REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
12-12-2022	Final Report	20-May-2013 - 19-Mar-2019

4. TITLE AND SUBTITLE
Final Report: 6.3 Atomic and Molecular Physics - New Synthetic Physics in Ultracold Quantum Gases

5a. CONTRACT NUMBER
W911NF-13-1-0172

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
611102

6. AUTHORS

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of Maryland - College Park
The University of Maryland
Office of Research Administration
College Park, MD 20742 -5141

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
63740-PE.35

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER
UU	UU	UU	UU		Victor Galitski / 301-405-6107

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 14-Dec-2022

Agency Code: 21XD

Proposal Number: 63740PE **Agreement Number: W911NF-13-1-0172**

INVESTIGATOR(S):

Name: Victor Galitski
Email: galitski@umd.edu
Phone Number: 3014056107
Principal: Y

Organization: **University of Maryland - College Park**
Address: The University of Maryland, College Park, MD 207425141
Country:

DUNS Number: 790934285 EIN: 526002033
Report Date: 19-Jun-2019 Date Received: 12-Dec-2022
Final Report for Period Beginning 20-May-2013 and Ending 19-Mar-2019
Title: 6.3 Atomic and Molecular Physics - New Synthetic Physics in Ultracold Quantum Gases
Begin Performance Period: 20-May-2013 **End Performance Period:** 19-Mar-2019
Report Term: 0-Other

Submitted By: Victor Galitski Email: galitski@umd.edu
Phone: (301) 405-6107

Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 7 **STEM Participants:** 10

Major Goals: This ARO research project "New Synthetic Physics in Ultra-Cold Quantum Gases" focused on theoretical investigations of fundamentally new quantum states that can be realized in ultra-cold atomic systems, where neutral atoms coupled to lasers are made behave as charged particles in an external field. Non-Abelian gauge ?fields and spin-orbit couplings can also be engineered and give rise to a variety of novel phenomena. The project objectives are to study:
(1) Stochastic synthetic gauge fields;
(2) Atom-laser dressed states, which would artificially emulate gravity effects;
(3) Non-linear phenomena in spin-orbit-coupled gases, including solitons;
(4) Topological dynamical systems in driven spin-orbit gases;
(5) Quantum liquids in optical lattices.

The fundamental scientific significance of the project is in bringing together methods and ideas from the diverse ? fields of atomic and molecular physics, quantum optics, condensed matter, non-linear dynamics, and topology. This ARO-funded research has led to both a better understanding of fundamental physics phenomena and creation of new "synthetic" quantum states with no existing analogues, and as such is has had strong impact on basic science. On the practical side, the effort has promise to contribute to the development of quantum simulators and cold-atom intereferometers.

Accomplishments: The PI and his group have accomplished all goals of the project (as stated in "Major Goals" sections and the original proposal Abstract). Below are particular thrusts of the proposal with relevant publications highlighting most important discoveries and progress:
(1) Stochastic synthetic gauge fields;
A new class of synthetic gauge fields has been proposed and realized (by experimental partners - the Ian Spielman group at NIST) as detailed in this review by the PI: Galitski et al, "Artificial gauge fields with ultracold atoms," Phys Today. 2019 Jan; 72(1): 10.1063/pt.3.4111

(2) Atom-laser dressed states, which would artificially emulate gravity effects;
The PI and collaborators have discovered new ways to simulate quantum gravity effects in superfluid (in addition to those already observed in experiment by the Steinhauer group and the Campbell group). This monograph (also published as a book) contains the new ideas:
A. Keser and V. Galitski, "Analogue stochastic gravity in strongly-interacting Bose–Einstein condensates," Annals of Physics Volume 395, August 2018, Pages 84-111

(3) Non-linear phenomena in spin-orbit-coupled gases, including solitons;
The PI and his experimental collaborators have theoretically described and observed for the first time diffusion of quantum solutions in superfluids:
Aycock et al, "Brownian motion of solitons in a Bose-Einstein condensate," PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA, 114 (10) , pp.2503-2508 (2017)

(4) Topological dynamical systems in driven spin-orbit gases;
(5) Quantum liquids in optical lattices.
Both topics have been addressed in the context of driven optical lattices, where topological state was predicted to occur in
Sedrakyan, Galitski, and Kamenev, "Statistical Transmutation in Floquet Driven Optical Lattices," Phys. Rev. Lett. 115, 195301 (2015)

Key aspects of the proposed setup have been realized experimentally by the Trey Porto group.

Training Opportunities: The following seven doctoral degrees have been defended by PI's students, supervised within this ARO project:

1. Joe Mitchell (2014;)
2. Justin Wilson (2015; moved to Postdoc at Caltech, now faculty at LSU)
3. Juraj Radic (2015; RGM Advisors, Austin)
4. Aydin Cem Keser (2016; Staff at the University of New South Wells)
5. Hilary Hurst (2017; moved Postdoc position at NIST, now faculty at Cal State)
6. Andrew Allocca (2019; moved to Postdoc position at Cambridge University)
7. Zachary Raines (2019; moved Postdoc Fellowship at Yale University)

In addition, the PI has supervised a number of postdoctoral associates, undergraduates, and high-school students. Overall, 15 PIs former postdocs & students are now University professors or permanent research staff at various institutions.

PI's high-school interns have represented the US in the international physics Olympiads and won major awards, such as the Intel Research Competition as described in this Washington Post article:
https://www.washingtonpost.com/local/education/montgomery-physics-phenom-tried-not-to-faint-as-he-won-national-award/2015/03/15/550d9bc4-c7e4-11e4-b2a1-bed1aaea2816_story.html

Results Dissemination: The PI presented ~80 invited talks, some of which are listed below:

1. “Topological Kondo Insulators,” Invited Seminar at the Physics Department, Princeton Uni- versity, Princeton, NJ (November, 2013)

2. “Topological Kondo Insulators,” Invited Seminar at the Physics Department, Yale University, (November, 2013)

3. “Topological Kondo Insulators,” Invited R. G. Herb Condensed Matter Seminar at the Univer- sity of Wisconsin,Madison (December, 2013)

4. “Many-body physics of spin-orbit-coupled quantum gases,” Invited talk at the March Meeting 2014 in Denver, Colorado (March, 2014)

5. “Topological Kondo Insulators,” Invited Seminar at the Physics Department, Brown University, Providence, RI (May, 2014)

6. “Strong correlation effects in a topological Kondo insulator,” Invited talk at the Gordon Re- search Conference, “Correlated Electron Systems,” Mount Holyoke College, South Hadley, MA (June, 2014)

7. “Synthetic spin-orbit coupling in cold atom systems,” invited seminar at the Institute of The- oretical Physics and Astronomy, Vilnius University, Vilnius, Lithuania (July, 2014)

8. “Strong correlation effects and fluctuations in topological Kondo insulators,” Invited talk at the Department of Energy Theory PI Meeting, Gaithersburg, MD (August, 2014)

9. “Moving solitons in fermionic superfluids,” presentation at the Workshop “Gauge Fields in Condensed Matter, Ultracold Atoms and Beyond,” Aspen Center for Physics, Aspen, CO (August, 2014)

10. “Moving solitons in fermionic superfluids,” keynote talk at the Australasian Workshop on Emergent QuantumMatter 2014, Dunwich, Queensland, Australia (November, 2014)

11. “Moving solitons in fermionic superfluids,” invited talk at the ARO/AFOSR Workshop “Fun- damental Issues in Non-Equilibrium Dynamics,” Rice University, Houston, TX (January, 2015)

12. “Soliton motion, dissipation, self-acceleration and death in a fermionic superfluid,” invited talk at the Workshop “Nonlinear Physics at the Nanoscale: A Cross-Fertilization on Stochastic Methods,” Rotorua, New Zealand (February, 2015)

13. “Soliton motion, dissipation, self-acceleration and death in a fermionic superfluid,” invited talk at the Workshop, “Nonequilibrium Quantum Matter,” Aspen Center for Physics, Aspen, CO (March, 2015)

14. Invited review talk: “Topological phases of matter” at the Workshop “Quantum Correlated Matter and Chaos,” Max Planck Institute, Dresden, Germany (June, 2015)

15. Invited review talk: “Topological phases of matter” at the Gordon Research Conference“Topological & Correlated Matter,” The Hong Kong University of Science and Technology, Hong Kong (July, 2015)

16. “Topological Kondo Insulators,” Invited Colloquium at the Physics Department, University of Sydney, Sydney, VIC, Australia (July, 2015)

17. “Topological Kondo Insulators,” Invited Colloquium at the Physics Department, University of Quneensland, Brisbane, QLD, Australia (August, 2015)

18. “ Statistical Transmutation in Floquet Driven Optical Lattices,” invited presentation at the Workshop “BeyondQuasiparticles,” Aspen Center for Physics, Aspen, CO (August, 2015)

19. “Stimulation of Quantum Phases by Time-dependent Perturbations,” Hamburg Photon Sci- ence Colloquium, DESY, Hamburg, Germany (January, 2016)

20. CQM Distinguished Lecture Soliton motion, dissipation, and death in quantum superfluids, Centre for Quantum Matter (CQM), Stony Brook University, Stony Brook, NY (February, 2016)

21. Invited condensed matter seminar, ”Strongly-Correlated Topological Kondo Insulators, Physics Department, University of Colorado, Boulder (March, 2016)

22. Invited seminar, ”Soliton motion, dissipation, and death in quantum superfluids,” JILA, Uni- versity of Colorado, Boulder (March, 2016)

23. Invited conference talk, ”Stimulation and engineering of quantum phases by time-dependent perturbations,” SPIEconference on Ultrafast Band Photonics, Baltimore, MD (March, 2016)

24. Invited workshop talk, “Non-Markovian Quantum Friction of Bright Solitons in Superfluids” Aspen Centre for Physics, Workshop Lightmatter Interaction and Quantum Control In Many- body Systems, Aspen, CO (June, 2016)

25. Invited Condensed Matter Seminar, “Topological Kondo Insulators,” Brookhaven National Laboratory, NY (June, 2016)

26. Invited conference talk, “Soliton motion, dissipation, and death in quantum superfluids,” Nordita program on Multi-Component and Strongly-Correlated Superconductors, Nordita, Stockholm, Sweden (July, 2016)

27. Invited conference talk, “Soliton motion, dissipation, and death in quantum superfluids,” Kavli Institute forTheoretical Physics of China (KITPC), Beijing, China (July, 2016)

28. Invited conference talk, “Spin-Orbit-Coupled Quantum Gases,” Qin Emperor Island Work- shop, “BeyondStandard Quantum Gases,” Qin Emperor Island, China (August, 2016)

29. Invited presenter/discussion leader on topic “Dynamics of strongly interacting fermions” at workshop “Quantum Gases 2016,” Institute for Advanced Study, Tsinghua University, Beijing, China (August, 2016)

30. Invited summer school presentation, “Soliton motion, dissipation, and death in quantum su- perfluids,” The Eleventh International School on Theoretical Physics “Symmetry and Struc- tural Properties of Condensed Matter,” Rzesz´ow, Poland (September, 2016)

31. Invited condensed matter seminar, “Soliton motion, dissipation, and death in quantum super- fluids,” New York University, New York, NY (September, 2016)

32. Invited condensed matter seminar, “Soliton motion, dissipation, and death in quantum super- fluids,” Harvard University, Cambridge, MA (October, 2016)

33. Invited conference talk, “Soliton motion, dissipation, and death in quantum superfluids,” at conference “Spin coherence, condensation, and superfluidity,” Berkeley Research Station, Moorea, French Polynesia (February, 2017)

34. Invited presentation, “Soliton motion, dissipation, and death in quantum superfluids,” at Workshop “Dynamics and hydrodynamics of certain quantum matter,” New York, NY (March, 2017)

35. Invited seminar, “Quantum friction effects in superfluids,” condensed matter seminar, Uni- versity of California, Berkeley (April, 2017)

36. Lead organizer of Workshop, “Non-equilibrium Quantum Matter,” University of Mainz, Ger- many (invited talk “Lyapunov Exponent and Four-Point Correlator’s Growth Rate in a Chaotic System” presented by a junior collaborator) (May, 2017)

37. Invited talk,“Lyapunov Exponent and Four-Point Correlator’s Growth Rate in a Chaotic Syste” at the

AnnualMeeting of the APS Division of Atomic, Molecular and Optical Physics (DAMOP), Sacramento, CA (June, 2017)

38. Presentation“New Synthetic Physics in Ultracold Quantum Gases” at the US Army Research Office Conference,Cocoa Beach, FL (June, 2017)

39. Invited talk “Exotic magnon-mediated superconductivity in topological insulator/ferromagnet heterostructures,” atthe Inaugural Symposium for NYU Quantum Center ”Frontiers in Emer- gent Quantum Phenomena,” New York, NY (June, 2017)

40. “Quantum Lyapunov exponent and out-of-time-ordered correlator in the standard model of quantum chaos,” Aspen Center for Physics, Aspen, CO

41. Invited talk, “Quantum Lyapunov Exponent in Disordered Metals” at Workshop, “Dissipative Quantum Chaos: from Semi-Groups to QED Experiments,” Seoul, Korea (October 2017)

42. Invited Colloquium, “Quantum Lyapunov Exponents,” Kent State University, Kent, OH (Oc- tober, 2017)

43. Invited Seminar, “Quantum friction effects in superfluids,” Michigan State university, East Lansing, MI (October, 2017)

44. Invited talk, “Quantum Lyapunov Exponent in Disordered Metals” at Workshop, “Dissipative Quantum Chaos: from Semi-Groups to QED Experiments,” Seoul, Korea (October 2017)

...

Honors and Awards: 2013, 2014, 2015, 2016: Named University of Maryland research leader
2013 : Simons Investigator Award
2014 : Future Fellowship from the Australian Research Council
2016 : Elected Member of the Board of the Aspen Center for Physics, Aspen, CO

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Victor Galitski
Person Months Worked: 2.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Hilary Hurst
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Joseph Mitchell
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Justin Wilson
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Andrew Allocca
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Zachary Raines
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Aydin Keser
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: High School Student
Participant: Michael Winer
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Max Dzero
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Dmitry Efimkin
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Johannes Hoffmann
Person Months Worked: 3.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Juraj Radic
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
National Academy Member: N

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: Publication Identifier:
Volume: 112 Issue: 0 First Page #: 95302
Date Submitted: Date Published:
Publication Location:
Article Title: Interaction-Tuned Dynamical Transitions in a Rashba Spin-Orbit Coupled Fermi Gas
Authors:
Keywords: synthetic gauge fields, spin-orbit coupling, dynamics
Abstract: We consider the time evolution of the magnetization in a Rashba spin-orbit-coupled Fermi gas, starting from a fully-polarized initial state. We model the dynamics using a Boltzmann equation, which we solve in the Hartree-Fock approximation. The resulting non-linear system of equations gives rise to three distinct dynamical regimes with qualitatively different asymptotic behaviors of the magnetization at long times. The distinct regimes and the transitions between them are controlled by the interaction strength: for weakly interacting fermions, the magnetization decays to zero. For intermediate interactions, it displays undamped oscillations about zero and for strong interactions, a partially magnetized state is dynamically stabilized. The dynamics we find is a spin analog of interaction induced self-trapping in double-well Bose Einstein condensates. The predicted phenomena can be realized in trapped Fermi gases with synthetic spin-orbit interactions.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.91.023616
Volume: 91 Issue: First Page #: 023616
Date Submitted: 12/12/22 12:00AM Date Published:
Publication Location:
Article Title: Moving solitons in a one-dimensional fermionic superfluid - an exact solution
Authors: D. Efimkin and V. Galitski
Keywords: solitons, dynamics, exactly-solvable models, superfluids, Majorana fermions
Abstract: Spin–orbit coupling links a particle's velocity to its quantum-mechanical spin, and is essential in numerous condensed matter phenomena, including topological insulators and Majorana fermions. In solid-state materials, spin–orbit coupling originates from the movement of electrons in a crystal's intrinsic electric field, which is uniquely prescribed in any given material. In contrast, for ultracold atomic systems, the engineered 'material parameters' are tunable: a variety of synthetic spin–orbit couplings can be engineered on demand using laser fields. Here we outline the current experimental and theoretical status of spin–orbit coupling in ultracold atomic systems, discussing unique features that enable physics impossible in any other known setting.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Phys. Rev. B
Publication Identifier Type: Publication Identifier:
Volume: 89 Issue: 0 First Page #: 94413
Date Submitted: Date Published:
Publication Location:
Article Title: Spiral antiferromagnets beyond the spin-wave approximation: frustrated XY and Heisenberg models in the honeycomb lattice
Authors:
Keywords: Optical lattices, spin liquids, synthetic gauge fields, quantum spin models
Abstract: We examine the stability of classical states with a generic incommensurate spiral order against quantum fluctuations. Specifically, we focus on the frustrated spin-1/2 XY and Heisenberg models on the honeycomb lattice with nearest-neighbor J1 and next-nearest-neighbor J2 antiferromagnetic couplings, which can be realized in optical lattices with cold atoms. Our variational approach is based on the Jastrow wave functions, which include quantum correlations on top of classical spin waves. We perform a systematic optimization of wave vectors and Jastrow pseudo-potentials within this class of variational states and find that quantum fluctuations favor collinear states over generic coplanar spirals. The N\'eel state with Q=(0,0) extends its stability well beyond the classical value J2/J1=1/6. Most importantly, the collinear states with Q=(0,2?/3???) (and the two symmetry-related states) are found to be stable in a large regime with intermediate frustration, while at the classical level they
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: N **Publication Status:** 1-Published
Journal: Physical Review Letters (submitted)
Publication Identifier Type: Other Publication Identifier:
Volume: 0 Issue: 0 First Page #: 0
Date Submitted: 10/31/18 12:00AM Date Published:
Publication Location:
Article Title: Stoner antiferromagnetism in a thermal gas of pseudo-spin-1/2 bosons
Authors: Galitski
Keywords: Spinor Bose-Einstein condensates, magnetism, ferromagnetism, phase transitions
Abstract: We compute the phase diagram of a homogeneous two-component Bose gas with contact interactions at finite temperature, using both mean-field theory and the random phase approximation (RPA). In three dimensions, we find a normal easy exist and easy-plane ferromagnetic phase for sufficiently strong repulsive or attractive inter-spin interactions respectively. The normal ferromagnetic phase discovered here is a bosonic analogue of Stoner antiferromagnetism in electronic systems. We also discuss the possibility of a bosonic version of a Cooper paired state and find an enhanced tendancy towards it in lower dimensions.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.91.063634
Volume: 9.1E+001 Issue: 6.0E+000 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Strong correlation effects in a two-dimensional Bose gas with quartic dispersion
Authors:
Keywords: New phases of matter, quantum gases, synthetic spin-orbit coupling
Abstract: Motivated by the fundamental question of the fate of interacting bosons in flat bands, we consider a twodimensional Bose gas at zero temperature with an underlying quartic single-particle dispersion in one spatial direction. This type of band structure can be realized using the NIST scheme of spin-orbit coupling [Y.-J. Li, K. Jimenez-Garcia, and I. B. Spielman, Nature (London) 471, 83 (2011)] or using the shaken lattice scheme of Parker et al. [C. V. Parker et al Nat. Phys. 9, 769 (2013)]. We numerically compare the ground-state energies of the mean-field Bose-Einstein condensate (BEC) and various trial wave functions, where bosons avoid each other at short distances. We discover that, at low densities, several types of strongly correlated states have an energy per particle, which scales with density (n) as └ n^4/3, in contrast to └ the linear-in-n behavior for the weakly interacting Bose gas. These competing states include a Wigner crystal, quasicondensates described in terms of prope
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.91.023616
Volume: 9.1E+001 Issue: 2.0E+000 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Moving solitons in a one-dimensional fermionic superfluid
Authors:
Keywords: Solitons, superconductors, superfluids, quantum dynamics
Abstract: A fully analytical theory of a traveling soliton in a one-dimensional fermionic superfluid is developed within the framework of time-dependent self-consistent Bogoliubov–de Gennes equations, which are solved exactly in the Andreev approximation. The soliton manifests itself in a kinklike profile of the superconducting order parameter and hosts a pair of Andreev bound states in its core. They adjust to the soliton's motion and play an important role in its stabilization. A phase jump across the soliton and its energy decrease with the soliton's velocity and vanish at the critical velocity, corresponding to the Landau criterion, where the soliton starts emitting quasiparticles and becomes unstable. The "inertial" and "gravitational" masses of the soliton are calculated and the former is shown to be orders of magnitude larger than the latter. This results in a slow motion of the soliton in a harmonic trap, reminiscent of the observed behavior of a solitonlike texture in related experiment
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.113.185302
Volume: 1.13E+002 Issue: 1.8E+001 First Page #: 0
Date Submitted: Date Published:
Publication Location:
Article Title: Stoner Ferromagnetism in a Thermal Pseudospin--1/2 Bose Gas
Authors:
Keywords: New phases of matter, ferromagnetism, quantum gases, synthetic spin-orbit coupling
Abstract: We compute the finite-temperature phase diagram of a pseudospin-1=2 Bose gas with contact interactions, using two complementary methods: the random-phase approximation and self-consistent Hartree-Fock theory. We show that the spin-dependent interactions, which break the (pseudo-) spin-rotational symmetry of the Hamiltonian, generally lead to the appearance of a magnetically ordered phase at temperatures above the superfluid transition. In three dimensions, we predict a normal easy-axis (easy-plane) ferromagnet for sufficiently strong repulsive (attractive) interspecies interactions, respectively. The normal easy-axis ferromagnet is the bosonic analog of Stoner ferromagnetism known in electronic systems. For the case of interspecies attraction, we also discuss the possibility of a bosonic analog of the Cooper-paired phase. This state is shown to significantly lose in energy to the transverse ferromagnet in three dimensions, but is more energetically competitive in lower dimensions. Exte
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.116.225301
Volume: 116 Issue: 22 First Page #:
Date Submitted: 11/2/16 12:00AM Date Published: 5/1/16 2:00PM
Publication Location:
Article Title: Non-Markovian Quantum Friction of Bright Solitons in Superfluids
Authors: Dmitry K. Efimkin, Johannes Hofmann, Victor Galitski
Keywords: soliton, quantum friction, stochastic processes
Abstract: We explore the quantum dynamics of a bright matter-wave soliton in a quasi-one-dimensional bosonic superfluid with attractive interactions. Specifically, we focus on the dissipative forces experienced by the soliton due to its interaction with Bogoliubov excitations. Using the collective coordinate approach and the Keldysh formalism, a Langevin equation of motion for the soliton is derived from first principles. The equation contains a stochastic Langevin force (associated with quantum noise) and a nonlocal in time dissipative force, which appears due to inelastic scattering of Bogoliubov quasiparticles off of the moving soliton. It is shown that Ohmic friction (i. e., a term proportional to the soliton's velocity) is absent in the integrable setup. However, the Markovian approximation gives rise to the Abraham-Lorentz force (i.e., a term proportional to soliton's acceleration).
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.115.195301
Volume: 115 Issue: 19 First Page #:
Date Submitted: 11/2/16 12:00AM Date Published: 11/1/15 12:00AM
Publication Location:
Article Title: Statistical Transmutation in Floquet Driven Optical Lattices
Authors: Tigran A. Sedrakyan, Victor M. Galitski, Alex Kamenev
Keywords: Flout perturbations, non-Fermi liquids, anyons
Abstract: We show that interacting bosons in a periodically driven two dimensional (2D) optical lattice may effectively exhibit fermionic statistics. The phenomenon is similar to the celebrated Tonks-Girardeau regime in 1D. The Floquet band of a driven lattice develops the moat shape, i.e., a minimum along a closed contour in the Brillouin zone. Such degeneracy of the kinetic energy favors fermionic quasiparticles. The statistical transmutation is achieved by the Chern-Simons flux attachment similar to the fractional quantum Hall case.We show that the velocity distribution of the released bosons is a sensitive probe of the fermionic nature of their stationary Floquet state.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevB.94.085120
Volume: 94 Issue: First Page #: 085120
Date Submitted: 11/2/16 12:00AM Date Published: 11/2/16 9:49PM
Publication Location:
Article Title: Dynamical many-body localization in an integrable model
Authors: Aydin Cem Keser, Sriram Ganeshan, Gil Refael, and Victor Galitski
Keywords: localization, Floquet systems
Abstract: We investigate dynamical many-body localization and delocalization in an integrable system of periodically-kicked, interacting linear rotors. The linear-in-momentum Hamiltonian makes the Floquet evolution operator analytically tractable for arbitrary interactions. One of the hallmarks of this model is that depending on certain parameters, it manifests both localization and delocalization in momentum space.We present a set of "emergent" integrals of motion, which can serve as a fundamental diagnostic of dynamical localization in the interacting case.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Proceedings of the National Academy of Sciences of the USA
Publication Identifier Type: DOI Publication Identifier: 10.1073/pnas.1615004114
Volume: 114 Issue: First Page #: 2503
Date Submitted: 10/9/17 12:00AM Date Published: 1/11/17 7:54AM
Publication Location:
Article Title: Brownian motion of solitons in a Bose–Einstein condensate
Authors: L. M. Aycock, H. M. Hurst, D. Genkina, H.-I Lu, V. Galitski, and I. B. Spielman
Keywords: solitons, Brownian motion, superfluids
Abstract: Solitons, spatially-localized, mobile excitations resulting from an interplay between nonlinearity and dispersion, are ubiquitous in physical systems from water channels1 and oceans to optical fibers and Bose-Einstein condensates (BECs). For the first time, we observed and controlled the Brownian motion5 of solitons. We launched long-lived dark solitons in highly elongated 87Rb BECs and showed that a dilute background of impurity atoms in a different internal state dramatically affects the soliton. With no impurities and in one-dimension (1-D), these solitons would have an infinite lifetime, a consequence of integrability. In our experiment, the added impurities scatter off the much larger soliton, contributing to its Brownian motion and decreasing its lifetime. We describe the soliton's diffusive behavior using a quasi-1-D scattering theory of impurity atoms interacting with a soliton, giving diffusion coefficients consistent with experiment.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: DOI Publication Identifier:
Volume: 95 Issue: First Page #: 064303
Date Submitted: 10/9/17 12:00AM Date Published: 11/7/16 3:00PM
Publication Location:
Article Title: Dynamical localization of coupled relativistic kicked rotors
Authors: Efim B. Rozenbaum and Victor Galitski
Keywords: quantum dynamics, Floquet, localization
Abstract: A periodically driven rotor is a prototypical model that exhibits a transition to chaos in the classical regime and dynamical localization (related to Anderson localization) in the quantum regime. In a recent work [Phys. Rev. B 94, 085120 (2016)], A. C. Keser et al. considered a many-body generalization of coupled quantum kicked rotors, and showed that in the special integrable linear case, dynamical localization survives interactions. By analogy with many-body localization, the phenomenon was dubbed dynamical many-body localization. In the present work, we study nonintegrable models of single and coupled quantum relativistic kicked rotors (QRKRs) that bridge the gap between the conventional quadratic rotors and the integrable linear models. We also analyze the dynamics of two coupled QRKRs in the highly unusual superballistic regime and find that the resonance conditions are relaxed due to interactions. Finally, we propose experimental realizations of the QRKR model in cold atoms.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review A
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevA.95.053604
Volume: 95 Issue: 5 First Page #:
Date Submitted: 10/31/18 12:00AM Date Published: 5/1/17 12:00PM
Publication Location:
Article Title: Kinetic theory of dark solitons with tunable friction
Authors: Hilary M. Hurst, Dmitry K. Efimkin, I. B. Spielman, Victor Galitski
Keywords: Bose-Einstein condensate, solitons, topological defects, diffusion
Abstract: We study controllable friction in a system consisting of a dark soliton in a one-dimensional Bose-Einstein condensate coupled to a noninteracting Fermi gas. The fermions act as impurity atoms, not part of the original condensate, that scatter off of the soliton. We study semiclassical dynamics of the dark soliton, a particlelike object with negative mass, and calculate its friction coefficient. Surprisingly, it depends periodically on the ratio of interspecies (impurity-condensate) to intraspecies (condensate-condensate) interaction strengths. By tuning this ratio, one can access a regime where the friction coefficient vanishes. We develop a general theory of stochastic dynamics for negative-mass objects and find that their dynamics are drastically different from their positive-mass counterparts. We find that the soliton can undergo Brownian motion only in the presence of friction and a confining potential. These results agree with experimental observations by Aycock et al.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Annals of Physics
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.aop.2018.05.009
Volume: 395 Issue: First Page #: 84
Date Submitted: 4/23/19 12:00AM Date Published: 8/1/18 4:00AM
Publication Location:
Article Title: Analogue stochastic gravity in strongly-interacting Bose–Einstein condensates
Authors: Aydin Keser, Victor Galitski
Keywords: cold atoms, hydrodynamics, synthetic general relativity
Abstract: Collective modes propagating in a moving superfluid are known to satisfy wave equations in a curved space time, with a metric determined by the underlying superflow. We use the Keldysh technique in a curved space-time to develop a quantum geometric theory of fluctuations in superfluid hydrodynamics. This theory relies on a 'quantized' generalization of the two-fluid description of Landau and Khalatnikov, where the superfluid component is viewed as a quasi-classical field coupled to a normal component -- the collective modes/phonons representing a quantum bath. This relates the problem in the hydrodynamic limit to the 'quantum friction' problem of Caldeira-Leggett type. By integrating out the phonons, we derive stochastic Langevin equations describing a coupling between the superfluid component and phonons. These equations have the form of Euler equations with additional source terms expressed through a fluctuating stress-energy tensor of phonons.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevB.97.161114
Volume: 97 Issue: 16 First Page #: 16111
Date Submitted: 10/31/18 12:00AM Date Published: 4/1/18 4:00AM
Publication Location:
Article Title: Out-of-time-order correlators in finite open systems
Authors: S. V. Syzranov, A. V. Gorshkov, V. Galitski
Keywords: cold atoms, quantum chaos
Abstract: We study out-of-time order correlators (OTOCs) for a quantum system weakly coupled to a dissipative environment. Such an open system may serve as a model of, e.g., a small region in a disordered interacting medium coupled to the rest of this medium considered as an environment. We demonstrate that for a system with discrete energy levels the OTOC saturates exponentially to a constant value, in contrast with quantum-chaotic systems which exhibit exponential growth of OTOCs. Focussing on the case of a two-level system, we calculate microscopically the decay times ?i and the value of the saturation constant. Because some OTOCs are immune to dephasing processes and some are not, such correlators may decay on two sets of parametrically different time scales related to inelastic transitions between the system levels and to pure dephasing processes, respectively. In the case of a classical environment, the evolution of the OTOC can be map
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevB.100.035112
Volume: 100 Issue: First Page #: .035112
Date Submitted: 12/12/22 12:00AM Date Published:
Publication Location:
Article Title: Universal Level Statistics of the Out-of-Time-Ordered Operator
Authors: Efim Rozenbaum, Sriram Ganeshan, Victor Galitski
Keywords: cold atoms, quantum chaos
Abstract: Spin–orbit coupling links a particle's velocity to its quantum-mechanical spin, and is essential in numerous condensed matter phenomena, including topological insulators and Majorana fermions. In solid-state materials, spin–orbit coupling originates from the movement of electrons in a crystal's intrinsic electric field, which is uniquely prescribed in any given material. In contrast, for ultracold atomic systems, the engineered 'material parameters' are tunable: a variety of synthetic spin–orbit couplings can be engineered on demand using laser fields. Here we outline the current experimental and theoretical status of spin–orbit coupling in ultracold atomic systems, discussing unique features that enable physics impossible in any other known setting.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Annals of Physics
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.aop.2019.03.008
Volume: 405 Issue: First Page #: 1
Date Submitted: 12/12/22 12:00AM Date Published: 9/27/17 4:00AM
Publication Location:
Article Title: Interaction-induced transition in the quantum chaotic dynamics
Authors: S.V. Syzranov, A.V. Gorshkov, and V.M. Galitski
Keywords: quantum chaos, interacting fermi gas
Abstract: Spin–orbit coupling links a particle's velocity to its quantum-mechanical spin, and is essential in numerous condensed matter phenomena, including topological insulators and Majorana fermions. In solid-state materials, spin–orbit coupling originates from the movement of electrons in a crystal's intrinsic electric field, which is uniquely prescribed in any given material. In contrast, for ultracold atomic systems, the engineered 'material parameters' are tunable: a variety of synthetic spin–orbit couplings can be engineered on demand using laser fields. Here we outline the current experimental and theoretical status of spin–orbit coupling in ultracold atomic systems, discussing unique features that enable physics impossible in any other known setting.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Annals of Physics
Publication Identifier Type: DOI Publication Identifier: 10.1016/j.aop.2019.04.017
Volume: 407 Issue: First Page #: 148
Date Submitted: 12/12/22 12:00AM Date Published: 1/5/18 10:00AM
Publication Location:
Article Title: Evanescent Horizon Modes Partnered to Acoustic Hawking Emission
Authors: Jonathan B. Curtis, Gil Refael, and Victor Galitski
Keywords: Hawking radiation, Bose-Einstein condensates
Abstract: Spin–orbit coupling links a particle's velocity to its quantum-mechanical spin, and is essential in numerous condensed matter phenomena, including topological insulators and Majorana fermions. In solid-state materials, spin–orbit coupling originates from the movement of electrons in a crystal's intrinsic electric field, which is uniquely prescribed in any given material. In contrast, for ultracold atomic systems, the engineered 'material parameters' are tunable: a variety of synthetic spin–orbit couplings can be engineered on demand using laser fields. Here we outline the current experimental and theoretical status of spin–orbit coupling in ultracold atomic systems, discussing unique features that enable physics impossible in any other known setting.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.122.167002
Volume: 122 Issue: First Page #: 167002
Date Submitted: 12/12/22 12:00AM Date Published: 8/3/18 8:00AM
Publication Location:
Article Title: Cavity Quantum Eliashberg Enhancement of Superconductivity
Authors: Jonathan B. Curtis, Zachary M. Raines, Andrew A. Allocca, Mohammad Hafezi, and Victor M. Galitski
Keywords: cavity, QED, superconductivity
Abstract: Spin–orbit coupling links a particle's velocity to its quantum-mechanical spin, and is essential in numerous condensed matter phenomena, including topological insulators and Majorana fermions. In solid-state materials, spin–orbit coupling originates from the movement of electrons in a crystal's intrinsic electric field, which is uniquely prescribed in any given material. In contrast, for ultracold atomic systems, the engineered 'material parameters' are tunable: a variety of synthetic spin–orbit couplings can be engineered on demand using laser fields. Here we outline the current experimental and theoretical status of spin–orbit coupling in ultracold atomic systems, discussing unique features that enable physics impossible in any other known setting.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: Other Publication Identifier: 10.1103/PhysRevB.99.020504
Volume: 99 Issue: First Page #:
Date Submitted: 12/12/22 12:00AM Date Published: 7/17/18 8:00AM
Publication Location:
Article Title: Cavity superconductor-polaritons
Authors: Andrew Allocca, Zachary M. Raines, Jonathan B. Curtis, and Victor M. Galitski
Keywords: cavity, QED, superfluidity, excitons
Abstract: Spin–orbit coupling links a particle's velocity to its quantum-mechanical spin, and is essential in numerous condensed matter phenomena, including topological insulators and Majorana fermions. In solid-state materials, spin–orbit coupling originates from the movement of electrons in a crystal's intrinsic electric field, which is uniquely prescribed in any given material. In contrast, for ultracold atomic systems, the engineered 'material parameters' are tunable: a variety of synthetic spin–orbit couplings can be engineered on demand using laser fields. Here we outline the current experimental and theoretical status of spin–orbit coupling in ultracold atomic systems, discussing unique features that enable physics impossible in any other known setting.
Distribution Statement: 2-Distribution Limited to U.S. Government agencies only; report contains proprietary info
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physics Today
Publication Identifier Type: DOI Publication Identifier: 10.1063/PT.3.4111
Volume: 72 Issue: First Page #: 38
Date Submitted: 12/12/22 12:00AM Date Published: 1/5/19 8:00PM
Publication Location:
Article Title: Artificial gauge fields with ultracold atoms
Authors: Victor Galitski, Ian Spielman, Gediminas Juzeli?nas
Keywords: gauge fields, cold atoms, quantum Hall
Abstract: Spin–orbit coupling links a particle's velocity to its quantum-mechanical spin, and is essential in numerous condensed matter phenomena, including topological insulators and Majorana fermions. In solid-state materials, spin–orbit coupling originates from the movement of electrons in a crystal's intrinsic electric field, which is uniquely prescribed in any given material. In contrast, for ultracold atomic systems, the engineered 'material parameters' are tunable: a variety of synthetic spin–orbit couplings can be engineered on demand using laser fields. Here we outline the current experimental and theoretical status of spin–orbit coupling in ultracold atomic systems, discussing unique features that enable physics impossible in any other known setting.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Nature
Publication Identifier Type: DOI Publication Identifier: 10.1038/nature11841
Volume: 494 Issue: 7435 First Page #: 49
Date Submitted: 12/12/22 12:00AM Date Published: 2/1/13 5:00AM
Publication Location:
Article Title: Spin–orbit coupling in quantum gases
Authors: Victor Galitski, Ian B. Spielman
Keywords: quantum gases, cold atoms
Abstract: Spin–orbit coupling links a particle's velocity to its quantum-mechanical spin, and is essential in numerous condensed matter phenomena, including topological insulators and Majorana fermions. In solid-state materials, spin–orbit coupling originates from the movement of electrons in a crystal's intrinsic electric field, which is uniquely prescribed in any given material. In contrast, for ultracold atomic systems, the engineered 'material parameters' are tunable: a variety of synthetic spin–orbit couplings can be engineered on demand using laser fields. Here we outline the current experimental and theoretical status of spin–orbit coupling in ultracold atomic systems, discussing unique features that enable physics impossible in any other known setting.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review B
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevB.89.094413
Volume: 89 Issue: 9 First Page #:
Date Submitted: 12/12/22 12:00AM Date Published: 3/1/14 5:00AM
Publication Location:
Article Title: Spiral antiferromagnets beyond the spin-wave approximation: Frustrated
Authors: Andrea Di Ciolo, Juan Carrasquilla, Federico Becca, Marcos Rigol, Victor Galitski
Keywords: quantum spin liquids
Abstract: Spin–orbit coupling links a particle's velocity to its quantum-mechanical spin, and is essential in numerous condensed matter phenomena, including topological insulators and Majorana fermions. In solid-state materials, spin–orbit coupling originates from the movement of electrons in a crystal's intrinsic electric field, which is uniquely prescribed in any given material. In contrast, for ultracold atomic systems, the engineered 'material parameters' are tunable: a variety of synthetic spin–orbit couplings can be engineered on demand using laser fields. Here we outline the current experimental and theoretical status of spin–orbit coupling in ultracold atomic systems, discussing unique features that enable physics impossible in any other known setting.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
Institution: University of Maryland
Date Received: 02-Nov-2016 Completion Date: 11/1/15 10:26PM
Title: Spin-orbit-coupled quantum gases
Authors: Jury Radic, advisor: Victor Galitski
Acknowledged Federal Support: **N**

Partners

,

I certify that the information in the report is complete and accurate:
Signature: Victor Galitski
Signature Date: 12/12/22 8:54PM

Required report attachment

This ARO research grant entitled “New Synthetic Physics in Ultracold Quantum Gases” focused on theoretical investigations of fundamentally new quantum states that can be realized in ultracold atomic systems, where neutral atoms coupled to lasers are made behave as charged particles in a magnetic field. Non-Abelian gauge fields and spin-orbit couplings can also be engineered and give rise to a variety of novel phenomena. The project objectives were to study:

(1) Atom-laser dressed states, which would artificially emulate gravity effects;
(2) Non-linear phenomena in spin-orbit-coupled gases, including spin turbulence and solitons;
(3) Stochastic synthetic gauge fields;
(4) Topological dynamical systems in driven spin-orbit gases;
(5) Quantum liquids in optical lattices.

The fundamental scientific significance of the project was in bringing together methods and ideas from the diverse fields of atomic and molecular physics, quantum optics, condensed matter, non-linear dynamics, and topology. The proposed research has led to both a better understanding of fundamental physics phenomena and creation of new “synthetic” quantum states with no existing analogues, and as such it has had and continues to have strong impact on basic science of relevance to the ARO mission.
Below are select publications of relevance to projects (1) – (5) listed above:

- Galitski et al, "Artificial gauge fields with ultracold atoms," Physics Today, **72**(1) (2019)
- Sedrakyan, Galitski, and Kamenev, "Statistical Transmutation in Floquet Driven Optical Lattices," Phys. Rev. Lett. **115**, 195301 (2015)
- Aycock et al, Proceedings of the National Academy of Sciences (PNAS)," Brownian motion of solitons in a Bose-Einstein condensate,", **114** (10) , pp.2503-2508 (2017)
- V. Galitski, I.B. Spielman, “Spin–orbit coupling in quantum gases,” Nature **494**, 49-54 (2013)