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QUANTUM FLAGSHIP

UNIVERSITÉ DE GENÈVE

DQMP Department of Quantum Matter Physics

	Monday Aug. 2	Tuesday Aug. 3	Wednesday Aug. 4	Thursday Aug. 5	Friday Aug. 6	
08h45	Welcome					08h45
09h00	Schmiedmayer [45+15]	Abanin	Scazza	Demler	Fallani	09h00
10h00	Vatre [20+10]	Grochowski	Jin	Klemmer	Zhou	10h00
10h30	Coffee Break	Coffee Break	Coffee Break	Coffee Break	Coffee Break	10h30
11h00	Clement [45+15]	Yao	Del Pace	Sobirey	Giamarchi	11h00
12h00	Scientific exchanges	Scientific exchanges	Scientific exchanges	Scientific exchanges	Scientific exchanges	12h00
12h30	Lunch and time for scientific exchanges	Lunch and time for scientific exchanges	Lunch and time for scientific exchanges	Lunch and time for scientific exchanges	Lunch and time for scientific exchanges or departure	12h30
16h30	Coffee Break	Coffee Break	Coffee Break	Coffee Break		16h30
17h00	Modugno [45+15]	Ferreira [10+10] Sonner Fedrizzi Pizzino Morpurgo Rousselle	Muzi [10+10] Thoenniss Wiater	Dawid		17h00
18h00	Biagioni [20+10]		Tusi	Lerose		18h00
18h30	Welcome aperitif		Cappellini	Guo		18h30
19h00	Dinner at the village	Dinner at the village	Dinner at the village	BBQ at the Institute	Diner at the village	19h00

A new approach to ergodic and non-ergodic many-body dynamics

Dmitry Abanin

University of Geneva

I will first overview different regimes of highly non-equilibrium dynamics in many-body systems, including thermalisation, many-body localization, quantum scars, and prethermalization. I will outline a new approach to these phenomena, based on the influence functional of a many-body system, which describes how the system acts as a bath for its small subsystems. This approach turns out to be surprisingly efficient in very different dynamical regimes, albeit for different physical reasons. Its efficiency is based on the low temporal entanglement, which is gives complementary information about system's dynamics compared to the conventional, real-space many-body entanglement of the wave functions. This approach provides a promising route towards classifying universality classes of highly non-equilibrium many-body dynamics.

Dimensional crossover in the superfluid-supersolid phase transition

Giulio Biagioni

University of Florence, Department of Physics and Astronomy and LENS

The supersolid is a fundamental state of matter in which the same atoms that form a crystalline lattice are also responsible for the coherent flow of mass, typical of superfluids. In 2018, my group realized for the first time a supersolid phase in a quantum gas of strongly dipolar atoms. During the talk, I will focus on our latest work, in which we study the nature of the transition to the supersolid phase both experimentally and theoretically. By changing the trap confinement and the atom number, we find two different transitions that are the finite-size counterpart of the continuous and discontinuous phase transitions expected to occur in the thermodynamic limit in 1D and 2D, respectively. The two kinds of phase transitions give rise to supersolids with different structures and dynamical properties.

A new programmable quantum simulator with atoms in optical tweezers in Florence

Giacomo Cappellini[1,2]

[1] *CNR-INO, Istituto Nazionale di Ottica del CNR*
[2] *LENS, European Laboratory for Nonlinea Spectroscopy*

I will present a new programmable quantum simulator based on Rydberg strontium atoms trapped in optical tweezers arrays at CNR-INO and LENS in Florence. This new experimental setup is supported by a infrastructural program of CNR and is now under construction in our laboratories. I will present the main features of the apparatus and the techniques that we will employ for the generation of programmable arrays of optical tweezers. I will also demonstrate the advantages offered by two-electron atoms, in particular the presence of a metastable states that provides an additional degree of freedom for atomic manipulation, including novel Rydberg excitation schemes, and a direct connection to frequency metrology. I will finally discuss the potential applications of this new setup, in particular the simulation of quantum spin models with different types of interactions and topologies, and the realization of multi-particle entangled states.

Observation of pairs of atoms with opposite momenta in the quantum depletion of interacting Bose gases

Antoine Tenart, Gaétan Hercé, Jan-Philipp Bureik, Alexandre Dareau, and David Clément

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

Quantum fluctuations play a central role in the properties of quantum matter. In non-interacting ensembles, they manifest as fluctuations of non-commuting observables. In the presence of interactions, additional quantum fluctuations appear, from which many-body correlations and entanglement arise. In this context, the Bogoliubov theory provides us with an illuminating microscopic picture of how this occurs for weakly-interacting bosons, with the appearance of the quantum depletion formed by pairs of bosons with opposite momenta. We will report the observation of these atom pairs in the depletion of an equilibrium interacting Bose gas [1]. Our experiment exploits the single-atom detection of metastable Helium in the momentum space [2] and the adiabatic preparation of interacting lattice gases [3]. We have studied the properties of the pair correlations (amplitude and width) and contrast them with those of Hanbury-Brown and Twiss type of correlations [4, 5]. We also show that the quantum depletion share the properties of two-mode squeezed states, including relative number squeezing at opposite momenta, which highlights the quantum coherences of the pairs in the many-body ground state.

[1] A. Tenart et al., arXiv:2105.05664 (2021).
[2] H. Cayla et al., Phys. Rev. A 97, 061609(R) (2018).
[3] C. Carcy et al., Phys. Rev. Lett. 126, 045301 (2021).
[4] H. Cayla et al., Phys. Rev. Lett. 125, 165301 (2020).
[5] S. Butera et al., Phys. Rev. A 103, 013302 (2021).

Let's open the black box: Hessian-based toolbox for more interpretable and reliable machines learning physics

Anna Dawid,[1,2] Patrick Huembeli,[3] Michał Tomza,[1] Maciej Lewenstein,[2,4] and Alexandre Dauphin[2]

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Identifying phase transitions is one of the key problems in quantum many-body physics. The challenge is the exponential growth of the complexity of quantum systems' description with the number of studied particles, which quickly renders exact numerical analysis impossible. A promising alternative is to harness the power of machine learning (ML) methods designed to deal with large datasets [1]. However, ML models, and especially neural networks (NNs), are known for their black-box construction, i.e., they usually hinder any insight into the reasoning behind their predictions. As a result, if we apply ML to novel problems, neither we can fully trust their predictions (lack of reliability) nor learn what the ML model learned (lack of interpretability).

We present a set of Hessian-based methods (including influence functions) opening the black box of ML models, increasing their interpretability and reliability. We demonstrate how these methods can guide physicists in understanding patterns responsible for the phase transition. We also show that influence functions allow checking that the NN, trained to recognize known quantum phases, can predict new unknown ones. We present this power both for the numerically simulated data from the one-dimensional extended spinless Fermi-Hubbard model [2] and experimental topological data [3]. We also show how we can generate error bars for the NN's predictions and check whether the NN predicts using extrapolation instead of extracting information from the training data [4]. The presented toolbox is entirely independent of the ML model's architecture and is thus applicable to various physical problems.

[1] J. Carrasquilla. (2020). Machine learning for quantum matter, Advances in Physics: X, 5:1.

[2] A. Dawid et al. (2020). Phase detection with neural networks: interpreting the black box. New J. Phys. 22, 115001.

[3] N. Käming, A. Dawid, K. Kottmann et al. (2021). Unsupervised machine learning of topological phase transitions from experimental data. arXiv:2101.05712.

[4] A. Dawid et al. (2021). Hessian-based toolbox for more interpretable and reliable machine learning in physics. In preparation.

Manipulating on demand circulation states of homogeneous fermionic superfluids

Giulia Del Pace,[1,2] Woo Jin Kwon,[1,2] Klejdja Xhani,[1,2] Luca Galantucci,[3] Alessandro Muzi Falconi,[1,2] Marco Fedrizzi,[1,2] Massimo Inguscio,[4] Francesco Scazza,[1,2,5] and Giacomo Roati[1,2]

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Here I report on our recent results in controlling the circulation states of homogeneous fermionic superfluids. The homogeneous trap is provided by the combination of a tight vertical trap and a DMD-made box potential in the trap. Exploiting the dynamical control over the optical potential provided by the device, we excite tunable and deterministic circulation states in superfluids across the BEC-BCS crossover. In our recent work [1], we realize a programmable vortex collider to investigate the dissipative dynamics of arbitrary configuration of vortices. By studying single vortex dipole dynamics and dipole-dipole collision, we decouple relaxation of the vortex energy due to sound emission and interactions with normal fluid, i.e. mutual friction. Our results show an increasing dissipation on the BCS side of the resonance, possibly due to the role of quasiparticles filling the vortex core in such regime. Finally, I present our preliminary study of persistent currents in fermionic superfluids trapped in a ring geometry. By imprinting a phase gradient onto the atomic cloud, we excite currents of well defined circulation, which are found to be long-lived in all the diverse superfluid regimes in the BEC-BCS crossover.

[1] W. J. Kwon, et al., 'Sound emission and annihilations in a programmable quantum vortex collider', arXiv:2105.15180 (2021).

A pointillist approach to quantum matter

Eugene Demler

Institute for Theoretical Physics, ETH, Zurich 8093

What can we learn about a many-body system when we measure every constituent particle? Current experiments with ultracold atoms provide snapshots of many-body states with single particle resolution. I will discuss new insights into strongly correlated states that came out of analyzing snapshots of the Fermi Hubbard model. For a broad range of fermion densities, experiments indicate an existence of magnetic polarons that can be understood as spinon-chargon pairs bound by geometric strings, in close analogy to quark-antiquark bound pairs forming mesons in QCD. I will review evidence for the crossover between the polaronic metal and the Fermi liquid state. The application of machine learning techniques to the analysis of snapshots of many-body states will also be discussed.

Multicomponent fermions with coherent state manipulation: from SU(N) physics and synthetic dimensions to state-dependent Mott localization

Leonardo Fallani

Dipartimento di Fisica e Astronomia, Università degli Studi di Firenze (Italy)

I will present an overview of experiments performed at University of Florence, where we have demonstrated new directions for quantum simulation via the optical manipulation of ultracold 173Yb fermions. I will focus on the optical control of the nuclear spin, which allowed us to study strongly interacting fermions with SU(N) interaction symmetry [1] and to engineer "synthetic dimensions" for the realization of synthetic gauge fields [2].
Specifically, I will report on recent progresses concerning the investigation of SU(N) Fermi-Hubbard systems, where the addition of a coherent Raman coupling between different spin states is used to induce a controlled breaking of the SU(N) global interaction symmetry [3]. This explicit symmetry-breaking action is shown to favour Mott localization and determines the onset of a state-selective behavior. I will discuss the experimental results and the connection with the physics of strongly correlated materials, where a similar orbital-selective localization arises from coupling between different orbitals.

[1] G. Pagano et al., Nature Phys. 10, 198 (2014).
[2] M. Mancini et al., Science 349, 1510 (2015).
[3] D. Tusi et al., arXiv:2104.13338 (2021).

Excitation and detection of persistent currents in ring-shaped strongly interacting Li-6 superfluids

Marco Fedrizzi,[1,2] Giulia Del Pace,[1,2] Woo Jin Kwon,[1,2] Klejdja Xhani,[1,2] Alessandro Muzi Falconi,[1,2] Massimo Inguscio,[3] Francesco Scazza,[1,2,4] and Giacomo Roati[1,2]

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I will present our recent experimental method to study persistent currents in strongly correlated Fermi superfluids. We prepare the system in a ring geometry, and then we excite currents in a controllable fashion by a phase imprinting technique. We detect them by counting number of spirals which result as the interference pattern during the time of flight evolution of the gas.

Exact description of quantum stochastic models as quantum resistors

Tony Jin,[1] S. Ferreira João,[1] Michele Filippone,[1,2] and Thierry Giamarchi[1]

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We study the transport properties of generic out-of-equilibrium quantum systems connected to fermionic reservoirs. We develop a new method, based on an expansion of the current in terms of the inverse system size and out of equilibrium formulations such as the Keldysh technique and the Meir-Wingreen formula. Our method allows a simple and compact derivation of the current for a large class of systems showing diffusive/ohmic behavior. In addition, we obtain exact solutions for a large class of quantum stochastic Hamiltonians (QSHs) with time and space-dependent noise, using a self-consistent Born diagrammatic method in the Keldysh representation. We show that these QSHs exhibit diffusive regimes which are encoded in the Keldysh component of the single-particle Green's function. The exact solution for these QSHs models confirms the validity of our system size expansion ansatz, and its efficiency in capturing the transport properties. We consider in particular three fermionic models: i)a model with local dephasing ii) the quantum simple symmetric exclusion process model iii) a model with long-range stochastic hopping. For i) and ii) we compute the full temperature and dephasing dependence of the conductance of the system, both for two- and four-point measurements. Our solution gives access to the regime of finite temperature of the reservoirs which could not be obtained by previous approaches. For iii), we unveil a novel ballistic-to-diffusive transition governed by the range and the nature (quantum or classical) of the hopping. As a by-product, our approach equally describes the mean behavior of quantum systems under continuous measurement.

Hall effect in quasi-1D systems

Thierry Giamarchi,[1]

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The Hall effect plays a central role in our understanding of materials in condensed matter physics. For non-interacting quantum problems the Hall effect has been shown to be related to topological invariants of the dispersion relation, providing a beautiful illustration of the importance of topology for quantum systems. Unfortunately our understanding of quantum Hall is much more primitive when interactions are present. In addition to remarkable phases such as fractional quantum Hall effects reached at very large magnetic fields, even the naively simpler case of the small magnetic field Hall effect is essentially not understood. Cold atomic systems have provided recently remarkable realization in which to probe in a controlled way such physics, through artificial gauge fields and synthetic dimensions. I will thus review in this talk the various theoretical questions pertaining to Hall effect in interacting systems [1,2,3] in the light of the recent realization in cold atomic gases.

[1] S. Greshner, M. Filippone, T. Giamarchi Phys. Rev. Lett. **122** 083402 (2019)

[2] M. Filippone, C.E. Bardyn, S. Greshner, T. Giamarchi Phys. Rev. Lett. **123** 086803 (2019)

[2] M. Buser, S. Greshner, U. Schollwöck, T. Giamarchi Phys. Rev. Lett. **126** 030501 (2021)

Repulsive dynamics of strongly attractive one-dimensional quantum gases

Maciej Łebek,[1,2] Andrzej Syrwid,[2] Piotr T. Grochowski,[1,4] and Kazimierz Rzążewski[1]

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We analyze the dynamics of one-dimensional quantum gases with strongly attractive contact interactions. We specify a class of initial states for which attractive forces effectively act as strongly repulsive ones during the time evolution. Our findings extend the theoretical results on the super-Tonks-Girardeau gas to a highly nonequilibrium dynamics. The novel mechanism is illustrated on the prototypical problem of the domain stability in a two-component Fermi gas. We also discuss nonlocal interactions and analyze universality of the presented results. Moreover, we use our conclusions to argue for the existence of metastable quantum droplets in the regime of strongly attractive contact and attractive dipolar interactions.

[1] arXiv:2107.05594.

Investigating transport of supersonic impurities in a strongly interacting one-dimensional quantum gas

Yanliang Guo, Milena Horvath, Sudipta Dhar, Manuele Landini, and Hanns-Christoph Nägerl

Institut für Experimentalphysik und Zentrum für Quantenphysik, Universität Innsbruck, 6020 Innsbruck, Austria

We study the transport of impurity atoms through a strongly correlated one-dimensional gas of Cs atoms (1D tubes) with tunable interactions. Our aim is to find evidence for the elusive quantum flutter effect, which has been proposed to occur for an intially uniformly moving supersonic impurity inside a Tonks-Girardeau gas[1][2]. In our experiment with Cs atoms in the (F=3, $m_F = 3$) hyperfine state and the 1D tubes oriented along gravity, we accelerate impurity atoms in the (F=3, $m_F = 2$) hyperfine state to below and above supersonic speeds, with about one impurity atom per 1D system, and let them interact with the host gas in the 1D tubes. We find that the subsequent evolution of the impurity momentum to a (non-zero) equilibrium value depends crucially on the initial conditions, with indications of an oscillatory motion for the supersonic case. In addition, the shape of the impurity's momentum distribution depends critically on where the impurity is created from the host gas, with a clear breakup into two components when the impurity is preferentially created at the bottom of the 1D tubes. We will discuss our data and present further, somewhat puzzling results. In addtion, we present our preparations towards generating coupled 1D tubes by means of the superlattice technique.

[1] Quantum flutter of supersonic particles in one-dimensional quantum liquids, C.J.M. Mathy et al., Nature Physics 2012.

[2] Quantum Flutter: Signatures and Robustness, M. Knap et al., PRL 2014.

Diffusive transport in boundary driven out-of-equilibrium quantum systems

Tony Jin,[1] Joao Ferreira,[1] Michele Filippone,[2] and Thierry Giamarchi[1]

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Diffusion is an ubiquitous transport phenomena observed in all areas of physics. Despite its simplicity, it is notoriously difficult to derive from first principles and the microscopic origins of diffusion are still subject to debate today. In this talk, I will present a class of quantum diffusive models named quantum stochastic Hamiltonians (QSHs) and study their stationary properties when driven out-of-equilibrium by unbalanced boundary reservoirs. Relying on an exact summation of the Dyson series, I will show that there exists an exact solution for these class of models . Learning from these results, we will zoom out and sketch a possibly very general perturbative approach in inverse system size, allowing to compute in a simple manner the stationary diffusive current in quantum systems. I will show that the perturbative approach is in perfect agreement with the exact results.

Quantum simulation of extended Hubbard-models using superlattices

Nick Klemmer

Physikalisches Institut, University of Bonn, Bonn, Germany

The quantum simulation of the Hubbard model using ultracold atoms in optical lattices has proven itself to be a useful tool to study the physics of strongly correlated matter. In recent years, two-dimensional systems were studied leading to the observation of several quantum phases including antiferromagnetic Mott insulators and charge-density waves.

The extension of the Hubbard model using superlattices enables the emulation of more complex systems that are closer to real materials like bilayer graphene. I will present our realisation of such a bilayer system by coupling two planes using an out of plane superlattice. Here, the inter-layer tunneling amplitude controls a crossover between a Mott insulating phase with antiferromagnetic correlations within the layers to a band insulator of singlet states between the layers[1].

Recently, we have added an in-plane superlattice that will push the boundary of realizable systems even further. As an outlook, I will present the current process of characterising the lattice and discuss possible applications.

[1] Gall, M., Wurz, N., Samland, J. et al. Competing magnetic orders in a bilayer Hubbard model with ultracold atoms. Nature 589, 40–43 (2021). https://doi.org/10.1038/s41586-020-03058-x.

Influence matrix approach to quantum many-body dynamics

Alessio Lerose, Michael Sonner, and Dmitry Abanin

University of Geneva, Department of Theoretical Physics

A basic and ubiquitous phenomenon in nonequilibrium dynamics of isolated quantum many-body systems is thermalization. This is commonly described as the ability of a system to act as an effective thermal bath for its local subsystems. Understanding the microscopic mechanism of quantum thermalization, and above all of its failures, is currently the subject of intensive theoretical and experimental investigations. In this talk, I will introduce an approach to study quantum many-body dynamics, inspired by the Feynman-Vernon influence functional theory of quantum baths. Its central object is the influence matrix (IM), which describes the effect of a Floquet many-body system on the evolution of its local subsystems. For translationally invariant one-dimensional systems, the IM obeys a self-consistency equation. For certain fine-tuned models, remarkably simple exact solutions appear, which physically represent perfect dephasers (PD), i.e., many-body systems acting as perfectly Markovian baths on their parts. Such PDs include certain solvable quantum circuits discovered and investigated in recent works. In the vicinity of PD points, the system is not perfectly Markovian, but rather acts as a quantum bath with a short memory time. In this case, we demonstrate that the self-consistency equation can be solved using matrix-product states (MPS) methods, as the IM temporal entanglement is low. The underlying "principle of efficiency" of quantum dynamics computations is complementary to that of standard methods, as it only relies on short-range temporal correlations. Using a combination of analytical insights and MPS computations, we characterize the structure of the IM in terms of an effective "statistical-mechanics" description for local quantum trajectories and illustrate its predictive power by analytically computing the relaxation rate of an impurity embedded in the system. In the last part of the talk, I will describe how to extend these ideas to study the many-body localized (MBL) phase of strongly disordered periodically kicked interacting spin chains. This approach allows to study exact disorder-averaged time evolution in the thermodynamic limit. MBL systems fail to act as efficient baths, and this property is encoded in their IM. I will discuss the structure of an MBL IM and link it to the onset of temporal long-range order.

[1] Influence matrix approach to many-body Floquet dynamics arXiv:2009.10105 (2020) Phys. Rev. X 11, 021040.

[2] Characterizing many-body localization via exact disorder-averaged quantum noise arXiv:2012.00777 (2020).

[3] Influence functional of many-body systems: temporal entanglement and matrix-product state representation arXiv:2103.13741 (2021) (to appear in Annals of Physics).

[4] Scaling of temporal entanglement in proximity to integrability arXiv:2104.07607 (2021).

Exploring the supersolid phase of matter

Giovanni Modugno

LENS and Dipartimento di Fisica e Astronomia, Università di Firenze

The long-sought supersolid is a fundamental phase for identical bosons that combines, paradoxically, some properties of solids with those of superfluids. The supersolid phase can now be realized in Bose-Einstein condensates of strongly magnetic atoms [1]. I will show how, despite the limited size and the inhomogeneity of the systems available in the laboratory, it is possible to explore the general properties of the supersolid. The first phenomena we have studies are the simultaneous breaking of two symmetries [2] and the persistence of superfluidity in the presence of a crystal-like structure [3]. More recently, we have characterized the quantum phase transitions from a superfluid to the supersolid, finding both continuous and discontinuous transitions depending on the dimensionality of the system.

[1] L. Tanzi et al., Observation of a dipolar quantum gas with transient supersolid properties, Phys. Rev. Lett. 122, 130405 (2019).
[2] L. Tanzi, S. et al., Supersolid symmetry breaking from compressional oscillations in a dipolar quantum gas, Nature 574, 382 (2019).
[3] L. Tanzi et al., Evidence of superfluidity in a dipolar supersolid from non-classical rotational inertia, Science, 371, 1162 (2021).

Study of out of equilibrium dynamics of Josephson Junction arrays

Giacomo Morpurgo and Thierry Giamarchi

DQMP, University of Geneva

In this work, we look at the out-of-equilibrium dynamics of a Josephson Junction array (JJA), where we study the effect of quenches in the Josephson coupling on this system.

We treat the JJA with a Langevin formalism to look at the phase coherence between the different superconductors. We investigate the effect on the phase coherence of the JJA by changing the temperature, the number of superconductors, the strength of the quenches and the friction parameter (which comes from the Langevin formalism). In a collaboration with the group of F. Ferlaino, we use this description of a JJA to investigate the phase coherence of out-of-equilibrium supersolid states in ultracold dipolar gases. [1]

[1] Ilzhöfer P., Sohmen M., Durastante G., Politi C., Trautmann A., Natale G., Morpurgo G., Giamarchi T., Chomaz L., Mark M. J. and Ferlaino F. Phase coherence in out-of-equilibrium supersolid states of ultracold dipolar atoms. Nat. Phys. 17, 356-361 (2021).

Spin-dependent optical potentials for transport measurements in ultracold Fermi gases

Alessandro Muzi Falconi,[1,2] Giulia Del Pace,[1,2] Woo Jin Kwon,[1,2] Marco Fedrizzi,[1,2] Giacomo Roati,[1,2] and Francesco Scazza[3,1,2]

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Spin transport is a widespread concept in physics, its implications ranging from spintronics to the exploration of quantum many body correlations. In particular, quantum correlations are expected to give rise to collisionless and non dissipative spin currents which are yet to be observed experimentally. Due to their high degree of controllability, ultracold quantum gases provide an ideal platform for both testing theories and observing new spin transport related phenomena. One of the main advantages of these systems is the possibility to manipulate single atomic spin states in a controlled way. In this work, we develop an optical scheme which exploits near resonant DMD-shaped light to generate spin-dependent optical potentials for the manipulation of Zeeman spin states in a degenerate ^{6}Li gas. In particular, we observe that these states can be selectively addressed by finely tuning the light polarization and frequency between the D_1 and D_2 lines of ^{6}Li. Through this new protocol we will explore the dynamical response of our system in presence of a spin dependent external perturbation, and we will determine the role of spin correlations across the BEC - BCS crossover, even in low dimensions.

Dimensional crossover in weakly-coupled chains

Lorenzo Pizzino and Thierry Giamarchi

University of Geneva

In this work we study the effects of a weak transverse coupling between 1D-chains made of bosons or fermions, in terms of dimensional crossover as a function of temperature. In the first part, we consider 1D chains of hard-core bosons, studied in the framework of Luttinger liquid theory and mean-field theory. We compute the gap induced by the presence of the transverse coupling, and the relative critical temperature, which coincides with the crossover temperature. We show that the ratio between them is completely controlled by the Luttinger parameter K and we compare the results with DMRG calculations [1]. Then, we study attractive interacting spinful fermions. For large interaction, via a Schrieffer-Wolff transformation we can explicitly link the pairs we form with hard-core bosons. For finite interaction, an ongoing work is to use the Renormalization group analysis to compute the interplay between transverse coupling and interaction. If the pair-hopping is the relevant coupling [2], we compute the critical temperature at which the dimensional crossover occurs.

[1] G. Bollmark, N. Laflorencie, and A. Kantian. "Dimensional crossover and phase transitions in coupled chains: Density matrix renormalization group results". In:Phys. Rev. B(2020).
[2] T. Giamarchi. "Theoretical Framework for Quasi-One Dimensional Systems". In: Chem. Rev.(2004).

Quantum interference measurement of the free fall of antihydrogen

Olivier Rousselle

Laboratoire Kastler Brossel (Sorbonne Université)

One of the main questions of fundamental physics is the problem of the asymmetry matter/antimatter in the universe and the action of gravity on antimatter. Ambitious projects are developed at CERN facilities to produce low energy antihydrogen with the aim of measuring the free fall of antihydrogen atoms. Among them, the GBAR experiment (Gravitational Behaviour of Antihydrogen at Rest) aims at measuring the gravity acceleration of antihydrogen atoms during a classical free fall in Earth gravitational field. In our research, we propose to improve the accuracy of the measurement by using the idea of quantum reflection drawn from experiments performed on ultracold neutrons. Antihydrogen atoms bounce several times above a reflecting mirror, and the quantum paths corresponding to different GQS (Gravitational Quantum States) interfere. The quantum interference pattern on the detector brings more information than the classical method, and then improves the accuracy of the experiment by approximately 3 orders of magnitude.
In parallel, we also investigate quantum interferences of hydrogen atoms (normal matter) bouncing on a reflecting mirror. The interference fringes produced at the end of the mirror are revealed by letting atom evolve through free flight to the detection plate.

Probing transport in correlated atomic Fermi gases

Francesco Scazza,[1,2,3] Giulia Del Pace,[2,3] Woojin Kwon,[2,3] Klejdja Xhani,[2,3] Massimo Inguscio,[2,3,4] and Giacomo Roati[2,3]

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Understanding transport in highly correlated quantum systems is amongst the central problems in modern physics. Ultracold Fermi gases with resonantly tunable interactions provide a powerful testbed for exploring a variety of central many-body phenomena in fermionic matter, for which accurate theoretical predictions remain challenging even with state-of-the-art computational techniques. In this talk, I will give an overview of recent experiments for the investigation of quantum transport with strongly interacting fermionic fluids. I will focus on studies of the tunneling conduction both in superfluid and normal Fermi gases [1,2], offering a selective probe of fermion condensation and pairing. As a novel intriguing direction, I will outline perspectives for exploring atomtronics and non-equilibrium dynamics in mesoscopic fermion systems with single-atom control realized by a new-generation atomic quantum simulator.

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Emergence Quantum Simulators

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Quantum Simulation promises insight into quantum physics problems which are beyond the ability to calculate with conventional methods. Quantum simulators can be built either using a 'digital' Trotter decomposition of the problem or by directly building the Hamiltonian in the lab and performing 'analogue' experiments. I will present here a different approach, by which the model to simulate emerges naturally from a completely different microscopic Hamiltonian. I will illustrate this in the example of the emergence of the Sine-Gordon quantum field theory from the microscopic description of two tunnel coupled super fluids. Special emphasis will be put on how to verify such emergent quantum simulators and how to characterize them. Thereby I will present two tools: High order correlation functions and their factorization [1], the evaluation of the quantum effective action and the momentum dependence of propagators and vertices (running couplings, renormalization of mass etc ..) of the emerging quantum field theory [2] and quantum field tomography that points to a new way to read out quantum simulators [3]. Together they establish general methods to analyse quantum systems through experiments and thus represents a crucial ingredient towards the implementation and verification of quantum simulators.

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Comparing fermionic superfluids in two and three dimensions

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Understanding the origins of unconventional superconductivity has been a major focus of condensed matter physics for many decades. While many questions remain unanswered, experiments have found that the systems with the highest critical temperatures tend to be layered ma- terials where superconductivity occurs in two-dimensional (2D) structures. However, to what extent the remarkable stability of these strongly correlated 2D superfluids is related to their reduced dimensionality is still an open question. Here, we use dilute gases of ultracold fermionic atoms as a model system to directly observe the influence of dimensionality on strongly interacting fermionic superfluids. We achieve this by measuring the superfluid gap of a strongly correlated quasi-2D Fermi gas over a wide range of interaction strengths and comparing the results to our recent measurements in 3D Fermi gases. We find that the superfluid gap follows the same universal function of the interaction strength in both systems, which suggests that there is no inherent difference in the stability of fermionic superfluidity between two- and three-dimensional quantum gases. Finally, we compare our data to results from solid state systems and find a similar relation between the interaction strength and the gap for a wide range of two- and three-dimensional superconductors.

Efficient simulation of quantum many-body systems

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A basic and ubiquitous phenomenon in nonequilibrium dynamics of isolated quantum many-body systems is thermalization. This is commonly described as the ability of a system to act as an effective thermal bath for its local subsystems. Understanding the microscopic mechanism of quantum thermalization, and above all of its failures, is currently the subject of intensive theoretical and experimental investigations. In this talk, I will introduce an approach to study quantum many-body dynamics, inspired by the Feynman-Vernon influence functional theory of quantum baths. Its central object is the influence matrix (IM), which describes the effect of a Floquet many-body system on the evolution of its local subsystems. For translationally invariant one-dimensional systems, the IM obeys a self-consistency equation. For certain fine-tuned models, remarkably simple exact solutions appear, which physically represent perfect dephasers (PD), i.e., many-body systems acting as perfectly Markovian baths on their parts. Such PDs include certain solvable quantum circuits discovered and investigated in recent works. In the vicinity of PD points, the system is not perfectly Markovian, but rather acts as a quantum bath with a short memory time. In this case, we demonstrate that the self-consistency equation can be solved using matrix-product states (MPS) methods, as the IM temporal entanglement is low. The underlying "principle of efficiency" of quantum dynamics computations is complementary to that of standard methods, as it only relies on short-range temporal correlations. Using a combination of analytical insights and MPS computations, we characterize the structure of the IM in terms of an effective "statistical-mechanics" description for local quantum trajectories and illustrate its predictive power by analytically computing the relaxation rate of an impurity embedded in the system. In the last part of the talk, I will describe how to extend these ideas to study the many-body localized (MBL) phase of strongly disordered periodically kicked interacting spin chains. This approach allows to study exact disorder-averaged time evolution in the thermodynamic limit. MBL systems fail to act as efficient baths, and this property is encoded in their IM. I will discuss the structure of an MBL IM and link it to the onset of temporal long-range order.

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Multiloop Functional Renormalization Group Approach to Frustrated Quantum Magnets

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The intriguing low-energy properties of frustrated magnets continue to attract considerable experimental and theoretical interest in the condensed-matter community. From a theoretical perspective, the computation of phase diagrams and spin correlation functions for models of frustrated quantum magnets in 3D is very challenging as most standard analytical approaches are restricted to semi-classical large-S limits and numerical techniques are typically either limited to small system sizes or low dimensionalities. One method that can circumvent these limitations is the Multiloop Functional Renormalization Group (mfRG) which has originally been developed for strongly correlated electron systems and is based on the self-consistent parquet equations [2]. We show how this framework can be extended to quantum spin systems where it allows for a simple evaluation of spin correlation functions. We present benchmark results from an application to the Heisenberg model on the Kagome lattice.

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Coherent Manipulation of Orbital Feshbach Molecules of Two-Electron Atoms

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Two-electrons-atoms such as Strontium or Ytterbium played a crucial role in the last few years of quantum gases research. Indeed, in addition to the ground state manifold that exhibits SU(N) interaction symmetry, the presence of a metastable state is interesting not only for metrological proposals, but also because it can be considered as a second "ground state" of the system that allows for the exploration of new physics, involving an extra degree of freedom, i.e. the orbital one. In recent works [1,2], for example, the presence of an Orbital Feshbach Resonance (OFR) has been reported in a fermionic Ytterbium 173 mixture of ground-state and metastable-state atoms. The observation of this phenomenon allows us to study shallow bound molecules formed in the proximity of the OFR for the same system [3]. We coherently create molecules in a 3D lattice, combining a ground-state fermion with an excited atom in the metastable state. We characterize the binding energy as a function of both the lattice depth and the applied magnetic field. Moreover, the coherent manipulation of the internal nuclear spin state of one of the two atoms forming the molecule is used as an unambiguous detection method for the presence of molecules. Finally, we measure their lifetime in a 2D environment, where molecule-molecule and atom-molecule interactions are present. In this work we have provided the first demonstration of long-living Orbital Feshbach molecules in a many-body environment, paving the way to the study of either BEC-BCS crossover or strongly interacting Fermi gas in an unexplored regime of narrow Feshbach Resonances involving multiple (orbital and nuclear spin) degrees of freedom.

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Exploring dissipation in 1D Bose gases

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Dissipation and relaxation are ubiquitous in quantum systems. Typically they lead to loss of coherence and disappearance of quantum interferences. As such, they constitute the main limitation for technological applications such as quantum simulation. As we will see in two instances, interactions can actually be an asset in reducing dissipation. I will discuss two experiments with one-dimensional quantum gases of bosonic Ytterbium atoms prepared in optical lattices. In both cases, we find that the relaxation of the many-body system is much slower than for a system of non-interacting particles.
In a first set of experiments, we study the decay of ^{174}Yb atoms in the metastable $^3P_0$ state, which exhibits fast two-body inelastic losses. I will explain how a many-body version of the quantum Zeno effect acts to stabilize the system against decay. The strong dissipation forces the system to behave as (almost) hard-core bosons, effectively reducing the probability of two atoms being on the same site and thereby slowing down the atom number decay [1]. Experimentally, we find that the decay is even slower than predicted for a uniform gas at unit filling [2].
In a second set of experiments, we expose atoms in the ground state to nearresonant light and study the evolution of the momentum distribution. Without interactions, an exponential relaxation towards a uniform quasi-momentum distribution would be expected. We find that the loss of coherence is exponential at early times, before entering a regime characterized by an algebraic decay law [3,4]. We focus here on the early exponential dynamics, and explore how it could be used to gain information on the initial equilibrium state [5].

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Spin dynamics in ultracold collisions between Yb^+ ion and Li atoms in the quantum regime.

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Significant advances in precision measurements in the quantum regime have been achieved with trapped ions and atomic gases at the lowest possible temperatures. These successes have inspired ideas to merge the two systems [1]. Remarkably, in spite of its importance, experiments with ion-atom mixtures remained firmly confined to the classical collision regime, but recently buffer gas cooling of a single ion in a Paul trap to the quantum regime of ion-atom collisions has been realized[2]. The collision energy as small as 1.15(0.23) times the s-wave energy (or 9.9(2.0) μK) has been achieved for a trapped ytterbium ion in an ultracold lithium gas. We have observed a deviation from classical Langevin theory by studying the spin-exchange dynamics, indicating quantum effects in the collisions. Here, we present a theoretical description of the quantum ion-atom scattering used to guide and interpret the recent experiment [2]. By developing a theoretical model of measured energy-dependent spin-exchange rate constants, we have obtained singlet and triplet ion-atom scattering lengths. Next, we identify experimentally accessible Feshbach resonances in the mentioned systems and predict their properties. Control of both elastic scattering and related cooling rates, as well as inelastic spin-changing collisions, with the magnetic field is proposed and investigated to guide ongoing experimental efforts. Ion-atom Feshbach resonances in analogy to well-established techniques for neutral systems will be an important tool to manipulated ultracold ion-atom mixtures.

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1D ultracold bosons in shallow quasiperiodic systems: Bose glass phase and fractal Mott lobes

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The emergence of a compressible insulator phase, known as the Bose glass, is characteristic of the interplay of interactions and disorder in correlated Bose fluids. While widely studied in tight-binding models, its observation remains elusive owing to stringent temperature effects. Here, we will present our results about the study of ultracold bosons in shallow 1D quasi-periodic potentials. First, we consider the non-interacting case. Thanks to exact diagonalization techniques, we determine the critical localization properties and the fractal dimension of the system [1]. We find the existence of finite critical potential and mobility edge, with no intermediate phase. Then, we move to the study of the interacting case based on the results of the ideal bosons. With quantum Monte Carlo calculations, we compute the phase diagram of Lieb-Liniger bosons in shallow quasiperiodic potentials [2]. A Bose glass, surrounded by superfluid and Mott phases, is found. At finite temperature, we show that the melting of the Mott lobes is characteristic of a fractal structure and find that the Bose glass is robust against thermal fluctuations up to temperatures accessible in experiments.

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Hall response in ladder systems of interacting fermions

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The concept of synthetic dimensions [1,2], which interprets the internal states coherently coupled by field-driven transitions as fictitious lattice sites, offers new capabilities for exploration of gauge fields and topological states using ultracold atoms in optical lattices [3,4]. Although this approach presents a wealth of possibilities of engineering single-particle Hamiltonians, observations of complex many-body interaction effects have been prominently inaccessible. Here we report a quantitatively measurement of the Hall response [5,6] in fermionic synthetic ladder systems, which is varied with the interplay of synthetic tunneling and atomic interactions. By instantaneously tilting the ladder system with a quenched linear potential along the real-lattice direction, the time-evolution of an induced particle current in the real dimension and spin polarization in the synthetic dimension are subsequently observed, from which the Hall polarization of the system can be inferred. We exploit the highly controllable synthetic tunneling and atomic interactions to investigate the emergence and universality of the Hall response. Our observation of Hall response physics opens the path towards strongly correlated quantum matter such as fractional quantum Hall states [7] and spin liquids [8].

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