Quantum Simulation with Ultracold Atoms

Italian-German WE-Heraeus-Seminar

30 September - 02 October 2024

at the Galileo Galilei Institute,
Florence, Italy

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the Italian-German WE-Heraeus-Seminar:

The exquisite control of the quantum states and of the interactions in ultracold atomic systems is offering new opportunities for quantum simulation of complex quantum systems. These simulations provide a unique platform for scientists to recreate and delve into complex quantum phenomena, often beyond the computational reach of classical computers, with impacts on both fundamental research and potential technological applications.

This seminar will bring together the German and Italian communities active in this rapidly evolving field, providing a unique environment to exchange ideas and create new collaborations. The topics will include new phases of matter, complex quantum systems in and out of equilibrium, quantum computing applications, new tunability and control methods. The seminar will bring together renowned experts, emerging young scientists and students, with a rich program of talks, poster presentations, and discussions that will maximise the exchange of ideas at all levels.

Scientific Organizers:

Prof. Immanuel Bloch	Max Planck Institute of Quantum Optics & LMU Munich Garching, Germany E-mail: immanuel.bloch@mpq.mpg.de
Prof. Giovanni Modugno	LENS and Department of Physics and Astronomy University of Florence, Italy E-mail: modugno@lens.unifi.it

Administrative Organization:

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Introduction

Venue:

Galileo Galilei Institute
Largo Enrico Fermi, 2
50125 Firenze, Italy

Phone: +39 055 275 5255
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Registration:

Monday morning, from 08:00 – 09:10 h
Reception office at the
Galileo Galilei Institute

Program

Program

Sunday, 29 September 2024

Individual Travel to Florence

Monday, 30 September 2024

08:00– 09:10	***REGISTRATION***	
09:10 - 09:20	Immanuel Bloch, Giovanni Modugno	**Welcome words**
09:20 – 10:10	Francesca Ferlaino	**Rotating dipolar quantum gases**
10:10 – 11:00	Alessio Recati	**Sound propagation and Doppler effect in Supersolid Dipolar gases**
11:00 – 11:20	*COFFEE BREAK*	
11:20 – 12:10	Giacomo Roati	**Vortex matter in strongly-correlated superfluids**
12:10 – 13:00	Giulia Semighini	**Towards new frontiers of quantum science with dual-species atom arrays**
13:00 – 14:00	*LUNCH*	
14:00 - 14:50	Ralf Klemt	**Sound and amplitude modes in trapped dipolar supersolids**
14:50 – 15:40	Tommaso Calarco	**Quantum firmware: optimal control for quantum simulators**
15:40 – 16:30	Marcello Dalmonte	**Data mining quantum simulators**

Program

Monday, 30 September 2024

16:30 – 17:00	*COFFEE BREAK*	
17:00 – 17:50	Annabelle Bohrdt	**How to explore high-temperature superconductivity in optical lattices**
17:50 – 18:40	Christian Groß	**Exploring pathways to lower temperatures for ultracold fermions**
19:00	*End of the scientific program*	
	*Open Dinner (**self-organized by the participants**)*	

Program

Tuesday, 01 October 2024

08:30 – 09:20	Markus Oberthaler	**Quantum Field Simulator: Connecting Cosmology and Supersolidity**
09:20 – 10:10	Gabriele Ferrari	**False vacuum decay via bubble formation in ferromagnetic superfluids**
10:10 – 11:00	Christof Weitenberg	**A phase microscope for quantum gases**
11:00 – 11:20	*COFFEE BREAK*	
11:20 – 11:35	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
11:35 – 12:25	Andrea Bergschneider	**Enhancing pair tunneling with Floquet engineering**
12:25 – 13:15	Francesco Scazza	**Fermionic ytterbium atoms for quantum simulations beyond the Hubbard model**
13:15 – 13:20	*CONFERENCE PHOTO*	
13:20 – 14:15	*LUNCH*	
14:15 – 16:30	**POSTER SESSION**	
16:30 – 17:00	*COFFEE BREAK*	
17:00 – 17:50	Monika Aidelsburger	**Quantum simulation of Floquet topological phases with cold atoms**
17:50 – 18:40	Luca Tanzi	**Exploring the supersolid phase of matter with an atomic quantum simulator**
18:40 – 20:00	*Visit of Galileo’s villa*	
20:00 – 22:00	*CONFERENCE DINNER*	

Program

Wednesday, 02 October 2024

08:30 – 09:20	Leonardo Fallani	**Strongly interacting lattice fermions: flavour-dependent Mott localization and universal Hall response**
09:20 – 10:10	Richard Schmidt	**Strongly interacting Bose-Fermi mixtures in cold atoms and two-dimensional materials**
10:10 – 11:00	Timon Hilker	**Hole-hole attraction mediated by magnetism in the doped Fermi Hubbard Model**
11:00 – 11:20	*COFFEE BREAK*	
11:20 – 12:10	Silke Ospelkaus	**Understanding and controlling collisions in quantum gases of polar molecules**
12:10 – 13:00	Simone Montangero	**Tensor network algorithms for quantum simulations**
13:00 – 14:00	*LUNCH*	
14:00 – 17:00	***Transfer to town and visit of LENS laboratories***	
17:00	**End of the seminar and departure**	

Posters

Poster Session, Tuesday 01 October 2024 14:15 h

Riccardo Andreoni	**Stochastic sampling-based classification of states of matter**
Nicolò Antolini	**Measurement of the superfluid fraction of a supersolid by Josephson effect**
Devendra Singh Bhakuni	**Diagnosing transport from wave function snapshots**
Stefan Birnkammer	**Prethermalization in one-dimensional quantum many-body systems with confinement**
Justus Brüggenjürgen	**A coherence microscope for quantum gases**
Giancarlo Calvanese Strinati	**Josephson current flowing through a nontrivial geometry**
Luca Cavicchioli	**Dynamical formation of multiple quantum droplets in a Bose-Bose mixture**
Cristina Cicali	**Atom transport optimization: theoretical frameworks, algorithms, and experimental integration**
Renan da Silva Souza	**Interplay of Short-Range and Long-Range Interactions in Ultracold Fermionic Lattice Systems: A Real-Space DMFT Approach**
Alexandre De Martino	**Report on the construction of a new Erbium-Lithium machine**
Giulia Del Pace	**Persistent currents in a Josephson junction necklace**
Marco Di Liberto	**Emergent orbital physics and chiral phases in dimerized pi-flux lattices**
Eugen Dizer	**Spectral properties of ultracold Fermi gases**

Poster Session, Tuesday 01 October 2024 14:15 h

Gustavo Alexis Dominguez Castro	**Relaxation in dipolar spin ladders: From pair production to false-vacuum decay**
Marco Fattori	**Differential Mach-Zehender interferometry with trapped Bose Einstein condensates**
Giovanni Ferioli	**Non-Gaussian Correlation in the steady state of a superradiant cloud**
Marcia Frometa Fernandez	**Shapiro steps in a ^{6}Li Fermi superfluid Josephson junction**
Albert Gallemí	**Two-fluid character of a binary dipolar quantum gas across the superfluid-supersolid-crystal phase transition**
Youqi Gang	**Towards low temperature states in a Fermi-Hubbard quantum simulator**
Patrick Geraghty	**Long range interactions in synthetic dimensions**
Nicola Grani	**Dissipative vortex dynamics in strongly interacting Fermi superfluid.**
Fabian Grusdt	**Quantum simulation of Hubbard models: From unconventional superconductors to gauge theories**
Luca Guariento	**Strontium atoms in optical tweezers**
Tobias Hammel	**A modular quantum gas platform**
Florian Hirsch	**Cold atomic excitons**
Florian Kiesel	**Report on the construction of a new Erbium-Lithium machine**
Lorenzo Maffi	**Vortex dynamics in strongly interacting superfluid**

Poster Session, Tuesday 01 October 2024 14:15 h

Arkajyoti Maity	**Driven-dissipative fermionized topological phases of strongly interacting composite bosons**
Salvatore R. Manmana	**What can we learn from time-dependent spectral functions?**
Fabio Mezzacapo	**Scalable spin squeezing from critical slowing down in short-range interacting systems**
Alessandro Muzi Falconi	**Ytterbium optical tweezers for single-atom resolved many-body physics**
Sara Nicoletti	**Optimal control transport of neutral atoms in optical tweezers**
Kristian Knakkergaard Nielsen	**Thermal localisation and pairing by disorder of dopants in a magnetic spin ladder**
David Pascual Solis	**Advancements towards simulating SYK Model and its variants in cQED platforms**
Luka Pavesic	**Constrained dynamics and confinement in the two-dimensional quantum Ising model**
Leonardo Pisani	**Critical Current throughout the BCS-BEC Crossover: Landau Critical Velocity and Persistent Currents**
Andrea Pizzi	**Quantum scars in many-body systems**
Niklas Rasch	**Anomalous non-thermal fixed point in a Quasi-2d Dipolar Bose Gas**
Michael Rautenberg	**Towards Fermi polarons with heavy impurities**
Matteo Rizzi	**Fractional quantum Hall states with variational projected entangled-pair states: A study of the bosonic Harper-Hofstadter model**

Poster Session, Tuesday 01 October 2024 14:15 h

Stephan Roschinski	**Towards deterministic entanglement generation in a new atom-cavity setup**
Christian Friedrich Schmidt	**Cosmological particle production in a Quantum Field Simulator as a Quantum-Mechanical scattering problem**
Carlo Sias	**Control of ion crystals for atom-ion quantum mixtures**
Rohan Srikumar	**Dynamical effects in trilobite molecules**
Arthur Vesperini	**Entanglement and quantum correlations in the Tavis-Cummings model**
Ekaterina Vlasiuk	**Two-dimensional spectroscopy of magnetic systems**
Darvin Wanisch	**Probing entanglement in open quantum systems with tree tensor networks**
Matteo Wauters	**Gauge protection in quantum simulations of non-Abelian LGTs by dynamical post-selection on qudit platforms**
Matthias Weidemüller	**Rydberg Spin Glas**
Tomasz Zawiślak	**Anomalous Doppler effect at zero temperature in density modulated superfluids and supersolid**
Philip Zechmann	**Fractonic phases in a constrained Bose-Hubbard model**

Abstracts of Lectures

(in alphabetical order)

Quantum simulation of Floquet topological phases with cold atoms

M. Aidelsburger

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Floquet engineering has emerged as a powerful experimental method for realizing topological phases in quantum simulators. Intriguingly, periodic driving can generate genuine out-of-equilibrium topological phases, known as anomalous Floquet topological phases, which have no static analog. These phases exhibit robust chiral edge modes despite all Chern numbers being zero.

We have established a versatile experimental toolbox to study a wide variety of Floquet topological phases in a periodically driven honeycomb optical lattice. In this setup, we explore the properties of distinct topological regimes via topological edge modes, local Hall deflection, expansion dynamics, and by probing the interplay with disorder introduced via an optical speckle potential.

One of the most fascinating properties of topological phases of matter is their robustness to disorder and imperfections. The tunability of our experimental setup allows us to investigate this robustness for both conventional and anomalous Floquet topological phases. These latter are expected to host new exotic phases, such as anomalous Floquet Anderson insulators, where fully localized bulk states coexist with extended edge modes.

Our results represent an important step toward understanding the rich interplay between topology and disorder in static and driven systems.

Enhancing pair tunneling with Floquet engineering

N. Klemmer[1], J. Fleper[1], V. Jonas[1], A. Sheikhan[1],
C. Kollath[1], M. Köhl[1] and A. Bergschneider[1]

[1]*Physikalisches Institut, University of Bonn, 53115 Bonn, Germany*

The Hubbard model has been very successful in describing quantum phases that emerge from the interplay of single-particle tunneling and on-site interaction. Its lack of explicit pair tunneling terms, however, makes the quantum simulation of various predicted quantum phases inaccessible.

We utilize Floquet engineering in chains of double wells to implement effectively interacting systems that show a crossover from explicit density-assistant to pair tunneling [1]. Exploring the effective parameters, we additionally observe an enhancement of pair tunneling amplitude beyond the effective superexchange of its undriven counterpart. These findings may bring the realization of novel quantum phases based on pairing mechanisms more within reach.

References

[1] Klemmer, N., Fleper, J., Jonas, V., Sheikhan, A., Kollath, C., Köhl, M., and Bergschneider, A., *Floquet-driven crossover from density-assisted tunneling to enhanced pair tunneling,* arXiv 2404.08482 (2024)

How to explore high-temperature superconductivity in optical lattices

Henning Schlömer, Hannah Lange, Sarah Hirthe, Dominik Bourgund, Titus Franz, Thomas Chalopin, Petar Bojović, Si Wang, Timon A. Hilker, Eugene Demler, Immanuel Bloch, Fabian Grusdt, and <u>Annabelle Bohrdt</u>

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5Laboratoire Charles Fabry, Institut d'Optique Graduate School, CNRS, Université Paris-Saclay, 91127 Palaiseau, France

6Institut für Theoretische Physik, Universität Regensburg, D-93035 Regensburg, Germany

The simulation of high-temperature superconducting materials by implementing strongly correlated fermionic models in optical lattices is one of the major objectives in the field of analog quantum simulation. The binding energies and critical temperatures in the plain vanilla Hubbard model are however significantly lower than currently achievable temperatures in cold atom experiments. In mixed-dimensional bilayer systems, the energy scales associated with the formation of pairs of charge carriers and superconductivity are both enhanced [1,2]. This has led to the observation of pairing in these models in a cold atom quantum simulator [3]. Recently, mixed-dimensional bilayer models have increasingly gained interest in the condensed matter community due to the discovery of high temperature superconductivity in the bilayer nickelates under pressure. Here we show how the critical temperature for superconductivity in these models can be achievable in current quantum simulators [2], enabling the long-sought realization of a state with long-range superconducting order. Additionally, we show how coherent pairing correlations can be accessed in a partially particle-hole transformed and rotated basis [4].

References

1. Bohrdt et al., Nature Physics 18 (2022)
2. Schlömer et al., arXiv:2311.03349
3. Hirthe et al., Nature 613 (2023)
4. Schlömer et al., arXiv:2406.02551

Quantum firmware: optimal control for quantum simulators

T. Calarco[1,2,3]

[1]Forschungszentrum Jülich, Jülich, Germany
[2]Universität zu Köln, Cologne, Germany
[3]Università di Bologna, Bologna, Italy

Quantum optimal control is well known to improve the performance of quantum technology devices up to their limits in terms e.g. of system size and speed of operation. I will introduce our recent results with a variety of quantum technology platforms, focusing in particular on ultracold atoms, and introduce the software we developed for automatic calibration of quantum operations. Focusing on neutral-atom implementations, I will present optimization results for each of the building blocks of a quantum simulator: from evaporative cooling to lattice loading, from qubit transport to entanglement generation and to higher stack functionality such as neural-network assisted gate synthesis for quantum compilation.

Data mining quantum simulators

M. Dalmonte[1]

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Recent experiments with quantum simulators and computersc have demonstrated unparalleled capabilities of probing many-body wave functions at the single quantum level via projective measurements. However, very little is known about to interpret and analyse such huge datasets. This represent a fundamental challenge for theory to understand experimental data, that is also relevant to other fields where similarly large data sets are routinely explored - from classical simulations of gauge theories, to observatory studies of many-body ensembles.

In this talk, I will show how it is possible to provide such characterisation of quantum hardware via direct and assumption-free data mining and modelling. The core idea of this programme is the fact that snapshots of many body systems can be construed as a very high-dimensional manifold. Such a manifold can be characterised via basic concepts, in particular, by their intrinsic dimension, and by advanced theoretical tools from network theory and (non-parametric) unsupervised learning.

This new approach to the many-body problem opens ups a cornucopia of methods to connect physical properties to a stochastic sampling of the system wave function. I will focus here on two specific applications. Firstly, I will discuss theoretical results for both classical and quantum many-body spin systems that illustrate how data structures undergo structural transitions whenever the underlying physical system does, and display universal (critical) behavior in both classical and quantum mechanical cases. These results pave the way for a systematic understanding of field theory aspects in data space, a topic of current interesting in particle and statistical physics. Secondly, I will discuss how our methods allow to track Kolmogorov complexity in quantum simulators and quantum computers, providing novel insights onto the working of such systems, in terms of both practical and fundamental aspects - including cross-certification of quantum devices, a grand challenge in the field. Finally, I will show how these developments can lead to a stochastic classification of quantum matter.

References

[1] T. Mendes-Santos et al., Phys. Rev. X 14, 021029 (2024), Phys. Rev. X Quantum 2, 030332 (2021); Phys. Rev. X 11, 011040 (2021);

[2] H. Sun et al., Phys Rev. E 109, 054305 (2024);

[3] R. Verdel et al., Phys. Rev. B 109, 075152 (2024).

Strongly interacting lattice fermions: flavour-dependent Mott localization and universal Hall response

L. Fallani[1,2,3]

[1] University of Florence, Dept. of Physics and Astronomy, Sesto Fiorentino, Italy
[2] LENS European Laboratory for Nonlinear Spectroscopy, Sesto Fiorentino, Italy
[3] CNR-INO, Sesto Fiorentino, Italy

I will present the results of recent experiments performed with ultracold ^{173}Yb fermions in optical lattices, in the presence of strong atom-atom interactions and coherent driving between different internal states.

I will discuss the realization of interacting SU(3) Fermi-Hubbard systems, where the addition of a coherent Raman coupling between different spin states is used to induce a controlled breaking of the SU(3) global interaction symmetry. This explicit symmetry-breaking action is shown to favour Mott localization and determines the onset of a flavour-selective behavior [1], in connection with the physics arising in strongly correlated materials from the coupling of different orbitals.

I will also discuss recent experiments where we have measured the Hall conductivity in interacting synthetic ladders obtained from a momentum-dependent Raman coupling, which implements the action of an external magnetic field on effectively charged particles. I will show a strong dependence of the Hall response upon changing atom-atom interactions and the emergence of a universal regime in the strongly interacting limit [2]. I will then discuss recent developments with the measurement of Hall voltages and Hall resistances [3], which provide a direct connection between quantum simulations and the most common measurements in solid-state systems.

References

[1] D. Tusi et al., Nature Physics **18**, 1201 (2022).
[2] T. Zhou et al., Science **381**, 427 (2023).
[3] T. Zhou et al., in preparation (2024).

Rotating dipolar quantum gases

Francesca Ferlaino
Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, A-6020 Innsbruck, Austria
Institute for Experimental Physics, University of Innsbruck, A-6020 Innsbruck, Austria

The talk will focus on the latest results of our research on ultracold dipolar quantum gases in Innsbruck. In particular, we will focus on the creation of quantized vortices in both the BEC [1] and in two-dimensional circular supersolid phases [2-3]. While in condensates, the density is nearly homogeneous and the vortices are almost free to move, in supersolids, a state in which local density maxima and minima alternate periodically with a wavelength comparable with the very radius of the vortex core, the vortices find intersize equilibrium positions and experience a pinning force that limits their motion.   Our experimental protocol uses an ultracold quantum gas of dysprosium atoms as the main resource, which is put into rotation by exploiting the new magnetostirring technique in which the atoms follow the rotational motion of an external magnetic field.

References

[1] L. Klaus, T. Bland et al., Nature Physics 18, 1453–1458 (2022).
[2] M. A. Norcia, C. Politi et al., Nature 596, 357-361 (2021).
[3] T. Bland et al., Phys. Rev. Lett. 128, 195302 (2022).

False vacuum decay via bubble formation in ferromagnetic superfluids

C. Rogora[1], D. Andreoni[1], C. Baroni[1,2], R. Cominotti[1], A. Zenesini[1,3], G. Lamporesi[1,3], G. Ferrari[1,3]

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Metastability stems from the finite lifetime of a state when a lower-energy configuration is available but only by tunneling through an energy barrier. In classical many-body systems, metastability naturally emerges in a first-order phase transition and a prototypical example is a supercooled vapor. The extension to quantum field theory and quantum many-body systems has attracted significant interest in the context of statistical physics, protein folding, and cosmology, for which thermal and quantum fluctuations are expected to trigger the transition from the metastable state (false vacuum) to the ground state (true vacuum) through the probabilistic nucleation of bubbles. However, the theoretical progress in estimating the relaxation rate of the metastable field through bubble nucleation has not been validated experimentally. Here, we discuss the experimental observation of bubble nucleation in isolated and coherently coupled atomic superfluids, and we support our observations with numerical simulations. More generally, we will discuss our experiments on magnetism based on superfluid multicomponent gases in an ultrastable magnetic field environment, which recently became available.

References

- Ferromagnetism in an extended coherently-coupled atomic superfluid, R. Cominotti et al., Phys. Rev. X. **13**, 021037 (2023).
- False vacuum decay via bubble formation in ferromagnetic superfluids, A. Zenesini et al., Nat. Phys. **20**, 558 (2024).
- Ultracold atomic spin mixtures in ultrastable magnetic field environments, R. Cominotti et al., Europhys. Lett. **146**, 45001 (2024).
- Towards a zero magnetic field environment for ultracold atoms experiments, C. Rogora et al., (2024), arXiv:2404.19565

Exploring pathways to lower temperatures for ultracold fermions

C. Groß[1]

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One of the most important challenges for fermionic systems in optical lattices is the quest for low temperatures. Only at temperatures below a few percent of the Fermi temperature correlation lengths become sizeable. This is the regime in which the system behaves highly collective, and where new quantum phases are expected to emerge. Despite significant progress in the recent years, the required temperatures have remained out of reach in optical lattices. Here we present a new experiment with a mixture of erbium and lithium atoms designed for optimized sympathetic cooling in optical lattices. We discuss the unique features of this surprisingly little explored mixture and present the current status of our new experimental setup designed to challenge the low-temperature frontier and to explore quantum many-body dynamics in new regimes.

Hole-hole attraction mediated by magnetism in the doped Fermi Hubbard Model

Timon A. Hilker[1,2]

[1] *Max Planck Institute of Quantum Optics, Garching near Munich, Germany*
[2] *University of Strathclyde, Glasgow, United Kingdom*

Unravelling the origin of unconventional superconductivity is one of the driving forces behind quantum simulations with ultracold Fermions in optical lattices. In these strongly correlated materials, the necessary pairing of charge carriers is often assumed to be related to the competition between antiferromagnetic correlations and dopant motion.
With our quantum gas microscope, we can see this interplay of spin and charge in snapshots of the many-body wavefunction. We find strong competition between a magnetically mediated hole-hole attraction and repulsion due to Pauli blocking. In a mixed-dimensional system, where we restrict the hole motion to one dimension while keeping the spin order two-dimensional, attraction dominates, and we directly image tightly bound pairs of holes [1] and find extended hole structures with signatures of stripes [2]. Also in the standard Hubbard model, we observed the first evidence of attraction between holes, when the system is cooled into the pseudo-gap regime.
Finally, I will present an outlook on how a few digital gates in an optical superlattice [3,4] can advance these analogue quantum simulations and finish with the question if a fully digital Fermionic quantum computer [5] is a goal worth pursuing.

References

[1] S. Hirthe, T. Chalopin, A. Bohrdt, D. Bourgund, P. Bojović, F. Grusdt, E. Demler, I. Bloch, and T. A. Hilker. „Magnetically mediated hole pairing in fermionic ladders of ultracold atoms". Nature **613** 463 (2023)

[2] D. Bourgund, T. Chalopin, P. Bojović, H. Schlömer, S. Wang, T. Franz, S. Hirthe, A. Bohrdt, F. Grusdt, I. Bloch, and T. A. Hilker. „Formation of stripes in a mixed-dimensional cold-atom Fermi-Hubbard system". arXiv:2312.14156.

[3] T. Chalopin, P. Bojović, D. Bourgund, S. Wang, T. Franz, I. Bloch, and T. A. Hilker. Optical superlattice for engineering Hubbard couplings in quantum simulation. arXiv:2405.19322.

[4] H. Schlömer, H. Lange, T. Franz, T. Chalopin, P. Bojović, S. Wang, I. Bloch, T. A. Hilker, F. Grusdt, and A. Bohrdt. Local control and mixed dimensions: Exploring high-temperature superconductivity in optical lattices. arXiv:2406.02551.

[5] González-Cuadra, *et al*., Fermionic quantum processing with programmable neutral atom arrays. PNAS, **120**(35), e2304294120. (2023)

Sound and amplitude modes in trapped dipolar supersolids

Jens Hertkorn[1], Philipp Stürmer[2], Koushik Mukherjee[2], Kevin SH Ng[1], Paul Uerlings[1], Fiona Hellstern[1], Lucas Lavoine[1], Stephanie Reimann[2], Tilman Pfau[1], Ralf Klemt[1]

[1]5. Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany [2]Division of Mathematical Physics and NanoLund, LTH, Lund University, Box 118, SE-221 00 Lund, Sweden

About five years ago, the emergence of supersolid properties was observed in harmonically trapped dipolar quantum gases in three groups in Pisa, Innsbruck and Stuttgart [1-3]. Since then, many additional experimental and theoretical studies have shed light on the nature of this novel phase including studies on the superfluid to supersolid phase transition, the coherence in the system including the emergence and structure of the low energy collective modes [4] and the appearance of quantized vortices [5].
In this talk, I will review these developments, with a particular focus on the experimental and theoretical study of defining sound and amplitude modes. In addition, I will also present very recent results from our group [6]:
In a numerical study, we have investigated how uncoupled amplitude and sound excitations emerge in a dipolar torus supersolid. The Higgs amplitude mode manifests itself as a pure amplitude oscillation of the order parameter while the sound modes of the superfluid splits up into two branches in the supersolid phase, which we interpret as first and second sound. This study allows us to unify previous notions of modes in finite trapped supersolids and allows us to establish a direct correspondence to infinitely extended linear supersolids.
I will also present a protocol for selectively probing theses modes in upcoming experiments and will give an update our current efforts towards a new generation Dysprosium quantum gas experiment in Stuttgart.

References

[1] L. Tanzi et al.: *Observation of a Dipolar Quantum Gas with Metastable Supersolid Properties,* Phys. Rev. Lett. **122**, 130405 (2019)

[2] L. Chomaz et al.: *Long-lived and transient supersolid behaviors in dipolar quantum gases,* Phys. Rev. X **9**, 021012 (2019)

[3] F. Böttcher et al.: *Transient Supersolid Properties in an Array of Dipolar Quantum Droplets,* Phys. Rev. X **9**, 011051 (2019)

[4] A. Recati and S. Stringari, *Supersolidity in ultracold dipolar gases*, Nature Preview Physics **5**, 735743 (2023)

[5] E. Casotti et al.: *Observation of vortices in a dipolar supersolid*, arXiv:2403.18510 (2024)

[6] J. Hertkorn et al.: *Decoupled sound and amplitude modes in trapped dipolar supersolids,* arXiv:2404.12384 (2024)

Tensor network algorithms for quantum simulations

S. Montangero

Padova University

We review some recent results on the development of efficient tree tensor network algorithms and their applications to high-dimensional many-body quantum systems. In particular, we present recent results on two and three-dimensional lattice gauge theories in presence of fermonic matter at finite densities. Moreover, we show how to compute the entanglement of formation in critical many-body quantum systems at finite temperature, resulting in the generalization of the logarithmic formula for entanglement to open systems. We present one and two-dimensional simulations of out of equilibrium dynamics and how to implement them on different quantum simulation platforms. Finally, we present a resources estimations for quantum and quantum-inspired for future simulation of lattice gauge theories.

Physical Review Research 6 (3), 033057 (2024)
Physical Review Letters 128 (4), 040501 (2022)
Nature communications 12 (1), 3600 (2021)

Quantum Field Simulator: Connecting Cosmology and Supersolidity

M.K. Oberthaler

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The study of space-continuous physics in the many-body limit is the natural regime of ultracold gases. The term quantum field simulator emphasizes the continuum aspect of space-time as well as the quasi-continuous observables, e.g. macroscopic spin degrees of freedom or density and phase of the order parameter. It also implies the ability to introduce and dial in unconventional initial conditions or general time dependencies in the quantum field theoretical settings under study.

Here, I will report on our recent findings with our quantum field simulation platform of a quasi-two-dimensional quantum gas of potassium atoms with additional control of two particle interaction and local density and phase of the order parameter. As an introduction, I will shortly review our studies on curved space-time and cosmological particle production [1]. These results are examples of analog gravity experiments and rely essentially on the perturbative regime where direct comparison between experiment and analytical theoretical predictions is possible. A mapping of the phenomenon of particle production onto a single particle scattering problem gives new insights and motivates the study of bouncing universes, a scenario that is not even described by the classical Einstein field equations. Nevertheless, the simulation platform allows the study of this regime and confirms the perturbative expectations. But, the platform also allows going beyond the perturbative regime. There we have discovered, that the cosmological principle, i.e. the homogeneity and isotropy of space-time, is spontaneously broken and a periodic spatial modulation of the metric emerges.

We show that this phenomenon can be understood as a drift towards an attractive nonlinear fixed point [2], which is theoretically discussed in the framework of multi-scale analysis [3]. Since the capability of our quantum field simulator also allows the preparation of the system *at* the predicted fixed point we can probe the excitation spectrum using the versatile local control of the order parameter. We find that the emerging crystalline structure has both superfluid and lattice excitation as expected for a one-dimensional supersolid. Since the system also allows the preparation and stabilization of a stripe phase, we can probe in detail the prediction of the recently discussed superfluid smectic-A liquid crystal phase [4].

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Understanding and controlling collisions in quantum gases of polar molecules

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Quantum gases of polar molecules offer a unique platform to investigate complex molecular interactions and collisions, with important implications for quantum simulation and precision measurement. In this talk, I will present recent experiments with quantum gases of polar bosonic $^{23}Na^{39}K$ molecules, focusing on inelastic atom-molecule and molecule-molecule collisions, their underlying mechanisms [1,2,3]. I will also discuss the control of atom-molecule collisions via Feshbach resonances, as well as a proposal for "blue shielding" of polar molecule collisions using optical photons at Raman resonance [4].

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Sound propagation and Doppler effect in Supersolid Dipolar gases

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Hydrodynamics modes are a key consequence of the presence of conserved quantities and order parameters in a many-body system. The identification and the experimental observation of such modes provide a wealth of information on the constitutive relations for the macroscopic dynamical variables. In this talk I will discuss the zero-temperature dispersive hydrodynamic modes for the modulated superfluid and supersolid phase of ultra-cold gases and propose a protocol to address the speeds of sound as well as the relation of them with the hydrodynamic parameters is discussed [1].
I will show how the speeds of sound of such systems present an anomalous Doppler shift in presence of a stationary flow [2]. Such a zero-temperature anomaly is due to the breaking of translational invariance and the consequent presence of superfluid and normal fraction in the gas. Such an effect represents the zero-temperature analogous of the anomalous Doppler shift discuss in the context of Helium-4 (e.g. [3]).

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Vortex matter in strongly-correlated superfluids

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Topological defects play a crucial role in shaping the properties and structures of various out-of-equilibrium physical and biological systems across a broad spectrum of scales. These systems range from planetary atmospheres and turbulent flows in classical and quantum fluids to the electrical signaling in excitable biological media [1]. In superfluids and superconductors, the motion of quantized vortices is linked to the onset of dissipation, which limits the superflow [2]. Comprehending vortex dynamics poses a significant challenge due to the intricate interplay among vortices, disorder, and system dimensionality.

We tackle this challenge by investigating vortex matter in planar homogeneous Fermi superfluids [3]. By engineering vortex configurations and monitoring their evolution through tracking vortex trajectories, we gain unparalleled control over vortex dynamics. This capability transforms our system into an ideal "quantum laboratory" for unraveling the fundamental nature of vortex-driven instabilities and dissipation [4,5]. Our research opens prospects for understanding vortex-matter phenomena in strongly correlated superfluids.

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Fermionic ytterbium atoms for quantum simulations beyond the Hubbard model

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In many quantum materials, the electronic orbital degree of freedom and its interplay with electrons spin play a decisive role. A notable example is the interaction of a conduction band with localized spin impurities, giving rise to the famous Kondo effect. Owing to the richness of atomic systems and the exceptional control over Hamiltonians, atomic quantum simulators provide now a unique playground for shedding light on the correlated behaviour of fermionic systems defying a single-band Hubbard-like description. Moreover, recent advances in microscopic optical manipulation have extended our experimental control capabilities down to the level of single atoms, affording exciting opportunities to explore quantum many-body problems with a novel bottom-up perspective. I will present a new experimental platform under completion in Trieste, allowing to manipulate individual ytterbium atoms for engineering mesoscopic multi-orbital fermion systems. Odd ytterbium isotopes present unparalleled features allowing to tackle open questions in Kondo physics, while also linking to the development of future optical clocks and digital quantum processors. I will report on our rapid experimental scheme for laser cooling, loading and imaging tweezer-trapped fermionic ytterbium arrays with Hz repetition rates, and I will illustrate our main research directions in quantum impurity problems and SU(N)-symmetric systems.

Strongly interacting Bose-Fermi mixtures in cold atoms and two-dimensional materials

Prof. Richard Schmidt
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In this talk I will discuss how one can transfer physical concepts and mechanisms originally explored in the context of ultracold atoms to atomically thin materials and back. Specifically, I will focus on strongly interacting Bose-Fermi mixtures realized in two universally connected settings. The first are ultracold mixtures of bosonic and fermionic atoms that interact with short-range or dipolar interactions. The second setting investigates mixtures comprised of excitons and electrons in the emerging research field of two-dimensional materials. Starting from the limit of large population imbalance between fermions and bosons, where polaron formation has been observed, we will review recent advances in understanding mixtures at finite density. We will discuss the competition of polaronic superfuid and molecular Fermi gas formation, and outline a new mechanism to realize an emerging BEC-BCS crossover in the form of boson-induced superconductivity. Finally, we will comment on prospects on the use of ultracold atoms in optical lattices to perform detailed quantum simulations of the physics of exciton formation in two-dimensional materials which may allow to address major open questions in the field of solid-state physics.

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Towards new frontiers of quantum science with dual-species atom arrays

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In this talk, we will explore recent advancements in quantum science using Rydberg atom arrays and present future applications enabled by the use of a dual-species array based on a mixture of alkali and alkaline-earth atoms. Trapped arrays of interacting Rydberg atoms have become a leading platform for quantum information processing and quantum simulation due to their large system size and programmability. The use of two atomic species allows for the independent control of two different sets of qubits for quantum error correction, and selective tuning of inter- and intra-species interactions for more flexible Hamiltonian engineering. These new features enable more efficient protocols for quantum information processing and would allow to simulate a broader class of highly-entangled phases of matter. We will present the current development of a new experimental platform based on Yb and Rb atom arrays, leveraging the distinct characteristics of these two atomic species to create a versatile platform for quantum simulation and quantum information processing.

Exploring the supersolid phase of matter with an atomic quantum simulator

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Supersolidity is a paradoxical quantum phase of matter that combines the properties of superfluids and crystals. Although it was proposed for helium more than 50 years ago, its experimental verification has long been elusive. In 2018, at the 'Dysprosium Lab' in Pisa, we discovered supersolidity in an ultracold sample of strongly magnetic atoms [1]. In this talk, I will report on a series of experiments aimed at revealing the fundamental nature of dipolar supersolids, shedding light on their intertwined superfluid and solid character. In particular, I will focus on a recent experiment that, for the first time, measures a subunity superfluid fraction in dipolar supersolids by exploiting the self-induced Josephson dynamics between the supersolid clusters [2]. Supersolids are a new phase of matter with unconventional properties, many of which are still unknown. Understanding their physical behaviour could also open up new avenues for potential applications, such as the creation of innovative quantum materials.

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A phase microscope for quantum gases

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Coherence properties are central to quantum many-body systems and are at the heart of phenomena such as superconductivity. Here we study coherence properties of an ultracold Bose gas in a two-dimensional optical lattice across the thermal phase transition. We use direct matter-wave imaging [1] of the Talbot revivals to infer the phase coherence. These tools will be vital for studying coherence properties in strongly-correlated quantum systems in a spatially resolved manner, e.g., for detecting phase domains or resolving superfluid domains in inhomogeneous systems. We also discuss implications for the strongly-correlated regime.

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Abstracts of Posters

(in alphabetical order)

Stochastic Sampling-Based Classification of States of Matter

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Classifying phases of matter traditionally requires knowledge of the symmetries and properties of the system in question. However, inspired by experimental capabilities for stochastic sampling of wave functions via projective measurements, we explore whether classification can be achieved based solely on these measurements, without prior system knowledge. We introduce a novel classification method for states of matter in one spatial dimension based on stochastic sampling of the system's wave function. This method employs two distinct analyses, which yield complementary info that allow a full classification of the distinct phases. The first one involves examining the intrinsic dimension of the dataset derived from the samples, which effectively discriminates between different phases. The second analysis constructs networks from the sample dataset, where the network properties are sensitive to phase transitions. Notably, we observe the emergence of scale-free networks near critical points and within critical phases. This method offers a practical way to classify phases of matter using only measurement data.

Measurement of the superfluid fraction of a supersolid by Josephson effect

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Many quantum materials in various systems, ranging from superconductors to superfluid helium, feature a spatially modulated macroscopic wavefunction resulting from the spontaneous breaking of gauge and translational symmetries. Their connection with supersolids [1], so far observed in different quantum gases platforms, has only been traced in a few cases since a universal property able to quantify the differences between supersolids, superfluids/superconductors, and crystals has not been established. A key quantity, introduced by A. Leggett in the 1970s, is the superfluid fraction [2] which measures the reduction of the superfluid stiffness due to spatial modulations. A reduced superfluid fraction leads to the non-standard superfluid dynamics of supersolids. We employ the Josephson effect [3] to locally measure the superfluid fraction in a supersolid. Even without a physical barrier, the Josephson effect arises spontaneously in supersolids, and single lattice cells act as self-induced Josephson junctions. We study a cold-atom dipolar supersolid [4], revealing a significant sub-unity superfluid fraction. Our results point to new research directions, like the study of partially quantized vortices and supercurrents, and have an impact on the understanding of other supersolid-like systems.

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Diagnosing transport from wave function snapshots

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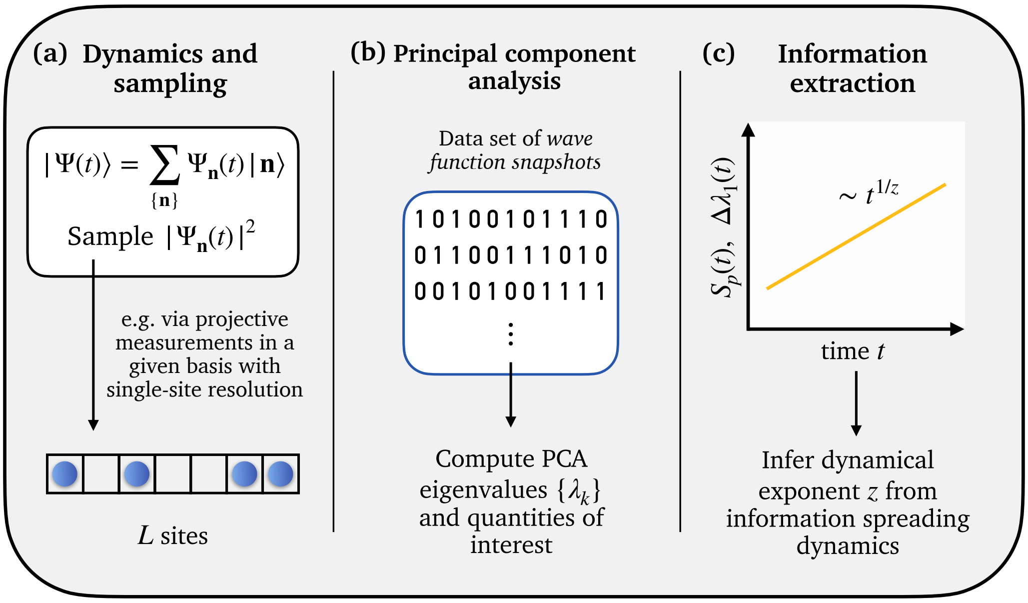
Quantum systems driven out-of-equilibrium exhibit many exciting features, such as non-trivial quantum transport and information propagation. I will discuss how the tools of non-parametric learning, specifically the principal component analysis (PCA) on data sets of wave function snapshots, can help identify distinct spin/energy transport in quantum spin chains with a limited number of data samples. Specifically, our approach enables an easy, data-driven, and importantly interpretable diagnostic to track energy transport with a limited number of samples, which is usually challenging without any assumption on the Hamiltonian form. The main findings, along with the methodology, are shown in the schematic below.



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Prethermalization in one-dimensional quantum many-body systems with confinement

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Unconventional nonequilibrium phases with restricted correlation spreading and slow entanglement growth have been proposed to emerge in systems with confined excitations, calling their thermalization dynamics into question. Here, we show that in confined systems the thermalization dynamics after a quantum quench instead exhibits multiple stages with well separated time scales. As an example, we consider the confined Ising spin chain, in which domain walls in the ordered phase form bound states reminiscent of mesons. The system first relaxes towards a prethermal state, described by a Gibbs ensemble with conserved meson number. The prethermal state arises from rare events in which mesons are created in close vicinity, leading to an avalanche of scattering events. Only at much later times a true thermal equilibrium is achieved in which the meson number conservation is violated by a mechanism akin to the Schwinger effect. The discussed prethermalization dynamics is directly relevant to generic one-dimensional, many-body systems with confined excitations.

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A coherence microscope for quantum gases

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Gaining insights into the complete wavefunction of a many-body system is fundamental for understanding its underlying mechanisms. Quantum gas microscopes have emerged as powerful tools capable of resolving density distributions on individual lattice sites, thus enabling precise reconstruction of the density component of the full wavefunction. Here, we present an innovative approach to resolve the phase of the wavefunction. Using matter-wave microscopy we achieve lattice site resolution of our triangular lattice of tubes. By harnessing the Talbot effect, we can measure coherence within the system and observe the loss of coherence for deeper lattice depths. Our method holds promise for detecting phases on each lattice site creating a full-fledged phase microscope in the future.

TITLE: "Josephson current flowing through a nontrivial geometry"

AUTHORS: V. Piselli, L. Pisani, G. Calvanese Strinati

ABSTRACT:
Most theoretical treatments of inhomogeneous superconductivity/ fermionic superfluidity have been based on the Bogoliubov-deGennes (BdG) equations (or, else, on their various simplified forms), which implement a standard mean-field decoupling in the presence of spatial inhomogeneities. This approach is reliable even at finite temperature for weak inter-particle attraction, when the Cooper pair size is much larger than the average inter-particle distance (corresponding to the BCS limit of the BCS-BEC crossover). However, it loses accuracy for increasing attraction when the Cooper pair size becomes comparable or even smaller than the average inter-particle distance (corresponding to the BEC limit of the BCS-BEC crossover), and in particular when finite-temperature effects are considered. In these cases, inclusion of pairing fluctuations beyond mean field is required, a task that turns out to be especially difficult in the presence of inhomogeneities. In this work, the inclusion of pairing fluctuations is implemented directly on a coarse-graining version of the BdG equations, which makes it simpler and faster to obtain a solution over the whole sector of the temperature-coupling phase diagram of the BCS-BEC crossover in the broken-symmetry phase. This method is applied in the presence of a supercurrent flow, such that problems related to the Josephson effect throughout the BCS-BEC crossover can be addressed under a variety of circumstances. This is especially relevant in the view of recent experimental data with ultra-cold Fermi atoms, to which the outcomes of the present approach are shown to favorably compare.

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Dynamical formation of multiple quantum droplets in a Bose-Bose mixture

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In our most recent work, we report on hydrodynamical instabilities of a ^{41}K-^{87}Rb quantum droplet: after preparation in an elongated trap, the droplet is kept in a waveguide, where the collective modes excited during the preparation cause it to elongate up to a certain critical length, after which the sample splits into two or more smaller droplets.

This behaviour, as well as its dependence on the interspecies interaction strength and the number of atoms, is consistent with what is expected for a kind of hydrodynamic instability known as capillary instability, where the surface tension of a liquid causes the break-up of a filament into smaller droplets; such a phenomenon is observed in classical liquids, and is also expected in their quantum counterparts [1].

With these results, we can begin to explore the new and relatively undiscovered phenomena related to quantum liquids, in general, and of quantum droplets, in particular, opening new possibilities in the improvement of our understanding of multi-component superfluids.

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Atom transport optimization: theoretical frameworks, algorithms, and experimental integration

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Quantum simulation has become a powerful approach for studying complex quantum systems that cannot be efficiently addressed by classical computational methods. Trapped neutral atoms offer unique advantages such as long coherence times and precise manipulation of external parameters, making them highly suitable for exploring optimization techniques. Optimization of atomic transport is critical for the implementation of quantum gates, allowing precise transport of individual atoms within quantum platforms such as optical tweezers [1,2,3]. We focus on the optimal shaping of control pulses and the formulation of theoretical frameworks to maximize transport fidelity. The d-CRAB optimization algorithm is used under different initial conditions to estimate the quantum speed limit of the system under consideration [5,6]. To further explore the control landscape, we compute pulse guesses using adiabatic shortcuts. Integrating this analytical approach into the optimization leads to a more stable and faster transport solution [1,4]. We investigate how increasing the trapping frequency of the moving tweezers and reducing the total transport time affects transport fidelity, with the goal of implementing the theoretical protocols in experimental setups.

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Interplay of Short-Range and Long-Range Interactions in Ultracold Fermionic Lattice Systems: A Real-Space DMFT Approach

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The recent realization of the self-organization phase transition of fermionic quantum gases in driven dissipative optical cavities has opened numerous new research avenues [1, 2]. This system enables the investigation of the interplay between short-range contact interactions and cavity-mediated long-range interactions. Due to the global nature of the coupling between the single cavity mode and the quantum gas, the relaxation rate is suppressed by the number of atoms, justifying the use of a thermal-equilibrium approach to the steady state of the system. In the additional presence of a background static optical lattice, such a system can be described by an extended Hubbard model. Our focus is on the emergence of different types of density and spin ordered phases. We apply real-space Dynamical Mean-Field Theory (DMFT) [3] to investigate this system for two dimensions, at half-filling, and with repulsive short-range interactions. Our objective is to determine the phase diagram, which is expected to include the homogeneous Fermi liquid, paramagnetic Mott insulator, antiferromagnetic Mott insulator, and insulating density wave phases. Preliminary results focus on the effects of long-range interactions on the paramagnetic metal-insulator phase transition as well as the on emergence of density wave ordering.

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Report on the construction of a new Erbium-Lithium machine

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We are building up a new mixture experiment with Erbium and Lithium. With the help of sympathetic cooling, we hope to explore unreached super low temperature regimes of the Fermi Hubbard model. With this simple, but strong and rich model, solid state systems can be described and simulated with another quantum system that can be highly controlled. With the participation of the seminar I hope to increase and deepen my knowledge about quantum simulations with ultra cold atoms by not only listen to great talks, but also in personal conversations about this thrilling topic.

Persistent currents in a Josephson junction necklace

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The emergence of persistent currents (PC) in rings is one of the most striking manifestations of quantum coherence. The periodic boundary of such a geometry constrains the wavefunction phase to wind in a loop of an integer multiple of 2π, which gives rise to a notably stable current, protected by its topological nature. Here, I will report on our recent experimental studies on the stability of PC in fermionic superfluid rings of ultracold atoms and its connection with vortices, excitations sharing the same topological nature. In the clean ring, PCs of high and on-demand winding number are created by the phase imprinting technique [1]. The current decay is triggered by introducing a localized obstacle in the ring, which fosters the emission of vortices and the consequent decrease of the current winding number [1, 2]. The current decays via a similar mechanism - vortex emission - even when turning the localized obstacle into a tunneling barrier. However, the coherence properties of the Josephson junction realized in the presence of the tunneling barrier yields to a counter-intuitive stabilization of the current upon increasing the number of junctions, namely increasing the number of barriers in the ring [3]. In agreement with an analytic treatment of the Josephson junction necklace problem and with numerical simulations, we observe stable supercurrents of high winding number in the presence of a large number of barriers. Our results demonstrate atomic ring superfluids as promising candidates for atomtronics applications.

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Emergent orbital physics and chiral phases in dimerized pi-flux lattices

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We show that a viable route to generate strongly-interacting chiral phases can exploit the interplay between onsite interactions and flux frustration for bosons in dimerized lattices with pi-flux. By constructing an effective theory, we demonstrate how this interacting setting favours the spontaneous breaking of time-reversal symmetry in a similar fashion as atoms in higher bands. This can lead to the realization of the long-sought chiral Mott insulator phases, which we characterize via DMRG and variational calculations. Furthermore, dynamical properties like the chiral motion of impurities is identified via spectroscopy and quenches. Protocols to perform state preparation and current measurements will also be discussed.

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Spectral properties of ultracold Fermi gases

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We calculate non-perturbative self-consistent fermionic and bosonic spectral functions of ultracold Fermi gases directly in real frequencies, without the need for numerical reconstruction methods. The spectral functions provide access to the transport and excitation properties of the ultracold gas and are used to determine various physical observables, like radio-frequency spectra or Tan's contact. The results are compared to state-of-the-art imaginary-time computations and quantitative differences are found. Our approach offers a wide range of applications, including the ab initio calculation of transport and spectral properties in the superfluid phase of the BCS-BEC crossover.

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Relaxation in dipolar spin ladders: From pair production to false-vacuum decay

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Ultracold dipolar particles pinned in optical lattices or tweezers provide an excellent platform for the study of the intriguing equilibration dynamics of spin models with dipolar exchange. Starting with an initial state in which spins of opposite orientation are prepared in each of the legs of a ladder lattice, we show that spin relaxation displays an unexpected dependence on interleg distance and dipole orientation. This dependence, stemming from the interplay between intra- and interleg interactions, results in three distinct relaxation regimes: (i) ergodic, characterized by the fast relaxation towards equilibrium of correlated pairs of excitations generated at exponentially fast rates from the initial state; (ii) metastable, in which the state is quasilocalized in the initial state and only decays in exceedingly long timescales, resembling false-vacuum decay; and, surprisingly, (iii) partially relaxed, with coexisting fast partial relaxation and partial quasilocalization. The realization of this intriguing dynamics is at hand in current state-of-the-art experiments in dipolar gases.

Differential Mach-Zehender interferometry with trapped Bose Einstein condensates

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We report on the first realization of a gradiometric sensor based on Mach-Zehender trapped atom interferometers. By using innovative Beat Note Superlattices [1] we create an array of double-well traps loaded with Bose Einstein condensates of atomic potassium (See Fig.1). Once the collisional scattering length is cancelled with a broad magnetic Feshbach resonance, we can operate the beam splitters of the interferometers with simple control of the tunneling probability of the atoms through the central barrier. This allows us to determine the phase of each interferometer without releasing the atoms from the trap and measuring the final atomic population in the two modes. The simultaneous operation of the interferometers allows us to perform a differential analysis and cancel the common phase noise of the sensors (See Fig. 2). A coherence times of several hundred milliseconds is reported.

Our system opens the possibility to exploit quantum entangled states in trapped atom interferometry, even in presence of strong noise and paves the way to high precision measurements of forces with high spatial resolution. In the long term, we envision the possibility of exploiting our system for the measurement of higher-order interaction terms, such as magnetic dipolar interaction and three-body elastic collisions and the production of maximally entangled atomic quantum states.

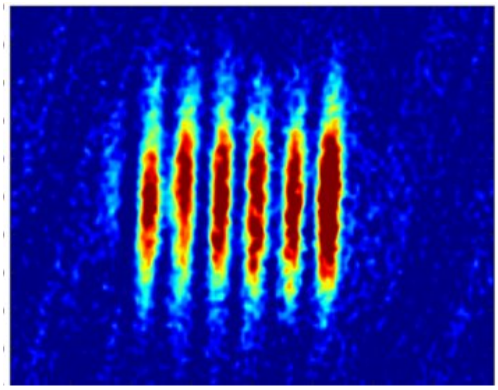
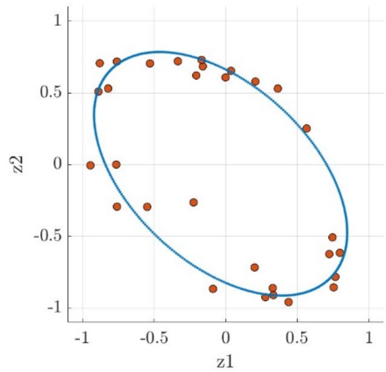


Fig. 2. Final atomic imbalance of interferometer 1 vs interferometer 2. The common mode noise distributes the data on an ellipse whose eccentricity is linked to the phase difference of the two interferometer output.



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Non-Gaussian Correlation in the steady state of a superradiant cloud

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We experimentally measure the second-order coherence function of the light emitted by a laser-driven dense ensemble of atoms, dyspling strong superradiant features [1,2]. We observe a clear departure from the Siegert relation valid for Gaussian chaotic light. Measuring intensity and first-order coherence, we conclude that the violation is not due to the emergence of a coherent field. This indicates that the light obeys non-Gaussian statistics, stemming from non-Gaussian correlations in the atomic medium [3].

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Shapiro steps in a ^{6}Li Fermi superfluid Josephson junction

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Josephson junctions represent a powerful tool to probe macroscopic phase coherence in different systems. They are also fundamental for atomtronics circuits, thanks to their well defined current-chemical potential and current-phase. In our experimental system, we create atomic Josephson junctions using Fermi superfluids of lithium-6, realized by coupling two quasi-two-dimensional atomic clouds with a tunneling barrier. By moving the tunneling barrier across the junction while modulating the position at a given frequency, we are able to inject an alternate current. Then, measuring the chemical potential imbalance developed across the junction after a few modulation periods, we can study the dynamics resulting in the system. Our experimental results show that the AC driving of the barrier introduces a step-like behavior in the current-chemical potential curve, with a number of plateaus at a chemical potential value that is an integer multiple of the driving frequency [1]. This behavior is the analog of Shapiro steps observed in superconducting Josephson junctions illuminated by an external electromagnetic field [2]. We studied the AC response for a molecular BEC and a unitary Fermi gas junction, finding that in both cases the plateaus in the current-chemical potential characteristic coincides with the emission of a well-defined number of vortices, suggesting that the stabilization of the current in the plateaus is operated by phase slippage processes.

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Two-fluid character of a binary dipolar quantum gas across the superfluid-supersolid-crystal phase transition

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Following Ref. [1] for the single-component case, we have studied the physics of a binary dipolar mixture across the unmodulated-supersolid-individual droplet crystal transition. We have studied first the phase diagram of the system as a function of the polarization and the intercomponent scattering length, displaying the characteristic catalyzation phenomenon [2]. Collective modes have been studied by means of two different approaches: analysis of the Fourier signal of a real-time dynamics, inspired by experiment [3] and by numerical diagonalization of the Bogoliubov equations. The softening of the Higgs mode across the supersolid-unmodulated transition is encountered [1], as well as the softening of the superfluid modes when the system enters the individual droplet regime. Such modes crash when the system enters the individual droplet regime, indicating that they are phase modes and therefore, crystallization in binary mixtures can not be explained by means of scalar two-fluid models.

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Towards low temperature states in a Fermi-Hubbard quantum simulator

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Ultracold fermionic atoms in an optical lattice provides a pristine realization of the Fermi-Hubbard model, a fundamental model in condensed matter physics that captures the essential characteristics of many strongly correlated systems. However, reaching the low temperatures required to observe exotic phases remains challenging for cold-atom quantum simulators. We report on recent progress in expanding the capabilities of our optical lattice for quantum gas microscopy of lithium-6 atoms. We implemented a dynamically tunable lattice potential, which enables us to reach lower temperatures in the square lattice by exploring schemes for entropy redistribution and adiabatic state preparation. Additionally, combined with a spatial light modulator, this tunable lattice enables us to study Hubbard models beyond the standard square lattice, where exotic phases can emerge even at higher temperatures.

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Long Range Interactions in Synthetic Dimensions

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In recent cold atom experiments, the utilization of internal degrees of freedom as synthetic dimensions has enabled the simulation of higher-dimensional systems. Specifically, magnetic quantum numbers have been employed to transform a 1D chain of atoms into a synthetic 2D lattice, resulting in the realization of an integer quantum Hall state. However, this configuration introduces highly anisotropic and long-range particle interactions. To facilitate theoretical analysis, we use finite size Tree Tensor Networks to simulate truly 2D physics. The high connectivity of this ansatz allows us to explore the impact of long-range interactions on the phases realized in the system. Our investigation delves into the emergence of new phases, the study of phase transitions, and the stability of configurations under the influence of extreme long-range interactions. This research contributes to a deeper understanding of the intricate interplay between synthetic dimensions and particle interactions in cold atom systems.

Dissipative vortex dynamics in strongly interacting Fermi superfluid.

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At zero temperature, quantum vortices exhibit nearly dissipation-free dynamics, following the motion of the surrounding superfluid. However, at finite temperature, the coexistence of both a normal and superfluid components alters this behavior. Quantized vortices act as a medium for momentum exchange between the normal and superfluid components leading to the emergence of dissipative mechanisms [1]. Here, vortex dynamics is described by the dissipative Point Vortex Model (PVM), where dissipation effects are encoded into α and α' phenomenological coefficients [1]. In Fermi superfluids, quasiparticles populating the Andreev bound states localized in the vortex cores are expected to introduce additional channels for dissipation compared to bosonic superfluids [1].
In our experiment, we investigated the dissipative dynamics of vortices in a homogeneous oblate unitary Fermi gas by generating a single vortex dipole [2-3]. Leveraging precise control over the position of individual vortices, we tracked their trajectories across different temperatures. We compared the dynamics with numerical simulations within the SLDA approximation. We analyzed both the experimental and theoretical vortex trajectories within the framework of the PVM to directly obtain the mutual friction coefficients [4]. The numerical simulations allowed us to connect α and α' to the density of localized and delocalized excitations of the system.

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Quantum simulation of Hubbard models: From unconventional superconductors to gauge theories

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Recent advances in quantum simulation, in a range of experimental platforms, allow for unprecedented microscopic studies of strongly correlated quantum matter. This talk will focus on a long-standing goal of the field: The study of fermionic Hubbard models. On one hand, the plain-vanilla square lattice Hubbard model is believed to underly high-temperature superconductivity. On the other hand, variations of the Hubbard model can describe other unconventional superconductors, and under appropriate circumstances allows to even realize emergent non-Abelian gauge theories akin to the models underlying quark confinement. We will provide an overview of the state of the field, highlighting symbiotic efforts of theoretical and experimental work, and explain future prospects such as reaching phase-coherent superconductivity and realizing lattice gauge theories in table-top experiments. New insights obtained, broadly speaking, by quantum simulation efforts into the origin of strong pairing in doped Hubbard models will also be discussed, showcasing the ability of quantum gas microscopy experiments to reveal the microscopic structure of the emergent charge carriers in these fascinating systems whose properties are governed by strong fermionic correlations.

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Strontium atoms in optical tweezers

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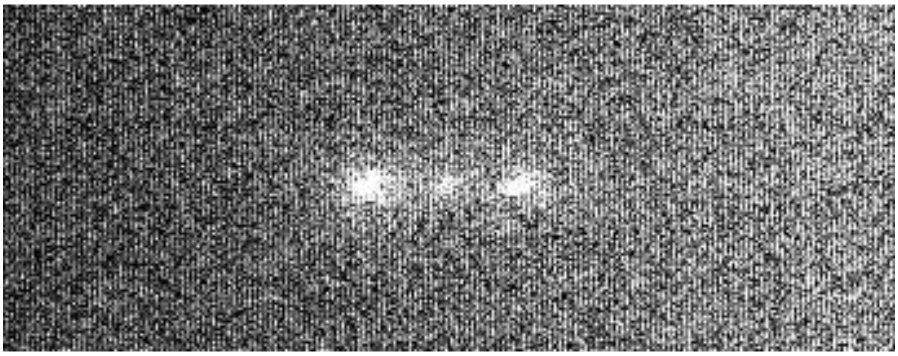
Rydberg atoms in optical tweezer arrays are rapidly becoming one of the most interesting platforms to approach both quantum simulation problems and quantum computing schemes. In my poster I will describe the progress of the Strontium Rydberg lab machine, based in Florence. The experimental platform will be described, with a particular focus on the vacuum and coils systems, and the realization of a two-stage three-dimensional Magneto Optical Trap (MOT) exploiting Strontium narrow transitions. I will report the characterization of the cold atomic cloud and the first trapped atoms in optical tweezers. Finally, the following steps towards the realization of the machine will be addressed, giving some perspectives on future studies employing Rydberg atoms in optical tweezers, such as the quantum simulation of 1D and 2D spin models, and the generation of multiparticle entangled states.



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A modular quantum gas platform

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We report on the development of a **fully modular platform**, which bears the potential to standardize the design and implementation of modern quantum gas experiments with broad applicability in quantum technologies. The platform offers all basic tools needed for typical quantum simulation setups and connects them in an easily expandable way to enable fast exchange of optical hardware. With this platform, called the "**Heidelberg Quantum Architecture**" [1], we want to pave the way for frequent exchange of designs and optical set ups between experiments that have adapted the interface of this design.

In this platform, all individual parts can be easily adapted to be used with any atomic species and be used in different configurations to realize a broad range of quantum systems. Here, we describe the configuration for our case using Lithium-6 fermions [2]. The platform consists of a miniaturized high flux atom source, enabling 3D-MOT **loading rates of up to 1e9 atoms/s** at a reasonably low oven temperature of 350°C. The vacuum setup is moveable on a rail system and due to the small total volume and inner surface large **vacuum lifetimes of above 1000s** have been achieved.

The unique aspect of this platform compared to other quantum simulation experiments is its perfectly modular design. All optical setups can be exchanged with a **repeatability of below 10µm,** making it possible to set up and align a module on a testbench and implement it in the experiment in a very short amount of time, instantly getting a signal on the atoms by, for example, a successful overlap of a new trap with already existing traps. This interchangeability we also implemented for all high NA optics boards generating for this experiment tweezers at 1064nm, large optical box potentials at 532nm and providing high resolution, single atom and spin resolved imaging at 671nm.

With this configuration of the platform we aim for **fast cycle times of below 200ms** for the deterministic preparation and detection of few fermion systems.

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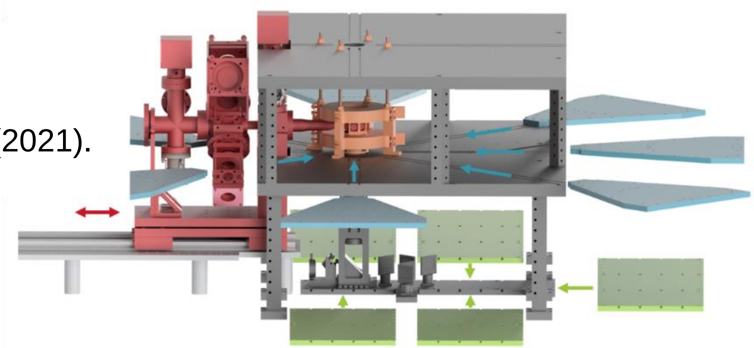

Cold Atomic Excitons

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In various solid state systems, the excitation of an electron from a completely filled valence band into an empty conduction band leads to a small binding energy between the electron-hole pair, called exciton. In the past years, cold atom systems have emerged as versatile platforms for simulating two-dimensional structures, such as hexagonal boron nitride (hBN) and transition metal dichalcogenides (TMDs). Recent experiments have for example managed to map the full band structure of a cold atom system in a honeycomb lattice. With all necessary experimental methods available and successfully utilized, we now investigate the existence of a different effect inspired from the solid state systems: excitons under short range interaction. We predict the existence of a similar atom-hole pair (atomic exciton) in a system of single-component fermionic atoms with nearest neighbour interactions. Our 2D lattice similar to hBN has a hexagonal structure with two different lattice site types, leading to a native two-band structure with nonzero bandgap. We use variational methods to find the energy spectrum of zero-momentum excitons in the single particle band operator basis, which form around the K/K'-point. We show that excitonic effects can be found over a large range of system parameters, which also includes currently accessible regions of band gap, tunnelling rate and nearest neighbour interaction strength. Furthermore, we use Fermis Golden Rule to propose an already existing experimental procedure consisting of a perturbation operator followed by time-of-flight spectroscopy to probe the predicted states.

Vortex Dynamics in Strongly Interacting Superfluid

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Interactions can play a determinant role in low dimensions for topological and chiral states of matter by giving rise to interesting emergent phenomena such as quasiparticle fractionalization and quantum phase transitions. Recent experimental evidence from Floquet engineered ultracold atomic systems [1], have provided a starting point for observing correlated vortex structures of the Laughlin bosonic Hall effect. Motivated by these experimental advances, we have investigated the quantum dynamics of large vortices in strongly interacting superfluids. For one quantum of flux and close to half-filling, the change in sign of the Hall conductivity [2] suggests an abrupt change in vortex response and dynamics, due to effective strong quantum fluctuations. In this contribution we will present some preliminary results obtained by using mean-field and beyond mean-field numerical approaches. These results will be of potential interest for both seeking theoretical tools to suggest transport measurements in bosonic platforms.

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Driven-dissipative fermionized topological phases of strongly interacting composite bosons

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We theoretically investigate the optical response of polaritons in a one-dimensional driven-dissipative Bose-Hubbard model with topological couplings. Strong correlations, accompanied by particle gain and loss can create non-trivial fermionised' non-equilibrium steady states(NESS). We observe clear signatures of Bose-Fermi mapping in the NESS and further investigate how changing experimentally controllable drive parameters can allow selective excitation of either the bulk, the edge or both, establishing non-trivial topological properties in the responses and correlations.

What can we learn from time-dependent spectral functions?

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The nonequilibrium dynamics of quantum many-body systems is a fascinating topic hosting a rich phenomenology. Going out of equilibrium, transient states can be realized, which are hard to obtain at equilibrium. One important tool for the investigation of such transient states is to examine the time evolution of spectral properties, like time-dependent band structures, single-electron spectral functions, or local densities of states. For example, periodically driven systems possess so-called Floquet side bands, and the band structure can be modified by the periodic driving such as to realize interesting states of matter, like topological phases (‘Floquet engineering’). In this poster, I show some examples for the nonequilibrium dynamics of spectral properties of strongly correlated quantum systems when performing a global quantum quench [1], periodic driving [2], and a local perturbation [3].

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Scalable spin squeezing from critical slowing down in short-range interacting systems

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Long-range spin-spin interactions are known to generate non-equilibrium dynamics which can squeeze the collective spin of a quantum spin ensemble in a scalable manner, leading to states whose metrologically useful entanglement grows with system size. Here[1], we show theoretically that scalable squeezing can be produced in 2d U(1)-symmetric systems even by short-range interactions, i.e. interactions that at equilibrium do not lead to long-range order at finite temperatures, but rather to an extended, Berezhinski-Kosterlitz-Thouless (BKT) critical phase. If the initial state is a coherent spin state in the easy plane of interactions, whose energy corresponds to a thermal state in the critical BKT phase, the non-equilibrium dynamics exhibits critical slowing down, corresponding to a power-law decay of the collective magnetization in time. This slow decay protects scalable squeezing, whose scaling reveals in turn the decay exponent of the magnetization. Our results open the path to realizing massive entangled states of potential metrological interest in many relevant platforms of quantum simulation and information processing -- such as Mott insulators of ultracold atoms, or superconducting circuits -- characterized by short-range interactions in planar geometries.

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Ytterbium optical tweezers for single-atom resolved many-body physics

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Understanding the nonequilibrium dynamics of fermionic systems is one of the major challenges of contemporary physics. Owing to their control on both motional and internal atomic states, optical tweezers provide a unique tool for investigating the build-up of correlations in many paradigmatic scenarios. Here I will report on the first results of a new experimental apparatus where we employ optical tweezers to manipulate and detect individual ytterbium atoms. Exploiting additional slowing beams after the Zeeman slower, we prepare a narrow-line MOT from which we directly load an optical tweezer array. We achieve single atom imaging with >99.99% fidelity by detecting fluorescence photons from a broad optical transition while simultaneously cooling with a narrow-line transition. As a complementary imaging scheme, we avoid cooling and apply high-intensity fluorescence pulses to collect many photons in a short time, at the cost of losing the atoms from the traps. This fast imaging presents various advantages over traditional imaging and cooling schemes, including reduced sensitivity to trapping wavelength. This scheme can also be employed to image single atoms in free-space, allowing to measure their momentum after being released from the tweezers and to avoid parity projection due to in-trap pairwise losses, a fundamental requirement for investigating systems in which tweezers are filled with more than one particle. Following pioneering works with lithium atoms, we will develop schemes for deterministically loading few-fermions in each tweezer and we will investigate few-body out-of-equilibrium dynamics by addressing phenomena such as spin equilibration and fermionic dynamics in SU(N) systems.

Optimal control transport of neutral atoms in optical tweezers

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Engineering a quantum system that evolves into a target state has a relevance in quantum information science [8]. In particular, the realization of a controllable quantum system is an interesting topic in modern physical science [6]. In recent years a new promising platform is emerged in the area of quantum simulation and quantum computing based on the so-called optical tweezers [4, 3, 9, 5], highly focused laser beams able to trap and move individual neutral atoms. In this setting it is possible to manipulate and move the tweezers and the atoms trapped within them in such a way to create an array of individual atoms with arbitrary geometry [1, 2]. Arrays of atoms represent a useful resource for quantum information because atoms in optical tweezers can be used as elementary quantum information carriers. In this context, we study an optimal control problem on the transport of neutral atoms in optical tweezers. The problem is formulated as an ensemble control problem based on the Wigner equation. The optimality system consists of the forward Wigner problem, the adjoint problem, and the optimality condition [7].

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Thermal localisation and pairing by disorder of dopants in a magnetic spin ladder

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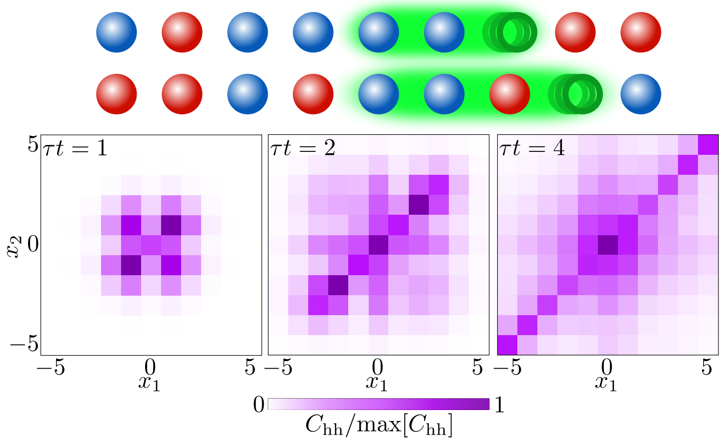
I unveil a novel variant of Anderson localisation. This emergent phenomenon pertains to the motion of a dopant in a thermal spin lattice, rendered localised by thermal fluctuations [1]. The system of interest consists of spin-1/2 particles organised in a two-leg ladder with nearest neighbour Ising interactions. The motion of a hole — the dopant — is initialised by suddenly removing a spin from the thermal spin ensemble, which then moves along the ladder via nearest neighbour hopping. I find that the hole remains localised for all nonzero spin couplings and temperatures. The origin is an effective disorder potential seen by the hole and induced by thermal spin fluctuations.



Top: Two holes (green) moving in separate legs of a disordered spin ladder with spin-up (red) and -down (blue). **Bottom**: The hole-hole correlator shows that the coordinates *(x1,x2)* of the holes along the ladder become strongly correlated over time (time τ shown in units of hopping t) As a result, the holes have a significant increased probability of sitting on the same rung (increased signal along the diagonal *x1 = x2),* a manifestation of their emergent dynamical pairing .

For two holes moving on separate legs of the ladder, the same effect leads to a novel pairing mechanism induced by thermal disorder of the underlying spin lattice [2]. At infinite temperature, the mean induced interaction between the holes vanishes identically. Nevertheless, the large fluctuations in the induced interactions frustrates the relative motion of the dopants and enforces them to co-propagate.
Finally, I show that the discovered localisation and pairing phenomena are realistically testable in state-of-the-art quantum simulation experiments with Rydberg-dressed atoms in optical lattices [3], providing a strong testing ground for my predictions.

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Advancements towards simulating SYK Model and its variants in cQED platforms

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Recently, the **Sachdev-Ye-Kitaev (SYK) model** has become a **prototype** for **holographic quantum matter** as it shares intriguing properties with those of **black holes** and **strange metals**. By considering a **cold gas of fermionic atoms** inside a **multi-mode optical cavity** subjected to **spatially random light-shifts**, a feasible route to **laboratory implementation** has been recently proposed. In this presentation, we shall discuss our present progress towards realizing the SYK model and its **variant**, by emphasizing the latter's potential **experimental advantages**. Our first-principle analysis on the models unveils deeper insights about the **correlations** present in the **interaction strengths** of the effective **microscopic Hamiltonian**. Furthermore, our numerical investigations on **chaos** and **scrambling markers** demonstrate intriguing characteristics of the effective model, thereby showcasing significant progress over the existing **cavity QED proposal**. These findings significantly contribute to our understanding of **holographic** and **quantum chaotic** properties of **strongly correlated systems**, and the effectiveness of **cQED platforms** in simulating such complex **quantum systems**.

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Constrained dynamics and confinement in the two-dimensional quantum Ising model

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We investigate the dynamics of the quantum Ising model on two-dimensional square lattices up to 16×16 spins.
In the ordered phase, the system's dynamics approximately conserve the total length of the domain walls. The time evolution with this emergent dynamical constraint leads to anomalously long thermalization times.
Within the long prethermal regime, we find confined elementary excitations, slow growth of entanglement, and suppression of the light-cone correlation spread.

We are interested in the dynamics of interfaces in this regime, probed through sudden quenches of product states with domains of opposite magnetization.
We identify dominant microscopic processes; resonant edge modes which originate at the corners and freely propagate along flat interfaces.
Finally, we investigate the crossover from 'resonant' to 'diffusive' melting in a square domain.

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Critical Current throughout the BCS-BEC Crossover: Landau Critical Velocity and Persistent Currents

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The present work [1] aims at providing a systematic analysis of the current density versus momentum characteristics for a fermionic superfluid throughout the BCS-BEC crossover. At low temperatures, where pairing fluctuations are not strong enough to invalidate a quasiparticle approach, a sharp threshold for the inception of a back-flow current is found, which sets the onset of dissipation and identifies the critical momentum according to Landau. This momentum is seen to smoothly evolve from the BCS to the BEC regimes, whereby a single expression for the single-particle current density that includes pairing fluctuations enables us to incorporate on equal footing two quite distinct dissipative mechanisms, namely, pair breaking and phonon excitations in the two sides of the BCS-BEC crossover, respectively. At finite temperature, where thermal fluctuations broaden the excitation spectrum and make the dissipative (kinetic and thermal) mechanisms intertwined with each other, an alternative criterion due to Bardeen is instead employed to signal the loss of superfluid behavior.

A detailed comparison is performed with available data from ultracold Fermi gases: 1) for the Landau critical velocity in a linear geometry and 2) for the decay of the persistent current in an annular geometry.

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Quantum scars in many-body systems

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Chaos makes isolated systems of many interacting particles quickly thermalize and forget about their past. Here[1], we show that quantum mechanics hinders chaos in many-body systems: although the quantum eigenstates are thermal and strongly entangled, exponentially many of them are scarred, that is, have an enlarged weight along underlying classical unstable periodic orbits. Scarring makes the system more likely to be found on an orbit it was initialized on, retaining a memory of its past and thus weakly breaking ergodicity, even at long times and despite the system being fully thermal. We demonstrate the ubiquity of quantum scarring in many-body systems by considering a large family of spin models, including some of the most popular ones from condensed matter physics. Our findings, at hand for modern quantum simulators, prove structure in spite of chaos in many-body quantum systems.

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Anomalous Non-Thermal Fixed Point in a Quasi-2d Dipolar Bose Gas

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In this work we focus on anomalous non-thermal fixed-points in the temporal evolution of a 2d dipolar Bose gas, exhibiting slow, subdiffusive coarsening characterized by algebraic growth of a characteristic length scale L(t)~t^beta with beta<<1/2. Starting from variously sampled vortices on a uniform background, we evolve the Bose gas using the semi-classical truncated-Wigner approach. In the semi-classical regime of a highly dilute gas, anomalous scaling prevails, with an exponent beta~1/5, due to strongly slowed mutual annihilation of vortices, for various dipolar strengths and tilting angles. For late times or strong dissipation we observe the transition into diffusive scaling with beta=1/2. In the quantum regime, realised for typical experimental coupling strengths and densities, we also find anomalously slow, subdiffusive scaling, albeit with more fluctuations than in the classical limit. Within a quasi-2d setting, we analyze the dependence of the observed scaling exponents on the effects of anisotropy and on the long-range nature of the dipolar interaction. For strong tilting angles of the polarization, anisotropy in the vortex configuration emerges; however, it is not reflected in the self-similar scaling. Further, we investigate the role of vortex (anti-)clustering and find both strong clustering as well as anti-clustering throughout the anomalous scaling regime. These results support the universal nature of the anomalous non-thermal fixed-point and hint towards three-vortex collision processes being the primary source for the subdiffusive coarsening.

Towards Fermi polarons with heavy impurities

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I will present the status of our ongoing work to observe heavy Fermi polarons in a mixture of fermionic ^{6}Li and bosonic ^{133}Cs. While Fermi polarons – quasiparticles formed by impurities dressed by the excitations of a surrounding Fermi sea – are interesting in their own right [1], the large mass ratio in the Li-Cs system additionally enables addressing questions about the fate of quasiparticles close to the infinitely heavy impurity limit. Specifically, connections to Anderson's orthogonality catastrophe (OC) can be examined. Anderson predicted that in the thermodynamic limit the insertion of a single, infinitely heavy impurity renders a Fermi sea orthogonal to its original state [2]. Precursors of this effect are predicted to be observable in mixtures of ultracold atoms with large mass ratio through time-domain spectroscopy [3].

To this end, we are currently optimizing the preparation of a spin-polarized Fermi gas of lithium deep in the degenerate regime together with a cloud of thermal caesium impurities. This includes spatially moving caesium in an optical dipole trap to mix both species after sequential MOT loading as well as identifying the optimal evaporation trajectory for sympathetic cooling of our mixture. Spectroscopic probes on both Li (via radio frequency) as well as Cs (using an optical two-photon Raman transition) give us full control over the internal spin states, enabling the observation of both the heavy Fermi polaron as well as signatures of the OC.

I will present our most recent progress on this experiment at the seminar in Florence, hopefully including first spectroscopic results.

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Fractional quantum Hall states with variational projected entangled-pair states: A study of the bosonic Harper-Hofstadter model

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An important class of model Hamiltonians for investigation of topological phases of matter consists of mobile, interacting particles on a lattice subject to a semi-classical gauge field, as exemplified by the bosonic Harper-Hofstadter model. A unique method for investigations of two-dimensional quantum systems are the infinite projected-entangled pair states (iPEPS), as they avoid spurious finite size effects that can alter the phase structure. However, due to no-go theorems in related cases, this was often conjectured to be impossible in the past.
In previous works, we made use of tree tensor network structures to circumvent the issue and to access topological fingerprints like degeneracy dependence on the boundary conditions, many-body Chern number, as well as charge and statistics of lattice quasi-holes from density depletion [1-2].
Here we report on our recent result [3] that — upon variational optimization [4] — the iPEPS can indeed be used to identify fractional Hall states in the bosonic Harper-Hofstadter model. The obtained states are characterized by showing exponential decay of bulk correlations, as dictated by a bulk gap, as well as chiral edge modes via the entanglement spectrum.

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Towards deterministic entanglement generation in a new atom-cavity setup

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The efficient and deterministic generation of entanglement in a manybody system poses a challenge for analog and digital quantum simulators. While atomic platforms provide great scalability, they mostly rely on local couplings, for instance, collisional or Rydberg interactions. We report on the current status of a new experimental apparatus to strongly couple an atomic tweezer array to a fiber-based Fabry-Pérot cavity. The cavity geometry with short length, small mirror diameter, and large curvature, places us in a unique regime with simultaneously high single-atom cooperativity and single-atom addressing and readout. Our setup is optimized for fast repetition rates, owing to loading the tweezer array from a magneto-optical trap which is placed within millimeters from the cavity. In future, harnessing this new control will enable us to engineer entanglement through photon-mediated interactions. Further advantages of this platform include partial nondestructive readout and efficient multi-qubit entanglement operations. In the long term, the proposed platform provides a scalable path to studying many-body systems with programmable connectivity, as well as an efficient atom-photon interface for quantum communication applications.

Cosmological Particle Production in a Quantum Field Simulator as a Quantum-Mechanical Scattering Problem

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Cosmological particle production describes the excitation of quantum fluctuations through time-dependent background spacetimes and is a hallmark prediction of quantum field theory in curved spacetime, resulting in the generation of primordial cosmological perturbations as an important consequence. Through rapid technological advances, this effect can be quantum-simulated using interacting Bose-Einstein condensates (BECs) with time-dependent scattering length [1], where an acoustic spacetime arises as an emergent phenomenon [2]. The dynamical evolution of the quantum field can be phrased as a quantum-mechanical scattering problem, which enables intuitive explanations for emergent spatial structures in both the BEC and the cosmological system [3]. An extension of the developed framework beyond the acoustic regime is provided, which captures a cosmological spacetime with modified dispersion relation beyond the analogue Planck scale [4]. These results are compared to experimental data from quantum simulations of linearly expanding and periodically modulated spacetimes in a BEC [5].

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Control of ion crystals for atom-ion quantum mixtures

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In this presentation, we will show the most recent advancements in the realization of our experimental setup combining trapped Barium ions with fermionic Lithium gases. In the design of our apparatus, we have conceived several technical innovations aimed at improving control over the atom-ion quantum mixture.

In particular, we have designed a bow-tie cavity for the generation of a deep optical lattice potential that together with a static electric field can confine the ions in a two-dimensional pancake-shaped trap. This electro-optical trap is embedded with a Paul trap, which was designed in order to maximize the trap matching between the two confining potentials.
The specific geometry of these traps [1] make it possible to continuously change the arrangement of the ions from a one-dimensional string to a two-dimensional crystal, and to study specific phenomena in two-dimensional crystals of ions, such as the occurrence of orientational melting [2], and the formation of metastable crystal configurations that are not thermodynamically stable [3].

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Dynamical effects in trilobite molecules

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Trilobite molecules are ultralong-range Rydberg molecules formed when a high angular momentum Rydberg electron scatters off of a ground-state atom. Their unique electronic structure and highly oscillatory potential energy curves support a rich variety of dynamical effects yet to be explored. We analyze the vibrational motion of these molecules using a framework of adiabatic wavepacket propagation dynamics and observe that for appropriate initial states, the trilobite potential acts as molecular diffraction grating. The quantum dynamic effects observed are explained using a Fourier analysis of the scattering potential and the associated scattered wavepacket. Furthermore, vibrational ground-states of the low angular momentum ultralong-range Rydberg molecules are found to be particularly suitable to prepare the relevant wavepackets. Hence, we propose a time resolved pump-probe scheme designed for the realization of the effect in question, and advertise the utilization of a single diatomic Rydberg molecule as a testbed for the study of exaggerated quantum dynamical phenomena.

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Entanglement and quantum correlations in the Tavis-Cummings model

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I will present the work published in [1] and [2], where I studied the Tavis-Cummings (TC) model, which involves two-level atoms coupled with a single-mode quantized electromagnetic field. This system undergoes a superradiant phase transition, even in finite sizes, marked by spontaneous symmetry breaking and many energy level crossings. In [1], I derived approximate expressions for the ground state, its energy, and the level crossing positions, valid when the number of photons is much larger than the number of atoms. In this limit, the photon number scales quadratically with coupling strength and linearly with system size, offering new insights into superradiance. Using measures developed by my research team, as well as other criteria of entanglement in Dicke states found in the literature, I showed that this phase transition involves a jump in quantum correlations and entanglement between atoms.

I further showed in [2] that, when the field energy is large with respect to that of the atomic transition, parametric state control can be implemented in order to obtain a targetted Dicke state as the ground state of the TC model.

I confirmed all of these results through numerical minimization of the energy, exploiting the conserved quantity present in the TC model to reduce its infinite-dimensional state-space to one scaling at most as the number of atoms.

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Two-dimensional spectroscopy of magnetic systems

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Higgs mode was predicted in many condensed-matter systems, such as cold atoms in periodic lattices, superconductors, and antiferromagnets. However, detecting the Higgs mode and measuring its properties is challenging due to its rapid decay into the low-laying Goldstone modes [1]. Here, we propose a new protocol allowing us to study the properties of the Higgs mode in a bilayer antiferromagnet, a system that can be simulated using cold atoms. Namely, we extend the recently introduced two-dimensional terahertz spectroscopy (2DTS) in the context of Josephson plasmons in layered superconductors [2] to the case of coupled collective excitations in bilayer antiferromagnets. We discuss similarities and discrepancies in 2D spectra of conventional quantum-level systems, e.g., coupled molecules [3] and strongly correlated materials with a continuum of coupled collective excitations. Additionally, we deliberate the simulation of the solid-state set-up using the experimental platform with Rydberg atoms.

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Probing entanglement in open quantum systems with tree tensor networks

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Entanglement is a crucial resource for future quantum technologies and a fundamental probe of complex quantum systems. Access to entanglement measures, such as the entanglement entropy, substantially improved our understanding of isolated quantum many-body systems. In open quantum systems, though, accessing entanglement becomes significantly more difficult. Here, we present a numerical framework capable of simulating entanglement dynamics in open quantum systems. The framework exploits the tree tensor network geometry, which allows for the efficient computation of entanglement monotones of mixed states, such as the entanglement of formation and negativity[1]. As a paradigmatic example, we study the current-driven XXZ spin-chain. Our results underline that we can distinguish entanglement among the constituents of the systems from correlations with the environment. Moreover, we find a dissipation-induced entanglement phase transition, revealing that the interplay of dissipation and coherent evolution can induce a non-trivial entanglement structure at late times. Our framework opens the door to studying entanglement in open quantum many-body systems out of equilibrium, which may be fruitful for various communities.

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Gauge protection in quantum simulations of non-Abelian LGTs by dynamical post-selection on qudit platforms

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Non-abelian gauge theories underlie our understanding of fundamental forces of nature and play a fundamental role in topological quantum computing and developing tailored quantum hardware and algorithms to simulate them is an outstanding challenge in the rapidly evolving field of quantum simulation. Because large symmetry groups can not be represented efficiently with qubits, encoding the gauge degrees of freedom in qudits is emerging as a promising alternative[1]. Yet, this approach also brings new challenges: in particular, it requires a rethinking of gauge protection and post-selection schemes for larger local Hilbert spaces and, most importantly, for non-commuting symmetry operators. Here, we propose a dynamical post-selection error mitigation method based on mid-circuit measurements[2], designed for digital quantum simulations qudit platforms. We illustrate our proposal for the non-abelian D3 group in 2+1 dimensions[3]. Our findings set the basis for further development of error mitigation and correction techniques and open new avenues for measurement-based control techniques in qudit quantum devices

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Rydberg Spin Glas

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Using our Rydberg platform as a quantum simulator for disordered Heisenberg systems [1], we have found signatures indicating that an isolated frozen gas of quantum spins under dipolar interactions shows similar features as a "classical" spin glass [2]. The relaxation of the magnetization after a quench follows a stretched-exponential function, which appears to be universal in the sense that it is independent on the degree of disorder [3] and the symmetries of the underlying Heisenberg Hamiltonian [4]. We observe a drastic change in the late-time magnetization when increasing disorder strength. The data is well described by models based on pairs of strongly interacting spins, which are treated as thermal for weak disorder and isolated for strong disorder. Our results indicate a crossover into a pair-localized prethermal regime in a closed quantum system of thousands of spins [5]. Most recently, we observed linear response to an external effective magnetic field indicating non-thermal behavior. Measurements of the magnetic susceptibilities as a function of the energy in the system show the existence of two regimes with different magnetic behavior. The lower energy regime exhibits pronounced hysteresis, which might indicate the existence of a glas-phase transition [6].

* Work done in collaboration with Gerhard Zürn, Eduard Braun, Sebastian Geier, Titus Franz (now at Max-Planck Institute for Quantum Optics), Valentina Salazar Silva, Annika Tebben, Adrian Brämer und Martin Gärttner (now at Universität Jena)

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Anomalous Doppler effect at zero temperature in density modulated superfluids and supersolid

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In a classical fluid moving at a certain velocity v the sound speed c_0 is modified by the kinematic Doppler shift as $c = c_0 \pm v$, where the sign of the correction depends on whether sound propagates parallel or antiparallel to the velocity v. However, studies on liquid helium have shown that the coexistence of normal fluids and superfluids modifies the Doppler shift in a non-trivial way [1, 2]. In this work, we are considering the Doppler shift in density-modulated atomic gases at zero temperature. We use hydrodynamics to investigate superfluids in optical lattices where the normal part is induced by an external periodic potential and supersolids, where it emerges as an effect of spontaneously broken translational symmetry. In supersolids, there exist two sound modes which we show to be differently affected by the Doppler effect. Moreover, we identify conditions under which the Doppler shift can become negative. Results of hydrodynamic models are in agreement with numerical calculations based on the extended Gross-Pitaevskii equation.

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Fractonic Phases in a Constrained Bose-Hubbard Model

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Quantum many-body systems with fracton constraints are widely conjectured to exhibit unconventional low-energy phases of matter. In this work, we demonstrate the existence of a variety of such exotic quantum phases in the ground states of a dipole-moment conserving Bose-Hubbard model in one dimension. For integer boson fillings, we perform a mapping of the system to a model of microscopic local dipoles, which are composites of fractons. We apply a combination of low-energy field theory and large-scale tensor network simulations to demonstrate the emergence of a dipole Luttinger liquid phase. At non-integer fillings our numerical approach shows an intriguing compressible state described by a quantum Lifshitz model in which charge density-wave order coexists with dipole long-range order and superfluidity — a “dipole supersolid”. Moreover, we study low-energy excitations of these fractonic phases by numerically computing spectral functions and investigating the dynamics after a quench, which shows signatures reminiscent of a gauge theory. We discuss potential experimental implications of our results.

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