Quantum Gases and Quantum Coherence

669. WE-Heraeus-Seminar

April 15 - 18, 2018
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation which supports research and education in science, especially in physics. A major activity is the organization of seminars. By German physicists the foundation is recognized as the most important private funding institution in their fields. Some activities of the foundation are carried out in cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft).

Aims and scope of the 669. WE-Heraeus-Seminar:

This conference brings together a broad community of senior and junior scientists to address the most recent developments in the emerging cross-disciplinary research field involing ultracold atoms, quantum many-body physics, quantum simulation and quantum information.

The main themes of this edition will be:

- Non-equilibrium physics and dynamics
- Artificial gauge fields
- Topological phases
- Strongly correlated systems
- Ultracold atoms and quantum technologies
- From few to many-body physics

Scientific Organizers:

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Program

Program

Sunday, April 15, 2018

11:00 – 21:00	Registration	
12:30 – 14:00	*LUNCH*	
14:30 – 14:40	Scientific organizers	**Welcome words**
Session I:	*Non-equilibrium & dynamics*	
14:40 – 15:40	Christian Gross	**Microscopic studies of many-body localization in two dimensions**
15:40 – 16:10	Zala Lenarčič	**Time-dependent generalized Gibbs ensembles in open quantum systems**
16:10 – 16:40	*COFFEE BREAK*	
16:40 – 17:10	Jean-Sébastien Bernier	**Propagation of correlations in dissipative systems: ballistic, diffusive, rare event and aging dynamics**
17:10-17:40	Russell Bisset	**Dynamics and interactions of quantum vortices in Bose-Einstein condensates**
17:40 – 18:10	Jean-Loup Ville	**Sound propagation in a superfluid two-dimensional Bose gas**
18:10 – 18:20	**Conference Photo** (in the front of the lecture hall)	
19:00	*DINNER*	

Program

Monday, April 16, 2018

08:00	*BREAKFAST*	
Session II:	*From few to many-body physics*	
09:00 – 10:00	Frank Pollmann	**Efficient simulation of quantum thermalization dynamics**
10:00 – 10:30	Nicola Wurz	**Coherent manipulation of spin correlations in the 2D Fermi Hubbard model**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:30	Tommaso Comparin	**Itinerant ferromagnetism for two-dimensional dipolar fermions**
11:30 – 12:00	Francesco Scazza	**Time-resolved probing of repulsive many-body states in ultracold Fermi gases**
12:00 – 12:30	Markus Heyl	**Dynamical quantum phase transitions**
12:30	*LUNCH*	

Program

Monday, April 16, 2018

Session III: *Gauge fields & topology*

14:30 – 15:30	Klaus Sengstock	**Topology in floquet engineered optical lattices**
15:30 – 16:00	Samuel Lellouch	**Parametric instabilities in shaken atomic gases**
16:00 – 16:30	*COFFEE BREAK*	
16:30 – 17:00	Alexandre Dauphin	**Topological characterization of chiral models through their long time dynamics**
17:00 – 17:30	Leonardo Mazza	**Laughlin-like physics in bosonic and fermionic atomic synthetic ladders**
17:30 – 18:00	Giacomo Cappellini	**Engineering synthetic gauge fields with ultracold two-electron atoms**
19:00	*DINNER*	
20:30 – 21:30	Cristiane de Morais-Smith	**Colloquium:** **There is plenty of room at the bottom... but even more in a fractal**

Program

Tuesday, April 17, 2018

08:00	*BREAKFAST*	
Session IV:	*Strongly correlated systems*	
09:00 – 10:00	Leticia Tarruell	**Quantum liquid droplets in a mixture of Bose-Einstein condensates**
10 :00 – 10:30	Andrea Bergschneider	**Detection of entanglement in a Fermi-Hubbard dimer**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:30	Cecile Repellin	**Creating a bosonic fractional quantum Hall state by pairing fermions**
11:30 – 12:00	Jean Decamp	**Correlations and symmetries in one-dimensional quantum gases**
12:00 – 12:30	Guillame Salomon	**Direct observation of incommensurate spin correlations in Hubbard chains**
12:30	*LUNCH*	
14:30 – 18:00	**Poster session with 2-minute presentations off the posters and**	
16:00	*COFFEE BREAK*	
19:00	*HERAEUS DINNER* *(social event with cold & warm buffet with complimentary drinks)*	

Program

Wednesday, April 18, 2018

08:00	*BREAKFAST*	
Session V:	*Quantum technologies & cold atoms*	
09:00 – 10 :00	Giovanna Morigi	**Collective dynamics of atomic ensembles confined within high-finesse optical cavities**
10 :00 – 10:30	Benoit Vermersch	**Measuring entanglement and scrambling via random unitaries**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:30	Philipp Hauke	**Many-body entanglement witnessed through the quantum Fisher information**
11:30– 12:00	Irénée Frérot	**Probing quantum superpositions in equilibrium many-body systems close to quantum and thermal critical points**
12:00 – 12:30	Daniel Barredo	**Quantum simulation of spin models with individual Rydberg atoms in arbitrary geometries**
12:30 – 12:45	Scientific organizers	**Closing words**
12:45	*LUNCH*	

End of the seminar and departure

NO DINNER for participants leaving on Thursday morning

Posters

Posters

Adriano Angelone	**Superglass phase of interaction-blockaded gases on a triangular lattice**
Lisa Arndt	**Dual Shapiro steps of a phase-slip junction in the presence of a parasitic capacitance**
Cosetta Baroni	**Interactions in a tunable Bose-Fermi mixture of ^{41}K and ^{6}Li: phase separation and spin transport**
Gianluca Bertaina	**Quantum critical behavior of one-dimensional soft bosons in the continuum**
Guillaume Berthet	**Non linear scattering of atomic bright solitons in disorder**
Thomas Bland	**Quantum ferrofluid turbulence**
Anton Buyskikh	**Spin model for 2-site resonant tunneling dynamics of bosons in a tilted optical superlattice**
Josep Cabedo Bru	**A three-mode treatment of spin-1 Bose-Einstein condensates with spin-orbit coupling**
Cecile Carcy	**Single-atom-resolved probing of lattice gases in momentum space**
Agnieszka Cichy	**Reentrant Fulde-Ferrell-Larkin-Ovchinnikov superfluidity in the honeycomb lattice**
Ricardo Costa de Almeida	**Measurement of multipartite entanglement in many-body systems using temporal fluctuations**

Posters

Marco Di Liberto	**Particle-hole character of Higgs and Goldstone modes in strongly interacting lattice bosons**
Arturo Farolfi	**Towards the study of many-body effects in resonantly coupled spinor BECs**
Serena Fazzini	**Non-local orders and SPT phases in Hubbard-Heisenberg models**
Wojciech Górecki	**Roton in a many-body dipolar system**
Piotr Grochowski	**Ferromagnetic instability in a dynamical system of a repulsive two-component Fermi gas**
Michael Hagemann	**Production of a molecular Lithium BEC in a single-chamber setup**
Catalin-Mihai Halati	**Cavity-induced artificial gauge field in a Bose-Hubbard ladder**
Yi-Ping Huang	**Dynamical quantum phase transitions in the particle-antiparticle production of a lattice gauge theory**
Dariusz Kajtoch	**Spin-squeezed atomic crystals**
Andreas Kerkmann	**Gray molasses laser cooling of fermionic Lithium**
Antonia Klein	**Towards quantum state assembly**
Thomas Kohlert	**Exploring the single-particle mobility edge and many-body localized phase in a 1D quasiperiodic optical lattice with ultracold atoms**

Posters

Johannes Kombe	**Observation of the Higgs mode in the superfluid BEC-BCS crossover in Fermi gases**
Arkadiusz Kosior	**Dynamical quantum phase transitions in discrete time crystals**
Avinash Kumar	**Producing superfluid circulation states using phase imprinting**
Alessio Lerose	**Chaotic dynamical phase induced by non-equilibrium quantum fluctuations**
Elia Macaluso	**Observing anyonic statistics via time-of-flight measurements**
Alfonso Maiellaro	**Topological phases of a two-leg Kitaev ladder**
Giovanni I. Martone	**Quantum depletion and coherence of an ultracold boson vapor after a quench**
Leonardo Masi	**Self-bound quantum droplets in atomic mixtures**
Paolo P. Mazza	**Non equilibrium dynamics and transport in non-integrable systems**
Raphal Menu	**Quench spectroscopy of unconventional excitations in Rydberg quantum simulators**
Silvia Musolino	**Dynamics of few-body correlations in a quenched unitarity Bose gas**
Aurélien Perrin	**Magnetic transport of cold atoms in a quadrupole trap**

Posters

Michele Pini	**Comparative study of many-body t-matrix theories for a Fermi gas through the BCS-BEC crossover**
Lukas Rammelmüller	**Spin and mass imbalance in strongly interacting Fermi gases**
Arko Roy	**Design and characterization of a quantum heat pump in a driven quantum gas**
Angelo Russomanno	**Dynamical localization and delocalization in a system of coupled kicked rotors**
Grazia Salerno	**Topological two-body bound states in the interacting Haldane model**
Peter Schauss	**Quantum gas microscopy of many-body dynamics in Fermi-Hubbard and Ising systems**
Thomas Secker	**Efimov physics for narrow Feshbach resonances**
Jasper Smits	**Faraday waves in Bose-Einstein condensates**
Andrzej Syrwid	**Time crystal behavior of excited eigenstate**
Konrad Szymański	**Spin self-rephasing in the system of several atoms**
Jérôme Thibaut	**Entanglement properties of lattice bosons from a variational wave function**
Roberto Verdel Aranda	**Quantum dynamics with artificial neural networks**
Nicolas Victorin	**Bosonic double lattice ring under a gauge field**

Posters

Botao Wang	**Floquet engineering of optical solenoids and quantized charge pumping along tailored paths in two-dimensional Chern insulators**
Yibo Wang	**Q-Walker: a fully-programmable quantum dynamics simulator with Rydberg-dressed atoms**
Zhi-Yuan Wei	**Directly measuring the degree of quantum coherence using interference fringes**
Stefan Wolff	**Dissipative dynamics of spin-1/2 chains by tensor network algorithms**
Hepeng Yao	**Full scaling function of the Tan contact for trapped Lieb-Liniger gases at finite temperature**
Henrik Zahn	**3D image reconstruction using symmetries applied to cold Rydberg gases**
Klaudia Zaremba-Kopczyk	**Magnetically tunable Feshbach resonances in an ultracold gas of europium atoms and a mixture of europium and alkali-metal atoms**

Abstracts of Talks

(in chronological order)

Microscopic Studies of Many-Body Localization in Two Dimensions

C.Gross[1]

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The breakdown of the thermalization of a generic isolated quantum system is one consequence of many-body localization. This aspect can be probed experimentally in systems of ultracold lattice atoms by the measurement of the long-time remaining traces of an initially prepared far from equilibrium distribution of the atomic density. We summarize our experiments performed in this spirit and report on recent progress on the characterization of the system in the seemingly localized phase, including the study of the stability of the localization when coupling to a well controlled atomic bath.

Time-dependent generalized Gibbs ensembles in open quantum systems

Z. Lenarčič, F. Lange, and A. Rosch

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Generalized Gibbs ensembles have been used as powerful tools to describe the steady state of integrable many-particle quantum systems after a sudden change of the Hamiltonian. Our work shows that their time-dependent version can be used for a much broader class of problems. I will consider integrable systems in the presence of integrability breaking driving terms due to coupling to a non-equilibrium environment, using the one-dimensional Heisenberg model with perturbations described by Lindblad operators or Floquet unitary driving as an example. I will show that the dynamics is fundamentally different from that with static perturbations. As demonstrated in quantum quench protocols, static integrability breaking terms always lead to simple thermalization. Our numerical results show that driving reactivates conserved quantities of the underlying integrable model, promoting features inherited from the integrability to be much more robust and experimentally observable. We show that dynamics is accurately captured by a time-dependent generalized Gibbs ensemble with steady state Lagrange parameters determined by the perturbations. This result significantly extends the application of the concept of generalized Gibbs ensembles.

References

[1] F. Lange, Z. Lenarčič, and A. Rosch, Nat. Comm. **8**, 15767 (2017)
[2] Z. Lenarčič, F. Lange, and A. Rosch, Phys. Rev. B **97**, 024302 (2018)
[3] F. Lange, Z. Lenarčič, and A. Rosch, arXiv:1801.07646 (2018)

Propagation of correlations in dissipative systems: ballistic, diffusive, rare event and aging dynamics

Jean-Sébastien Bernier

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In recent years, considerable experimental efforts have been devoted to dynamically generate complex states and monitor their evolution. Despite remarkable advances, the theoretical principles behind the non-equilibrium dynamics of strongly correlated quantum matter are still far from being fully understood. In particular, very few studies have sought to clarify the influence of environmental couplings on the propagation of correlations. We attempt here to fill this gap. As a first step, we consider an interaction quench in the Bose-Hubbard model under the effect of dephasing, and observe that dissipation effectively speeds up the propagation of single-particle correlations while reducing their coherence. In contrast, for two-point density correlations, the initial ballistic propagation regime gives way to diffusion at intermediate times. As a second step, we consider the evolution of two-time correlations in the XXZ spin-1/2 model in contact with a similar environment. We find this system to display rare event and aging dynamics. The latter dynamical regime is characterized by a breakdown of time-translation invariance, a slow non-exponential relaxation of two-time correlations and the presence of dynamical scaling.

Dynamics and interactions of quantum vortices in Bose-Einstein condensates

R. N. Bisset, S. Serafini, L. Galantucci, E. Iseni, T Bienaimé, M. Barbiero, C. F. Barenghi, G. Lamporesi, G. Ferrari, F. Dalfovo

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Boundaries strongly affect the behavior of quantized vortices in Bose-Einstein condensates, a phenomenon particularly evident in elongated cigar-shaped traps where vortices tend to orient along a short direction to minimize energy. Remarkably, contributions to the angular momentum of such vortices are tightly confined to the region surrounding the core, in stark contrast to untrapped condensates where every atom would contribute hbar. We theoretically and experimentally (using real-time imaging) explore the intriguing consequences. On the one hand, we demonstrate that such localized vortices precess in a manner analogous to a classical spinning top [1]. On the other hand, the elongated nature of the condensate allows us to channel two vortices towards one another. The local character of the vortices means that the ensuing collisions occur within a well-defined interaction region [2].

References

[1] R. N. Bisset, S. Serafini, E. Iseni, M. Barbiero, T. Bienaimé, G. Lamporesi, G. Ferrari, and F. Dalfovo, Phys. Rev. A **96**, 053605 (2017)

[2] S. Serafini, L. Galantucci, E. Iseni, T. Bienaimé, R. N. Bisset, C. F. Barenghi, F. Dalfovo, G. Lamporesi, and G. Ferrari Phys. Rev. X **7**, 021031 (2017)

Sound propagation in a superfluid two-dimensional Bose gas

J.-L. Ville[1], R. Saint-Jalm[1], E. Le-Cerf[1], M. Aidelsburger[1], S. Nacimbène[1], J. Dalibard[1] and J. Beugnon[1]

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In superfluid systems different sound modes can be excited, like first and second sound in liquid helium. We investigated the propagation of sound in a two-dimensional weakly interacting Bose gas. The gas is confined in a box-like potential and both propagating and standing waves can be excited and observed. We characterized the variation of the speed of sound and the damping rate of these excitations with temperature from the Bogoliubov regime to above the critical point. We find good agreement between our data and a two-fluid hydrodynamic model applied to two-dimensional Bose gases [1].

References

[1] T. Ozawa and S. Stringari, PRL **112**, 025302 (2014)

Efficient Simulation of Quantum Thermalization Dynamics

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The past decade has seen a great interest in the question about whether and how quantum many-body system locally thermalize. It has been driven by theoretical findings involving the long sought demonstration that many-body localization (MBL) exists as well as the derivation of exact bounds on chaos. In my talk, I will introduce matrix-product state (MPS) based methods that allow for an efficient numerical simulation of the quantum thermalization dynamics. Firstly, I will show that, contrary to the common belief that the rapid growth of entanglement restricts simulations to short times, the long time limit of local observables can be well captured using the MPS based time-dependent variational principle [1]. Secondly, I will discuss how mixed states can be represented using dynamically disentangled purified states. These novel methods allow to extract transport coefficients efficiently [2].

References

[1] E. Leviatan, F. Pollmann, J. H. Bardarson, D. A. Huse, E. Altman, arXiv:1702.08894

[2] J. Hauschild, E. Leviatan, J. H. Bardarson, E. Altman, M. P. Zaletel, F. Pollmann, arXiv:1711.01288

Coherent Manipulation of Spin Correlations in the 2D Fermi Hubbard Model

N. Wurz[1], C. F. Chan[1], M. Gall[1], J. H. Drewes[1], E. Cocchi[1,2], L. A. Miller[1,2], D. Pertot[1], F. Brennecke[1] and M. Köhl[1]

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Quantum gases of interacting fermionic atoms in optical lattices promise to shed light on the low-temperature phases of Hubbard-type models, such as the anti-ferromagnet. We study the physics of the two-dimensional Hubbard model by loading a quantum degenerate two-component Fermi gas of 40K atoms into a three-dimensional optical lattice geometry with strongly suppressed tunneling along the vertical direction. Using high-resolution absorption imaging combined with radio-frequency spectroscopy we spin-selectively record the in-trap density distribution of singly occupied lattice sites in a single horizontal plane [1].

We coherently manipulate spin correlations within a plane using spatially and time-resolved Ramsey spectroscopy [2]. This novel technique allows us not only to imprint spin patterns but also to probe the static magnetic structure factor at arbitrary wave vector, in particular the staggered structure factor. From a measurement along the diagonal of the 1st Brillouin zone of the optical lattice, we determine the magnetic correlation length and the individual spatial spin correlators. At half filling, the staggered magnetic structure factor serves as a sensitive thermometer for the spin temperature, which we employ to study the thermalization of spin and density degrees of freedom during a slow quench of the lattice depth.

References

[1] J. H. Drewes et al., PRL **118**, 170401 (2017)
[2] N. Wurz et al., arXiv:1709.08231 (2017)

Itinerant ferromagnetism for two-dimensional dipolar fermions

T. Comparin[1], **R. Bombin**[2], **M. Holzmann**[3,4], **F. Mazzanti**[2], **J. Boronat**[2], **and S. Giorgini**[1]

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Itinerant ferromagnetism appears when a system of spins which are free to move in space - rather than being localized on a lattice - have a tendency to align, leading to a state with non-zero polarization. Identifying this phenomenon for the ground state of an electron gas has been a long-standing challenge, which required significant advances in quantum many-body techniques.
The same phenomenon was later searched for in the context of ultracold atoms with short-range interactions, with two hyperfine representing the different spin states. This corresponds to the textbook case of the Stoner ferromagnetic instability.

In this work, we consider a mixture of two fermionic species in two dimensions, with a repulsive interaction potential proportional to the inverse cube distance between particles. This model represents the experimentally relevant case of dipolar atoms or molecules, with dipole moments aligned in the direction perpendicular to the plane.
We compute the zero-temperature phase diagram of this system by means of the Diffusion Monte Carlo technique, by comparing the energy of states at different polarizations. For increasing interaction strength, we identify a transition from an unpolarized to a polarized ground state, while for even stronger interactions the system enters the Wigner-crystal phase. To verify the stability of this polarized phase, we set up an additional calculation for the polaron problem, where a single impurity is immersed in a polarized bath.
The interaction-strength regime which is relevant for the polarized phase may become accessible in near-future experiments with ultracold molecules, where this instability could be identified through the observation of magnetic domains.

Time-resolved probing of repulsive many-body states in ultracold Fermi gases

F. Scazza[1,2], A. Amico[1,2], M. Inguscio[1,2], G. Roati[1,2], and M. Zaccanti[1,2]

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Strong repulsive interactions lie at the heart of a variety of electron correlation phenomena in condensed matter. In particular, strong repulsion between itinerant fermions fosters the emergence of ferromagnetism. I will report on our experimental investigations of repulsive many-body states in the minimal framework offered by ultracold Fermi gases with tunable short-range interactions and tunable spin polarization. I will first present our study of repulsive Fermi polarons in a strongly imbalanced resonant spin mixture [1]. The Fermi polaron impurity problem and the associated repulsive quasiparticle are centrally important for the description and the stability of ferromagnetic phases and spin domain walls. Through fast radio-frequency (RF) spectroscopy probing, we observe well-defined repulsive quasiparticles up to very strong repulsion and we characterise them by extracting all key elastic and inelastic quasiparticle properties: the energy E_+, the effective mass m^*, the residue Z and the decay rate Γ. Importantly, we find the polaron energy to exceed the Fermi energy of the bath at a critical coupling strength, while the effective mass diverges and even turns negative, revealing an energetic and thermodynamic instability of the repulsive Fermi liquid. I will also present our recent study of balanced spin mixtures quenched to strong repulsion, employing time-resolved pump-probe RF spectroscopy and local noise correlation measurements [2]. We monitor the evolution of the spectral response and of the spin-resolved density correlations of the system after a sudden RF transfer to the strongly repulsive regime, which is performed on a time scale much faster than the fermion pairing one. We reveal how the competing pairing and ferromagnetic instabilities lead to the rapid emergence of a long-lived inhomogeneous phase where pairing and magnetic correlations coexist, resembling a micro-scale emulsion of atoms and molecules.

References

[1] F. Scazza, G. Valtolina, P. Massignan, A. Recati, A. Amico, A. Burchianti, C. Fort, M. Inguscio, M. Zaccanti, and G. Roati, *Phys. Rev. Lett.* **118**, 083602 (2017)

[2] A. Amico, F. Scazza, G. Valtolina, P. E. S. Tavares, W. Ketterle, M. Inguscio, G. Roati, and M. Zaccanti, in preparation (2018)

Dynamical quantum phase transitions

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Quantum theory provides an extensive framework for the description of the equilibrium properties of quantum matter. Yet experiments in quantum simulators have now opened up a route towards generating quantum states beyond this equilibrium paradigm. While these states promise to show properties not constrained by equilibrium principles such as the equal a priori probability of the microcanonical ensemble, identifying general properties of nonequilibrium quantum dynamics remains a major challenge especially in view of the lack of conventional concepts such as free energies. The theory of dynamical quantum phase transitions [1,2] attempts to identify such general principles by lifting the concept of phase transitions to coherent quantum real-time evolution. In this talk I will give a pedagogical introduction to this field. Starting from the general setting of nonequilibrium dynamics in closed quantum many-body systems, first the general definition of dynamical quantum phase transitions as phase transitions in time will be given and recent experimental observations [3,4] will be outlined. And secondly, I will explain how few-particle experimental systems such as in trapped ions [3] or for photonic quantum walks can be used to extract dynamical quantum phase transitions from finite system sizes although these transitions become infinitely sharp only in the thermodynamic limit as is the case for equilibrium phase transitions.

References

[1] M. Heyl, A. Polkovnikov, and S. Kehrein, Phys. Rev. Lett. **110**, 135704 (2013)
[2] M. Heyl, arXiv:1709.07461 (2017)
[3] P. Jurcevic *et al.*, Phys. Rev. Lett. **119**, 080501 (2017)
[4] N. Fläschner *et al.,* Nature Physics AOP (2017)

Topology in Floquet Engineered Optical Lattices

Klaus Sengstock

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Topological properties lie at the heart of many fascinating phenomena in solid-state systems such as quantum Hall systems or Chern insulators. The topology of the bands can be captured by the distribution of Berry curvature, which describes the geometry of the eigenstates across the Brillouin zone. Using fermionic ultracold atoms in a hexagonal optical lattice, we engineered the Berry curvature of the Bloch bands using resonant driving and show a full momentum-resolved state tomography from which we obtain the Berry curvature and Chern number (Science 352, 1091 (2016)).

Furthermore, we study the time-evolution of the many-body wavefunction after a sudden quench of the lattce parameters and observe the appearance, movement, and annihilation of vortices in reciprocal space. We identify their number as a dynamical topological order parameter, which suddenly changes its value at critical times. Our measurements constitute the first observation of a so called ‚dynamical topological phase transition', which we show to be a fruitful concept for the understanding of quantum dynamics far from equilibrium (arXiv 1608.05616).

The talk will discuss general concepts of topology and dynamics of ultracold quantum gases in optical lattices.

Parametric instabilities in shaken atomic gases

S. Lellouch[1] and N. Goldman[2]

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Ultracold gases subjected to a time-dependent modulation are attracting a growing attention. One main reason is that such "driven" systems have proven efficient tools to design artificial gauge fields and topological phases for neutral atoms [1,2]. More generally, they open numerous perspectives in the general program of quantum simulation with ultracold atoms. However, most of the theory for driven systems still relies on a singleparticle description, and recent experiments in interacting regimes [3,4] have reported significant heating, losses, and instabilities in modulated Bose-Einstein condensates. A precise understanding of the physics at stake would therefore be highly welcome to guide experiments to stable regimes, opening new perspectives in quantum simulation, among which the realization of novel topological phases that have never been observed with ultracold atoms.

We report here [5] on a theoretical study of the instabilities that can arise in weakly-interacting Bose gases subjected to a time-dependent modulation. We first present a generic numerical method able to determine *ab initio* the stability regimes of a wide class of modulated systems, and to extract the associated instability rates. In a second step, we develop an analytical approach which allows to trace the observed instabilities back to the phenomenon of parametric resonances, and provides quantitative analytical estimates of the heating rates. We identify in the dynamics different instability regimes associated with different timescales, as well as clear signatures of those instabilities that could be directly probed in experiments. Extensions to other types of modulated systems [6] are discussed.

References

[1] N. Goldman and J. Dalibard, Physical Review X **4**, 031027 (2014)

[2] N. Goldman, G. Juzeliūnas, P. Öhberg, and I. B. Spielman, Rep. Prog. Phys. **77** 126401 (2014)

[3] M. Aidelsburger, M. Atala, M. Lohse, J. Barreiro, B. Paredes and I. Bloch, Physical Review Letters **111** 185301 (2013)

[4] H. Miyake, G. Siviloglou, C. Kennedy, W. Burton and W. Ketterle, Physical Review Letters **111** 185302 (2013)

[5] S. Lellouch, M. Bukov, E. Demler, N. Goldman, Physical Review X **7**, 021015 (2017).

[6] S. Lellouch and N. Goldman, arxiv:1711.08832 (2017).

Topological characterization of chiral models through their long time dynamics

A. Dauphin[1]

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Initially discovered in condensed matter, topological phases have so far been simulated in a variety of synthetic systems (ultracold atoms in optical lattices, photonic bandgap materials, mechanical systems, ...). Current theoretical research is showing that periodically-driven systems generate much richer and more complex topological properties than their static counterparts. Therefore, the accurate detection of these topological properties is a key challenge.

In this talk, we derive and design a flexible and efficient theoretical method which allows to measure the winding number of one dimensional systems with chiral symmetry by direct imaging of single particle dynamics in their bulk [1,2]. We then observe experimentally our theoretical findings by measuring the winding number in a chiral quantum walk realized by twisted photons, i.e., in a photonic platform exploiting the spin and orbital angular momenta of light [1]. We also discuss the recent observation of disorder driven topological phases and in particular the topological Anderson insulator in a static one-dimensional chiral symmetric wires with controllable disorder via spectroscopic Hamiltonian engineering, based on the laser-driven coupling of discrete momentum states of ultracold atoms [3].

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Laughlin-like physics in Bosonic and Fermionic Atomic Synthetic Ladders

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The exception transport properties of fractional quantum Hall liquids are determined by their topologically-protected edge modes. In this talk I will discuss how the exotic properties of the boundary modes of Laughlin states can be realized in cold-atom gases realizing ladders with one synthetic dimension. We named the states supporting these boundary properties "Laughlin-like states" and theoretically diagnose them by focusing on the chiral current flowing in the ladder, on the central charge of the low-energy theory, and on the properties of the entanglement entropy. Our results employ extensive simulations based on matrix-product states. The possibility of characterizing the transport properties of these states in cold-atom setups is discussed and a realistic proposal for a fractional Laughlin pump is presented.

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Engineering synthetic gauge fields with ultracold two-electron atoms

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Alkaline-earth(-like) two-electron atoms represent a very powerful platform for the implementation of novel quantum simulation schemes, due to the native SU(N) symmetry of inter-atomic interactions as well as to the existence of a metastable electronic state accessible with optical clock technology which can be exploited in experiments as an additional stable state.
In this talk I will describe how internal degrees of freedom of Ytterbium atoms, coherently coupled through laser light, can be exploited to realize a "synthetic dimension" that, used in combination with real-space optical lattices, allows for the engineering of strong magnetic field fluxes through a synthetic Hall ribbon. In particular, in a first experiment [1] we use nuclear spin states coupled by Raman transitions to realize the extra dimension and observe for the first time the onset of chiral edge states in a system of neutral fermions by probing the deformation of the spin-resolved momentum distribution, as well as the edge-truncated cyclotron dynamics of the atoms. In a second experiment [2], the synthetic dimension is implemented exploiting the ground and metastable electronic states coupled through clock laser light and we study the behavior of the chiral edge currents as a function of the synthetic magnetic field flux. This second systems appears particularly interesting due to the existence of a recently discovered Orbital Feshbach Resonance [3,4] between atoms in ground and excited electronic states that could be exploited in future studies to investigate the role of interaction in synthetic Hall-like systems.

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There is plenty of room at the bottom... but even more in a fractal

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Feynman's original idea of using one quantum system that can be controlled and manipulated at will to simulate the behaviour of another more complex one has flourished during the last decades in the field of cold atoms. More recently, this concept started to be developed in nano photonics and in condensed matter. In this talk, I will review some of the achievements with ultracold atoms and discuss a few recent experiments, in which 2D electron lattices were engineered on the nanoscale. The first is the Lieb lattice [1], and the second is a Sierpinski gasket [2]. The realisation of fractal lattices opens up the path to electronics in fractional dimensions.

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Quantum liquid droplets in a mixture of Bose-Einstein condensates

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Self-bound states appear in contexts as diverse as solitary waves in channels, optical solitons in non-linear media and liquid droplets. Their binding results from a balance between attractive forces, which tend to make the system collapse, and repulsive ones, which stabilize it to a finite size. This talk will present our recent experiments on dilute quantum liquid droplets: macroscopic clusters of ultra-cold atoms that are eight orders of magnitude more dilute than liquid Helium, but have similar liquid-like properties. In particular, they remain self-trapped in the absence of external confinement due to the compensation of attractive mean-field forces and an effective repulsion stemming from quantum fluctuations [1].

We observe these self-bound droplets in a mixture of two Bose-Einstein condensates with attractive inter-state and repulsive intra-state interactions. Exploiting in situ imaging, we directly measure their ultra-low densities and micro-meter scaled sizes, and demonstrate the many-body origin of their stabilization mechanism. Furthermore, we observe that for small atom numbers quantum pressure is sufficient to dissociate the droplets and drive a liquid-to-gas transition, which we map out as a function of atom number and interaction strength [2].

In a second series of experiments, we study the difference existing between these liquid droplets and more conventional bright solitons. In analogy to non-linear optics, the former can be seen as one-dimensional matter-wave solitons stabilized by dispersion, whereas the latter correspond to high-dimensional solitons stabilized by a higher order non-linearity due to quantum fluctuations. We find that depending on the system parameters, solitons and droplets can be smoothly connected or remain distinct states coexisting only in a bi-stable region, and we determine experimentally its boundary [3].

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Detection of entanglement in a Fermi-Hubbard dimer

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Correlations and entanglement are defining features of quantum many-body states and can be used to characterize quantum phases. In itinerant systems, where they emerge naturally through coherent particle motion and interactions, it is notoriously challenging to detect experimentally.

We probe correlations and the presence of entanglement in the fundamental unit cell of the Fermi-Hubbard model. Using fermionic Lithium 6 in optical microtraps, we deterministically realize quantum states in a tunable double-well potential [1]. A new imaging technique allows us to characterize the states with spin- and particle resolution in position and in momentum space.

We observe strong correlations in both degrees of freedom, indicating the high coherence of the two-particle system. We establish witness criteria that are based on the correlation functions to certify the presence of entanglement in the Fermi-Hubbard dimer and separately observe the emergence of entanglement between modes and between particles.

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Creating a bosonic fractional quantum Hall state by pairing fermions

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We numerically study the behavior of spin--1/2 fermions on a two-dimensional square lattice subject to a uniform magnetic field, where opposite spins interact via an on-site attractive interaction. The single-particle Hamiltonian is the Harper-Hofstadter model which was recently realized in several cold atomic gas experiments using artificial gauge fields. In this context, a Feschbach resonance can be used to implement a highly tunable on-site interaction. Starting from the non-interacting case where each spin population is prepared in a quantum Hall state with unity filling, we follow the evolution of the system as the interaction strength is increased. Above a critical value and for sufficiently low flux density, we observe the emergence of a twofold quasidegeneracy accompanied by the opening of an energy gap to the third level. Analysis of the entanglement spectra shows that the gapped ground state is the bosonic 1/2 Laughlin state. Our work therefore provides compelling evidence of a topological phase transition from the fermionic integer quantum Hall state to the bosonic Laughlin state at a critical attraction strength. I will present the numerical signatures of these two phases, and analyze the equilibrium properties of the phase transition. Finally, I will discuss some preliminary results concerning the dynamics of the phase transition.

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Correlations and symmetries in one-dimensional quantum gases

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We consider multi-component quantum mixtures (fermionic [1], bosonic or mixed [2]) with strongly repulsive delta interactions, in the experimentally relevant case of a one-dimensional harmonic trap. In the limit of infinitely strong repulsion and zero temperature, using the *class-sum method*, we study the symmetries of the spatial wave function of the mixture. We find that the ground state of the system has the most symmetric spatial wave function allowed by the type of mixture, which can be seen as a generalized Lieb–Mattis theorem. Moreover, we study the density profiles and momentum distribution of such mixtures. In particular, we show that the symmetry properties of the mixture are embedded in the large-momentum tails of the momentum distribution, namely the Tan's contacts. Furthermore, we derive scaling laws for these quantities as a function of the temperature and interaction strength [1]. The influence of the transverse confinement on Tan's contact is also studied in the simpler case of a one-component dilute Bose gas [3].

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Direct observation of incommensurate spin correlations in Hubbard chains

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The interplay between magnetism and doping is at the origin of exotic strongly correlated electronic phases appearing in high-T_C superconductors. One effect is the emergence of incommensurate spin-density waves where the wave vector doesn't belong to the reciprocal lattice. In the one-dimensional Hubbard model Luttinger liquid theory predicts incommensurate spin correlations to arise both from doping or from an external magnetic field imbalancing the spin populations. Here, we report on the direct observation of such incommensurate spin correlations in doped and spin-imbalanced Hubbard chains using spin-resolved quantum gas microscopy [1]. Doping is found to induce a linear change of the spin-density wave vector with density in excellent agreement with Luttinger theory predictions. For non-zero polarization we observe a decrease of the wave vector with magnetization as expected from the Heisenberg model in a magnetic field. We trace the microscopic origin of these incommensurate correlations to holes, doublons and excess spins which act as domain walls for the antiferromagnetic order [2]. Finally, by inducing interchain coupling we report on the evolution of the antiferromagnetic ordering around holes and doublons revealing a qualitative change in the crossover from one to two-dimensions.

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Collective dynamics of atomic ensembles confined within high-finesse optical cavities

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In this talk we will present recent theoretical work on cooling and spontaneous spatio-temporal pattern formation of atomic and molecular ensembles in optical resonators, where the key ingredient of the dynamics are the coherent and dissipative long-range optomechanical forces mediated by multiple scattering of the cavity photons. These dynamics reveal the existence of prethermalized states which are expected to be stable over the experimental time scales even in the bad cavity limit.

Measuring entanglement and scrambling via random unitaries.

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Entanglement plays a central role in our understanding of quantum many body physics, and is fundamental in characterizing quantum phases and quantum phase transitions. In this talk, I will first show how to measure Renyi entropies [1,2] in many-body quantum systems. Our approach consists in implementing an ensemble of random unitary evolution operators, applying them on the measured many-body state and extracting the desired functions from ensemble averaged observables [3]. I will present applications in one and two-dimensional Fermi (Bose-) Hubbard models and spin models, and discuss on-going experiments with trapped ions (R. Blatt and C. Roos group).

In the second part of my talk, I will extend these ideas by showing that random measurements provide us with protocols to measure any nonlinear function of a density matrix, or of a unitary time-evolution operator. I will illustrate this approach by showing that out of time order correlations (OTOCs) can be simply expressed as local response to local random perturbations, and are thus measurable directly in current AMO setups.

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Many-body entanglement witnessed through the quantum Fisher information

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The experimental detection of large-scale entanglement in quantum many-body systems is extremely challenging. Here, we discuss scenarios where it becomes accessible via the quantum Fisher information (QFI), a known witness for genuinely multipartite entanglement, which quantifies the potential for quantum-enhanced metrology [1]. First, we introduce a direct relation of the QFI in thermal states with linear response functions, which makes the QFI measurable with standard experimental methods [2]. Using this relationship, we show that close to continuous quantum phase transitions the QFI, and thus multipartite entanglement, can be strongly divergent. Moreover, we discuss relations of the quantum Fisher information to many-body localization [3] as well as to measures for many-body coherence [4]. As these results demonstrate, the quantum Fisher information represents a useful and efficiently measurable witness for many-body entanglement.

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Probing quantum superpositions in equilibrium many-body systems close to quantum and thermal critical points

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Uncertainty of physical quantities may have two origins : the (incoherent) noise resulting from the coupling to the environment and the intrinsic (coherent) quantum noise stemming from Heisenberg principle. We show how these two contributions to the variance of an arbitrary observable can be isolated for quantum systems at thermal equilibrium via basic statistical mechanics considerations. The thereby defined *quantum variance* turns out to be closely related to the quantum Fisher information (central for quantum metrology considerations), to which it provides both a lower and an upper bound, and is also a multipartite entanglement witness. Importantly, the quantum variance is measurable and computable for generic (namely non-integrable) many-body systems. In a second part, we investigate the structure of coherent *vs* incoherent fluctuations in the vicinity of the Ising critical point, in arbitrary spatial dimensions. We show that the coherent fluctuations are critical only close to the quantum (*ie* zero-temperature) critical point, where they are responsible for an enhanced interferometric sensitivity of the many-body state beyond the standard quantum limit, and take the form of spin squeezing robust against finite-temperature effects. In a last part, we show that the quantum variance of the order parameter, while being non-critical at a thermal (*ie* finite-temperature) critical point, are nonetheless singular, with a surprising sensitivity to the dynamical critical exponent. We illustrate this general finding by providing an estimate for the dynamical critical exponent of the superfluid transition based on quantum Monte Carlo simulations of the 3d XX model, circumventing the challenging problem of estimating dynamical correlations directly.

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Quantum simulation of spin models with individual Rydberg atoms in arbitrary geometries

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We report on our progress towards the quantum simulation of spin models with two-dimensional arrays of single Rydberg atoms [1]. We use a spatial light modulator to create arbitrary-shaped arrays of traps separated by distances of a few micrometres and load them with single atoms at near unit filling (Fig. 1) [2]. Laser excitation of the atoms to Rydberg states provides the strong, tuneable dipolar interactions needed to engineer several types of spin Hamiltonians [3,4,5].
We will present the implementation of the quantum Ising model in several configurations, including one-dimensional chains of atoms with periodic boundary conditions, square and triangular lattices containing up to 36 atoms. By dynamically tuning the parameters of the Hamiltonian, we observe the build-up of correlations in the system and study their propagation in the lattice. Our experiments are in very good agreement with numerical simulations which take into account experimental imperfections measured at the single particle level. These results enable the simulation of quantum magnetism in this platform.

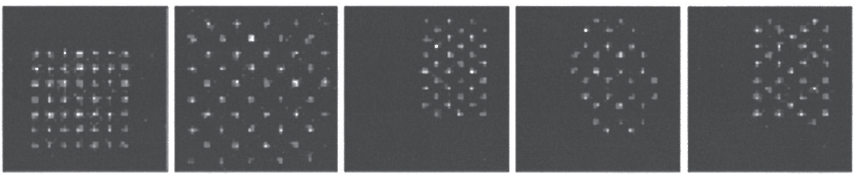

Figure 1. Fluorescence images of single atoms trapped in several geometries. All images are single shots.

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Abstracts of Posters

(in alphabetical order)

Superglass phase of interaction-blockaded gases on a triangular lattice

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The search for phases showing coexistence of different physical phenomena in systems of experimental interest is an active direction of research in condensed matter physics. Such scenarios include supersolids or superglasses, where macroscopic quantum phenomena coexist with a crystalline structure or glassy phenomena, respectively. In particular, superglasses have been predicted to appear in several numerical and theoretical studies, but without any conclusive experimental realization.

We investigate the quantum phases of monodispersed bosons on a triangular lattice and interacting via soft-shoulder potentials. Using exact Path Integral Monte Carlo simulations, we determine the equilibrium phases of the model to be a superfluid, a supersolid, and a crystal for weak, intermediate, and strong interactions, respectively. Simulated temperature quenches result in the appearance of out-of-equilibrium glass and superglass regions, for strong and intermediate values of the interaction strength, respectively. The investigated Hamiltonian is free of external frustration sources, usually employed to engender glassy phenomena, and the interactions of choice are relevant for experiments with Rydberg-dressed atoms in optical lattices, making our prediction of a superglass state of direct experimental interest.

Dual Shapiro steps of a phase-slip junction in the presence of a parasitic capacitance

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Bloch oscillations in a single Josephson junction in the phase-slip regime relate current to frequency. They can be measured by applying a periodic drive to a DC-biased, small Josephson junction. Phase-locking between the periodic drive and the Bloch oscillations then gives rise to steps at constant current in the I–V curves, also known as dual Shapiro steps. Unlike conventional Shapiro steps, a measurement of these dual Shapiro steps is impeded by the presence of a parasitic capacitance. This capacitance shunts the junction resulting in a suppression of the amplitude of the Bloch oscillations. This detrimental effect of the parasitic capacitance can be remedied by an on-chip superinductance. Additionally, we introduce a large off-chip resistance to provide the necessary dissipation. We investigate the resulting system by a set of analytical and numerical methods. In particular, we obtain an explicit analytical expression for the height of dual Shapiro steps as a function of the ratio of the parasitic capacitance to the superinductance. Using this result, we provide a quantitative estimate of the dual Shapiro step height. Our calculations reveal that even in the presence of a parasitic capacitance, it should be possible to observe Bloch oscillations with realistic experimental parameters.

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Interactions in a tunable Bose-Fermi mixture of ^{41}K and ^{6}Li: phase separation and spin transport

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We investigate the interaction properties of a ^{41}K Bose-Einstein condensate (BEC) immersed in a degenerate ^{6}Li Fermi sea. The scattering length between the lowest Zeeman spin states of the two species can be tuned in a precise controlled way by using a Feshbach resonance near 335 G. We observed the onset of a phase separation between the two species for sufficiently strong repulsive inter-species interaction, by investigating the spatial overlap thanks to K-K-Li three-body loss rate of the mixture[1]. Oscillations of a small BEC surrounded by a Fermi sea in the phase-separated regime can be theoretically studied by solving the hydrodynamic equations for the BEC and the Vlasov-Boltzmann equations for the fermions[2] and are now experimentally under investigation in our group. Our forthcoming goal is the characterization of non-equilibrium spin transport in a two-component spin-imbalanced Fermi sea caused by the presence of a small BEC that interacts solely with one fermionic component.

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Quantum Critical Behavior of One-Dimensional Soft Bosons in the Continuum

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We consider a zero-temperature one-dimensional system of bosons interacting via the soft-shoulder potential in the continuum, typical of dressed Rydberg gases. We employ quantum Monte Carlo simulations, which allow for the exact calculation of imaginary-time correlations, and a stochastic analytic continuation method, to extract the dynamical structure factor. At finite densities, in the weakly interacting homogeneous regime, a rotonic spectrum marks the tendency to clustering. With strong interactions, we indeed observe cluster liquid phases emerging, characterized by the spectrum of a composite harmonic chain. Luttinger theory has to be adapted by changing the reference lattice density field. In both the liquid and cluster liquid phases, we find convincing evidence of a secondary mode, which becomes gapless only at the transition. In that region, we also measure the central charge and observe its increase towards c=3/2, as recently evaluated in a related extended Bose-Hubbard model, and we note a fast reduction of the Luttinger parameter. For two-particle clusters, we then interpret such observations in terms of the compresence of a Luttinger liquid and a critical transverse Ising model, related to the instability of the reference lattice density field towards coalescence of sites, typical of potentials which are flat at short distances. Even in the absence of a true lattice, we are able to evaluate the spatial correlation function of a suitable pseudospin operator, which manifests ferromagnetic order in the cluster liquid phase, exponential decay in the liquid phase, and algebraic order at criticality.

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Non linear scattering of atomic bright solitons in disorder

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We observe nonlinear scattering of 39K atomic bright solitons [1] launched in a one-dimensional (1D) speckle disorder. We directly compare it with the scattering of non interacting particles in the same disorder. The atoms in the soliton tend to be collectively either reflected or transmitted, in contrast with the behavior of independent particles in the single scattering regime, thus demonstrating a clear nonlinear effect in scattering. The observed strong fluctuations in the reflected fraction, between zero and 100%, are interpreted as a consequence of the strong sensitivity of the system to the experimental conditions and in particular to the soliton velocity [2]. This behavior is reproduced in a mean-field framework by Gross Pitaevskii simulations, and mesoscopic quantum superpositions of the soliton being fully reflected and fully transmitted are not expected for our parameters. We discuss the conditions for observing such superpositions, which would find applications in atom interferometry beyond the standard quantum limit [3].

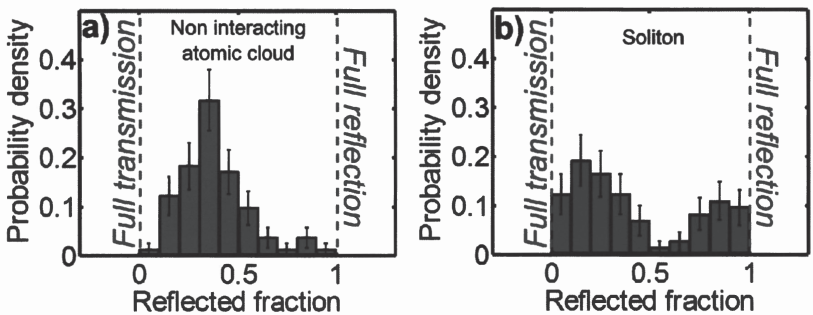

Figure 1: (Color online) Histograms of the experimentally measured reflected fractions of noninteracting atoms ((a) in blue) and solitons ((b) in red). The double-peak structure in (b) is a clear signature of nonlinear scattering.

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Quantum Ferrofluid Turbulence

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We study the elementary characteristics of turbulence in a quantum ferrofluid through the context of a dipolar Bose gas condensing from a highly non-equilibrium thermal state. Our simulations reveal that the dipolar interactions drive the emergence of polarized turbulence and density corrugations. The superfluid vortex lines and density fluctuations adopt a columnar or stratified configuration, depending on the sign of the dipolar interactions. When the interactions are dominantly dipolar, coherent vortex structures are formed, and quasi-classical quantum turbulence emerges through the quench. This system poses exciting prospects for realizing stratified quantum turbulence and new levels of generating and controlling turbulence using magnetic fields.

Spin model for 2-site resonant tunneling dynamics of bosons in a tilted optical superlattice

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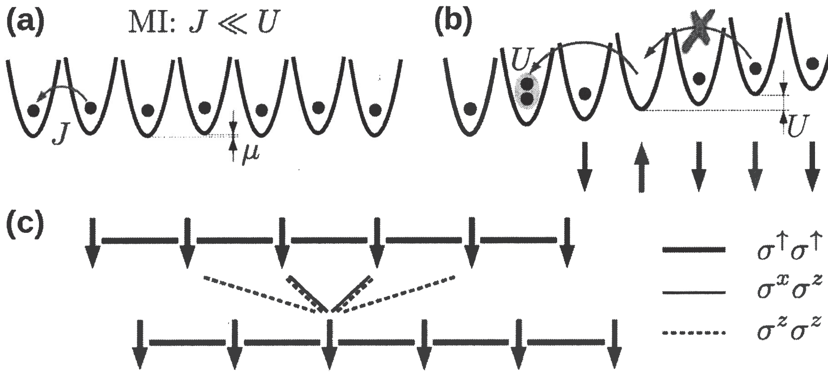
We study the non-equilibrium dynamics of a 1D tilted Bose-Hubbard model, beginning from unit filling in the Mott insulator regime. Studying a quench to the resonance point for tunneling of the particles over two sites, we show how in the presence of a superlattice, a spin model emerges involving two subchains described by an Ising model that are then coupled by interaction terms. Using the finite size scaling and specific heat calculations we conclude that the phase transition belongs to the tricritical Ising universality class and not Ising as it happens in the case of the first neighbor resonant tunneling. Using this model we study the out-of-equilibrium dynamics in the vicinity of the resonance and compare with dynamics of recent experiments realized without the superlattice geometry. This model is an interesting candidate for future experiments as it can be a platform for studying complicated magnetic interactions in quantum many-body systems in highly controllable regimes.



A three-mode treatment of spin-1 Bose-Einstein condensates with spin-orbit coupling

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Spin-orbit coupling (SOC) links a particle's spin to its motion and has a crucial role in the electronic properties of many condensed matter systems, being at the basis of phenomena such as the spin-Hall effect and topological insulators. The high level of control of ultracold atoms makes them ideal candidates to engineer the spin-orbit coupling in neutral systems [1]. In particular, it has been shown that by dressing two atomic spin states of a Bose-Einstein condensate (BEC) with a pair of lasers in a Raman configuration, spin-1\2 SOC can be realized, with equal Rashba and Dresselhaus couplings. Its phase diagram is characterized by the existence of three phases: the stripe, the plane-wave and the single-minimum phase, which merge in a characteristic tricritical point [2,3,4].

Furthermore, larger spin SOC can be realized by dressing three or more internal atomic states [5,6]. Spin-1 SOC can be engineered by two simultaneous Raman transitions, which at weak coupling lead to a triple-well in the lowest band of the single atom dispersion relation. Here we investigate the properties of spin-1 SOC BEC following a three-mode approximation [7]. We derive a many body Hamiltonian for a trapped and dressed weakly interacting BEC and numerically determine its ground state. In the homogeneous limit, an effective two-particle tunneling arises from the two-body interactions. This provides a completely new scenario for the ground state of the system compared to a position space three-well, which is numerically and analytically addressed.

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Single-atom-resolved probing of lattice gases in momentum space

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Correlations between the degrees of freedom of individual quantum particles has been identified as a key resource to solve open many-body problems. So far, a large experimental effort has been devoted to the building of apparatus capable of measuring spatial and spin correlations in one and two dimensions. We will present an experiment that provides access to multi-particle correlations between the momentum degree of freedom in three-dimensional lattice systems.

We produce Bose-Einstein condensates of Helium-4 atoms in a metastable state [1, 2], whose internal energy (19.6 eV) is large enough to allow for an electronic detection of individual atoms in three dimensions [3, 4].

When released from a 3D optical lattice, we probe the gas in the far-field regime of expansion where the atom distribution can be exactly mapped on the in-trap momentum distribution. Comparison with ab-initio Quantum-Monte Carlo calculations in the Bose-Hubbard regime qualifies our apparatus as a single-atom probe delivering momentum distribution of strongly interacting systems as large as 60*60*60 sites.

We also illustrate novel capabilities to access physical quantities of interest, like the condensed fraction, by investigating the superfuid-to-normal phase transition.

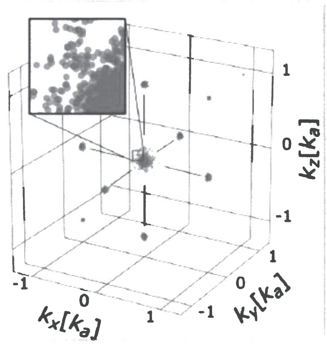

Fig: 3D atom-resolved momentum distribution of lattice gases in the superfluid regime.

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Reentrant Fulde-Ferrell-Larkin-Ovchinnikov superfluidity in the honeycomb lattice

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We study superconducting properties of population-imbalanced ultracold Fermi mixtures in the honeycomb lattice that can be effectively described by the spin-imbalanced attractive Hubbard model in the presence of a Zeeman magnetic field.
We use the mean-field theory approach to obtain ground state phase diagrams including the unconventional Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) phase, which is characterized by atypical behavior of the Cooper pairs total momentum.
We show that the momentum changes its value as well as direction with change of the system parameters. We discuss the influence of van Hove singularities on the possibility of the reentrant FFLO phase occurrence, without a BCS precursor.

Measurement of multipartite entanglement in many-body systems using temporal fluctuations

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Thanks to rapid experimental advances, ultracold atomic systems can be used to produce highly entangled states which are the key resources for future quantum technologies. However, the necessity to quantify and measure entanglement in many-particle quantum states presents strong challenges, both theoretically and experimentally. In this work, we demonstrate that the quantum Fisher information, a witness for genuinely multipartite entanglement, can be detected through the temporal fluctuations of thermal states subjected to a small quench. We showcase our proposal by studying strongly correlated quantum many-body systems after a small quench and compute the quantum Fisher information in different scenarios. Our work opens a path for experimentally measuring multipartite entanglement in current cold atoms experiments.

Particle-Hole Character of Higgs and Goldstone Modes in Strongly Interacting Lattice Bosons

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We study the low-energy excitations of the Bose-Hubbard model in the strongly-interacting superfluid phase using a Gutzwiller approach. We extract the single-particle and single-hole excitation amplitudes for each mode and report emergent mode-dependent particle-hole symmetry on specific arc-shaped lines in the phase diagram connecting the well-known Lorentz-invariant limits of the Bose-Hubbard model. By tracking the in-phase particle-hole symmetric oscillations of the order parameter, we provide an answer to the long-standing question about the fate of the pure amplitude Higgs mode away from the integer-density critical point. Furthermore, we point out that out-of-phase symmetric oscillations in the gapless Goldstone mode are responsible for a full suppression of the condensate density oscillations. Possible detection protocols are also discussed.

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Towards the study of many-body effects in resonantly coupled spinor BECs

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The realization of mixtures of BECs of different components, where no buoyancy between the two components is present, opens the possibility of studying many-body effects in spinor condensates, both at zero and finite temperature[?, ?]. When the two components of this mixture are resonantly coupled with an external field, it is theorically predicted[?] a stationary solution where the relative phase between the two components exhibits a 2π winding when crossing a domain wall. This solution is interesting to study for instance, the quantum simulation of confinement in QCD. In our lab it was recently shown[?] the possibility to create miscible and stable two-components BECs using atomic Sodium in the $|3^2S_{1/2}, F=1, m_F=+1\rangle = |\uparrow\rangle$ and $|3^2S_{1/2}, F=1, m_F=-1\rangle = |\downarrow\rangle$ states.

Towards the realization of these systems, we have realized a source of ultracold sodium atom (similar to [?]) that is able to produce samples of $4 \cdot 10^9$ atoms trapped in a 3D Dark-Spot MOT. The atoms are then cooled with gray molasses [?] down to $\approx 14\mu K$ before being loaded into a hybrid magneto-optical trap, that has been specifically designed to work inside a passive magnetic shield made of an high magnetic permeability alloy (μ-metal) in order to stabilize the magnetic field in the region down to the μG level. The hybrid trap consists of a quadrupole magnetic trap (QMT) and a tight optical dipole trap (ODT) focused below the center of the QMT[?]. The ODT is slowly loaded with atoms coming in the QMT, increasing the phase-space density by three orders of magnitude as well as preventing spin-flips at the center of the QMT. Performing evaporative cooling ramping down the ODT power we achieve condensation of $6 \cdot 10^6$ atoms[?].

The next steps will be the installation of the magnetic shield and characterization of the magnetic field stability, realization of a coherently coupled two-components BEC and moving towards the experimental study of the formation of the couples of vortices and of the confinement behaviour.

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Non-local orders and SPT phases in Hubbard-Heisenberg models

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Low-dimensional Hubbard- and Heisenberg-like systems play a crucial role in condensed matter physics, and their scientific interest has exponentially increased thanks to the experiments with cold atoms, which have opened the opportunity to simulate this type of lattice models. The high level of control of the Hamiltonian parameters has allowed to reach several regimes with hidden orders that can be revealed by the different behavior of proper non-local order parameters. Here we provide some analytical and numerical results proving the capability of non-local order parameters to detect fully and partly gapped quantum phases and capture their essential microscopic features. In particular we show the appearance of an Haldane-like gap and non-trivial topological properties in a Hubbard-Heisenberg model.

Roton in a many-body dipolar system

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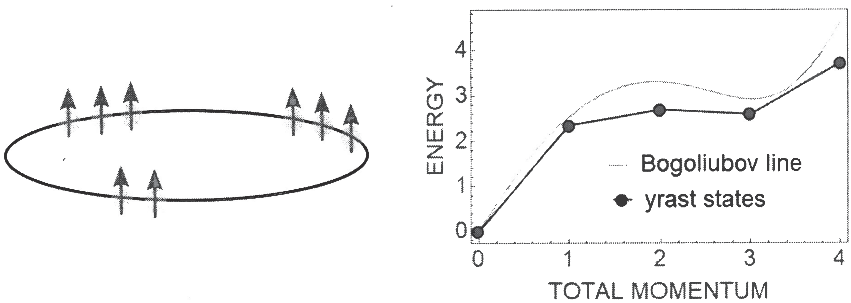
The roton quasiparticle is an object of interest of both theoretical and experimental physicists since early 40th, when L. Landau introduced peculiar dispersion relation for excitations in Helium-II to explain phenomenon of super-fluidity. This topic has been broadly discussed, especially within the Bogoliubov approximation. However, the roton state has never been found as the exact solution of many-body Hamiltonian.

In our work [1] we solve exactly the many-body 1D model of atoms interacting via short range attractive and long range repulsive dipole-dipole forces. We show that in such a system a roton-like state can appear as the yrast state (i.e. the lowest energy state with the fixed total momentum). We also discuss a possibility of verifying our results by an experiment with disprosium atoms. Especially, we observe that for the roton state the second order correlation function g_2 exhibits enhanced regular modulation.



Left panel: artist's view of the system of many dipolar atoms on the ring. Right panel: the dispersion relation for excitations is presented. The result of numerical calculations is compared with the Bogoliubov approximation.

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Ferromagnetic instability in a dynamical system of a repulsive two-component Fermi gas

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We study a binary spin-mixture of a zero-temperature repulsively interacting ^{6}Li atoms using both the atomic-orbital and the density functional approaches [1]. The gas is initially prepared in a configuration of two magnetic domains and we determine the frequency of the spin-dipole oscillations which are emerging after the repulsive barrier, initially separating the domains, is removed [2]. We find, in quantitative agreement with recent experiment [3], the occurrence of a ferromagnetic instability in an atomic gas while the interaction strength between different spin states is increased, after which the system becomes ferromagnetic (see Fig. 1). Our approach is easily extendable into different geometries, dimensions and types of fermionic species, bringing an opportunity to model ongoing experiments.

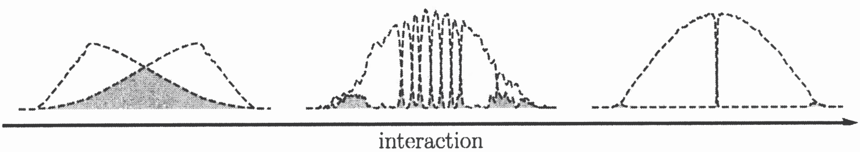

Fig 1. Densities of both fermionic species after the release of the barrier for different values of interaction strength. For a small repulsion both clouds penetrate each other, whereas for a strong one they enter immiscible regime, staying separated and bouncing off each other. Between these two regimes we observe the creation of a dynamical domain structure.

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Production of a molecular lithium BEC in a single-chamber setup

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We are setting up a new quantum gas microscope for the preparation and detection of degenerate samples of ^{6}Li / ^{7}Li atoms to study strong correlations in small quantum systems. Our design is optimized for a short cycle time allowing good statistics even in the case of just a few atoms. It consists of a compact 2D- / 3D-MOT chamber without any transport of the atoms after the 3D-MOT phase. We report on the realization of a molecular BEC of fermionic ^{6}Li atoms using an all-optical cooling procedure.

Cavity-induced artificial gauge field in a Bose-Hubbard ladder

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We consider theoretically ultracold interacting bosonic atoms confined to quasi-one-dimensional ladder structures formed by optical lattices and coupled to the field of an optical cavity. The atoms can collect a spatial phase imprint during a cavity-assisted tunneling along a rung via Raman transitions employing a cavity mode and a transverse running wave pump beam. By adiabatic elimination of the cavity field we obtain an effective Hamiltonian for the bosonic atoms, with a self-consistency condition. Using the numerical density matrix renormalization group method, we obtain a rich steady state diagram of self-organized steady states. Transitions between superfluid to Mott-insulating states occur, on top of which we can have Meissner, vortex liquid, and vortex lattice phases.

Dynamical quantum phase transitions in the particle-antiparticle production of a lattice gauge theory

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Particle-antiparticle production in the presence of a static classical electric field, known as the Schwinger mechanism, represents a central physical phenomenon in gauge theories. How the particle production is affected in the quantum limit, where the backaction onto the electric field becomes essential, remains a major challenge. In this work, we study particle-antiparticle production in the quantum quench dynamics after a strong coupling of the bare particles to dynamical gauge field in a quantum link model. We find that for a strong coupling the system experiences dynamical quantum phase transitions (DQPTs) where the vacuum persistence probability (Loschmidt echo) develops non-analytic behavior at critical times. As opposed to the Schwinger mechanism, where matter fields are suddenly coupled to a classical electric field, we observe that the dynamics of the vacuum persistence probability and therefore the DQPTs cannot be understood using the classical picture of particle production. Instead, a quantum dynamical pattern emerges from the strongly coupled matter fields and dynamical gauge fields. We discuss how these findings can be experimentally observed in quantum simulators such as trapped ions.

References

Spin-squeezed atomic crystals

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We present our recent work [1] concerning a method to obtain a regular arrangement of two-level atoms in a three-dimensional optical lattice with unit filling, where all the atoms share internal state coherence and metrologically useful quantum correlations. Such a spin-squeezed atomic crystal is obtained by adiabatically raising an optical lattice in an interacting two-component Bose-Einstein condensate. The scheme could be directly implemented on a microwave transition with state-of-the art techniques and used in optical-lattice atomic clocks with bosonic atoms to strongly suppress the collisional shift and benefit from the spins quantum correlations at the same time.

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Gray molasses laser cooling of fermionic lithium

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Laser cooling techniques are essential enabling tools in cold atom experiments. The discovery of lambda enhanced gray molasses has recently revoked interest in these techniques.
Here we present data of gray molasses cooling of lithium-6 atoms where we characterized the behavior near the Raman resonance. It is the key feature that allows us to compress the cloud in phase space and to reach temperatures of 80 μK. This is an excellent starting condition for the all-optical production of degenerate samples.
The experiments are performed in a single chamber setup which is designed for the fast production and single atom resolved read out of small quantum systems.

Towards Quantum State Assembly

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Initializing a system in a desired low entropy state is one of the main challenges of quantum simulation employing ultracold atoms. In most experiments a bulk gas is evaporatively cooled down and loaded into the desired potential.
On this poster we present our new setup following a different bottom-up approach. The idea is to assemble a complicated potential out of many separately prepared building blocks, which can be initialized with very low initial entropy. The required tailor made potentials are created by using a phase modulating Spatial Light Modulator implemented in our group's 2D lithium experiment.
This extended setup could significantly improve our understanding of strongly correlated fermionic systems, including the Fermi-Hubbard model. We show first measurements performed with the new setup and explore the feasibility of several lattice geometries.

Exploring the Single-Particle Mobility Edge and Many-Body Localized Phase in a 1D Quasiperiodic Optical Lattice with Ultracold Atoms

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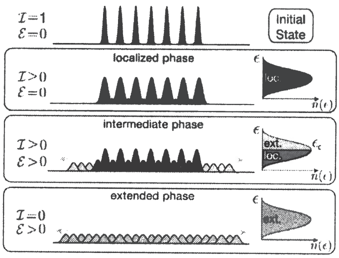

A single-particle mobility edge (SPME) marks a critical energy separating extended from localized states in a quantum system. In one-dimensional systems with uncorrelated disorder, a SPME cannot exist, since all single-particle states localize for arbitrarily weak disorder strengths. However, if correlations are present in the disorder potential, the localization transition can occur at a finite disorder strength and SPMEs become possible. In this work, we find experimental evidence for the existence of such a SPME in a one-dimensional quasi-periodic optical lattice [1]. Specifically, we find a regime where extended and localized single-particle states coexist, in good agreement with theoretical simulations, which predict a SPME in this regime [2].

In the corresponding interacting system we find that the dynamics is continuously slowing down as we approach a critical disorder strength, indicating that the system shows many-body localization (MBL) despite the presence of a SPME. We juxtapose two models with and without SPME and compare their dynamics on short and long timescales and find that the interacting system does not delocalize on short timescales despite the presence of single-particle extended states. Finally, we discuss whether a many-body mobility edge (MBME) might be present in our system [3].

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Observation of the Higgs mode in the superfluid BEC-BCS crossover in Fermi gases

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Thanks to recent advances, investigating the non-equilibrium dynamics of interacting systems is now possible. Using time-dependent perturbations, one can probe from a different angle the mechanisms responsible for the collective phenomena present in correlated systems. Taking advantage of this progress, we investigate both theoretically and experimentally the evolution of a three-dimensional Fermi gas while the interaction strength is effectively modulated. Our study, carried out on the BCS side, reveals various collective excitations. Interestingly, this approach highlights the presence of the Higgs mode.

Dynamical quantum phase transitions in discrete time crystals

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Discrete time crystals are related to non-equilibrium dynamics of periodically driven quantum many-body systems where the discrete time translation symmetry of the Hamiltonian is spontaneously broken into another discrete symmetry. Recently, the concept of phase transitions has been extended to non-equilibrium dynamics of time-independent systems induced by a quantum quench, i.e. a sudden change of some parameter of the Hamiltonian. There, the return probability of a system to the ground state reveals singularities in time which are dubbed dynamical quantum phase transitions. We show that the quantum quench in a discrete time crystal leads to dynamical quantum phase transitions where the return probability of a periodically driven system to a Floquet eigenstate before the quench reveals singularities in time. It indicates that dynamical quantum phase transitions are not restricted to time-independent systems and can be also observed in systems that are periodically driven. We discuss how the phenomenon can be observed in ultra-cold atomic gases.

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Producing superfluid circulation states using phase imprinting

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The study of quantum transport in ultracold gases holds potential to simulate the celebrated condensed matter phenomenon of superconductivity. Among the versatile range of trapping geometries available in ultracold gas experiments, the most suitable geometry to study persistent flow is the annular geometry. Setting superfluid flow in ring geometry has been a topic of interest and demonstrated using the technique of two-photon momentum transfer[1,2] and a barrier rotation[3]. Here we propose a method to prepare states of given quantized circulation in annular Bose-Einstein condensates (BEC) using the method of phase imprinting[4,5]. The desired phase profile is imprinted on the atomic wave function using a short light pulse with a tailored intensity pattern generated using a Spatial Light Modulator. We investigate the effect of imprinting an intensity profile smoothened by a finite optical resolution with a numerical simulation of the time-dependent Gross-Pitaevskii equation. This allows us to optimize the intensity pattern for a given target circulation[6].

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Chaotic dynamical phase induced by non-equilibrium quantum fluctuations

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We investigate the robustness of a dynamical phase transition against quantum fluctuations by studying the impact of a ferromagnetic nearest-neighbour spin interaction in one spatial dimension on the non-equilibrium dynamical phase diagram of the fully-connected quantum Ising model. In particular, we focus on the transient dynamics after a quantum quench and study the pre-thermal state via a combination of analytic time-dependent spin-wave theory and numerical methods based on matrix product states. We find that, upon increasing the strength of the quantum fluctuations, the dynamical critical point fans out into a chaotic dynamical phase within which the asymptotic ordering is characterised by strong sensitivity to the parameters and initial conditions. We argue that such a phenomenon is general, as it arises from the impact of quantum fluctuations on the mean-field out of equilibrium dynamics of any system which exhibits a broken discrete symmetry.

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Observing anyonic statistics via time-of-flight measurements

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We propose a standard time-of-flight experiment as a method to observe the anyonic statistics of quasiholes in a fractional quantum Hall state of ultracold atoms. The quasihole states can be stably prepared by pinning the quasiholes with localized potentials and a measurement of the mean square radius of the freely expanding cloud, which is related to the average total angular momentum of the initial state, offers direct signatures of the statistical phase. Our proposed method is validated by Monte Carlo calculations for ν=1/2 and 1/3 fractional quantum Hall liquids containing realistic number of particles.

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Topological phases of a two-leg Kitaev ladder

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We investigate the topological proprieties of a Kitaev ladder, i.e. a system made of two Kitaev chains coupled together site to site by transversal hopping and pairing term Δ_1 and t_1, respectively. Using the Chern number invariant, we present the topological phase diagrams of the system. It is shown that beyond a non-topological phase, the system exhibits a topological phase either with four or two Majorana (zero energy) modes. In particular, we find that for some critical values of the transversal hopping t_1, and at a given transversal paring Δ_1, the topological phase survives also when the Kitaev criterion for the single chain ($\Delta > 0, |\mu| < 2t$) is violated. Using a numerical analysis, we verify the bulk-edge correspondence of the non-trivial phases.

Quantum depletion and coherence of an ultracold boson vapor after a quench

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We consider a weakly interacting Bose-Einstein condensate with a time-dependent nonlinear coupling constant. By developing a suitable Bogoliubov treatment we investigate the time evolution of several observables, including the momentum distribution, the degree of coherence in the system, and their dependence on dimensionality and temperature. We rigorously prove that the low-momentum Bogoliubov modes remain frozen during the whole evolution, while the high-momentum ones adiabatically follow the change in time of the interaction strength. At intermediate momenta we point out the occurrence of Sakharov oscillations, analogous to those exhibited by the power spectrum of the cosmic microwave background. Finally, we identify two wide classes of time-dependent behaviors of the coupling for which an exact solution of the problem can be found, allowing for an analytic computation of all the relevant observables.

Self-bound quantum droplets in atomic mixtures

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Ultracold atomic systems are commonly found in a gas phase. However, self-bound quantum droplets have been recently discovered [1-4] as a new liquid-like phase. At the origin of this new phase is the coexistence of repulsive and attractive forces that perfectly balance to generate the self-binding mechanism. We report their experimental realization using a bosonic mixture, where spherical droplets form due to the balance of the attractive mean-field energy close to the collapse threshold and the repulsive first-order correction due to quantum fluctuations, the so-called Lee-Huang-Yang (LHY) term [1]. Thanks to an optical levitating potential with negligible residual confinement, we observe self-bound droplets in free space and we characterize the conditions for their formation as well as their equilibrium properties. This work paves the way to the study of the peculiar features of this new phase, among which is the unprecedented capability to spontaneously expel excitations and reach zero temperature, peculiar of these particular type of quantum droplets.

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Non equilibrium dynamics and transport in non-integrable systems

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In this work we investigate the transport properties of a 1-D non-integrable system after a quantum quench. For this purpose we use the prototypical quantum Ising chain with a *longitudinal magnetic* field that breaks the integrability, recently studied in [1]. The longitudinal field acts a ***confining potential*** *f*or the excitations produced in the quench. This confining ***strongly*** affects the dynamics and the transport after the quench.

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Quench spectroscopy of unconventional excitations in Rydberg quantum simulators

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Recent progress in atomic physics enable the engineering of the arrays of individually trapped atoms with highly tuneable geometry. The use of Rydberg excitations in such setups allows for the quantum simulation of quantum spin Hamiltonians (Ising and XY models) and provides a very promising platform for the study of exotic phases induced by magnetic frustration or positional disorder. A unique trait of frustrated and disordered systems is the appearance of localized excitations: localization can be either due to destructive interference stemming from the geometry of the couplings, or from the strong energy offset between different sites of the lattice. We shall illustrate theoretically that local and global quenches in Rydberg quantum simulators offer a unique opportunity to visualize the localized nature of such excitations. Moreover the Fourier analysis of the real-time evolution of correlation functions gives access to the dispersion relation of the excitations, singling out their possible non-dispersive (or flat-band) structure.

Dynamics of Few-Body Correlations in a Quenched Unitarity Bose Gas

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Recent experimental works [1, 2, 3, 4] highlight how signatures of few-body physics influence the observables of strongly-interacting Bose gases. Therefore, it is crucial to theoretically understand how few-body physics evolves into the many-body problem. We use the method of cumulants [5] to generalize the many-body equations including few-body physics and finite-range potentials. These ideas are based on a successful model of the unitary Fermi gas, coined resonance superfluidity [6]. In particular, we mimic experimental magnetic-field sequences to simulate a quench from non-interacting regime to unitarity and vice versa. Many-body observables show dependences on few-body phenomena, as three-body recombination. We also consider the dependence on the rate of change of the magnetic field including analysis of dressed molecules [7]. This work represents a basis for direct studies of the three-body correlation function in a many-body context. Importantly, this function contains the probability to find a three-body bound state, an Efimov state, in the presence of many particles.

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Magnetic transport of cold atoms in a quadrupole trap

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We have investigated the magnetic transport of a cold sodium gas confined in a quadrupole trap. In our experiment [1], on the order of 10^8 atoms at a temperature of 150 μK are displaced over 30,66 cm thanks to a succession of pairs of coils in a anti-Helmholtz configuration. We have compared different temporal shapes for the magnetic transport in terms of atom losses and heating of the cloud. The best results are obtained for smooth trajectories where a compromise is found to limit extreme values of the acceleration of the trap center position while minimizing the duration of the acceleration phases at the beginning and at the end of the magnetic transport. Relying on classical simulations of the dynamics of single atoms within the trap, we can show that this observation is a result of a trade-off between Majorana losses which increase significantly during the acceleration phases and finite trap depth losses due to too sudden changes in the trap center velocity. We have investigated how these effects scales with the magnetic gradient of the quadrupole trap and the temperature of the gas. For our experimental parameters the optimal minimum transport duration is about 500 ms.

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Comparative study of many-body *t*-matrix theories for a Fermi gas through the BCS-BEC crossover

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In the latest several years, diagrammatic theories based on the *t*-matrix approximation with different degrees of self-consistency have been developed to describe a Fermi gas through the BCS-BEC crossover [1,2,3,4]. A comprehensive comparison between the results obtained by the different approaches for both thermodynamical and dynamical quantities is, however, still lacking. In the present work, we consider all the possible ways of implementing self-consistency in the *t*-matrix approximation and we compare the outcomes of the different approaches between each other (and with the available experimental and Quantum Monte Carlo data) through the whole BCS-BEC crossover. In this way, we expect to provide a guideline on the virtues and the drawbacks of each scheme that can help future research in this field.

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Spin and mass imbalance in strongly interacting Fermi gases

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A wide range of stochastic methods has been applied to approach the non-relativistic fermionic many-body problem. Despite the huge success of these approaches, the sign problem prohibits exploration of a large class of systems due to exponential scaling of computational effort. Recently the complex Langevin method, known from relativistic lattice models, was adapted to non-relativistic theories. With this method at hand, we are able to extract properties for spin-polarized Fermi mixtures of arbitrary masses in the ground state as well as at finite temperature. More specifically, we are able to compute equations of state for Fermi mixtures of arbitrary mass and polarization as a function of interaction strength in one, two and three spatial dimensions. Additionally, we discuss pairing correlations in spin-polarized Fermi gases, ultimately aiming at a detection of the formation of an inhomogeneous superfluid condensate.

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Design and characterization of a quantum heat pump in a driven quantum gas

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We propose a novel scheme for quantum heat pumps powered by weak rapid time-periodic driving that enables heat flow from a colder to a hotter reservoir. We focus our investigation on a system consisting of two coupled driven quantum dots in contact with fermionic reservoirs at different temperatures and chemical potentials. To this end, we theoretically characterize the device by describing the coupling to the reservoirs using the Floquet-Born-Markov approximation. We reveal that the relative temperature and chemical potential difference governs the working of the heat-pump. Furthermore we show that for strong driving, the device departs away from working as a heat-pump. This is attributed to the contribution from the higher energy Floquet states. Finally, we compute the efficiency and the maximal temperature difference in which the proposed mechanism is useful for refrigeration. Experimentally, such a configuration can be realized in a quantum-gas microscope.

Dynamical localization and delocalization in a system of coupled kicked rotors

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We study the effect of many-body quantum interference on the dynamics of coupled periodically kicked systems whose classical dynamics is chaotic and shows an unbounded energy increase. We specifically focus on an N -coupled kicked rotors model: We find that the interplay of quantumness and interactions dramatically modifies the system dynamics, inducing a transition between energy saturation and unbounded energy increase. We discuss this phenomenon both numerically and analytically through a mapping onto an N -dimensional Anderson model. The thermodynamic limit $N \to \infty$, in particular, always shows unbounded energy growth. This dynamical delocalization is genuinely quantum and very different from the classical one: Using a mean-field approximation, we see that the system self-organizes so that the energy per site increases in time as a power law with exponent smaller than 1. This wealth of phenomena is a genuine effect of quantum interference: The classical system for N 2 always behaves ergodically with an energy per site linearly increasing in time. Our results show that quantum mechanics can deeply alter the regularity or ergodicity properties of a many-body-driven system.

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Topological two-body bound states in the interacting Haldane model

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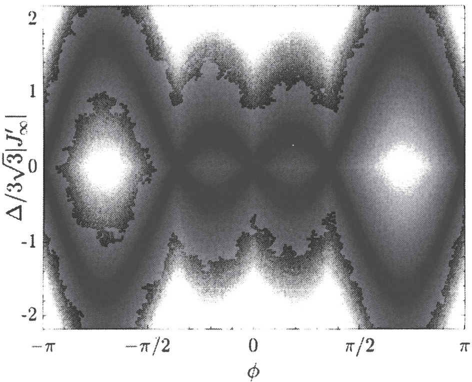
We study the topological properties of the two-body bound states in an interacting Haldane model as a function of interparticle interactions. In particular, we identify topological phases where the two-body edge states have either the same or the opposite chirality as compared to single-particle edge states. We highlight that in the moderately interacting regime, which is relevant for the experimental realization with ultracold atoms, the topological transition is affected by the internal structure of the bound state, and the phase boundaries are consequently deformed.



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Quantum gas microscopy of many-body dynamics in Fermi-Hubbard and Ising systems

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The ability to probe and manipulate cold atoms in optical lattices at the atomic level using quantum gas microscopes enables quantitative studies of quantum many-body dynamics. While there are many well-developed theoretical tools to study many-body quantum systems in equilibrium, gaining insight into dynamics is challenging with available techniques. Approximate methods need to be benchmarked, creating an urgent need for measurements in experimental model systems. Here, we will show two such measurements.

First, we present a study that probes the relaxation of density modulations in the doped Fermi-Hubbard model [1]. This leads to a hydrodynamic description that allows us to determine the conductivity. We observe bad metallic behavior that we compare to predictions from finite-temperature Lanczos calculations and dynamical mean field theory.

Second, we introduce a new platform to study the 2D quantum Ising model [2]. Via optical coupling of atoms in an optical lattice to a low-lying Rydberg state, we observe quench dynamics in the resulting Ising model and prepare states with antiferromagnetic correlations.

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Efimov physics for narrow Feshbach resonances

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The recent experimental exploration of the unitary Bose gas opens new directions in the study of strongly-correlated quantum many-body systems. Close to unitarity those systems are affected by three-body phenomena such as the universal Efimov effect. Experiments with atomic gases revealed that the long-range part of the two-body interaction plays a prominent role in this context [1]. Therefore, we study finite range effects of three strongly-interacting particles via the off-shell two-body T-operator in momentum space and investigate effects resulting from the multi-channel nature of the interaction. Especially in the context of narrow Feshbach resonances those effects are expected to be crucial for the interpretation of experimental observations [2].

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Faraday waves in Bose-Einstein condensates

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Degenerate atomic gases have made it possible to study matter-wave interference effects in atomic matter. The superfluidic behavior of Bose-condensed gases also makes them an excellent candidate for the study of quantum hydrodynamics. Excitations in coherent matter are well-described by theory and elementary excitations such as the dipole and quadrupole modes were among the first things to be measured. In a cigar-shaped Bose-condensed gas, a higher-order axial pattern, the Faraday pattern, is observed when the radial quadrupole mode is excited with a sufficiently large amplitude. [1]

We describe a single kick-experiment. By rapid compression and decompression of the atomic gas, the radial quadrupole mode is excited. Subsequently evolution of the atomic gas is studied and a Faraday pattern is experimentally observed to appear and disappear several times.

By numerically and theoretically studying the system, the mode functions are determined and the coupling strengths between the radial quadrupole mode and the longitudinal modes are determined. The coupling strength is found to be strongly peaked and Bose-enhancement in the coupling ensures that a single longitudinal mode dominates. In the presence of a longitudinal quadrupole mode, such as is the case in the experiment, several modes are excited and compete throughout a period of the longitudinal quadrupole oscillation.

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Time crystal behavior of excited eigenstate

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In analogy to spontaneous breaking of continuous space translation symmetry in the process of space crystal formation, it was proposed that spontaneous breaking of continuous time translation symmetry could lead to time crystal formation. In other words, a time-independent system prepared in the energy ground state is expected to reveal periodic mot ion under infinitely weak perturbation. In the case of the system proposed originally by Frank Wilczek, spontaneous breaking of time translation symmetry can not be observed if one starts with the ground state. We point out that the symmetry breaking can take place if the system is prepared in an excited eigenstate. Thelatter can be realized experimentally in ultra-cold atomic gases. We simulate the process of the spontaneous symmetry breaking due to measurements of particle positions and analyze the lifetime of the resulting symmetry broken state.

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Spin self-rephasing in the system of several atoms

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In this work a system consisting of a number of atoms evolving under the influence of external magnetic field is analyzed. Due to the inhomogenities of the external field, the atomic spins undergo dephasing: classically, since each atom feels different field along its trajectory, the spin rotation differs as well and the average spin decays. In a quantum mechanical context this corresponds to entanglement of spin and spatial degrees of freedom; additionally, two other modes of dephasing are possible: formation of internally (spin-spin) entangled state and population transfer to antisymmetric spin state.

The spin dephasing can be prevented by tuning the interaction between the atoms: such an effect, called spin self-rephasing has been observed experimentally [1] and can increase the coherence time by a large factor.

While such systems have been studied from a semiclassical point of view, a quantum mechanical description does not exist yet. In this work we fill in the gap by providing a numerical simulation of the behavior of the quantum mechanical system of several interacting, indistiguishable particles in the presence of inhomogenous magnetic field and analysis of the spin rephasing and coherence.

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Entanglement properties of lattice bosons from a variational wave function

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Entanglement is a defining characteristic of many-body quantum systems, expressing the degree of non-locality required by the description of the state of the system, and quantifying the amount of classical information demanded to faithfully reproduce the reduced state of any subsystem. The ground states of many-body Hamiltonians with short-range interactions are generically characterized by area-law scaling of entanglement entropies of a subsystem, implying that the classical information required to store the reduced density matrix is exponential in the surface of the subsystem itself this aspect impairs scalable simulations with methods based on the explicit reconstruction of reduced density matrix, such as DMRG, in dimensions higher than one. A viable alternative is based on variational ground states explicitly exhibiting an area-law scaling of entanglement. Here we explore the entanglement properties of entangled plaquette states (EPS) [1] representing a systematically improvable variational Ansatz for lattice boson models, and lending itself to an efficient optimization based on variational Monte Carlo. We evaluate the explicit dependence of the entanglement entropy on the number of coefficients in the variational Ansatz, and contrast the entanglement properties of local vs. nonlocal plaquettes in the EPS structure. Applying the EPS approach to a lattice boson model (the spatially anisotropic pi-flux triangular lattice) which bridges 1d and 2d physics, we investigate how the entanglement scaling reveals the effective dimensionality of correlations

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Quantum Dynamics with Artificial Neural Networks

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In the last years, there has been a growing interest in using machine learning techniques for the description of quantum many-body systems. In particular, artificial neural networks (ANNs) have been recently proposed as variational quantum many-body wave functions [1]. Using this approach, we study the unitary dynamics in transverse field Ising models (TFIMs) in one and two dimensions. The scenario we consider consists of a quantum quench which comprises a dynamical quantum phase transition [2]. Going beyond recent studies, we also include a longitudinal magnetic field, which is relevant for current experiments [3, 4]. We show that the representation of quantum many-body states using ANNs is able to accurately capture not only the transient dynamics, but also long-time dynamics.

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Bosonic Double Lattice Ring Under A Gauge Field

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We consider a system of weakly interacting bosons confined on a planar double lattice ring subject to two artificial gauge fields. We determine its ground state by solving coupled discrete non-linear Schrödinger equations at mean field level. At varying inter-ring tunnel coupling, flux and interactions we identify the vortex, Meissner (experimentally observed [1]) and biased-ladder phases also predicted for a bosonic linear ladder by a variational Ansatz [2], as well as other phases, such as a density wave and an imbalanced vortex phase. We also find peculiar features associated to the ring geometry, in particular parity effects in the number of vortices, and the appearance of a single vortex in the Meissner phase regime. We show that the persistent currents on the rings carry precise information on the various phases. Finally, we propose a way of observing the Meissner and vortex phases via spiral interferogram techniques.

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Floquet engineering of optical solenoids and quantized charge pumping along tailored paths in two-dimensional Chern insulators

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The insertion of a local magnetic flux, as the one created by a thin solenoid, plays an important role in \emph{gedanken} experiments of quantum Hall physics. By combining Floquet engineering of artificial magnetic fields with the ability of singlesite addressing in quantum-gas microscopes, we propose a scheme for the realization of such local solenoid-type magnetic fields in optical lattices. We show that it can be employed to manipulate and probe elementary excitations of a topological Chern insulator. This includes quantized adiabatic charge pumping along tailored paths inside the bulk, as well as the controlled population of edge modes.

Q-Walker: a fully-programmable quantum dynamics simulator with Rydberg-dressed atoms

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The transport of energy, charge and information is of fundamental importance in nature and technology ranging from (bio)physical processes to the operation of nano-electronic devices and in future quantum information networks. Building on remarkable experimental advances with Rydberg atoms as controlled quantum many-body systems, we aim to establish a programmable quantum dynamics simulator "Q-Walker", which is specifically suited to studying quantum transport on complex networks. It will make use of Rydberg-dressed atoms (nodes) coupled by coherent dipole-dipole interactions (links).

In this poster we will outline the key components of Q-Walker, including: fully configurable arrays of individual atoms, tunable long-range interactions for mediating all-to-all couplings, local control over system-reservoir interactions, and time- space- and state-resolved readout. The first applications of Q-Walker will be to study quantum and classical transport in complex networks and to mimic the fundamental process at play in biological networks such as photosynthetic light harvesting complexes. By finding the ingredients leading to the most efficient and robust quantum transport, we hope to answer longstanding questions concerning the role of quantum coherence in photosynthesis and devise new methods for classifying complex quantum networks.

Directly Measuring the Degree of Quantum Coherence using Interference Fringes

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Quantum coherence is the most distinguished feature of quantum mechanics. It lies at the heart of the quantum-information technologies as the fundamental resource. Nevertheless, the rigorous and systematic resource-theoretic framework of coherence has just been developed recently. Here, we develop a method to measure coherence directly using its most essential behavior—the interference fringes. The ancilla states are mixed into the target state with various ratios, and the minimal ratio that makes the interference fringes of the "mixed state" vanish is taken as the quantity of coherence. We also use the witness observable to witness coherence, and the optimal witness constitutes another direct method to measure coherence. For comparison, we perform tomography and calculate l_1 norm of coherence, which coincides with the results of the other two methods in our situation. Our methods are explicit and robust, providing a nice alternative to the tomographic technique.

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Dissipative Dynamics of Spin-1/2 Chains by Tensor Network Algorithms

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We report results on the non-equilibrium dissipative dynamics of open spin-1/2 XXZ chains. Applying time-dependent matrix product state (tMPS) algorithms [1], we perform numerically exact simulations for the full evolution of this open quantum system. We identify and characterize three different dynamical regimes. Our numerical findings are complemented by analytical investigations done within the framework of adiabatic elimination.

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Full scaling function of the Tan contact for trapped Lieb-Liniger Gases at Finite Temperature

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The Tan contact is a key quantity to determine many universal thermodynamic properties of quantum systems with short-range interactions. For instance, it characterizes the weight of the large-momentum tails in momentum distribution, the zero-range two-body correlations as well as the interaction energy. In this contribution, we report the determination of the full scaling function of the Tan contact for 1D Bose gases. We firstly propose a two-parameter scaling for the contact. Then, we calculate the full scaling function of the contact based on the Yang-Yang thermodynamics with local density approximation (LDA) and quantum Monte-Carlo calculations (QMC). We then discuss the non-monotonic behavior of the contact, where a maximum of the contact versus temperature appears. We argue that it provides a non-ambiguous signature of the crossover to fermionization in the strongly-interacting regime, and the crossing from quasi-condensate to ideal bosons in weakly-interacting regime. Our results offer new prospects to experiments with ultracold atoms in one-dimensional optical traps.

3D image reconstruction using symmetries applied to cold Rydberg gases

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This poster introduces an algorithm to reconstruct a three dimensional object from its two dimensional projection. It discretizes the problem in a coordinate system given by *a priori* knowledge of the object's symmetry. For certain cases the resulting system of linear equations can be solved in a least squares sense, including the case of rotational symmetry about an axis perpendicular to the line of sight, making the algorithm a generalization of the Abel transform [1]. The method is applied to a strongly interacting Rydberg gas in order to study saturation effects and scaling laws in the excitation dynamics.

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Magnetically tunable Feshbach resonances in an ultracold gas of europium atoms and a mixture of europium and alkali-metal atoms

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We investigate magnetically tunable Feshbach resonances between ultracold europium atoms and between europium and alkali-metal atoms. For ultracold gas of europium atoms both homonuclear ^{153}Eu+^{153}Eu and heteronuclear ^{151}Eu+^{153}Eu systems are investigated. Calculations for mixtures of europium and alkali-metal atoms are carried out for prototype systems of ^{153}Eu+^{87}Rb and ^{153}Eu+^{7}Li. We analyze the prospects for magnetoassociation into ultracold polar and paramagnetic molecules, observation of quantum chaotic behavior, and control of scattering properties in the investigated systems. Presented results may be useful for realization and application of dipolar atomic and molecular quantum gases based on europium atoms in many-body physics.