin, Hrant Gharibyan, Tarun Grover, M. Eric Tai, Matthew Rispoli, Rrobert Schittko, Philipp M. Preiss, Adam M. Kaufman, Markus Greiner, Hannes Pichler, Patrick Hayden, **Quantum virtual cooling**, *Phys. Rev. X* 9, 031013, doi:10.1103/PhysRevX.9.031013 (Jul 29 2019).
7. Christie S.Chiu, Geoffrey Ji, Annabelle Bohrdt, Muqing Xu, Michael Knap, Eugene Demler, Fabian Grusdt, Markus Greiner, Daniel Greif, **String patterns in the doped Hubbard model**, *Science* 365, 6450: 251-256, doi: 10.1126/science.aav3587 (Jul 19 2019)
8. Annabelle Bohrdt, Christie S. Chiu, Geoffrey Ji, Muqing Xu, Daniel Greif, Markus Greiner, Eugene Demler, **Classifying snapshots of the doped Hubbard model with machine learning**, *Nature Phys.* 15: 921-924, doi:10.1038/s41567-019-0565-x (Jul 1 2019).
9. Alexander Lukin, Matthew Rispoli, Robert Schittko, M. Eric Tai, Adam M. Kaufman, Soonwon Choi, Vedika Khemani, Julian Leonard, Markus Greiner, **Probing entanglement in a many-body-localized system**, *Science* 364, 6437: 256-260, doi:10.1126/science.aau0818 (Apr 19 2019).
10. Christie S.Chiu, Geoffrey Ji, Anton Mazurenko, D. Greif, M. Greiner, **Quantum state engineering of a Hubbard system with ultracold fermions**, *Phys. Rev. Lett.* 120, 243201, doi:10.1103/PhysRevLett.120.243201 (Jun 14 2018).
11. M. Eric Tai, Alexander Lukin, Matthew Rispoli, Robert Schittko, Tim Menke, Dan Borgnia, Philipp M. Preiss, Fabian Grusdt, Adam M. Kaufman, Markus Greiner, **Microscopy of the interacting Harper-Hofstadter model in the few-body limit**, *Nature* 546, 519-523, doi:10.1038/nature22811 (Jun 21 2017).
12. Marton Kanasz-Nagy, Izabella Lovas, Fabian Grusdt, Daniel Greif, Markus Greiner, Eugene A. Demler, **Quantum Correlations at infinite temperature: the dynamical Nagaoka effect**, *Phys. Rev. B* 96, 014303, doi:10.1103/PhysRevB.96.014303 (Jul 14 2017).
13. Anton Mazurenko, Christie S. Chiu, Geoffrey Ji, Maxwell Parsons, Marton Kanasz-Nagy, Richard Schmidt, Fabian Grusdt, Eugene Demler, Daniel Greif, Markus Greiner, **A cold-atom Fermi-Hubbard antiferromagnet**, *Nature* 545: 462-466, doi:10.1038/nature22362 (May 25 2017).
14. Maxwell F. Parsons, Anton Mazurenko, Christie S. Chiu, Geoffrey Ji, Daniel Greif, Markus Greiner, **Site-resolved measurement of the spin-correlation function in the Fermi-Hubbard model**, *Science* 353, 6305: 1253-1256, doi:10.1126/science.aag1430 (Sep 16 2016).
15. Adam M. Kaufman, M. Eric Tai, Alexander Lukin, Matthew Rispoli, Robert Schittko, Philipp M. Preiss, Markus Greiner, **Quantum thermalization through entanglement in an isolated many-body system**, *Science* 353, 6301: 794-800, doi:10.1126/science.aaf6725 (Aug 16 2016).
16. Philip Zupancic, Philipp M. Preiss, Ruichao Ma, Alexander Lukin, M. Eric Tai, Matthew Rispoli, Rajibul Islam, Markus Greiner, **Ultra-precise holographic beam shaping for microscopic quantum control**, *Optics Express* 24, 13: 13881-13893, doi:10.1364/OE.24.013881 (Jun 15 2016).
17. Daniel Greif, Maxwell F. Parsons, Anton Mazurenko, Christie S. Chiu, Sebastian Blatt, Florian Huber, Geoffrey Ji, Markus Greiner, **Site-resolved imaging of a fermionic Mott insulator**, *Science* 351, 6276: 953-957, doi:10.1126/science.aad9041 (Feb 26 2016).

18. Rajibul Islam, Ruichao Ma, Philipp M. Preiss, M. Eric Tai, Alexander Lukin, Matthew Rispoli, Markus Greiner, **Measuring entanglement entropy in a quantum many-body system**, *Nature* 528: 77-83, doi: 10.1038/nature15750 (Dec 2 2015).
19. M.F. Parsons, F. Huber, A. Mazurenko, C.S. Chiu, W. Setiawan, K. Wooley-Brown, S. Blatt, M. Greiner, **Site-Resolved Imaging of a Fermion in 6Li in an Optical Lattice**, *Phys. Rev. Lett.* 114, 213002, doi:10.1103/PhysRevLett.114.213002 (2015).
20. S. Blatt, A. Mazurenko, M.F. Parsons, C.S. Chiu, F. Huber, M. Greiner, **Low-noise optical lattices for ultracold 6Li**, *Phys. Rev. A* 92, 021402(R), doi:10.1103/PhysRevA.92.021402 (2015).
21. P.M. Preiss, R. Ma, M.E. Tai, J. Simon, M. Greiner. **Quantum gas microscopy with spin, atom-number, and multilayer readout**, *Phys. Rev. A* 91, 041602, doi:10.1103/PhysRevA.91.041602 (2015).
22. P.M. Preiss, R. Ma, M.E. Tai, A. Lukin, M. Rispoli, P. Zupancic, Y. Lahini, R. Islam, M. Greiner, **Strongly Correlated Quantum Walks in Optical Lattices**, *Science* 347: 1229-1233, doi: 10.1126/science.1260364 (2015).

MIT – Martin Zwierlein

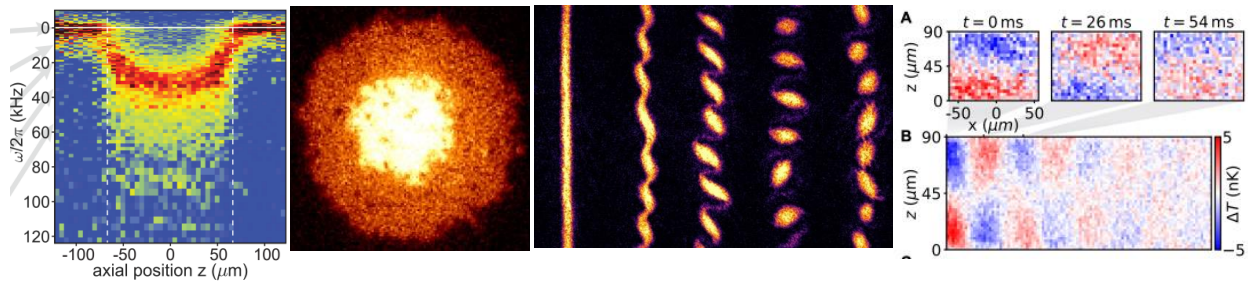


Figure 1 From left to right: Observation of Bose polarons [1], Mott and Band Insulators under the Fermi gas microscope [2], Crystallization of Bosonic Quantum Hall states [3], and observation of wave-like heat propagation, second sound, in a fermionic superfluid [4].

In the period of the MURI, the Zwierlein group has created and studied a rich variety of exotic states of matter: Strongly interacting Fermi superfluids [5, 6, 7, 8, 9, 4, 10], Fermi-Hubbard lattice gases [11, 12, 13, 14, 2, 15, 16], Bose gases under rapid rotation realizing mean-field quantum Hall states [17, 3], and strongly interacting Bose-Fermi mixtures [1] and gases of dipolar molecules [18, 19, 20, 21, 22]. In fermionic superfluids the group created solitonic excitations, from planar solitons to vortex rings and solitonic vortices [5]. In the presence of spin imbalance, these topological defects should become stabilized and yield a new state of matter, an FFLO (Fulde-Ferrell-Larkin-Ovchinnikov) magnetized superfluid state. An important step towards the observation of this elusive phase was the creation of a homogeneous box potential for Fermi gases [7]. These then allowed for unprecedented precision in measurements of the spectral response and short-range correlations in balanced [6] and spin-imbalanced Fermi gases [9]. The homogeneous gas allowed the study of universal sound propagation and diffusion [8] in these strongly interacting Fermi gases, as well as the observation of wave-like propagation of heat in the superfluid phase, second sound [4].

In work on optical lattices, the group built the first microscope for fermionic atoms [11], which was among the [10 breakthroughs of the year in physics 2015](#). The new microscope allowed the observation of Mott insulators [12], the direct measurement of spin and charge correlations in the Fermi-Hubbard model, including the first observation of the Pauli hole [13], and studies of spin transport in a fermionic Mott insulator [14]. A novel bilayer Fermi gas microscope enabled imaging the total density, directly revealing doublon-hole correlations and providing a direct way of thermometry via the fluctuation-dissipation theorem [2]. Fermion pairs under this microscope were found to realize excellent qubits, using their relative and center-of-mass motion as qubit states [15]. Via spin-resolved microscopy, the group directly observed non-local fermion pairing in the attractive Hubbard model [16], an intriguing starting point for investigation of competing superfluid and charge-density-wave order, pseudo-gap phases, and non-Fermi liquid behavior.

The group realized chemically stable fermionic molecules ($^{23}\text{Na}^{40}\text{K}$) [18, 19] which has since become a work-horse in the quest to realize strongly interacting dipolar molecules. The molecules feature second-long spin coherence times [20] and their interactions can be tuned

into resonance via microwave dressing [21, 22, 23]. This raises the hopes that a stable, strongly interacting gas of dipolar molecules can be created, enabling the exploration of novel regimes such as topological superfluidity. The Bose-Fermi mixture (Na-K) itself turned out to also host intriguing quasi-particles, Bose polarons, which for strong interactions feature “Planckian” scattering rates given by temperature divided by Planck’s constant [1]. The further exploration of these strongly interacting Bose-Fermi mixtures promises exciting discoveries such as boson-induced superfluidity and supersolid phases.

A novel route towards quantum Hall physics was developed using rapidly rotating Bose-Einstein condensates, brought into the lowest Landau level by a technique called “geometric squeezing” [17]. These “Landau gauge condensates” enabled to study the fate of interacting quantum matter in “flat land”, under the sole influence of an effective magnetic field. An intriguing instability towards crystallization was observed [3], and shown to be the quantum analogue of a classical Kelvin-Helmholtz instability. In future studies, the group will explore chiral edge states of bosons and hopes to bring the gas into the regime of fractional quantum Hall physics.

Bibliography

- [1] Z. Z. Yan, Y. Ni, C. Robens and M. W. Zwierlein, "Bose polarons near quantum criticality," *Science*, vol. 368, no. 6487, p. 190, 04 2020.
- [2] T. Hartke, B. Oreg, N. Jia and M. Zwierlein, "Doublon-Hole Correlations and Fluctuation Thermometry in a Fermi-Hubbard Gas," *Phys. Rev. Lett.*, vol. 125, p. 113601, Sep 2020.
- [3] B. Mukherjee, A. Shaffer, P. B. Patel, Z. Yan, C. C. Wilson, V. Crépel, R. J. Fletcher and M. Zwierlein, "Crystallization of bosonic quantum Hall states in a rotating quantum gas," *Nature*, vol. 601, no. 7891, pp. 58--62, 2022.
- [4] Z. Yan, P. B. Patel, B. Mukherjee, C. J. Vale, R. J. Fletcher and M. Zwierlein, "Thermography of the superfluid transition in a strongly interacting Fermi gas," *arxiv:2212.13752*, 2022.
- [5] M. J. H. Ku, B. Mukherjee, T. Yefsah and M. W. Zwierlein, "Cascade of Solitonic Excitations in a Superfluid Fermi gas: From Planar Solitons to Vortex Rings and Lines," *Physical Review Letters*, vol. 116, no. 4, p. 045304, jan 2016.
- [6] B. Mukherjee, P. B. Patel, Z. Yan, R. J. Fletcher, J. Struck and M. W. Zwierlein, "Spectral Response and Contact of the Unitary Fermi Gas," *Physical Review Letters*, vol. 122, no. 20, p. 203402, may 2019.
- [7] B. Mukherjee, Z. Yan, P. B. Patel, Z. Hadzibabic, T. Yefsah, J. Struck and M. W. Zwierlein, "Homogeneous Atomic Fermi Gases," *Physical Review Letters*, vol. 118, no. 12, 2017.
- [8] P. B. Patel, Z. Yan, B. Mukherjee, R. J. Fletcher, J. Struck and M. W. Zwierlein, "Universal sound diffusion in a strongly interacting Fermi gas," *Science*, vol. 370, no. 6521, pp. 1222--1226, 2020.
- [9] Z. Yan, P. B. Patel, B. Mukherjee, R. J. Fletcher, J. Struck and M. W. Zwierlein, "Boiling a Unitary Fermi Liquid," *Physical Review Letters*, vol. 122, no. 9, mar 2019.

- [10] M. Zwierlein, "Thermodynamics of strongly interacting Fermi gases," *Proceedings of the International School of Physics "Enrico Fermi"2*, pp. 143--220, 2016.
- [11] L. W. Cheuk, M. A. Nichols, M. Okan, T. Gersdorf, V. V. Ramasesh, W. S. Bakr, T. Lompe and M. W. Zwierlein, "Quantum-Gas Microscope for Fermionic Atoms," *Physical Review Letters*, vol. 114, no. 19, p. 193001, 2015.
- [12] L. W. Cheuk, M. A. Nichols, K. R. Lawrence, M. Okan, H. Zhang and M. W. Zwierlein, "Observation of 2D Fermionic Mott Insulators of 40K with Single-Site Resolution," *Physical Review Letters*, vol. 116, no. 23, p. 235301, jun 2016.
- [13] L. W. Cheuk, M. A. Nichols, K. R. Lawrence, M. Okan, H. Zhang, E. Khatami, N. Trivedi, T. Paiva, M. Rigol and M. W. Zwierlein, "Observation of spatial charge and spin correlations in the 2D Fermi-Hubbard model," *Science*, vol. 353, no. 6305, pp. 1260--1264, sep 2016.
- [14] M. A. Nichols, L. W. Cheuk, M. Okan, T. R. Hartke, E. Mendez, T. Senthil, E. Khatami, H. Zhang and M. W. Zwierlein, "Spin transport in a Mott insulator of ultracold fermions," *Science*, vol. 363, no. 6425, pp. 383--387, jan 2019.
- [15] T. Hartke, B. Oreg, N. Jia and M. Zwierlein, "Quantum register of fermion pairs," *Nature*, vol. 601, no. 7894, pp. 537--541, 2022.
- [16] T. Hartke, B. Oreg, C. Turnbaugh, N. Jia and M. Zwierlein, "Direct observation of non-local fermion pairing in an attractive Fermi-Hubbard gas," *arxiv:2208.05948*, 2022.
- [17] R. J. Fletcher, A. Shaffer, C. C. Wilson, P. B. Patel, Z. Yan, V. Crépel, B. Mukherjee and M. W. Zwierlein, "Geometric squeezing into the lowest Landau level," *Science*, vol. 372, no. 6548, pp. 1318--1322, 2021.
- [18] J. W. Park, S. A. Will and M. W. Zwierlein, "Ultracold Dipolar Gas of Fermionic $^{23}\text{Na}^{40}\text{K}$ Molecules in Their Absolute Ground State," *Physical Review Letters*, vol. 114, no. 20, p. 205302, 2015.
- [19] J. W. Park, S. A. Will and M. W. Zwierlein, "Two-photon pathway to ultracold ground state molecules of $^{23}\text{Na}^{40}\text{K}$," *New Journal of Physics*, vol. 17, no. 7, p. 075016, jul 2015.
- [20] J. W. Park, Z. Z. Yan, H. Loh, S. A. Will and M. W. Zwierlein, "Second-scale nuclear spin coherence time of ultracold $^{23}\text{Na}^{40}\text{K}$ molecules," *Science*, vol. 357, no. 6349, pp. 372--375, jul 2017.
- [21] S. A. Will, J. W. Park, Z. Z. Yan, H. Loh and M. W. Zwierlein, "Coherent Microwave Control of Ultracold $^{23}\text{Na}^{40}\text{K}$ Molecules," *Physical Review Letters*, vol. 116, no. 22, p. 225306, jun 2016.
- [22] Z. Z. Yan, J. W. Park, Y. Ni, H. Loh, S. Will, T. Karman and M. Zwierlein, "Resonant Dipolar Collisions of Ultracold Molecules Induced by Microwave Dressing," *Phys. Rev. Lett.*, vol. 125, p. 063401, Aug 2020.
- [23] T. Karman, Z. Z. Yan and M. Zwierlein, "Resonant and first-order dipolar interactions between ultracold molecules in static and microwave electric fields," *Phys. Rev. A*, vol. 105, no. 1, jan 2022.
- [24] T. Rvachov, H. Son, J. Park, S. Ebadi, M. Zwierlein, W. Ketterle and A. Jamison, "Two-photon spectroscopy of the NaLi triplet ground state," *Physical Chemistry Chemical Physics*, vol. 20, no. 7, 2018.

- [25] E. Altman, K. R. Brown, G. Carleo, L. D. Carr, E. Demler, C. Chin, B. DeMarco, S. E. Economou, M. A. Eriksson, K.-M. C. Fu, M. Greiner, K. R. Hazzard, R. G. Hulet, A. J. Kollmar, B. L. Lev, M. D. Lukin, R. Ma, X. Mi, S. Misra, C. Monroe, K. Murch, Z. Nazario, K.-K. Ni, A. C. Potter, P. Roushan, M. Saffman, M. Schleier-Smith, I. Siddiqi, R. Simmonds, M. Singh, I. Spielman, K. Temme, D. S. Weiss, J. Vuckovic, V. Vuletic, J. Ye and M. Zwierlein, "Quantum Simulators: Architectures and Opportunities," *PRX Quantum*, vol. 2, p. 017003, Feb 2021.
- [26] A. Christianen, M. W. Zwierlein, G. C. Groenenboom and T. Karman, "Photoinduced Two-Body Loss of Ultracold Molecules," *Physical Review Letters*, vol. 123, no. 12, may 2019.
- [27] R. J. Fletcher, R. Lopes, J. Man, N. Navon, R. P. Smith, M. W. Zwierlein and Z. Hadzibabic, "Two- and three-body contacts in the unitary Bose gas," *Science*, vol. 355, no. 6323, pp. 377--380, 2017.
- [28] T. Rvachov, H. Son, J. Park, P. Notz, T. Wang, M. Zwierlein, W. Ketterle and A. Jamison, "Photoassociation of ultracold NaLi," *Physical Chemistry Chemical Physics*, vol. 20, no. 7, 2018.
- [29] T. M. Rvachov, H. Son, A. T. Sommer, S. Ebadi, J. J. Park, M. W. Zwierlein, W. Ketterle and A. O. Jamison, "Long-Lived Ultracold Molecules with Electric and Magnetic Dipole Moments," *Physical Review Letters*, vol. 119, no. 14, p. 143001, oct 2017.

MIT – Wolfgang Ketterle

The main activities in the Ketterle group were:

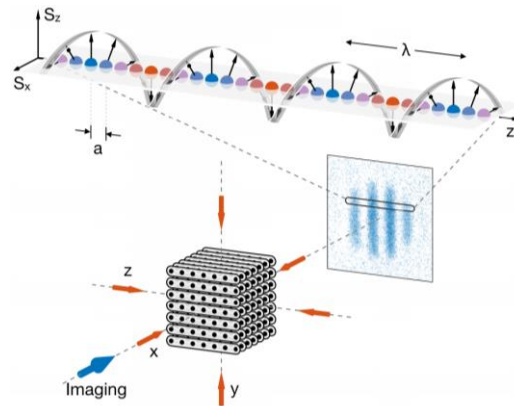
- Realization of new forms of matter --- the most important results were Bose-Einstein condensation in synthetic magnetic fields, and the first realization of a supersolid.
- Spin physics in optical lattices. The most important result was the study of spin dynamics for anisotropic Heisenberg models.

In the following, we are highlighting the two most important results, and provide a full list of publications during the funding period.

1. Simulation of the Anisotropic Spin-1/2 Heisenberg Model

N. Jepsen, J. Amato-Grill, I. Dimitrova, W.W. Ho, E. Demler, and W. Ketterle, *Spin transport in a tunable Heisenberg model realized with ultracold atoms*, Nature 403–407 (2020), <https://doi.org/10.1038/s41586-020-3033-y>

Simple models of interacting spins play an important role in physics. They capture the properties of many magnetic materials, but also extend to other systems, such as bosons and fermions in a lattice, systems with gauge fields, high- T_c superconductors, and systems with exotic particles such as anyons and Majorana fermions. In order to study and compare these models, a versatile platform is needed. Realizing such a system has been a long-standing goal in the field of ultracold atoms. So far, spin transport has only been studied in the isotropic Heisenberg model. Here we implement the Heisenberg XXZ model with adjustable anisotropy and use this system to study spin transport far from equilibrium after quantum quenches from imprinted spin helix patterns (see figure).



Creation of a spin helix state, realized from two hyperfine states (spin $|\uparrow\rangle$ and $|\downarrow\rangle$). The spin S winds within the S_z - S_x -plane as a function of position z in the spin chain. Deep optical lattices along x and y create an array of independent spin chains. The z -lattice is shallower and controls spin transport along each chain.

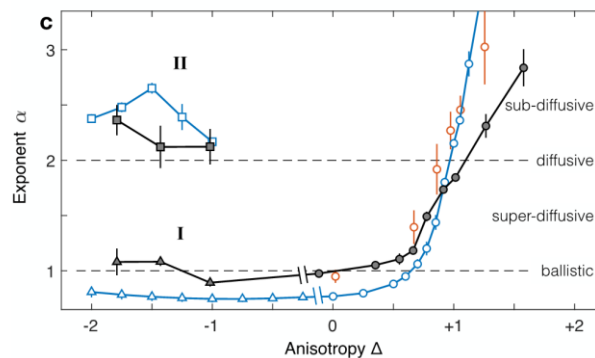
All work with ultracold atoms has addressed the isotropic Heisenberg model where $J_x=J_y=J_z$ in the spin-spin interactions between atoms on neighboring sides:

$$\mathcal{H} = \sum_{i,j} J_x S_i^x S_j^x + J_y S_i^y S_j^y + J_z S_i^z S_j^z$$

Using lithium-7 and Feshbach resonances, we were able to realize the Heisenberg model with widely tunable interaction parameters, and in particular, study spin physics over the whole range

of anisotropies $\Delta=J_z/J_{x,y}$. For $\Delta=1$, we retrieve the isotropic Heisenberg model. For $\Delta=0$, we realize the so-called XX-model which is a special starting point for investigations since it is exactly solvable in one dimension by mapping the spins to non-interacting fermions.

An important question is how the relaxation time depends on the spatial period of the spin pattern. A quadratic dependence implies diffusive transport, whereas a linear dependence characterizes ballistic transport. For anisotropy $\Delta=0$, we observe ballistic transport. When the anisotropy is increased a crossover to diffusive transport occurs. For positive anisotropies, the dynamics ranges from anomalous super-diffusion to sub-diffusion depending on anisotropy, whereas for negative anisotropies, we observe a crossover in the time domain from ballistic to diffusive transport. This behavior contrasts with expectations for the linear response regime and raises new questions in understanding quantum many-body dynamics far away from equilibrium.



Different regimes of spin transport depending on the anisotropy Δ of the Heisenberg model. The exponent in the spin transport time increases smoothly from ballistic (red) to super-diffusive (yellow) to diffusive (blue) to sub-diffusive (green). For $\Delta < 0$ we observe behavior reminiscent of a classical gas: Transport is ballistic at (I) short times (triangles) and diffusive at (II) longer times (squares).

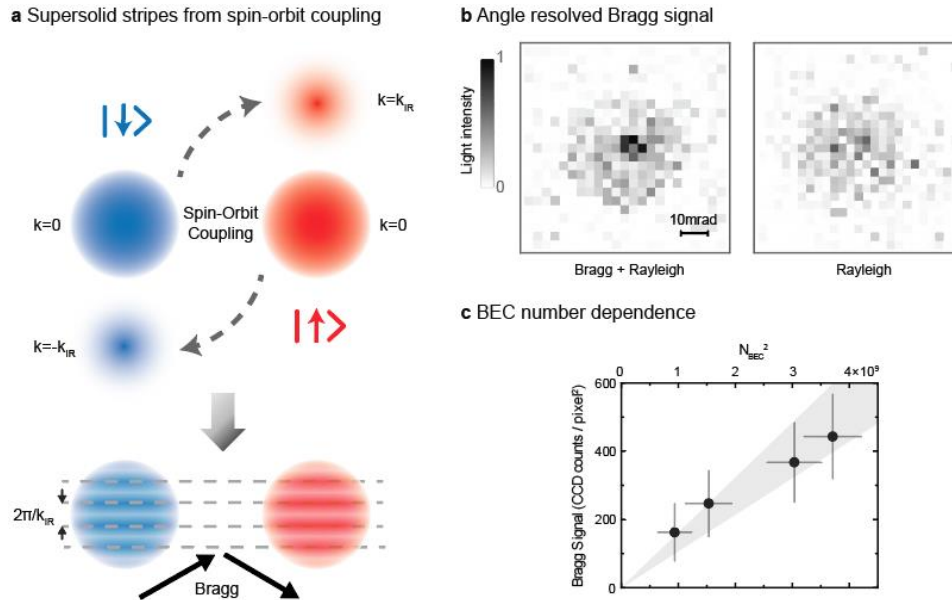
Observation of the supersolid stripe phase in spin-orbit coupled Bose-Einstein condensates

J. Li, J. Lee, W. Huang, S. Burchesky, B. Shteynas, F.C. Top, A.O. Jamison, and W. Ketterle, *Observation of the supersolid stripe phase in spin-orbit coupled Bose-Einstein condensates*, Nature **543**, 91 (2017), <https://doi.org/10.1038/nature21431>

A supersolid is an unusual form of matter which combines the property of superfluid flow with the long-range spatial periodicity of solids. Though long predicted, the observation in solid helium has been elusive. The concept of supersolidity was generalized to include other superfluid systems which break the translational symmetry of space. One candidate has been a Bose-Einstein condensate with spin-orbit coupling where the stripe phase features a density modulation.

We recently reported the first observation of this modulated density. For this, we used a novel spin-orbit coupling scheme developed in our previous work [J. Li *et al.* Phys. Rev. Lett. 117, 185301] where the two pseudospins are the two lowest states in a lattice of double wells (superlattice). The new scheme allowed us to not only increase the contrast of the stripes but also gave us a background free signal. The associated density modulation was probed with Bragg

scattering. The main results are shown in the figure below: we observed a specular Bragg enhanced reflection along the direction satisfying the Bragg condition for the predicted periodicity of the stripes when spin-orbit coupling was present. The angular width and the strength of the Bragg reflection signal implied long-range coherence in the system. This work establishes a system with unique continuous symmetry breaking properties and associated Goldstone mode and superfluid behaviour.



Origin of supersolid stripes and detection via Bragg scattering. **a**, Spin-orbit coupling adds momentum components, $+\hbar k_{IR}$ or $-\hbar k_{IR}$ of the opposite spin state to the spin up and spin down Bose Einstein condensates (top panel: spin states in momentum space). Matter wave interference leads to a spatial density modulation of period $2\pi/k_{IR}$ (bottom panel: spin states in real space). The spatial periodicity can be directly probed by Bragg scattering. **b**, Detection of the supersolid stripe phase by angle resolved light scattering. A sharp specular feature in the left panel is the Bragg signal due to the periodic density modulation. The diffuse signal is Rayleigh scattering filling the round aperture of the imaging system. Without spin-orbit coupling, only Rayleigh scattering is observed (right panel). **c**, Bragg signal versus the BEC number. Shown is the count rate integrated over the Bragg peak. The grey wedge is the theoretical prediction without any adjustable parameters, assuming full phase coherence of the stripes implying a quadratic dependence on BEC number.

1. P.N. Jepsen, J. Amato-Grill, I. Dimitrova, W.W. Ho, E. Demler, and W. Ketterle: *Spin transport in a tunable Heisenberg model realized with ultracold atoms*. Nature **588**, 403–407 (2020), <https://doi.org/10.1038/s41586-020-3033-y>
2. A. Venegas-Gomez, J. Schachenmayer, A.S. Buyskikh, W. Ketterle, M.L. Chiofalo, and A. J. Daley: *Adiabatic preparation of entangled, magnetically ordered states with cold bosons in optical lattices*. Quantum Sci. Technol. **5**, 045013 (2020), <https://dx.doi.org/10.1088/2058-9565/abb004>
3. A. Venegas-Gomez, A.S Buyskikh, J. Schachenmayer, W. Ketterle, and A.J. Daley: *Dynamics of rotated spin states and magnetic ordering with two-component bosonic atoms in optical lattices*. Phys. Rev. A **102**, 023321 (2020), <https://doi.org/10.1103/PhysRevA.102.023321>

4. T. Secker, J. Amato-Grill, W. Ketterle, and S. Kokkelmans:
High-precision analysis of Feshbach resonances in a Mott insulator.
Phys. Rev. A **101**, 04270 (2020), <https://doi.org/10.1103/PhysRevA.101.042703>
5. F. Scazza, G. Valtolina, A. Amico, P. E. S. Tavares, M. Inguscio, W. Ketterle, G. Roati, and M. Zaccanti:
Exploring emergent heterogeneous phases in strongly repulsive Fermi gases.
Phys. Rev. A **101**, 013603 (2020), <https://doi.org/10.1103/PhysRevA.101.013603>
6. I. Dimitrova, N. Jepsen, A. Buyskikh, A. Venegas-Gomez, J. Amato-Grill, A. Daley, and W. Ketterle:
Enhanced Superexchange in a Tilted Mott Insulator.
Phys. Rev. Lett. **124**, 043204 (2020), <https://doi.org/10.1103/PhysRevLett.124.043204>
7. J.-R. Li, B. Shteynas, and W. Ketterle:
Floquet Heating in Interacting Atomic Gases with an Oscillating Force.
Phys. Rev. A **100**, 033406 (2019), <https://doi.org/10.1103/PhysRevA.100.033406>
8. J. Amato-Grill, N. Jepsen, I. Dimitrova, W. Lunden, and W. Ketterle:
Interaction Spectroscopy of a Two-component Mott Insulator.
Phys. Rev. A **99**, 033612 (2019), <https://doi.org/10.1103/PhysRevA.99.033612>
9. B. Shteynas, J. Lee, F.C. Top, J.-R. Li, A.O. Jamison, G. Juzeliunas, and W. Ketterle:
How to dress radio-frequency photons with tunable momentum.
Phys. Rev. Lett. **123**, 033203 (2019), <https://doi.org/10.1103/PhysRevLett.123.033203>
10. A. Amico, F. Scazza, G. Valtolina, P. E. S. Tavares, W. Ketterle, M. Inguscio, G. Roati, and M. Zaccanti:
Time-Resolved Observation of Competing Attractive and Repulsive Short-Range Correlations in Strongly Interacting Fermi Gases.
Phys. Rev. Lett. **121**, 253602 (2018), <https://doi.org/10.1103/PhysRevLett.121.253602>
11. I. Dimitrova, W. Lunden, J. Amato-Grill, N. Jepsen, Y. Yu, M. Messer, T. Rigaldo, G. Puentes, D. Weld, and W. Ketterle:
Observation of two-beam collective scattering phenomena in a Bose-Einstein condensate.
Phys. Rev. A **96**, 051603(R) (2017), <https://doi.org/10.1103/PhysRevA.96.051603>
12. J. Li, J. Lee, W. Huang, S. Burchesky, B. Shteynas, F.C. Top, A.O. Jamison, and W. Ketterle:
Observation of the supersolid stripe phase in spin-orbit coupled Bose-Einstein condensates.
Nature **543**, 91 (2017), <https://doi.org/10.1038/nature21431>
13. W.C. Burton, C.J. Kennedy, W.C. Chung, S. Vadia, W. Chen, and W. Ketterle:
Coherence Times of Bose-Einstein Condensates beyond the Shot-Noise Limit via Superfluid Shielding.
Phys. Rev. Lett. **117**, 275301 (2016), <https://doi.org/10.1103/PhysRevLett.117.275301>
14. J. Li, W. Huang, B. Shteynas, S. Burchesky, F.C. Top, E. Su, J. Lee, A.O. Jamison, and W. Ketterle:
Spin-Orbit Coupling and Spin Textures in Optical Superlattices.
Phys. Rev. Lett. **117**, 185301 (2016), <https://doi.org/10.1103/PhysRevLett.117.185301>
15. C.J. Kennedy, W.C. Burton, W.C. Chung, and W. Ketterle:
Observation of Bose-Einstein Condensation in a Strong Synthetic Magnetic Field.
Nature Physics **11**, 859–864 (2015), <http://dx.doi.org/10.1038/nphys3421>
16. J. Schachenmayer, D.M. Weld, H. Miyake, G.A. Siviloglou, W. Ketterle, and A.J. Daley:
Adiabatic cooling of bosons in lattices to magnetically-ordered quantum states.
Phys. Rev. A **92**, 041602(R) (2015), <http://link.aps.org/doi/10.1103/PhysRevA.92.041602>

17. T. Dubček, C.J. Kennedy, L. Lu, W. Ketterle, M. Soljačić, and H. Buljan:
Weyl points in three-dimensional optical lattices: synthetic magnetic monopoles in momentum space.
Phys. Rev. Lett. **114**, 225301 (2015), <http://link.aps.org/doi/10.1103/PhysRevLett.114.225301>
18. H. Veksler, S. Fishman, and W. Ketterle:
A simple model for interactions and corrections to the Gross-Pitaevskii Equation.
Phys. Rev. A **90**, 023620 (2014), <http://link.aps.org/doi/10.1103/PhysRevA.90.023620>

Berkeley – Dan Stamper-Kurn

Berkeley effort within the MIT-led MURI project on
“Advanced quantum materials – a new frontier for ultracold atoms”

Geometric frustration describes a complex system within which energy constraints, which are established by the connectivity and geometric proximity of interacting objects, cannot all be satisfied simultaneously. In quantum systems geometric frustration is a route for creating many-body quantum systems that are prevented from adopting simple (trivial) forms of order at low temperature; rather, they may adopt entangled phases of matter. The Berkeley effort within our MURI project focused on the behavior of atoms in geometrically frustrated, two dimensional triangular lattices, generated using an optical superlattice approach first pioneered in Ref. [1] and extended greatly during the MURI project.

Experiments were performed in three different triangular-lattice setups. First, as described in Ref. [2], we developed the use of matter wave diffraction to characterize a two-dimensional honeycomb lattice – a non-primitive triangular lattice with two sites in the unit cell. We were looking specifically for a weak spatial inversion asymmetry that is introduced into a honeycomb optical lattice through the vector ac Stark effect. We showed that one could tune the interaction time between the optical lattice and coherent matter waves so that the percent-level potential asymmetry could produce $O(1)$ modifications in a matter-wave diffraction pattern.

Second, we performed a quantum simulation to test a scaling hypothesis for the Bose-Hubbard phase diagram, namely that the properties of a gas in two dissimilar lattices are identical so long as the ratio of interaction to tunneling energy (U/J) is scaled the lattice coordination number z . This hypothesis derives from mean-field theory, but need not apply precisely when considering beyond-mean-field effects, which are particularly pronounced in two dimensions. Our two-dimensional quantum simulation compared Bose gases in triangular ($z = 6$) and kagome ($z = 4$) lattices. Somewhat to our surprise, our data were consistent with the scaling hypothesis [3].

Third, we demonstrated the use of an optical superlattice to generate a new lattice geometry for quantum simulation. Specifically, we constructed a trimerized kagome lattice, one in which inversion symmetry is broken in that triangular plaquettes of the kagome lattice with one orientation are more strongly coordinated than those of the opposite orientation. This trimierized (or breathing) kagome lattice is an important theoretical construct in the study of spin-liquid magnetic states in the kagome antiferromagnet. We placed strongly interacting bosons in this lattice, and probed the short and long-range spatial coherence of the gas. We observed the persistence of short-range coherence even deep in the Mott insulating regime, and, using an interferometric approach, ascribed that coherence to the strongly coordinated plaquettes within the lattice [4].

Fourth, we measured the group velocity of a quantum gas that was placed within an excited band of the kagome lattice. Specifically, geometric frustration causes the third (s -orbital) band of the kagome lattice to be flat, reflecting the frustration of particle motion. In such a flat band, the group velocity, being proportional to the gradient of the band energy with quasimomentum, should be zero. We measured this group velocity by detecting the velocity distribution of a Bose-Einstein condensate excited to a Bloch state with this band; the average of this distribution is exactly the group velocity. We found this velocity to be far from zero, and significantly different than that expected based on single-particle band-

structure calculation. Through simulation and experiment, we confirmed this enhancement of the group velocity to be caused by interaction-driven band-structure renormalization [5].

Our collaboration within the MURI team produced also two important theoretical works. In one, we developed the concepts of quantum chaos, fast scrambling and the out-of-time-ordered-correlation function. We discussed in particular how this function could be measured by interfering two many-body systems, providing a direct measure of information scrambling [6]. In a second important work, inspired by the realization of lattice-trapped dipolar molecules by members of our MURI team, we considered a new model for quantum magnetism in which antiferromagnetic interactions extend in strength across a lattice according to a power-law fall-off with distance. We showed that this natural model (i.e. not requiring fine tuning) robustly yields spin liquid states in both triangular and kagome geometries. We are pleased that this work has inspired further work not only in the area of quantum simulation and ultracold AMO physics, but also in solid-state systems [7].

Publications:

- Tsz-Him Leung, Malte N. Schwarz, Shao-Wen Chang, Charles D. Brown, Govind Unnikrishnan, and Dan M. Stamper-Kurn. “Interaction-Enhanced Group Velocity of Bosons in the Flat Band of an Optical Kagome Lattice,” *Physical Review Letters* **125**, 133001 (2020).
- Thomas H. Barter, Tsz-Him Leung, Masayuki Okano, Maxwell Block, Norman Y. Yao, and Dan M. Stamper-Kurn, “Spatial Coherence of a Strongly Interacting Bose Gas in the Trimerized Kagome Lattice,” *Physical Review A* **101**, 011601 (2020)
- Norman Y. Yao, Michael P. Zaletel, Dan M. Stamper-Kurn, and Ashvin Vishwanath, “A Quantum Dipolar Spin Liquid,” *Nature Physics* **14**, 405 (2018).
- Claire K. Thomas, Thomas H. Barter, Tsz-Him Leung, Masayuki Okano, Gyu-Boong Jo, Jennie Guzman, Itamar Kimchi, Ashvin Vishwanath, and Dan M. Stamper-Kurn, “Mean-field scaling of the superfluid to Mott insulator transition in a two-dimensional optical superlattice,” *Physical Review Letters* **119**, 100402 (2017)
- C. K. Thomas, T. H. Barter, T.-H. Leung, S. Daiss, D. M. Stamper-Kurn, “Signatures of spatial inversion asymmetry of an optical lattice observed in matter-wave diffraction,” *Physical Review A* **93**, 063613 (2016)
- Norman Y. Yao, Fabian Grusdt, Brian Swingle, Mikhail D. Lukin, Dan M. Stamper-Kurn, Joel E. Moore, and Eugene A. Demler, “Interferometric Approach to Probing Fast Scrambling,” preprint arxiv:1607.01801 (2016)

References

- [1] Jo, G.-B., et al., *Ultracold Atoms in a Tunable Optical Kagome Lattice*. *Physical Review Letters*, 2012. **108**(4): p. 045305.
- [2] Thomas, C.K., et al., *Signatures of spatial inversion asymmetry of an optical lattice observed in matter-wave diffraction*. *Physical Review A*, 2016. **93**: p. 063613.
- [3] Thomas, C.K., et al., *Mean-Field Scaling of the Superfluid to Mott Insulator Transition in a 2D Optical Superlattice*. *Physical Review Letters*, 2017. **119**(10): p. 100402.
- [4] Barter, T.H., et al., *Spatial Coherence of a Strongly Interacting Bose Gas in the Trimerized Kagome Lattice*. 2019.
- [5] Leung, T.-H., et al., *Interaction-Enhanced Group Velocity of Bosons in the Flat Band of an Optical Kagome Lattice*. *Physical Review Letters*, 2020. **125**(13): p. 133001.

- [6] Yao, N.Y., et al., *Interferometric Approach to Probing Fast Scrambling*. 2016.
- [7] Yao, N.Y., et al., *A quantum dipolar spin liquid*. *Nature Physics*, 2018. **14**(4): p. 405-410.

University of Maryland – Ian Spielman

The University of Maryland / Joint Quantum Institute team made numerous advances during the Feb. 2014 to March 2021 funding period of the AFOSR MURI “**Advanced quantum materials – a new frontier for ultracold atoms.**” These ranged in nature from fundamental experiment and results to more technical outcomes.

For example, the work period lead-off with our 2015 realization of a 3-site wide quantum-Hall strip constructed using synthetic dimensions. That same line of research delivered a tube geometry 2021 that featured a quasi-disorder induced suppression of decoherence. Similarly in 2016 we proposed a new technique for creating Rashba-type spin orbit coupling in atomic BECs and published the experimental realization in 2021.

Throughout the program we have published theoretical results including new techniques for engineering ultracold atom quantum materials, as well studying the resulting many body physics. Examples include new ways to create topological lattices controlled by frequency combs, to detecting topological p -wave superfluid by quenching between phases.

On the technical front we imported the concept of dynamical decoupling from quantum information in order to eliminate the impact of magnetic field noise on otherwise field-sensitive transitions. Further we devoted effort in describing techniques to correct for imaging aberrations. Lastly we showed the effectiveness of using Fourier transform spectroscopy in describing the excitation spectra of cold atom quantum materials.

Graduate Students involved: 12

Undergraduate Students supported: 4

References

1. *Wilson loop and Wilczek-Zee phase from a non-Abelian gauge field*; S. Sugawa, F. Salces-Carcoba, Y. Yue, A. Putra, and I. B. Spielman; npj Quantum Information **7** 144 (2021). doi:10.1038/s41534-021-00483-2
2. *Multiple-camera defocus imaging of ultracold atomic gases*; A. R. Perry, S. Sugawa, F. Salces-Carcoba, Y. Yue, and I. B. Spielman; Opt. Express **29** 17029--17041 (2021). doi: 10.1364/OE.422981 **Featured as an Editors' pick in Optics Express.**
3. *Coherence and decoherence in the Harper-Hofstadter model*; Q.-Y. Liang, D. Trypogeorgos, A. Valdés-Curiel, J. Tao, M. Zhao, and I. B. Spielman; Phys. Rev. Research **3** 023058 (2021). doi:10.1103/PhysRevResearch.3.023058
4. *Topological features without a lattice in Rashba spin-orbit coupled atoms*; A. Valdés-Curiel, D. Trypogeorgos, Q.-Y. Liang, R. P. Anderson, and I. B. Spielman; Nature Communications **12** 593 (2021). doi:10.1038/s41467-020-20762-4
5. *Feedback induced magnetic phases in binary Bose-Einstein condensates*; H. M. Hurst, S. Guo, and I. B. Spielman; Phys. Rev. Research **2** 043325 (2020). doi:10.1103/PhysRevResearch.2.043325
6. *Enhanced transport of spin-orbit-coupled Bose gases in disordered potentials*; Y. Yue, C.

- A. R. Sá de Melo, and I. B. Spielman; Phys. Rev. A **102** 033325 (2020).
doi:10.1103/PhysRevA.102.033325
7. *Creating solitons with controllable and near-zero velocity in Bose-Einstein condensates*; A. R. Fritsch, M. Lu, G. H. Reid, A. M. Piñero, and I. B. Spielman; Phys. Rev. A **101** 053629 (2020). doi:10.1103/PhysRevA.101.053629 **Featured as an Editors' selection in Phys. Rev. A. Written up in Physics.**
 8. *Realization of a deeply subwavelength adiabatic optical lattice*; R. P. Anderson, D. Trypogeorgos, A. Valdés-Curiel, Q.-Y. Liang, J. Tao, M. Zhao, T. Andrijauskas, G. Juzeliūnas, and I. B. Spielman; Phys. Rev. Research **2** 013149 (2020).
doi:10.1103/PhysRevResearch.2.013149
 9. *Spatial Coherence of Spin-Orbit-Coupled Bose Gases*; A. Putra, F. Salces-Cárcoba, Y. Yue, S. Sugawa, and I. B. Spielman; Phys. Rev. Lett. **124** 053605 (2020).
doi:10.1103/PhysRevLett.124.053605
 10. *Repeated measurements with minimally destructive partial-transfer absorption imaging*; E. M. Seroka, A. Valdés-Curiel, D. Trypogeorgos, N. Lundblad, and I. B. Spielman; Opt. Express **27** 36611--36624 (2019). doi:10.1364/OE.27.036611
 11. *Sauter-Schwinger effect with a quantum gas*; A. M. Piñero, D. Genkina, M. Lu, and I. B. Spielman; New Journal of Physics **21** 083035 (2019). doi:10.1088/1367-2630/ab3840
 12. *Emergent gauge field and the Lifshitz transition of spin-orbit coupled bosons in one dimension*; W. S. Cole, J. Lee, K. W. Mahmud, Y. Alavirad, I. B. Spielman, and J. D. Sau; Scientific Reports **9** 7471 (2019). doi:10.1038/s41598-019-43929-6
 13. *Measurement-induced dynamics and stabilization of spinor-condensate domain walls*; H. M. Hurst and I. B. Spielman; Phys. Rev. A **99** 053612 (2019).
doi:10.1103/PhysRevA.99.053612
 14. *Imaging topology of Hofstadter ribbons*; D. Genkina, L. M. Aycok, H.-I. Lu, M. Lu, A. M. Pineiro, and I. B. Spielman; New Journal of Physics **21** 053021 (2019).
doi:10.1088/1367-2630/ab165b
 15. *Scale-Invariant Continuous Entanglement Renormalization of a Chern Insulator*; S.-K. Chu, G. Zhu, J. R. Garrison, Z. Eldredge, A. V. Curiel, P. Bienias, I. B. Spielman, and A. V. Gorshkov; Phys. Rev. Lett. **122** 120502 (2019). doi:10.1103/PhysRevLett.122.120502
 16. *Topological bands for ultracold atoms*; N. R. Cooper, J. Dalibard, and I. B. Spielman; Rev. Mod. Phys. **91** 015005 (2019). doi:10.1103/RevModPhys.91.015005
 17. *Equations of state from individual one-dimensional Bose gases*; F. Salces-Carcoba, C. J. Billington, A. Putra, Y. Yue, S. Sugawa, and I. B. Spielman; New Journal of Physics **20** 113032 (2018). doi: 10.1088/1367-2630/aaef9b
 18. *Perpetual emulation threshold of PT-symmetric Hamiltonians*; D. Trypogeorgos, A. Valdés-Curiel, I. B. Spielman, and C. Emary; Journal of Physics A: Mathematical and Theoretical **51** 325302 (2018). doi:10.1088/1751-8121/aacc5e
 19. *Second Chern number of a quantum-simulated non-Abelian Yang monopole*; S. Sugawa, F. Salces-Carcoba, A. R. Perry, Y. Yue, and I. B. Spielman; Science **360** 1429 (2018).
doi:10.1126/science.aam9031

20. *Topological lattice using multi-frequency radiation*; T. Andrijauskas, I. B. Spielman, and G. Juzeliūnas; *New Journal of Physics* **20** 055001 (2018). doi:10.1088/1367-2630/aab7a3
21. *A rapidly expanding Bose-Einstein condensate: an expanding universe in the lab*; S. Eckel, A. Kumar, T. Jacobson, I.B. Spielman, G.K. Campbell; *Phys. Rev. X* **8** 021021 (2018). doi:10.1103/PhysRevX.8.021021
22. *Synthetic clock transitions via continuous dynamical decoupling*; D. Trypogeorgos, A. Valdés-Curiel, N. Lundblad, and I. B. Spielman; *Phys. Rev. A* **97** 013407 (2018). doi:10.1103/PhysRevA.97.013407
23. *Quantum Phases of Two-Component Bosons with Spin-Orbit Coupling in Optical Lattices*; D. Yamamoto, I. B. Spielman, C. A. R. Sá de Melo; *Phys. Rev. A* **96** 061603(R) (2017). doi:10.1103/PhysRevA.96.061603
24. *Strong-coupling phases of the spin-orbit-coupled spin-1 Bose-Hubbard chain: Odd-integer Mott lobes and helical magnetic phases*; J. H. Pixley, W. S. Cole, I. B. Spielman, M. Rizzi, and S. Das Sarma; *Phys. Rev. A* **96** 043622 (2017). doi:10.1103/PhysRevA.96.043622
25. *Kinetic theory of dark solitons with tunable friction*; H. M. Hurst, D. K. Efimkin, I. B. Spielman, and V. Galitski; *Phys. Rev. A* **95** 053604 (2017). doi:10.1103/PhysRevA.95.053604
26. *Fourier transform spectroscopy of a spin-orbit coupled Bose gas*; A. Valdés-Curiel, D. Trypogeorgos, E. E. Marshall, and I. B. Spielman; *New Journal of Physics* **19** 033025 (2017). doi:10.1088/1367-2630/aa6279
27. *Brownian motion of solitons in a Bose-Einstein condensate*; L. M. Aycok, H. M. Hurst, D. K. Efimkin, D. Genkina, H.-I. Lu, V. M. Galitski, and I. B. Spielman; *Proceedings of the National Academy of Sciences* (2017). doi:10.1073/pnas.1615004114
28. *Semisynthetic zigzag optical lattice for ultracold bosons*; E. Anisimovas, M. Račiūnas, C. Sträter, A. Eckardt, I. B. Spielman, and G. Juzeliūnas; *Phys. Rev. A* **94** 063632 (2016). doi:10.1103/PhysRevA.94.063632
29. *Real-space mean-field theory of a spin-1 Bose gas in synthetic dimensions*; H. M. Hurst, J. H. Wilson, J. H. Pixley, I. B. Spielman, and S. S. Natu; *Phys. Rev. A* **94** 063613 (2016). doi:10.1103/PhysRevA.94.063613
30. *Vortex nucleation in a Bose-Einstein condensate: from the inside out*; R. M. Price, D. Trypogeorgos, D. L. Campbell, A. Putra, A. Valdés-Curiel, and I. B. Spielman; *New Journal of Physics* **18** 113009 (2016). doi:
31. *Synthetic gauge potentials for ultracold neutral atoms*; Y.-J. Lin and I. B. Spielman; *Journal of Physics B: Atomic, Molecular and Optical Physics* **49** 183001 (2016). doi:10.1088/0953-4075/49/18/183001
32. *Geometrical Pumping with a Bose-Einstein Condensate*; H.-I. Lu, M. Schemmer, L. M. Aycok, D. Genkina, S. Sugawa, and I. B. Spielman; *Phys. Rev. Lett.* **116** 200402 (2016). doi:10.1103/PhysRevLett.116.200402
33. *Rashba realization: Raman with RF*; D. L. Campbell and I. B. Spielman; *New Journal of Physics* **18** 033035 (2016). doi:10.1088/1367-2630/18/3/033035

34. *Magnetic phases of spin-1 spin-orbit-coupled Bose gases*; D. L. Campbell, R. M. Price, A. Putra, A. Valdés-Curiel, D. Trypogeorgos, and I. B. Spielman; *Nat Commun* **7** (2016). doi: 10.1038/ncomms10897
35. *Interaction-driven exotic quantum phases in spin-orbit-coupled spin-1 bosons*; J. H. Pixley, S. S. Natu, I. B. Spielman, and S. Das Sarma; *Phys. Rev. B* **93** 081101 (2016). doi:10.1103/PhysRevB.93.081101
36. *Feshbach enhanced s-wave scattering of fermions: direct observation with optimized absorption imaging*; D. Genkina, L. M. Aycock, B. K. Stuhl, H.-I. Lu, R. A. Williams, and I. B. Spielman; *New Journal of Physics* **18** 013001 (2016). doi:10.1088/1367-2630/18/1/013001
37. *Dynamical Detection of Topological Phase Transitions in Short-Lived Atomic Systems*; F. Setiawan, K. Sengupta, I. B. Spielman, and J. D. Sau; *Phys. Rev. Lett.* **115** 190401 (2015). doi:10.1103/PhysRevLett.115.190401
38. *Visualizing edge states with an atomic Bose gas in the quantum Hall regime*; B. K. Stuhl, H.-I Lu, L. M. Aycock, D. Genkina, and I. B. Spielman; *Science* **349**, 1514–1518 (2015). doi:10.1126/science.aaa8515

Summary of activities

For bosonic systems, we (i) discovered the phenomenon of trapping collapse when weak potential traps capture an infinite number of particles with repulsive interactions, (ii) investigated striped superfluid phases in two dimensional lattice models with extended interaction range (mimicking Rydberg blockade systems), (iii) studied novel polaronic states arising from the displacement modulated hopping and prospects for supporting the bi-polaron mechanism of high-temperature superconductivity, (iv) suggested experimental protocols for observing time-crystallization in multicomponent superfluids, (v) provided further evidence for the mysterious phenomenon of quantum-to-classical correspondence in two-dimensional frustrated quantum Heisenberg models, and (vi) investigated quantum critical phenomena (Higgs modes, universal conductivity, impurity states).

For fermionic systems, we (i) investigated extended crossover from a Fermi liquid to quasi-antiferromagnet in the half-filled 2D Hubbard model in the temperature and interaction regimes of interest to ongoing experiments with ultra-cold atoms, (ii) established the phase diagram of the interacting Haldane model that plays central role in the field of topological insulators, (iii) resolved a longstanding question regarding orthogonality catastrophe in Coulomb systems; and (iv) introduced a new way of analyzing superconducting transition temperatures in systems with emergent pairing correlations.

In terms of methods, we (i) developed the Diagrammatic Monte Carlo algorithm for the resonant Fermi gas that takes full advantage of known series singularities and applied it to the equation of state of the unitary Fermi gas to provide the most accurate results for direct comparison with experiments, (ii) formulated the so-called "shifted action" and "homotopic action" schemes for strongly interacting fermions that provide a generic pathway to constructing convergent diagrammatic theories, (iii) refined numeric analytic continuation protocols.

Educational Impact

MURI program provided support for six graduate students (Kun Chen, Yuan Huang, Zhiyuan Yao, Zhongjin Zhang, Tao Wang, and Xiansheng Cai) and one postdoc (Chao Zhang). Chao Zhang has received and accepted an offer for faculty position at the East China Normal University.

Publications for reported period

1. K. Chen, L. Liu, Y. Deng, L. Pollet, and N. Prokof'ev, "Universal Conductivity in a Two-dimensional Superfluid-to-Insulator Quantum Critical System", **Phys. Rev. Lett.** **112**, 030402 (2014).
2. Z. Yao, K.P.C. da Costa, M. Kiselev, and N. Prokof'ev, "Critical Exponents of the Superfluid-Bose Glass Transition in Three-Dimensions", **Phys. Rev. Lett.** **112**, 225301 (2014); **Featured in Physics, Editors' Suggestion.**
3. A.S. Mishchenko, N. Nagaosa, and N. Prokof'ev "Diagrammatic Monte Carlo method for many-polaron problems", **Phys. Rev. Lett.** **113**, 166402 (2014).
4. J. Gukelberger, E. Kozik, L. Pollet, N. Prokof'ev, M. Sigrist, B. Svistunov, and M. Troyer, "p-wave Superfluidity by Spin-Nematic Fermi Surface Deformation", **Phys. Rev. Lett.** **113**, 195301 (2014).
5. Y. Deng, E. Kozik, N.V. Prokof'ev, and B.V. Svistunov, "Emergent BCS regime of the two-dimensional fermionic Hubbard model: ground-state phase diagram", **Euro. Phys. Lett.** **110**, 57001 (2015).
6. L. Liu, K. Chen, Y. Deng, M. Endres, L. Pollet, and N. Prokof'ev, "Massive Goldstone (Higgs) mode in two-dimensional ultracold atomic lattice systems", **Phys. Rev. B** **92**, 174521 (2015).
7. R. Rossi, F. Werner, N. Prokof'ev, and B. Svistunov, "Shifted-Action Expansion and Applicability of Dressed Diagrammatic Schemes", **Phys. Rev. B** **93**, 161102(R) (2016).

8. Z. Yao, L. Pollet, N. Prokof'ev, and B. Svistunov, "Superfluid-Insulator Transition in Strongly Disordered One-dimensional Systems", **New J. of Phys.** **18**, 045018 (2016).
9. Y. Huang, K. Chen, Y. Deng, N. Prokof'ev, and B. Svistunov, "Spin-Ice State of the Quantum Heisenberg Antiferromagnet on the Pyrochlore Lattice", **Phys. Rev. Lett.** **116**, 177203 (2016).
10. I.S. Tupitsyn, A.S. Mishchenko, N. Nagaosa, and N. Prokof'ev, "Coulomb and electron-phonon interactions in metals", **Phys. Rev. B** **94**, 155145 (2016).
11. J. Carlström, N. Prokof'ev, and B. Svistunov, "Quantum Walk in Degenerate Spin Environments", **Phys. Rev. Lett.** **116**, 247202 (2016).
12. Z. Yao, L. Pollet, N. Prokof'ev, and B. Svistunov, "Superfluid-Insulator Transition in Strongly Disordered One-dimensional Systems", **New Journal of Physics** **18**, 045018 (2016).
13. Y. Huang, K. Chen, Y. Deng, and B. V. Svistunov, "Trapping Centers at the Superfluid-Mott-insulator Criticality: Transition between Charge-quantized States", **Phys. Rev. B** **94**, 220502 (2016).
14. I. Tupitsyn, N. Prokof'ev, "Stability of Dirac Liquids with Strong Coulomb Interaction", **Phys. Rev. Lett.** **118**, 026403 (2017).
15. O. Gouliko, A.S. Mishchenko, L. Pollet, N. Prokof'ev, and B. Svistunov, "Numerical analytic continuation: Answers to well-posed questions", **Phys. Rev. B** **95**, 014102 (2017).
16. K. Van Houcke, I.S. Tupitsyn, A.S. Mishchenko, N.V. Prokof'ev, "Dielectric function and thermodynamic properties of jellium in the GW approximation", **Phys. Rev. B** **95**, 195131 (2017).
17. R. Rossi, N. Prokof'ev, B. Svistunov, K. Van Houcke, and F. Werner, "Polynomial complexity despite the fermionic sign", **Euro Phys. Lett.** **118**, 10004 (2017).
18. F. Simkovic IV., Youjin Deng, N. V. Prokof'ev, B. V. Svistunov, I. Tupitsyn, and Evgeny Kozik, "Magnetic Correlations in the Two-dimensional Repulsive Fermi-Hubbard Model", **Phys. Rev. B** **96**, 081117 (2017).
19. K. Van Houcke, F. Werner, E. Kozik, N. Prokof'ev, and B. Svistunov, "Contact and Momentum Distribution of the Unitary Fermi Gas by Bold Diagrammatic Monte Carlo", **Phys. Rev. Lett.** **121**, 130406 (2018).
20. K. Chen, N.V. Prokof'ev, and B.V. Svistunov, "Trapping collapse: Infinite number of repulsive bosons trapped by a generic short-range potential", **Phys. Rev. A** **98**, 041602(R) (2018).
21. I.S. Tupitsyn and N.V. Prokof'ev, "Orthogonality catastrophe in Coulomb systems", **Phys. Rev. B** **99**, 245122 (2019).
22. I.S. Tupitsyn, and N.V. Prokof'ev, "Phase diagram topology of the Haldane-Hubbard-Coulomb model", **Phys. Rev. B** **99**, 121113(R) (2019).
23. K. Van Houcke, F. Werner, T. Ohgoe, N. Prokof'ev, and B. Svistunov, "Diagrammatic Monte Carlo algorithm for the resonant Fermi gas", **Phys. Rev. B** **99**, 035140 (2019).
24. G. Masella, A. Angelone, F. Mezzacapo, G. Pupillo, and N.V. Prokof'ev, "Supersolid stripe crystal from finite-range interactions on a lattice", **Phys. Rev. Lett.** **123**, 045301 (2019).
25. A. Chubukov, N.V. Prokof'ev, and B.V. Svistunov, "Implicit renormalization approach to the problem of Cooper instability", **Phys. Rev. B** **100**, 064513 (2019) - Editors' Suggestion.
26. N. Prokof'ev and B. Svistunov, "Space- and time-crystallization effects in multicomponent superfluids", **Phys. Rev. B** **101**, 020505 (2020).
27. T. Wang, X. Cai, K. Chen, N.V. Prokof'ev, and B.V. Svistunov, "Quantum-to-classical correspondence in two-dimensional Heisenberg models", **Phys. Rev. B** **101**, 035132 (2020).
28. F. Simkovic, J.P.F. LeBlanc, A.J. Kim, Y. Deng, N.V. Prokof'ev, B.V. Svistunov, and E. Kozik, "Extended crossover from a Fermi liquid to quasi-antiferromagnet in the half-filled 2D Hubbard model", **Phys. Rev. Lett.** **124**, 017003 (2020).
29. A.J. Kim, N.V. Prokof'ev, B.V. Svistunov, and E. Kozik, "Homotopic Action: A Pathway to Convergent Diagrammatic Theories", **Phys. Rev. Lett.** **126**, 257001 (2021).
30. C. Zang, N.V. Prokof'ev, and B.V. Svistunov, "Peierls/Su-Schrieffer-Heeger polarons in two dimensions", **Phys. Rev. B** **104**, 035143 (2021).

University of Colorado – Ana Maria Rey and Jun Ye

Major achievements during funding period (Ye, Rey)

(I) **Alkaline earth-atoms (AEA):**

We studied an $SU(N)$ -symmetric Fermi liquid of ^{87}Sr atoms, where N can be tuned to be as large as 10. In the deeply degenerate regime, we showed through precise measurements of density fluctuations and expansion dynamics that the large N of spin states under $SU(N)$ symmetry leads to pronounced interaction effects in a system with a nominally negligible interaction parameter. Accounting for these effects, we demonstrated thermometry accurate to 1% of the Fermi energy. We also demonstrated record speed for preparing degenerate Fermi seas enabled by the $SU(N)$ -symmetric interactions, reaching $T/T_F = 0.22$ with 10 nuclear spin states in 0.6 s working with a laser-cooled sample. This, along with the introduction of a new spin polarizing method, enables the operation of a three-dimensional optical lattice clock in the band insulating regime opening unique opportunities for quantum simulation.

We investigated the role of many-body interactions in spin-orbit coupled fermionic atoms in the JILA's 1D optical lattice clock. Using clock spectroscopy, we observed the precession of the collective magnetization and the emergence of spin-locking effects arising from an interplay between p -wave and SOC-induced exchange interactions. The many-body dynamics were well captured by a collective XXZ spin model, which describes a broad class of condensed matter systems ranging from superconductors to quantum magnets.

We also studied arrays of isolated few-body systems in a fermionic ^{87}Sr three-dimensional (3D) optical lattice clock and used high resolution clock spectroscopy to directly observe the onset of both elastic and inelastic multi-body interactions. These interactions cannot be broken down into sums over the underlying pairwise interactions. We measured particle-number-dependent frequency shifts of the clock transition for atom numbers n ranging from 1 to 5, and observed nonlinear interaction shifts, which are characteristic of $SU(N)$ -symmetric elastic multi-body effects. To study inelastic multi-body effects, we used these frequency shifts to isolate n -occupied sites and measured the corresponding lifetimes. This allowed us to access the short-range few-body physics free from systematic effects encountered in a bulk gas.

We proposed how to realize novel many-body states relevant for quantum simulation and quantum computing using the interplay between spin orbit coupling and interactions. They include topological superfluids, Cluster states and chiral metals in the regimes where without spin-orbit coupling otherwise the system would remain an insulator.

(II) **Dipolar quantum matter:**

We have used the rotational degrees of freedom of KRb molecules to encode a spin degree of freedom and explored many-body dynamics induced by dipolar exchange when molecules are pinned in a 3D lattice. Those measurements were done first in very dilute samples. We then increased the molecule filling fraction from 5% to 25% and decreased the entropy per molecule to $2.2 k_B$ by using a quantum synthesis protocol. The optimal loading conditions found experimentally were in agreement with Monte-Carlo simulations that account for interaction effects during the loading of the Rb and K mixture on a lattice. A new experimental apparatus was built bringing us improved capabilities of field control and imaging resolution. We also proposed to use dipolar interactions to naturally engineer spin orbit coupling and non-trivial topological excitations.

We presented a proposal for the implementation of quantum gas microscopy for polar molecules, and specifically discussed a technique for spin-resolved molecular detection. We used numerical simulation of spin dynamics of lattice-confined polar molecules to show how such a scheme would be of utility in a spin-diffusion experiment.

We also wrote a review in *Science* on “Cold molecules: Progress in quantum engineering of chemistry and quantum matter”. There we discuss how the more recent application of sophisticated cooling techniques to molecules, which has been more challenging to implement owing to the complexity of molecular structures, has now opened the door to the longstanding goal of precisely controlling molecular internal and external degrees of freedom and the resulting interaction processes. This line of research can leverage fundamental insights into how molecules interact and evolve to enable the control of reaction chemistry and the design and realization of a range of advanced quantum materials

We investigated and measured the role of retarded dipolar interaction in electronically excited Sr atoms by probing collective emission from coherently driven ultracold ^{88}Sr atoms. The dipolar interactions were signaled by a strong polarization dependence of the fluorescence intensity and line broadening. We demonstrated that a single, self-consistent, microscopic theory model can provide a unifying picture for the majority of the experimental observations.

In collaboration with Bruno Laburthe’s chromium experimental group of in Paris and Francesca Ferlaino’s group in Innsbruck, we studied the dynamics and approach towards thermal equilibrium of a macroscopic ensemble of spins initially tilted compared to the magnetic field, under the effect of dipole-dipole interactions. The experiment used a unit filled array of 10^4 chromium atoms in a 3D optical lattice, realizing large XXZ Heisenberg model. By monitoring the population of the spin components after a collective rotation of an initially polarized ensemble, as a function of the angle between the initial coherent state with respect to the magnetic field, we found that the approach to thermal equilibrium is increasingly driven by quantum correlations as the angle approaches $\pi/2$. The quantum dynamics was benchmarked by comparison with an improved numerical quantum phase-space method . Although the measurements only allowed us to reconstruct the entropy generated by the diagonal components of the average local density matrix, the excellent agreement with the theory supported entanglement build-up and the corresponding approach to local thermal equilibrium.

List of publications INCLUDING HYPERLINKS

2020

Simulation of XXZ Spin Models using Sideband Transitions in Trapped Bosonic Gases

Chu A., J. Will, J. Arlt, C. Klempt, and A.M. Rey, *Physical Review Letters* 125, 240504 (2020).

[DOI | https://doi.org/10.1103/PhysRevLett.125.240504](https://doi.org/10.1103/PhysRevLett.125.240504)

Detecting out-of-time-order correlations via quasiadiabatic echoes as a tool to reveal quantum coherence in equilibrium quantum phase transitions

Lewis-Swan R.J., S.R. Muleady, and A.M. Rey, *Physical Review Letters* 125, 240605 (2020).

[DOI | https://doi.org/10.1103/PhysRevLett.125.240605](https://doi.org/10.1103/PhysRevLett.125.240605)

Relaxation of the collective magnetization of a dense 3D array of interacting dipolar $S=3$ atoms

Gabardos L., B. Zhu, S. Lepoutre, A.M. Rey, B. Laburthe-Tolra, and L. Vernac, *Physical Review Letters* 125, 143401 (2020).

[DOI | https://doi.org/10.1103/PhysRevLett.125.143401](https://doi.org/10.1103/PhysRevLett.125.143401)

Thermodynamics of a deeply degenerate SU(N)-symmetric Fermi gas
Sonderhouse L., C. Sanner, R.B. Hutson, A. Goban, T. Bilitewski, L. Yan, W. Milner, A.M. Rey,
and J. Ye, Nature Physics 16, 1216 (2020).

[DOI](https://www.nature.com/articles/s41567-020-0986-6) | <https://www.nature.com/articles/s41567-020-0986-6>

Generating Multipartite Spin States with Fermionic Atoms in a Driven Optical Lattice
Mamaev M., and A.M. Rey, Physical Review Letters 124, 240401 (2020).

[DOI](https://doi.org/10.1103/PhysRevLett.124.240401) | <https://doi.org/10.1103/PhysRevLett.124.240401>

Controlling Dipolar Exchange Interactions in a Dense 3D Array of Large Spin Fermions
Patscheider A., B. Zhu, L. Chomaz, D. Petter, S. Baier, A.M. Rey, F. Ferlaino, and M. Mark,
Physical Review Research 2, 023050 (2020).

[DOI](https://doi.org/10.1103/PhysRevResearch.2.023050) | <https://doi.org/10.1103/PhysRevResearch.2.023050>

Subradiance of multilevel fermionic atoms in arrays with filling $n \geq 2$
Orioli P., and A.M. Rey, Physical Review Letters A 101, 043816 (2020).

[DOI](https://doi.org/10.1103/PhysRevA.101.043816) | <https://doi.org/10.1103/PhysRevA.101.043816>

2019

Engineering spin squeezing in a 3D optical lattice with interacting spin-orbit-coupled fermions
He P., M. Perlin, S.R. Muleady, R.J. Lewis-Swan, R.B. Hutson, J. Ye, and A.M. Rey, Physical
Review Research 1, 033075 (2019).

[DOI](https://doi.org/10.1103/PhysRevResearch.1.033075) | <https://doi.org/10.1103/PhysRevResearch.1.033075>

doublon dynamics of Bose-Fermi mixtures in optical lattices
Gärttner M., A. Safavi-Naini, J. Schachenmayer, and A.M. Rey, Physical Review A 100, 053607
(2019).

[DOI](https://doi.org/10.1103/PhysRevA.100.053607) | <https://doi.org/10.1103/PhysRevA.100.053607>

Dark States of Multilevel Fermionic Atoms in Doubly Filled Optical Lattices
Orioli P., and A.M. Rey, Physical Review Letters 123, 223601 (2019).

[DOI](https://doi.org/10.1103/PhysRevLett.123.223601) | <https://doi.org/10.1103/PhysRevLett.123.223601>

Spin-Squeezing and Many-Body Dipolar Dynamics in Optical Lattice Clocks
Qu C., and A.M. Rey, Physical Review A 100, 041602(R) (2019).

[DOI](https://doi.org/10.1103/PhysRevA.100.041602) | <https://doi.org/10.1103/PhysRevA.100.041602>

Dynamics of an itinerant spin-3 atomic dipolar gas in an optical lattice
Fersterer P., A. Safavi-Naini, B. Zhu, L. Gabardos, S. Lepoutre, L. Vernac, B. Laburthe-Tolra, B.
Blakie, and A.M. Rey, Physical Review A 100, 033609 (2019).

[DOI](https://doi.org/10.1103/PhysRevA.100.033609) | <https://doi.org/10.1103/PhysRevA.100.033609>

Quantum Entropic Self-Localization with Ultracold Fermions

Mamaev M., I. Kimchi, M. Perlin, R. Nandkishore, and A.M. Rey, *Physical Review Letters* 123, 130402 (2019).

[DOI | https://doi.org/10.1103/PhysRevLett.123.130402](https://doi.org/10.1103/PhysRevLett.123.130402)

Observation of a transition between dynamical phases in a quantum degenerate Fermi gas
Smale S., P. He, B. Olsen, K. Jackson, H. Sharum, S. Trotzky, J. Marino, A.M. Rey, and J. Thywissen, *Science Advances* 5, eaax1568 (2019).

[DOI | https://www.science.org/doi/10.1126/sciadv.aax1568](https://www.science.org/doi/10.1126/sciadv.aax1568)

Dynamics of quantum information

Lewis-Swan R.J., A. Safavi-Naini, A.M. Kaufman, and A.M. Rey, *Nature Reviews Physics* 1, 627–634 (2019).

[DOI | https://www.nature.com/articles/s42254-019-0090-y](https://www.nature.com/articles/s42254-019-0090-y)

generalized phase space approach for solving quantum spin dynamics

Zhu B., A.M. Rey, and J. Schachenmayer, *New Journal Of Physics* 21, 082001 (2019).

[DOI | 10.1088/1367-2630/ab354d](https://doi.org/10.1088/1367-2630/ab354d)

Topological superfluidity with repulsive alkaline-earth atoms in optical lattices

Isaev L., A.M. Kaufman, G. Ortiz, and A.M. Rey, *New Journal Of Physics* 21, 073049 (2019).

[DOI | 10.1088/1367-2630/ab2ee0](https://doi.org/10.1088/1367-2630/ab2ee0)

Driven-dissipative quantum dynamics in ultra-long-lived dipoles in an optical cavity

Barberena D., R.J. Lewis-Swan, J.K. Thompson, and A.M. Rey, *Physical Review A* 99, 053411 (2019).

[DOI | https://doi.org/10.1103/PhysRevA.99.053411](https://doi.org/10.1103/PhysRevA.99.053411)

Cavity-QED simulator of slow and fast scrambling

Marino J., and A.M. Rey, *Physical Review A* 99, 051803(R) (2019).

[DOI |](https://doi.org/10.1103/PhysRevA.99.051803)

Unifying scrambling, thermalization and entanglement through measurement of fidelity out-of-time-order correlators in the Dicke model

Lewis-Swan R.J., A. Safavi-Naini, J.J. Bollinger, and A.M. Rey, *Nature Communications* 10, 1581 (2019).

[DOI | https://doi.org/10.1103/PhysRevA.99.051803](https://doi.org/10.1103/PhysRevA.99.051803)

Exploring out-of-equilibrium quantum magnetism and thermalization in a spin-3 many-body dipolar lattice system

Lepoutre S., J. Schachenmayer, L. Gabardos, B. Zhu, B. Naylor, E. Maréchal, O. Gorceix, A.M. Rey, L. Vernac, and B. Laburthe-Tolra, *Nature Communications* 10, 1714 (2019).

[DOI | https://www.nature.com/articles/s41467-019-09699-5#abs1](https://www.nature.com/articles/s41467-019-09699-5#abs1)

Cluster State Generation with Spin-Orbit Coupled Fermionic Atoms in Optical Lattices

Mamaev M., R. Blatt, J. Ye, and A.M. Rey, Physical Review Letters 122, 160402 (2019).

[DOI](https://doi.org/10.1103/PhysRevLett.122.160402) | <https://doi.org/10.1103/PhysRevLett.122.160402>

Effective multi-body SU(N)-symmetric interactions of ultracold fermionic atoms on a 3-D lattice
Perlin M., and A.M. Rey, New Journal Of Physics 21, 043039 (2019).

[DOI](https://doi.org/10.1088/1367-2630/ab0e50) | [10.1088/1367-2630/ab0e50](https://doi.org/10.1088/1367-2630/ab0e50)

Quantum dynamics of disordered spin chains with power-law interactions

Safavi-Naini A., M.L. Wall, O.L. Acevedo, A.M. Rey, and R. Nandkishore, Physical Review A 99, 033610 (2019).

[DOI](https://doi.org/10.1103/PhysRevA.99.033610) | <https://doi.org/10.1103/PhysRevA.99.033610>

2018

S. Lepoutre, Kechadi, K. , Naylor, B. , Zhu, B. , Gabardos, L. , Isaev, L. , Pedri, P. , Rey, A. M. , Vernac, L. , and Laburthe-Tolra, B. , “Spin mixing and protection of ferromagnetism in a spinor dipolar condensate”, Phys. Rev. A, vol. 97, no. 2, p. 023610, 2018.

<https://doi.org/10.1103/PhysRevA.97.023610>

S. L. Bromley, Kolkowitz, S. , Bothwell, T. , Kedar, D. , Safavi-Naini, A. , Wall, M. L. , Saloman, C. , Rey, A. M. , and Ye, J. , “Dynamics of interacting fermions under spin-orbit coupling in an optical lattice clock”, Nature Physics 14, 399–404,2018. <https://doi.org/10.1038/s41567-017-0029-0>

M. Gaerrtner, Hauke, P. , and Rey, A. M. , “Relating out-of-time-order correlations to entanglement via multiple-quantum coherences”, Phys. Rev. Lett., vol. 120, no. 4, p. 040402, 2018.

<https://doi.org/10.1103/PhysRevLett.120.040402>

M. E. Beverland, Haah, J. , Alagic, G. , Campbell, G. K. , Rey, A. M. , and Gorshkov, A. V. , “Spectrum estimation of density operators with alkaline-earth atoms”, Phys. Rev. Lett, vol. 120, p. 025301, 2018.

<https://doi.org/10.1103/PhysRevLett.120.025301>

J. P. Covey, De Marco, L. , Acevedo, O. L. , Rey, A. M. , and Ye, J. , “An approach to quantum gas microscopy of polar molecules”, NJP, 20 043031, (2018) <https://doi.org/10.1088/1367-2630/aaba65>

BJ. Lester, Lin, Y. , Brown, M. O. , Kaufman, A. M. , Ball, R. J. , Knill, E. , Rey, A. M. , and Regal, C. A. , “Measurement-based entanglement of non-interacting bosonic atoms”, Phys. Rev. Lett. 120, 193602 (2018). <https://doi.org/10.1103/PhysRevLett.120.193602>

R. J. Lewis-Swan, Norcia, M. A. , Cline, J. R. K. , Thompson, J. K. , and Rey, A. M. , “Robust spin squeezing via photon-mediated interactions on an optical clock transition”, Physical Review Letters 121, (2018). <https://doi.org/10.1103/PhysRevLett.121.070403>

A. Goban, Hutson, R. B. , Marti, G. E. , Campbell, S. L. , Perlin, M. A. , Julienne, P. S. , D’Incao, J. P. , Rey, A. M. , and Ye, J. , “Emergence of multi-body interactions in few-atom sites of a fermionic lattice clock”, <https://doi.org/10.1038/s41586-018-0661-6> Nature 563, 369-373 (2018).

Verification of a Many-Ion Simulator of the Dicke Model Through Slow Quenches across a Phase Transition, Safavi-Naini A., R.J. Lewis-Swan, J.G. Bohnet, M. Gärttner, K. Gilmore, J.E. Jordan, J. Cohn, J.K. Freericks, A.M. Rey, and J.J. Bollinger, Physical Review Letters 121, (2018).
<https://doi.org/10.1103/PhysRevLett.121.040503>

The Hong-Ou-Mandel Effect With Atoms Kaufman A.M., M.C. Tichy, F. Mintert, A.M. Rey, and C.A. Regal, The Hong-Ou-Mandel Effect With Atoms (Elsevier, 2018), pp. 377-427.
<https://doi.org/10.1016/bs.aamop.2018.03.003>

2017

M. L. Wall, Safavi-Naini, A. , and Rey, A. M. , “Boson-mediated quantum spin simulators in transverse fields.”, Physical Review A, vol. 95, no. 1, 2017. <https://doi.org/10.1103/PhysRevA.95.013602>

O. Acevedo, Safavi-Naini, A. , Schachenmayer, J. , Wall, M. L. , Nandkishore, R. , and Rey, A. M. , “Exploring many body localization and thermalization using semiclassical method”, Phys. Rev. A, 96, 033604, 2017. <https://doi.org/10.1103/PhysRevA.96.033604>

A. Pineiro-Orioli, Safavi-Naini, A. , Wall, M. L. , and Rey, A. M. , “Nonequilibrium dynamics of spin-boson models from phase space methods”, Phys. Rev. A, vol. 96, no. 3, 2017.
<https://doi.org/10.1103/PhysRevA.96.033607>

J. L. Bohn, Rey, A. M. , and Ye, J. , “Cold molecules: Progress in quantum engineering of chemistry and quantum matter”, Science, vol. 357, no. 6355, 2017. <https://doi.org/10.1126/science.aam6299>

M. Gärttner, Bohnet, J. G. , Safavi-Naini, A. , Wall, M. L. , Bollinger, J. J. , and Rey, A. M. , “Measuring out-of-time-order correlations and multiple quantum spectra in a trapped-ion quantum magnet”, Nature Physics, vol. 13, 2017. <https://doi.org/10.1038/nphys4119>

2016

M. L. Wall, A. P. Koller, S. Li, X. Zhang, N.R. Cooper, J. Ye, and A. M. Rey, “Synthetic spin-orbit coupling in an optical lattice clock”, Phys. Rev. Lett., vol. 116, 035301, 2016. DOI: [10.1103/PhysRevLett.116.035301](https://doi.org/10.1103/PhysRevLett.116.035301)

S.L. Bromley, B. Zhu, M. Bishof, X. Zhang, T. Bothwell, J. Schachenmayer, T. L. Nicholson, R. Kaiser, S. F. Yelin, M. D. Lukin, A. M. Rey, and J. Ye, “Collective atomic scattering and motional effects in a dense coherent medium”, Nature Communications, vol. 7, 11039, 2016. DOI: [10.1038/ncomms11039](https://doi.org/10.1038/ncomms11039)

J. P. Covey, S. A. Moses, M. Gärttner, A. Safavi-Naini, M. T. Miecnikowski, Z. Fu, J. Schachenmayer, P. S. Julienne, A. M. Rey, D. S. Jin, and J. Ye, “Doublon dynamics and polar molecule production in an optical lattice”, Nature Communication, vol. 7, 11279, 2016. DOI: [10.1038/ncomms11279](https://doi.org/10.1038/ncomms11279)

J. G. Bohnet, B. C. Sawyer, J. W. Britton, M. L. Wall, A. M. Rey, M. Foss-Feig, and J. J. Bollinger, “Quantum spin dynamics and entanglement generation with hundreds of trapped ions”, Science 352, 1297-1301 (2016). <https://www.science.org/doi/10.1126/science.aad9958>

L. Isaev, J. Schachenmayer, A. M. Rey, “Correlated metal phase in Kondo lattices with alkaline-earth atoms”, Phys. Physical Review Letters 117, 135302 (2016).
<https://doi.org/10.1103/PhysRevLett.117.135302>

Syzranov S.V., M.L. Wall, B. Zhu, V. Gurarie, and A.M. Rey ,Emergent Weyl excitations in systems of polar particles, Nature Communications 7, 13543 (2016). <https://doi.org/10.1038/ncomms13543>

G. Chen, K. R. A. Hazzard, A. M. Rey, and M. Hermele, “Synthetic gauge fields stabilize a chiral spin liquid phase”, Physical Review A 93, (2016). <https://doi.org/10.1103/PhysRevA.93.061601>

M. E. Beverland, G. Alagic, M. J. Martin, A. P. Koller, A. M. Rey, and A.V. Gorshkov, “Realizing Exactly Solvable SU(N) Magnets with Thermal Atoms”, Physical Review A 93, 051601 (2016).
<https://doi.org/10.1103/PhysRevA.93.051601>

D. Dylewsky, J. K. Freericks, M. L. Wall, A. M. Rey, and M. Foss-Feig, Non-perturbative calculation of phonon effects on spin squeezing, Phys. Rev. A 93, 013415, 2016. [DOI:10.1103/PhysRevA.93.013415](https://doi.org/10.1103/PhysRevA.93.013415)

E. S. Polzik and J. Ye, “Entanglement and spin squeezing in a network of distant optical lattice clocks”, Physical Review A, vol. 93, no. 2, 2016. [DOI:10.1103/PhysRevA.93.021404](https://doi.org/10.1103/PhysRevA.93.021404)

2015

A. Safavi-Naini, M. L. Wall, and A. M. Rey, “Role of interspecies interactions in the preparation of a low-entropy gas of polar molecules in a lattice”, Phys. Rev. A vol. 92, 063416, 2015. [DOI: 10.1103/PhysRevA.92.063416](https://doi.org/10.1103/PhysRevA.92.063416)

C. Zhang, A. Safavi-Naini, A. M. Rey and B. Capogrosso-Sansone, “Equilibrium phases of tilted dipolar lattice bosons”, New J. Phys., vol. 17, 123014, 2015. [DOI:10.1088/13672630/17/12/123014](https://doi.org/10.1088/13672630/17/12/123014)

A. M. Kaufman, B. J. Lester, M. Foss-Feig, M. L. Wall, A. M. Rey and C. A. Regal, “Entangling two transportable neutral atoms via local spin exchange,” Nature, vol. 527, 208 2015.
[DOI:10.1038/nature16073](https://doi.org/10.1038/nature16073)

L. Isaev and A. M. Rey, Heavy-Fermion Valence-Bond Liquids in Ultracold Atoms: “Cooperation of the Kondo Effect and Geometric Frustration”, Phys. Rev. Lett. Vol. 115, 165302, 2015.
[DOI:10.1103/PhysRevLett.115.165302](https://doi.org/10.1103/PhysRevLett.115.165302)

A. P. Koller, J. Mundinger, M. L. Wall, and A. M. Rey, “Demagnetization dynamics of non-interacting trapped fermions”, Phys. Rev. A, vol. 92, 033608, 2015. [DOI:/10.1103/PhysRevA.92.033608](https://doi.org/10.1103/PhysRevA.92.033608)

N. R. Cooper and A. M. Rey, “Adiabatic Control of Atomic Dressed States for Transport and Sensing”, Phys. Rev. A. Rapid, vol. 92, 021401, 2015. [DOI: /10.1103/PhysRevA.92.021401](https://doi.org/10.1103/PhysRevA.92.021401)

B. Zhu, J. Schachenmayer, F. H. Urbina, J. G. Restrepo, J. G. , M. J. Holland, and A. M. Rey, “Synchronization of Interacting Quantum Dipoles”, New Journal of Physics, vol. 17, 083063, 2015.
[DOI:10.1088/1367-2630/17/8/083063](https://doi.org/10.1088/1367-2630/17/8/083063)

M. L. Wall, K. R. A. Hazzard, and A. M. Rey, “Effective many-body parameters for atoms in non-separable Gaussian optical potentials”, Phys. Rev. A, vol. 92, 013610, 2015. DOI: [10.1103/PhysRevA.92.013610](https://doi.org/10.1103/PhysRevA.92.013610)

M. Garttner, S. V. Syzranov, A. M. Rey, V. Gurarie, and L. Radzihovsky, “Disorder-driven transition in a chain with power-law hopping, Phys. Rev. B Rapid vol. 92, 041406(R),2015. DOI: [10.1103/PhysRevB.92.041406](https://doi.org/10.1103/PhysRevB.92.041406)

J. Schachenmayer, A. Pikovski, and A. M. Rey, “Dynamics of correlations in two-dimensional spin models with long-range interactions: A phase-space Monte-Carlo study”, New Journal of Physics, vol. 17, 065009, 2015. DOI:[10.1088/1367-2630/17/6/065009](https://doi.org/10.1088/1367-2630/17/6/065009)

J. Schachenmayer, A. Pikovski, and A. M. Rey, “Many-body quantum spin dynamics with Monte Carlo trajectories on a discrete phase space”, Physical Review X, vol. 5, 011022, 2015. DOI: [10.1103/PhysRevX.5.011022](https://doi.org/10.1103/PhysRevX.5.011022)

T. L. Nicholson, Blatt, S., Bloom, B. J., Williams, J. R., Thomsen, J. W., Ye, J., and Julienne, P. S., “Optical Feshbach resonances: Field-dressed theory and comparison with experiments”, Physical Review A, vol. 92, no. 2, p. 022709, 2015. DOI:[10.1103/PhysRevA.92.022709](https://doi.org/10.1103/PhysRevA.92.022709)

A. D. Ludlow, Boyd, M. M., Ye, J., Peik, E., and Schmidt, O., “Optical atomic clocks”, Reviews of Modern Physics, vol. 87, no. 2, pp. 637 - 701, 2015. DOI:[10.1103/RevModPhys.87.637](https://doi.org/10.1103/RevModPhys.87.637)

T. L. Nicholson, Campbell, S. L., Hutson, R. B., Marti, G. E., Bloom, B. J., McNally, R. L., Zhang, W., Barrett, M. D., Safronova, M. S., Strouse, G. F., Tew, W. L., and Ye, J., “Systematic evaluation of an atomic clock at 2×10^{-18} total uncertainty”, Nature Communications, vol. 6, pp. 6896, 2015. DOI:[10.1038/ncomms7896](https://doi.org/10.1038/ncomms7896)

2014

S. V. Syzranov, M. L. Wall, V. Gurarie, and A. M. Rey, “Spin-orbital dynamics in a system of polar molecules”, Nature Communications, vol. 5, 5391, 2014. DOI: [10.1038/ncomms6391](https://doi.org/10.1038/ncomms6391)

K. R. A. Hazzard, M. van den Worm, M. Foss-Feig, S. R. Manmana, E. G. Dalla Torre, T. Pfau, M. Kastner, and A. M. Rey, “Quantum correlations and entanglement in far-from equilibrium spin systems, Physical Review A, vol. 90, 063622, 2014. DOI:[10.1103/PhysRevA.90.063622](https://doi.org/10.1103/PhysRevA.90.063622)

M. A. Cazalilla and A. M. Rey, “Ultracold Fermi gases with emergent $SU(N)$ symmetry”, Reports on Progress in Physics, vol. 77(12), 124401, 2014. DOI:[10.1088/00344885/77/12/124401](https://doi.org/10.1088/00344885/77/12/124401)

K. R. A. Hazzard, B. Gadway, M. Foss-Feig, B. Yan, S. A. Moses, S. A. , J.P. Covey, N.Y. Yao, M. D. Lukin, J. Ye, D. S. Jin, and A. M. Rey, “Many-Body Dynamics of Dipolar Molecules in an Optical Lattice”, Physical Review Letters, vol. 113(19), 195302, 2014. DOI:[10.1103/PhysRevLett.113.195302](https://doi.org/10.1103/PhysRevLett.113.195302).

A. M. Kaufman, B. J. Lester, C. M. Reynolds, M. L. Wall, M. Foss-Feig, K. R. A. Hazzard, A. M. Rey, and C. A. Regal, Two-particle quantum interference in tunnel-coupled optical tweezers”, Science, vol. 345, 306, 2014. DOI:[10.1126/science.1250057](https://doi.org/10.1126/science.1250057)

A. P. Koller, M. Beverland, A. V. Gorshkov, and A. M. Rey, “Beyond the Spin Model Approximation for Ramsey Spectroscopy”, Physical Review Letters, vol. 112, 123001, 2014.

[DOI:10.1103/PhysRevLett.112.123001](https://doi.org/10.1103/PhysRevLett.112.123001)

X. Zhang, M. Bishof, S. L Bromley, C. V. Kraus, M. S. Safronova, P. Zoller, A. M. Rey, and J. Ye, “Spectroscopic observation of SU(N)-symmetric interactions in Sr orbital magnetism,” Science, vol. 345, 1467, 2014. [DOI:10.1126/science.1254978](https://doi.org/10.1126/science.1254978)

Kómár, Kessler, E. M., Bishof, M., Jiang, L., Sørensen, A. S., Ye, J., and Lukin, M. D., “A quantum network of clocks”, Nature Physics, vol. 10, pp. 582 - 587, 2014. [DOI:10.1038/nphys3000](https://doi.org/10.1038/nphys3000)

M. Kessler, Kómár, P., Bishof, M., Jiang, L., Sørensen, A. S., Ye, J., and Lukin, D., “Heisenberg-Limited Atom Clocks Based on Entangled Qubits”, Physical Review Letters, vol. 112, no. 19, pp. 190403, 2014. DOI: [10.1103/PhysRevLett.112.190403](https://doi.org/10.1103/PhysRevLett.112.190403)

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Arghavan Safavi-Naini (postdoc)

Oscar Acevedo (postdoc)

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