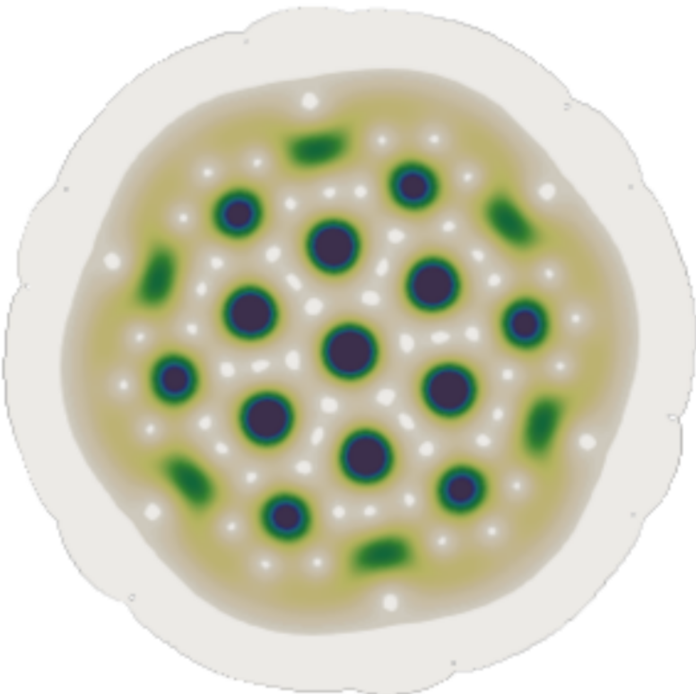
Center on **Bose-Einstein Condensation**, Trento, Italy

BEC

Scientific Report
January 2020 - June 2021



CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

UNIVERSITÀ DI TRENTO
Dipartimento di Fisica

The BEC Center is a joint initiative of

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

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Contents

Overview

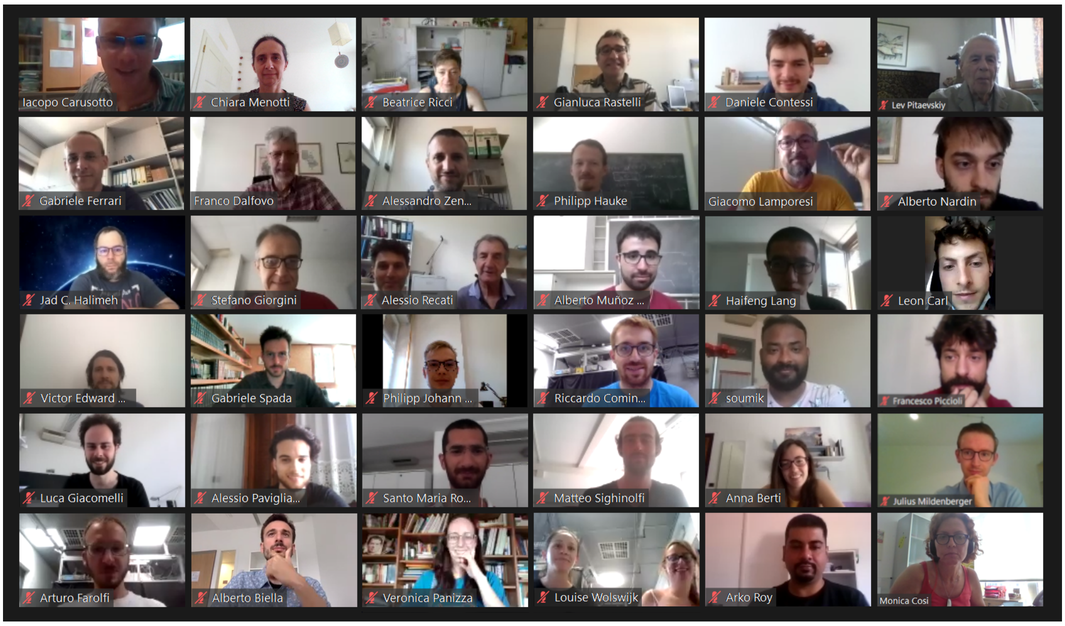
This is the final report on the research activities of the Center on Bose-Einstein Condensation (BEC Center) within the program funded by the Provincia Autonoma di Trento (PAT) from January 2020 to June 2021.

The BEC Center was established in 2002 by the Istituto Nazionale per la Fisica della Materia and is now part of the Istituto Nazionale di Ottica (INO) of the Consiglio Nazionale delle Ricerche (CNR). It is hosted by the Department of Physics of the University of Trento which provides facilities and services as well as a multidisciplinary scientific environment. Personnel and researchers of CNR and UniTrento work together in the BEC Center, sharing projects and resources. Graduate and undergraduate students of the University actively participate in the scientific activities and seminars, and CNR researchers are regularly involved in education and training programs. In this sense, the BEC Center in Trento can be considered as an excellent example of close collaboration and fruitful integration between CNR and University.

The agreement with PAT is aimed at supporting the experimental and theoretical research of the BEC Center on the physics of ultracold atoms and quantum gases. The main objective of the project is to support the activities of the experimental laboratory and further reinforce its capacity of working on frontier research topics. The experimental laboratory workflow has included the measurement of the equation of state of a weakly interacting Bose gas and the study of the dynamics of spin excitations in quantum mixtures. The experimental activities are developed in close connection with the theory group of the BEC Center who provides theoretical support and guidance to the experiments. In addition to this, the theoretical group is pushing forward a number of other research directions on a broader spectrum of topics on quantum gases and fluids, superfluidity and coherence phenomena, quantum optics, and, more generally, in systems where quantum mechanics manifests itself at a macroscopic level.

The excellent reputation accumulated by the BEC Center over the years on the national and international stage has been instrumental to attract to Trento several new researchers. In the previous report we have already mentioned the arrival of Philipp Hauke in 2019, whose activities on quantum gases with applications to theoretical quantum science and technology are supported by an ERC grant. More recently, three winners of national CNR competitive examinations (Alessandro Zenesini, Gianluca Rastelli and Alberto Biella) have chosen the BEC Center as their destination. Zenesini has joined the experimental team at the end of 2019, immediately providing a crucial reinforcement to the manpower available to its activities. Rastelli has successfully integrated the theoretical team in late 2020. Biella has officially joined the theoretical team in March 2021, is presently on leave in Paris to conclude his on-going projects, but he is already actively participating to the online scientific activities of the Trento group. The expertise of these two new researchers is complementary to the one of the rest of the staff: Rastelli is an expert of solid-state physics and superconductors, while Biella has a background in quantum and non-equilibrium many-body physics. As such, their arrival is opening new directions in close collaboration with the rest of the team and is also providing new techniques to the existing research lines.

The period of this report has overlapped with the hardest times of the COVID emergency. During this period, most of the scientific activities of the BEC Center including research discussions, teaching, seminars and colloquia had to be held online and all in-presence international events had to be postponed. In spite of these difficulties, researchers have made all efforts to keep the scientific activities running and, most importantly, to ensure the usual high-quality supervision to students and postdocs. By spring 2021, research is slowly getting back to normality, with in-presence scientific discussions recovering their usual intense rate, visitors starting to flow again to the BEC Center and international scientific events being again organized.



Zoom meeting at the BEC Center with staff members, postdocs, PhD and MSc students.

In quantitative terms, since January 2020 the researchers of the BEC Center have published about 60 articles in peer reviewed journals, including 9 Physical Review Letters, 2 Physical Review X, 2 Nature, 2 Nature Physics, 1 Science, 1 PRX Quantum, 1 Reports on Progress in Physics, and have received by Nature Physics an invitation to write a News & Views article. The activities of the BEC Center have involved 33 graduate students and postdocs, 14 of them coming from abroad, namely from India, Japan, Spain, Great Britain, Greece, USA, Lebanon, China, Germany, and Brasil. In addition, 3 undergraduate and graduate students, coming from France, have spent a few months in Trento for internships and stages. The Center has organized and co-organized 46 seminars and colloquia with international speakers, out of which 10 in presence before the beginning of the COVID pandemics and the rest online. The BEC Center has co-organized 1 online international meeting and, as soon as and as long as the conditions will allow, is ready to host or organize 5 international meetings (including, beyond the ones previously scheduled till June 2021 and listed in this report, a Varenna International School of Physics "Enrico Fermi" on Quantum Mixtures with Ultra-cold Atoms initially scheduled for July 2021 and the BEC Sant Feliu Workshop 2021).

In Spring 2020, the website of the BEC Center (http://bec.science.unitn.it) has undergone a complete restyling to the aim of making all information more accessible. The website is regularly updated and contains an overview on the people working at the BEC Center and the main research lines, the list of publications together with news and highlights such as honours and press releases, the calendar of past and scheduled events, and – last but not least – information about teaching, Master and PhD programs.

In this report, a detailed description of the achievements in the period January 1, 2020 – June 30, 2021 is provided.

Trento, July 30, 2021

Staff, researchers, scientific board

Principal investigators

Iacopo Carusotto (CNR)
Franco Dalfovo (UniTrento)
Gabriele Ferrari (UniTrento)
Stefano Giorgini (UniTrento)
Philipp Hauke (UniTrento)
Giacomo Lamporesi (CNR)
Chiara Menotti (CNR)
Lev P. Pitaevskii (UniTrento)
Gianluca Rastelli (CNR, since October 1st, 2020)
Alessio Recati (CNR)
Sandro Stringari (UniTrento)
Alessandro Zenesini (CNR)
Alberto Biella (CNR, since March 1st, 2021, on leave till December 31th, 2021)

Postdocs

Luca Parisi
Dimitrios Trypogeorgos
Carmelo Mordini
Jacopo Nespolo
Albert Gallemí
Victor E. Colussi
Luca Giacomelli
Arturo Farolfi
Arko Roy
Soumik Bandyopadhyay
Jad C. Halimeh
Gabriele Spada

PhD Students

Elia Macaluso (Thesis Defence on January 27th, 2020)
Miki Ota (Thesis Defence on January 31th, 2020)
Ivan Amelio (Thesis Defence on December 4th, 2020)
Luca Giacomelli (Thesis Defence on March 4th, 2021)
Arturo Farolfi (Thesis Defence on April 14th, 2021)

Santo Maria Roccuzzo – Q@TN student co-supervised by A. Recati, S. Stringari, J. Wambach (ECT*)

Matteo Sighinolfi – Q@TN student co-supervised by A. Recati, S. Giorgini, P. Faccioli (UniTrento), G. Garberoglio (FBK ECT*).

Louise Wolswijk

Alberto Muñoz de las Heras – Q@TN student co-supervised by I. Carusotto and L. Pavesi (UniTrento).

Nick Keepfer – joint program with Newcastle University, co-supervisor N. P. Proukakis

Julius Mildenberger – Q@TN student co-supervised by P. Hauke and I. Carusotto.

Philipp Johann Uhrich

Francesco Piccioli – cotutelle doctoral program with Rostock University, co-supervisor A. Szameit

Daniele Contessi – joint PhD program within Q@TN con Köln University, co-supervised by A. Recati and M. Rizzi

Kevin Geier – cotutelle doctoral program with Heidelberg University, co-supervisor J. Berges

Ricardo Costa De Almeida – cotutelle doctoral program with Heidelberg University, co-supervisor J. Berges

Alberto Nardin

Haifeng Lang

Riccardo Cominotti

Sebastiano Bresolin

Anna Berti – Q@TN student co-supervised by I. Carusotto and G. Ferrari

International student internships and stages

Jules Givois (École Normale Supérieure de Cachan, France), Nov 2019 - Aug 2020

Quentin Lamouret (École Normale Supérieure, Paris, France), March 2021-July 2021

Romain Usciati (École Normale Supérieure, Paris, France), February 2021-July 2021

Secretariat

Beatrice Ricci (CNR)

Monica Cosi (UniTrento)

Scientific board

Jean Dalibard

Rudolf Grimm

Christopher J. Pethick

William D. Phillips

Gora Shlyapnikov

Visiting scientists and scientific collaborations

Long visits

Matteo Rizzi (Universität zu Köln, Germany), Humboldt Fellowship: visits in Trento October 2019 - January 2020, February - May 2021 (planned but postponed to September-December 2021 due to Covid)

Carlos Lobo (University of Southampton, February 20th - July 6th, 2020)

Grigori Astrakharchik (Universitat Politecnica de Catalunya, Barcelona), January 5th - 19th, 2020

Short visits

Nicolas Pavloff (LPTMS, Université Paris-Saclay and CNRS), January 7 - 9 2020

Debasish Banerjee (Institut fur Physik, Humboldt-Univerität, Berlin), January 7-10, 2020

Marco Miniaci (CNRS, Lille, France), January 22, 2020

Michele Modugno (Universidad del Pais Vasco, Bilbao), January 20 - February 4, 2020

Giovanni Martone (LKB, Université Pierre et Marie Curie, Paris), Fabruary 24-28, 2020

Scientific collaborations

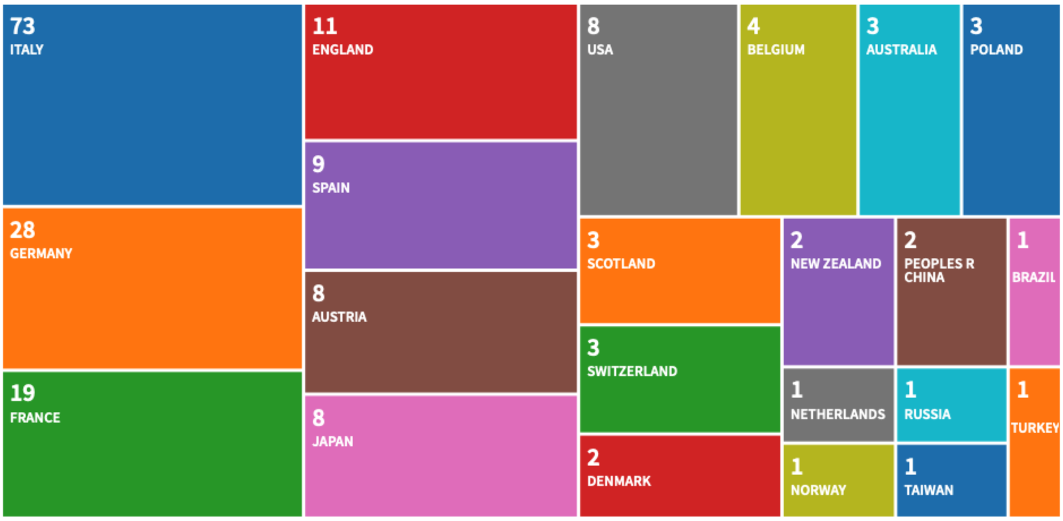
The BEC Center operates within a wide network of scientific collaborations. Well established scientific exchanges at the local level involve colleagues at the Physics Department of the University of Trento, among which Lorenzo Pavesi, Pietro Faccioli, Francesco Pederiva and Massimiliano Rinaldi. Recently interdisciplinary collaborations with other Departments of the University of Trento, ECT*, and FBK have been boosted by the Q@TN initiative and led to shared PhD fellowships on topics related to quantum technologies.

A large fraction of the papers published by the BEC Center are the result of joint projects with many groups around the world. Longstanding and fruitful collaborations have been established over the years with many groups at LENS-Florence; with the experimental and theory groups at Innsbruck; with several groups in the Paris area at ENS, Paris Sorbonne, Paris Diderot, Institut d'Optique, Laboratoire C2N; with several groups in Munich at LMU and MPI; with several groups in different institutions in Barcelona such as UPC and ICFO.

To those historical ones, new important collaborations have been added by the recent arrival at the BEC Center of new staff members. Philipp Hauke can count among his most important collaborators the Google Quantum AI team (in particular Zhang Jiang); Fred Jendrzejewski, Jürgen Berges and Markus Oberthaler (Heidelberg); Jian-Wei Pan and Zhen-Sheng Yuan (Hefei/Heidelberg). Alessandro Zenesini can count among his most important collaborators Silke Ospelkaus, Eberhard Tiemann and Luis Santos (Hannover). Gianluca Rastelli can count among his most important collaborators Wolfgang Belzig and Elke Scheer (Universität

Konstanz), Eva Weig (Technische Universität München), and Juan Carlos Cuevas (Universidad Autónoma de Madrid).

The following picture represents the countries of the co-authors of the articles published by the BEC Center; the data are extracted from ISI - Web of Science, for the 73 publications since 2019, having at least one of the staff members of the BEC Center as an author; the number assigned to each country is the number of articles involving a co-author from that country.



Below, a list of italian and international research institutions involved in co-authorship with the BEC Center and the corresponding number of joint publications.

10. UNIV PARIS SACLAY

9. HEIDELBERG UNIV, UNIV KONSTANZ

7. UNIV INNSBRUCK

6. MPI PHYS KOMPLEXER SYST

5. SISSA, RIKEN

4. AUSTRIAN ACAD SCI, UNIV LILLE, UNIV POLITECN CATALUNA, UNIV SOUTHAMPTON

3. CNR IOM DEMOCRITOS, FDN BRUNO KESSLER, NEWCASTLE UNIV, UNIV BIRMINGHAM, UNIV GLASGOW, UNIV GRENOBLE ALPES , UNIV LIBRE BRUXELLES, UNIV MARYLAND

2. AARHUS UNIV, CNR IOM, FORSCHUNGSZENTRUM JULICH, JOINT QUANTUM INST, LEIBNIZ UNIV HANNOVER, LUDWIG MAX UNIV MUNCHEN, SORBONNE UNIV, SWISS FED INST TECHNOL , TOHOKU UNIV, UNIV CHICAGO, UNIV COLOGNE, UNIV FIRENZE and CNR-INO, UNIV QUEENSLAND

1. BROOKHAVEN NATL LAB, CALTECH, CHINESE ACAD SCI, CY CERGY PARIS UNIV, DONOSTIA INT PHYS CTR, EINDHOVEN UNIV TECHNOL, GOOGLE INC, HARVARD UNIV, IKERBASQUE FDN SCI , INST LAUE LANGEVIN, INST TECNOL QUIM CSIC UPV, IQM GERMANY GMBH, IST NAZL RIC METROL, JAGIELLONIAN UNIV, JOHANNES GUTENBERG UNIV MAINZ, KEIO UNIV, MICHIGAN STATE UNIV, MICROSOFT CORP, MIMAR SINAN FINE ARTS UNIV, MIT, NATL CHANGHUA UNIV EDUC, NORWEGIAN UNIV SCI TECHNOL , PENN STATE UNIV, POLISH ACAD SCI, PRINCETON UNIV, PURDUE UNIV, RAS, RIKEN ITHEMS,

SONGSHAN LAKE MAT LAB, TECH UNIV DARMSTADT, TECH UNIV MUNICH, TOKYO INST TECHNOL, TU WIEN, UCL, UNIV AUTONOMA MADRID, UNIV AUTONOMA MADRID UAM, UNIV CERGY PONTOISE, UNIV COMPLUTENSE MADRID, UNIV DUISBURG ESSEN, UNIV FED RURAL RIO DE JANEIRO, UNIV GENEVA , UNIV LIBRE BRUXELLES ULB, UNIV LYON, UNIV MASSACHUSETTS, UNIV MILAN, UNIV NOTTINGHAM, UNIV OTAGO, UNIV PADUA, UNIV PARIS, UNIV PARIS SUD, UNIV PARIS SUD PARIS SACLAY, UNIV SCI TECHNOL CHINA, UNIV STUTTGART, UNIV SYDNEY, UNIV ULM, UNIV UTRECHT, UNIV WARSAW, UNIV WARWICK, VICTORIA UNIV WELLINGTON

Experiments with ultracold atoms

During the period of the project, the experimental activity mainly focused on the two following lines:
i) Measurement of the equation of state of a weakly interacting Bose gas;
ii) Spin excitations in quantum mixtures.

The apparatus in the first laboratory (BEC1) has been upgraded in order to improve the imaging resolution. The technical improvements, together with the development of a new technique to reconstruct the atomic density of dense samples, gave us the possibility to study the equilibrium features of dense weakly interacting bosonic gases. In particular we extracted the canonical Equation of State of uniform gases by measuring the density of harmonically trapped bosonic gases.

The new machine (BEC2) is characterized by a magnetic shield that allows for a field attenuation of five orders of magnitude. In this extremely low field noise environment, we studied topological structures in a two-component superfluid mixture. First we realized pairs of magnetic solitons and investigated their dynamics and their collisional properties. A second experiment consisted in the observation of the spin dynamics of a far-from-equilibrium elongated system in the presence of coherent coupling. This lead to the observation of magnetic domain walls that break because of quantum torque and create strongly fluctuating regions that show antiferromagnetic correlations. This represents an important preliminary work for the study of domain walls and vortex dipoles in 2D coherently-coupled mixtures as a quantum simulator of high-energy physics phenomena, that are being investigated within the INFN project FISh.

For both activities the lab team worked in strong collaboration with theory members of the BEC Center, and the strong synergy produced complete descriptions of the studied phenomena. The results have been published in international peer-reviewed journals such as Physical Review Letters and Optics Express.

In the following, we provide a brief summary of the main publications of the experimental group.

Optics Express 28, 29408 (2020)

Single-shot reconstruction of the density profile of a dense atomic gas

C. Mordini, D. Trypogeorgos, L. Wolswijk, G. Lamporesi, G. Ferrari

In this work, we describe a new imaging technique that is particularly useful for accurate density measurements of a dense atomic sample. The technique is based on partial transfer atomic imaging (PTAI), that can be used to piece together the non-uniform spatial profile of high-density atomic samples using multiple measurements. We achieved a thirty-fold increase of the effective dynamic range of our imaging, and were able to image otherwise saturated samples with unprecedented accuracy of both low- and high-density features.

The fraction imaged within each PTAI snapshot is optimized to different ranges of the OD, while the merging of the information from different snapshots is implemented thanks to the accurate knowledge of the extracted fraction. The final outcome is the complete optical density distribution. We also devised a procedure for measuring the Rabi frequency of the microwave transitions which is highly insensitive to inhomogeneities across the atomic system. The method is based on the iterated application of short microwave pulses of constant duration and is benchmarked against usual Rabi flopping.

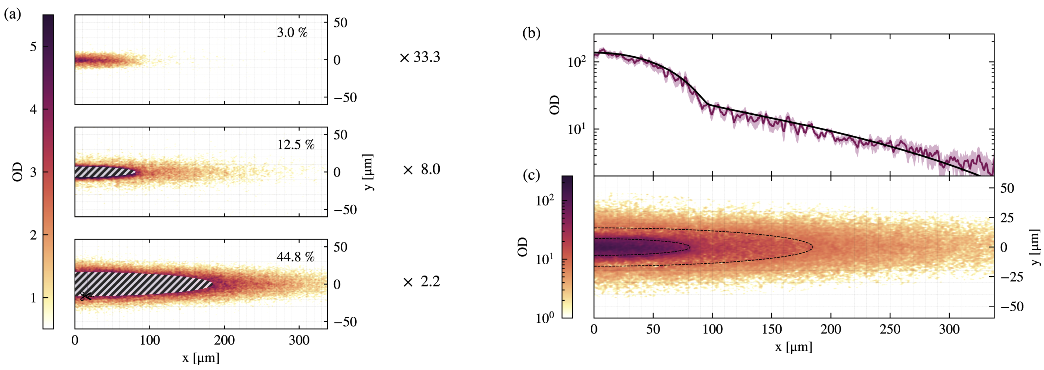


Figure 1: Optical density reconstruction method. (a) Three partial-transfer images of the same BEC taken in a single shot with different extraction fractions. (b,c) The atomic optical density is reconstructed by weighing the frames reported in panel (a).

Phys. Rev. Lett. 125, 150404 (2020)

Measurement of the Canonical Equation of State of a Weakly Interacting 3D Bose Gas

C. Mordini, D. Trypogeorgos, A. Farolfi, L. Wolswijk, S. Stringari, G. Lamporesi, G. Ferrari

We determined the equation of state of uniform matter across the critical transition point, within the local density approximation. This goal was achieved by reconstructing the 3D density of a harmonically trapped Bose gas through a multiple-image reconstruction method. Our experimental results provide the canonical Equation of State by reporting pressure as a function of the specific volume. Our experimental data emphasize the dramatic deviations from the ideal Bose gas behavior caused by interactions. They also provide clear evidence for the nonmonotonic behavior with temperature of the chemical potential, which is a consequence of superfluidity and Bose-Einstein condensation. The measured thermodynamic quantities are compared to mean-field predictions available for the interacting Bose gas. The limits of applicability of the local density approximation near the critical point are also discussed, focusing on the behavior of the isothermal compressibility.

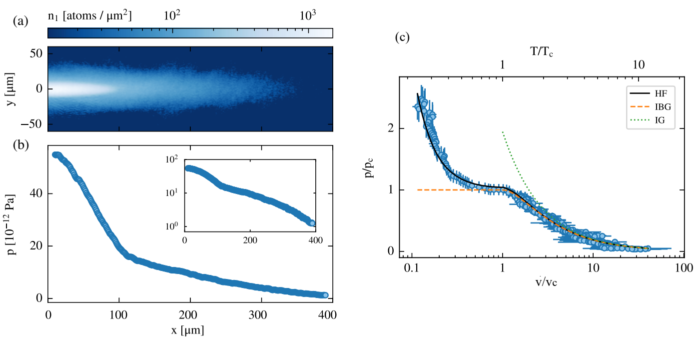


Figure 2: In-situ optical density (a) and measurement of the gas pressure (b) along its long axis. (c) Equation of state of a uniform gas showing the normalized pressure versus the normalized volume (or temperature). (d) Nonmonotonic behaviour of normalized chemical potential as a function of T/T_c. The experimental data are compared to different theoretical models: the classical ideal gas (dotted orange), the ideal Bose gas (dashed orange) and the Hartree-Fock prediction (solid black).

Phys. Rev. Lett. 125, 030401 (2020)

Observation of Magnetic Solitons in Two-Component Bose-Einstein Condensates

A. Farolfi, D. Trypogeorgos, C. Mordini, G. Lamporesi, and G. Ferrari

The work on the observation of magnetic solitons in a two-component quantum gas started at the end of 2019, during the previous project. In the first months of 2020 we finalized the measurements and submitted the final version.

We used a particular spin mixture of sodium atoms in the internal states $|F, m_F\rangle = |1, \pm 1\rangle$ that is characterized by interaction constants that allow to generate solitons in the spin channel that are larger than the corresponding ones in the density channel. For a given radial confinement of the elongated trap, this feature favors the one-dimensionality of the system and hence the stability of magnetic solitons. We generated pairs of magnetic solitons through phase imprinting and observed their dynamics on long timescales. Magnetic solitons oscillate back and forth in the trap and collide depending on the magnetization (sign) of the colliding solitons.

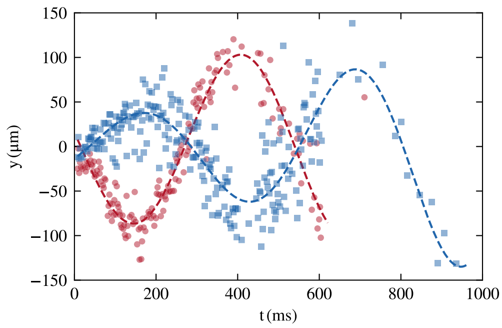


Figure 3: Oscillation of two long-living magnetic solitons in a harmonic trap.

The novelty of the work made it possible to have our paper highlighted by Physical Review Letters as an Editors' Suggestion and by the online journal Physics in the form of a Synopsis entitled "Magnetic Solitons in a Bose-Einstein Condensate".

arXiv:2011.04271 (2020)

Quantum-torque-induced breaking of magnetic domain walls in ultracold gases

A. Farolfi, A. Zenesini, D. Trypogeorgos, C. Mordini, A. Gallemí, A. Roy, A. Recati, G. Lamporesi, G. Ferrari

In this work, we use a coherently-coupled quantum mixture of ultracold bosonic gases to realize analogues of magnetic junctions. The spatial inhomogeneity of the atomic gas, provided by the harmonic trapping, makes the system change its behavior from regions with oscillating magnetization, resembling a magnetic material in the presence of an external transverse field, to regions with a defined magnetization, as in magnetic materials with a ferromagnetic anisotropy stronger than external fields. Starting from a far-from-equilibrium fully polarized state, magnetic interfaces rapidly form. At the interfaces, we observe the formation of short-wavelength magnetic waves. They are generated by the so-called quantum torque and show strong spatial anticorrelations in the magnetization. Coupled Gross-Pitaevskii equations fully reproduce the experimental observations. Furthermore, thanks to the negligible excitation of the total density of the system, Landau-Lifshits equations can be used to describe the spin dynamics in the 1D coupled mixture, allowing for a stronger connection between our system and magnetic materials. Our results provide a novel platform for the study of far-from-equilibrium spin dynamics, free from dissipation and in regimes that are not easily accessible in solid-state systems.

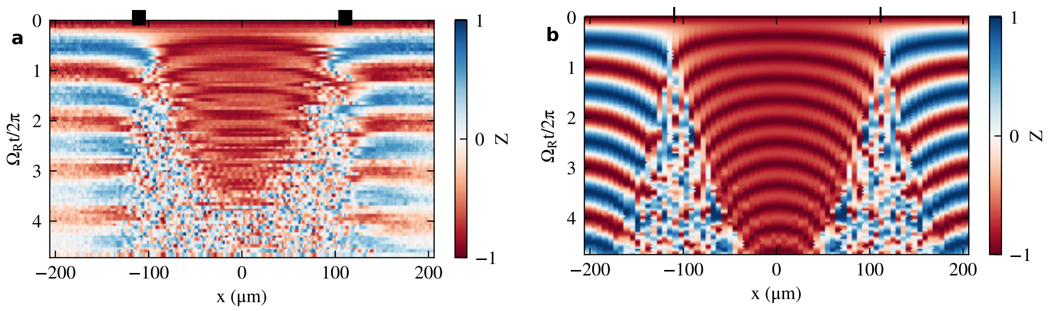


Figure 4: Experimental data (a) and numerical simulation through LLE (b) showing the local magnetization Z along the 1D system as a function of time. Initially the system is fully in one state ($Z = -1$), then inhomogeneities make it evolve differently in the center and in the tails. The spin current accumulates at the interfaces, that break and cause the generation of strongly fluctuating regions.

Theory

The theoretical activity of the BEC Center has covered a wide range of topics. Here below we present a brief summary of the main research lines, followed by extended abstracts of a few selected articles.

Collaborations with the experimental team

A significant part of the theory activity has consisted in a direct collaboration with the experimental group of the BEC Center. In particular, a theoretical model has been developed for the breaking dynamics of the magnetic domain wall as discussed in detail in one of the previous abstracts.

Another important topic of theoretical-experimental collaboration consisted in the assessment of the potential of the spinor gases as a novel platform for analog models of gravity with improved features. Preliminary studies give promising results: the reduced value of the spin-sound velocity with respect to the standard sound velocity reinforce the robustness of the configuration against external disturbances and allows for the generation of wide ergoregions around vortices where to address the physics of superradiance.

Equilibrium and dynamics of uniform Bose gases at finite temperature

We have investigated the properties of Bose gases at finite temperature using the Stochastic Gross-Pitaevskii (SGPE) theory along the line of previous projects of the group. In particular, within a long-term collaboration with Newcastle University, we have been exploring the 2D-3D dimensional crossover for a single component Bose gas confined in a planar rectangular box with harmonic confinement in the orthogonal direction, with the aim to characterize the transition from a 2D behavior, with the BKT phase transition, to a 3D behavior with the BEC phase transition. In parallel, we have studied the evolution of a trapped 3D gas subject to a temperature quench across the BEC transition in order to find evidence of the Kibble-Zurek mechanism. Finally, we are applying the SGPE methods to the case of two-component condensates in a rectangular box in 2D, with and without Rabi coupling.

Bose polarons at finite temperature

We have further pursued the research line on impurities coupled to a bosonic bath (Bose polarons) by investigating equilibrium and transport properties of the impurity particle when the temperature of the bath is increased up to the Bose-Einstein transition point where the gas becomes normal. We made use of exact path integral Monte Carlo methods which are well suited to treat configurations where the interaction between the impurity and the bath can be tuned from the weak to the strong coupling regime.

Repulsive Bose mixtures at finite temperature

We have investigated two-component bosonic mixtures at finite temperature. Following an intriguing prediction which we put forward some time ago, concerning the occurrence of phase separation at high temperature of a mixture that is miscible at low temperature, we have started to address this question using exact path integral Monte Carlo methods which allow us to overcome the limitations of perturbative approaches. In particular, our study was focused on the mixture of two hyperfine states of 23Na which is relevant for experiments carried out in Trento.

Andreev-Bashkin effect

The Trento team has continued its exploration of the the physics of the so-called Andreev-Bashkin effect, proposed over 40 years ago and never observed in experiments. It is believed to play a fundamental role in different area of physics from superfluid liquids to neutron stars. The Andreev-Bashkin effect is based on the coupling between two superfluids that give rise to a superfluid matrix: due to quantum correlations, the velocity in a superfluid induces a current in the other superfluid, producing a transport *without dissipation*. The work of the BEC Center has led to the identification of the proper theoretical framework for the study of the Andreev-Bashkin effect in terms of the current-current response functions and the effect of the drag on the sum rules of the superfluid mixtures. In this way we could also provide a new technique, based on fast response, which should allow experimentalists to measure this elusive effect.

In collaboration with Prof. Matteo Rizzi (Köln University, D), an expert in Tensor Network approaches, we have quantitatively determined the collisionless drag for a one dimensional Bose mixture on a ring lattice. We have shown how having attraction between the components can largely enhance the drag if the system can be prepared close to the pair superfluid phase. The study completes and extends a previous work of the Trento groupg where only repulsive interaction was considered within a Monte-Carlo approach.

Unfortunately Tensor Network simulations are limited to one-dimensional systems. However by generalising our recently developed Quantum Gutzwiller method to multi-component Bose-Hubbard models, we could study the drag in a two dimensional configuration.

The Andreev-Bashkin effect has been also studied using the formalism of response function to fast spin selective perturbations. This approach provides a natural experimental protocol to investigate collisionless spin drag effects and has been applied to a variety of many-body systems including, in addition to the Andreev-Bashkin effect, coherently coupled Bose mixtures, interacting Fermi gases in the normal phase and the problem of the polaron.

Fermionic mixtures

We continue the study of Fermi mixtures and Fermi polarons. In particular in collaboration with Dr. Tajima (RIKEN) and Prof. Ohashi (Keio University), we investigate the spin-dipole oscillation of a strongly interacting Fermi gas in a harmonic trap in order to emphasize the role of the Fermi-Fermi pairing. We clarify the temperature dependence of the spin-dipole frequency near unitarity, which is deeply related to the spin susceptibility as well as pairing correlations. While the spin-dipole frequency exactly coincides with the trap frequency in a non-interacting Fermi gas, it is shown to be remarkably enhanced in the superfluid state, because of the suppression of the spin degree of freedom due to the spin-singlet Cooper-pair formation. In strongly interacting Fermi gases, this enhancement occurs also above the superfluid phase transition temperature, due to the strong pairing correlations even in the normal phase.

The Trento team is also pursuing the study of the polaron dynamics following two main ideas. In collaboration with Pietro Faccioli (UniTrento), we are developing a semiclassical approach for the dynamics of two or more impurities due to the bath-mediated interaction, equivalent – to some extent – to the well known RKKY interaction for electrons in solid state structures. At a more quantum level, in collaboration with the Max Planck for Complex System in Dresden, we use the Keldysh formalism to obtain the dynamics of polarons under the action of a Rabi coupling in order to explain some recent experimental results on the decoherence of polarons due to the presence of the bath. Our study will clarify the role of the quasi-particle life time vs the spreading of the momentum due to finite temperature in determining the coherence time of the Rabi oscillations.

Supersolidity of Bose-Einstein condensed atomic gases

In the last few years, ultra-cold dipolar gases have attracted a lot of attention in the scientific community as a consequence of the observation of coherently coupled array of droplets. The latter state – which breaks simultaneously and independently the $U(1)$ and the translational symmetry – is believed to be an instance of the long sought supersolid state. At the moment three groups around the world have been able to realise a supersolid by using dipolar gases. Many questions are still open concerning in particular the interplay between the superfluid and the solid nature of the new phase as well as the characterisation of the superfluid-to-supersolid and the supersolid-to-incoherent droplet crystal phase transitions.

In the last year and a half, the Trento group has addressed the rotational properties of the new system. We focused in particular on the moment of inertia of a 2-dimensional supersolid and the possibility to create and host vortices in a supersolid. Till a few months ago only one-dimensional structures have been experimentally realised, however new experiments have highlighted the possibility of implementing the 2 dimensional configuration, fundamental in the study of superfluidity and quantum vortices.

In a collaboration with the LPTMS and LKB in Paris we have been able to show that there exists a stationary non-ground state configuration of standard Bose-Einstein condensates, which shows a supersolid behaviour. In this case the system is amenable of an exact treatment.

The Trento team has also further developed the theoretical studies on the supersolid features of spin-orbit coupled Bose-Einstein condensates, by developing a protocol to reveal supersolidity in the stripe phase of these configurations. Our approach, based on the study of the collective oscillations in the presence of harmonic trapping, has explicitly revealed the existence of novel

Goldstone modes associated with the spontaneous breaking of translational invariance and exhibiting a characteristic spin nature. Supersolidity in spin-orbit coupled gases then reveals very peculiar and distinct features with respect to the case of dipolar gases.

Excitations and correlations in the Bose-Hubbard model

We have pursued the research line on the excitations in the Bose-Hubbard model. The theoretical method is based on the time-dependent Gutzwiller ansatz, which writes the ground state of the system in the form of a site-factorized wavefunction. In order to suggest useful experimental protocols, we have applied the time-dependent Gutzwiller ansatz to identify the effects of a perturbation in real time and we have extended the investigation to inhomogenous systems where the co-existence of insulating and superfluid phases leads to the presence of interface modes. Furthermore, we have considered the Extended Bose Hubbard model where nearest-neighbors interactions are present and phases with broken translational symmetry such as checkerboard and supersolid can appear, crucially modifying the excitation spectrum.

We have successfully quantized the theory and first applied the quantized formalisms to the standard single-species Bose-Hubbard model. We have calculated the off-diagonal single particle correlation functions, the superfluid stiffness and the density-density correlation function, finding excellent agreement with the results of numerically more sophisticated methods, such as Quantum Monte Carlo simulations, where available. This demonstrates that the Quantum Gutzwiller approach can account for non-local correlations in spite of the local initial ansatz for the ground state. We have extended the Quantum Gutzwiller treatment to the case of balanced bosonic mixtures and we are now moving towards the unbalanced case in order to tackle the polaron problem.

Hanbury-Brown and Twiss with cold atoms

Taking inspiration from quantum optics concepts of Hanbury-Brown and Twiss correlation measurements, we have participated to a joint experimental-theoretical study of the momentum-space correlations in interacting gases of trapped atoms, revealing the crucial role of the quantum depletion and of the collective excitation modes of the condensate. This study was performed in collaboration with the experimental team at the Institut d'Optique in Palaiseau (France) and one of our former post-docs, now researcher in Glasgow.

Fluids of light

A main thread in our activity on quantum fluids of light consisted in theoretical studies of the generation and characterization of interesting many-body states of a photon gas. On one hand, we have pushed forward our study of new pumping schemes based on a frequency-selective incoherent pumping scheme to generate specific strongly correlated states such as fractional quantum Hall liquids. On the other hand, a big effort has been devoted to the study of the peculiar collective dynamics of non-equilibrium condensates in different geometries, including standard lattice and microcavity geometries as well as topological edge states, the so-called topological laser operation. Our study of Kardar-Parisi-Zhang features in the phase fluctuation dynamics of topological laser devices has been completed, highlighting a remarkable robustness of coherence against disorder effects. The collective excitations of topological laser devices have also been investigated in terms of Goldstone modes. The stability of topological laser operation in more complex photonic crystal platforms has been investigated, pinpointing a possible crucial role of frequency-dependent gain. All these theoretical activities have led to the reinforcement of our on-going collaborations with C2N in Palaiseau and LKB in Paris aiming at an experimental verification of our predictions, as well as the kick-off of new ones.

On top of our activity on quantum fluids of light in the infrared and visible domain, we have reinforced our activity in the microwave domain of circuit-QED which features crucial advantages in the direction of strongly correlated fluids. Motivated by the tremendous success of our previous review articles, in particular the latest one on “Topological Photonics” (which has attracted a huge number of citations and has quickly been listed as “Highly Cited” and “Hot paper” on the Web-of-Science), we have been involved in the writing of a invited short review on quantum fluids of light in a circuit-QED platform. Another review on Bose-Einstein condensation in photonic systems has been just submitted.

Topological and Quantum Hall effects with light and atoms

As usual, our activities on quantum Hall fluids have simultaneously addressed photonic and atomic systems. In particular, we have continued our investigations on the physical meaning of fractional statistics in the bulk of such fluids: realistic configurations to experimentally highlight such intriguing features have been proposed and characterized in simple physical terms. We have investigated the effect of a synthetic magnetic field on the mixing of localized matter excitations with topological bands, giving rise to the so-called Landau-photon polaritons. More recently, our activity has extended from the nowadays well understood bulk towards the edge excitations. As a first step, we have built a simple yet quantitatively accurate theory of nonlinear propagation in the integer case and we have validated it on top of numerical simulations of the many-body dynamics. A joint campaign of analytical studies and numerical simulations for the more complex fractional case are presently in progress.

Theory of topological superconducting systems

With the arrival of Gianluca Rastelli, the BEC Center has extended its activities to the field of solid-state superconducting systems, in particular topological ones. In spite of the marked difference of physical platform, this research shares many theoretical and conceptual ingredients with the research topics that are traditionally investigated at the BEC Center.

Topological superconducting systems have become of paramount interest because they have the potential to host exotic physical phenomena, as Majorana states, which can be used for quantum computation. At the same time, the continuous search for new types of topological quantum matter has recently led to the discovery of topologically nontrivial quantum states in conventional multiterminal Josephson junctions (MJJs) which are made of conventional superconductors. In such systems there is no need for exotic topological materials such as semiconducting nanowires with strong spin-orbit interaction. MJJs have turned out to be an ideal platform in which synthetic topological materials can be engineered almost at will.

We theoretically demonstrate that engineered superconducting systems, formed by superconducting contacts coupled to quantum dots, can implement higher-dimensional topological systems. We show that the nontrivial topology is experimentally accessible in the microwave response of the system and that a non-Abelian Berry phase can be generated and measured through absorption. Our proposal sets the stage for future experimental explorations of higher-dimensional topological phases in superconducting quantum systems that are, in principle, scalable. All ingredients of our proposals are within reach using current Josephson junctions and quantum microwave technologies. Moreover, similarly to Majorana particles, the non-Abelian quantum ground state of our proposal can in principle be utilized for holonomic quantum manipulations.

Another important and natural direction for engineered Josephson junction systems is the physics of the so-called Yu-Shiba-Rusinov states (YSR) which are localized states around magnetic impurities on top of a superconducting substrate. Here, the interaction of the impurity magnetization with the superconductor leads to the formation of bound (quasi-particle) spin-dependent states, inside the superconducting gap similarly to the Andreev and Majorana bound states. Indeed, part of the interest in the YSR states lies in the fact that they can serve as building blocks to create Majorana states in designer structures such as chains of magnetic impurities. This research is motivated by recent experimental developments on scanning tunneling microscopy (STM) of YSR states, in which it is possible to study the interplay between multiple Andreev reflections and a single pair of fully spin-polarized YSR states and determine the current-voltage characteristics.

Analog models

A main activity on analog models of gravity and quantum simulation of quantum field theories on curved space-times has concerned the study of superradiant effects. In vortex configurations, an interesting link has been unveiled between gravitational concepts and the different instability processes of quantized vortex configurations. In this way, we have been able to provide new and complete explanations for known effects, such as the instability of multiply-charged vortices, as well as predictions for new instability mechanisms for singly-charged vortices in specifically designed geometries. A new concept of analog model based on synthetic gauge fields was then introduced, which allows the generation of a wider variety of analog models without being constrained by the usual irrotationality constraint of superfluids. This has allowed to shine new light on superradiant phenomena by using simpler geometries that allow to disentangle the different effects at play, from superradiant scattering to instabilities. Extension of the theory to the quantum regime of superradiant emission of entangled pairs was finally put forward.

Another direction of research in the field of analog models has addressed the so-called cosmic reheating describing the transition of the post-inflationary universe to a hot and thermal state. In order to shed light on the nature of this process, we propose a quantum simulation of cosmic reheating using a temporally modulated ultracold Bose gas. By means of classical-statistical simulations we showed how the dynamics of the atomic system exhibits the characteristic stages of far-from-equilibrium reheating, including the amplification of fluctuations via parametric instabilities and the subsequent turbulent transport of energy towards higher momenta as governed by a non-thermal fixed point. An implementation of this proposal is currently under way in the group of M. Oberthaler, Heidelberg University.

At present, we are taking advantage of the accumulated expertise on analog models based on single component condensates to investigate analog models based on spin excitations in two-component condensates. As already mentioned, this last activity is being carried out in close synergy with the experimental labs in view of developing an experimental activity at the BEC Center.

Quantum simulation of high-energy and nuclear physics

Controlled quantum devices open the exciting prospect of tackling quantum many-body problems beyond the possibilities of classical computers. A particularly exciting target is given by models from high-energy and nuclear physics, whose simulation is currently one of the main drivers of (classical) scientific high-performance computing.

We have developed feasible protocols for optical lattices, which have enabled the largest-scale quantum simulation of such models to date, performed in the group of Jian-Wei Pan, Hefei/Heidelberg. At the same time, we have collaborated in an implementation of a scalable building block that accesses a more challenging regime of large simulated electric fields, which was performed in the group of F. Jendrzejewski, Heidelberg. Such large-scale quantum simulations open the door to investigating quantum many-body effects with unprecedented precision in previously unattainable regimes.

In order to process even further, it is, hoewever, crucial to establish how such large-scale devices behave under unavoidable errors and to design ways to mitigate them. We have performed a series of investigations into the reliability of such quantum simulations, and we have developed error-protection methods based on engineering suitable energy penalties, which have enabled the progresses mentioned above. In the wake of these analyses, we have also identified novel phenomena that are worthy of investigation in their own right, such as a peculiar staircase form under which the model systems approach thermal equilibrium, rather than a smooth approach that one would naively expect.

Quantum computing for solving hard classical problems

With a novel generation of quantum computers being available, it is a pressing question to design feasible and efficient algorithms that solve problems of practical relevance.

In collaboration with the group of P. Faccioli, UniTrento, we have designed quantum algorithms to tackle outstanding problems from computational biophysics. In particular, we found a paradigmatically new way to treat the dynamics of configurational changes of macromolecules using a quantum computer, as well as the problem of sampling from different polymer configurations. In our benchmark analyses, we found an extremely promising quantum computational performance for both algorithms. These breakthrough results open the door to a range of extensions and follow-up investigations, which the potential for wide-spread applications in biology, chemistry, and related fields, opening future prospects of application, e.g., in pharmacology.

Further, we designed a novel platform for universal quantum computation in a mixture of two species of cold atoms. This project has been developed in collaboration with the group of F. Jendrzejewski, who is currently performing benchmark experiments to test the performance of this novel quantum platform and to implement first simple algorithms.

Detection of entanglement and quantum correlations in many-body systems

The ability to engineer exotic quantum systems concomitantly makes it necessary to develop paradigmatically novel probes to characterize them. Such novel detection tools also have important applications in the characterization and certification of a new generation of quantum devices. Cold atoms and similar devices open here unique possibilities thanks to the ability to design protocols of unprecedented precision that use, e.g., induced dynamics or engineered dissipation.

We have proposed a scalable measurement protocol to extract the quantum Fisher information, which is the central quantity for quantum sensing and which characterizes many-particle entanglement. The protocol is based on simply perturbing a thermal quantum state and can be realized with standard experimental abilities.

We have also developed a method to detect unequal time correlators using engineered dissipation. Using the example of a Bose-Hubbard system, we have illustrated that our framework enables one to probe fluctuation-dissipation relations in an unbiased way and thus to monitor the evolution of a quantum system towards thermal equilibrium, a long-standing research question that is attracting interest for many decades. A first proof-of-concept in an ultracold atomic Rydberg experiment is currently being realized by the group led by M. Weidemüller, Heidelberg. In an extension of the work, we have applied engineered dissipation to measuring current operators, which will enable experimentalists to characterize important transport properties of quantum many-body systems.

Further, we have introduced multipartite fermionic mode entanglement, which we employed to numerically certify entanglement in a paradigmatic and experimentally relevant fermion system. Such experimentally accessible entanglement witnesses are important in order to characterize quantum devices.

The full list of pubblications will be give in the section "Articles, preprints, highlights". In the next pages, we briefly summarize the content of few selected articles.

Physical Review Research 2, 033183 (2020)

Kibble-Zurek dynamics in a trapped ultracold Bose gas

I-Kang Liu, Jacek Dziarmaga, Shih-Chuan Gou, Franco Dalfovo, and Nick P. Proukakis

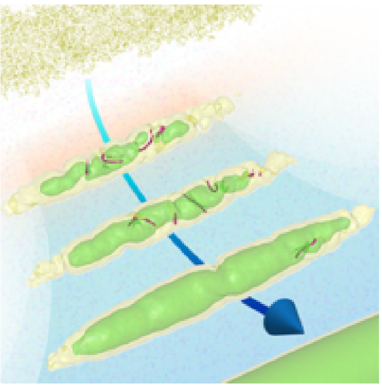


Figure 5: Simulation of a temperature quench across the BEC phase transition for a trapped gas of sodium atoms. As the gas cools, a condensate emerges from a regime of large fluctuations and vorticity.

This work examines the growth of a Bose-Einstein condensate in a trapped ultracold bosonic gas quenched across the phase transition. The validity of the Kibble-Zurek framework in the early stages of the symmetry-breaking dynamics is assessed, clarifying the role of different time and spatial scales in the quench and filling in the gap between the early evolution and the corresponding long-time evolution observed in the experiments.

The results are obtained by performing a detailed numerical analysis of externally-driven spontaneous symmetry breaking and dynamical growth of an elongated, harmonically confined, three-dimensional condensate by solving the stochastic Gross-Pitaevskii equation (SGPE) in realistic experimental parameter regimes, which were identified in previous quantitative analysis of the late-time relaxation dynamics probed experimentally in the laboratory of the BEC Center in Trento.

Analytical predictions are also obtained in the linearized limit of the same equation and the comparison between analytic and numerical results shows that the evolution determined by the stochastic Gross-Pitaevskii equation is consistent at early times with the predictions of the homogeneous Kibble-Zurek mechanism.

The work fills the gap between the experimentally observed long time evolution of a temperature quenched condensate and the Kibble-Zurek dynamics at earlier times, near the transition. The study of the early time dynamics is relevant for at least three reasons: (i) it is needed to prove that there is an overall consistency in the interpretation of the SGPE simulations over the whole range of timescales, including the effects of the KZ mechanism which can be understood in terms of a linearized theory and can be related to the later time evolution of the condensate; (ii) it clarifies the role of different time and spatial scales in the quench, thus helping to place the homogeneous versus inhomogeneous KZ mechanism in the proper context of realistic trapped condensates; and (iii) new experiments are planned to observe the early time dynamics during a temperature quench and this work is also meant to serve as a guide for the choice of the appropriate observables and parameters.

Physical Review Research 3, 013161 (2021)

Finite temperature spin dynamics of a two-dimensional Bose-Bose atomic mixture

Arko Roy, Miki Ota, Alessio Recati, and Franco Dalfovo

This work shows that thermal fluctuations in a two-dimensional mixture of two Bose gases inhibit true Bose-Einstein condensation and smoothen all sharp features in the miscible to immiscible phase transition at finite temperature.

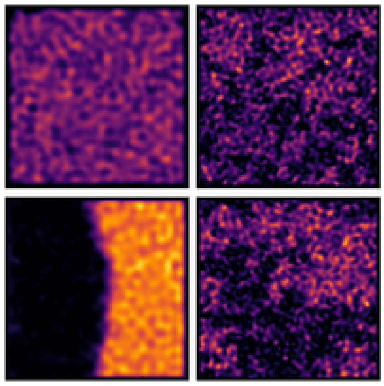


Figure 6: Equilibrium density profiles obtained from single runs of SGPE simulations at different interspecies interaction strengths and temperatures in a uniform 2D hard-wall square box.

The goal was to extend the investigation of phase-separation in a two-component quantum mixture going beyond mean-field level and exploring the case of a uniform 2D Bose-Bose mixture occupying two different hyperfine states and satisfying the miscibility condition at zero temperature. As a first step, we calculated the phase diagram as a function of temperature and inter-species interaction strength and identified the miscible and immiscible regions using the mean-field Hartree-Fock theory. By treating the atoms in the two components as up and down spin states of spin- $1/2$ particles, the transition from a miscible to an immiscible mixture can be seen as a magnetic phase-transition.

As a second step, we used the stochastic Gross-Pitaevskii (SGPE) theory for the same mixtures. This formalism describes the system and its fluctuations by using noisy classical fields coupled to a thermal bath, and includes effects of thermal fluctuations both in the density and spin channels, going beyond the HF description. We calculated the density profiles of the two components at equilibrium at different temperatures and interaction strengths and we simulated the response of the system to a weak external perturbation producing a spin oscillation (i.e., an out-of-phase motion of the two components). From the spin dynamics we also obtained the velocity of spin sound waves. The SGPE simulations show evidences of the miscible-immiscible phase transition in the expected range of parameters, in qualitative agreement with the HF theory; however, thermal fluctuations makes the transition much smoother, thus hindering the sharp features predicted by the mean-field theory. This, we believe, would also be the scenario in actual experiments. The recent availability of box like traps would be of value to corroborate these features.

Phys. Rev. A 102, 023318 (2020)

Quantum droplets in one-dimensional Bose mixtures: a quantum Monte-Carlo study

L. Parisi and S. Giorgini

We use exact Quantum Monte Carlo techniques to study the properties of quantum droplets in two-component bosonic mixtures with contact interactions in one spatial dimension. We systematically study the surface tension, the density profile and the breathing mode as a function of the number of particles in the droplet and of the ratio of coupling strengths between intra-species repulsion and inter-species attraction. We find that deviations from the predictions of the generalized Gross-Pitaevskii equation are small in most cases of interest.

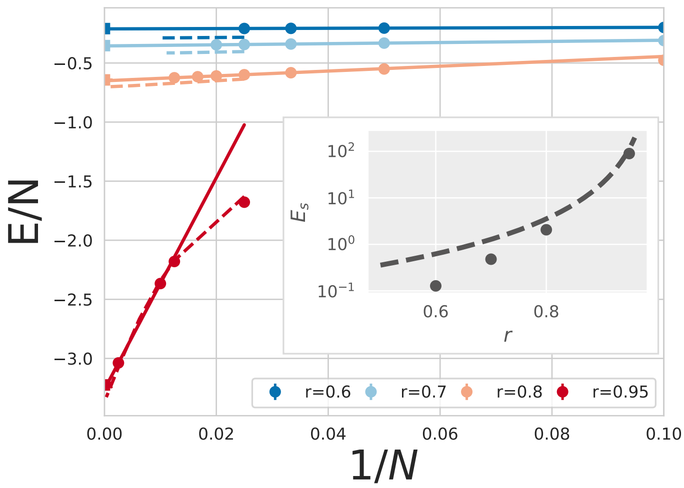


Figure 7: Energy per particle, in units of $\hbar^2/(ma^2)$, as a function of the inverse particle number $1/N$ for increasing ratio r between attraction and repulsion from the topmost to the lowermost. Solid dots are the results of our DMC simulations and solid lines are linear fits to the DMC data in the limit of large N. Solid squares at $1/N = 0$ correspond to the bulk energy calculated in a previous paper of ours [Phys. Rev. Lett. **122**, 105302 (2019)]. Dashed lines show instead the GGP predictions. The slope of the linear fit, corresponding to the surface energy E_S, is shown in the inset together with the GGP result.

Phys. Rev. Res. 2, 023405 (2020)

Strong coupling Bose polarons in a two-dimensional gas

L. A. Peña Ardila, G. E. Astrakharchik and S. Giorgini

We study the properties of Bose polarons in two dimensions using quantum Monte Carlo techniques. Results for the binding energy, the effective mass and the quasiparticle residue are reported for a typical strength of interactions in the gas and for a wide range of impurity-gas coupling strengths. A lower and an upper branch of the quasiparticle exist. The lower branch corresponds to an attractive polaron and spans from the regime of weak coupling, where the impurity acts as a small density perturbation of the surrounding medium, to deep bound states which involve many particles from the bath and extend as far as the healing length. The upper branch corresponds to an excited state where due to repulsion a low density bubble forms around the impurity, but is unstable against decay into many-body bound states. Interaction effects strongly affect the quasiparticle properties of the polaron. In particular, in the strongly correlated regime the impurity features a vanishing quasiparticle residue, signalling the transition from an almost free quasiparticle to a bound state involving many atoms from the bath.

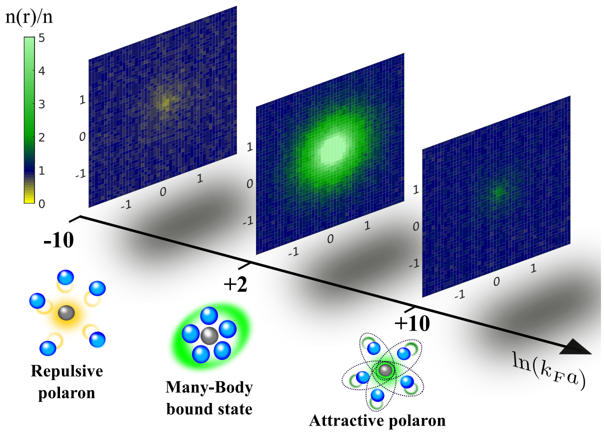


Figure 8: Average over many snapshots of the particle positions around the impurity for three characteristic values of the impurity-bath coupling constant $\ln(k_F a)$. The impurity is located in the center and distances are in units of the healing length ξ. The local density $n(r)$ is estimated by summing particles over a square grid of size $L/100$, where L is the size of the simulation box, and the color-bar indicates the ratio $n(r)/n$ over the bulk density n. At weak coupling impurities form polarons, *i.e.* almost free quasiparticles slightly dressed by the medium (right and left upper panels). On the attractive branch as the coupling $\ln(k_F a) > 0$ is decreased, the impurity forms a many-body bound state involving up to few tens of particles and whose size is as large as the healing length (central upper panel).

Phys. Rev. Research 2, 033276 (2020)

Quantum fluctuations beyond the Gutzwiller approximation in the Bose-Hubbard model

Fabio Caleffi, Massimo Capone, Chiara Menotti, Iacopo Carusotto, Alessio Recati

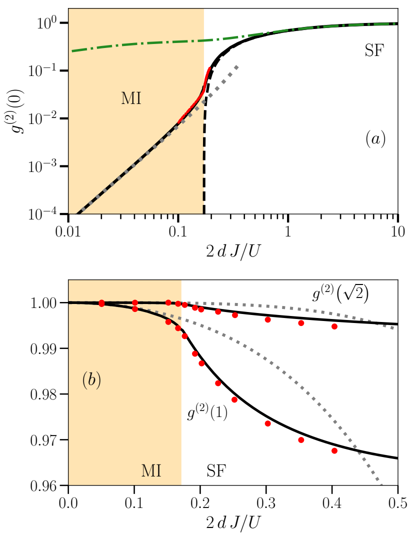


Figure 9: Density-density correlation as a function of the inverse interaction coupling constant $2dJ/U$ across the unity commensurate SF-MI transition. Orange (white) background identifies the MI (SF) region. Panel (a): On-site correlation function. Panel (b): Nearest and next-to-nearest density correlations. The quantum Gutzwiller results (black solid lines) are in good agreemnt with Quantum Monte Carlo simulation [Sci. Rep. 9, 8687 (2019)] and [Phys. Rep. 607, 1 (2016)].

Strongly correlated many-body system challenge physicists since the fundation of the quantum theory. The emergent phenomena are usually very far for the physics of the bare constituents. A prototypical model for strongly interacting systems is the so-called Hubbard model, where the particles live on a lattice. Such models, which describe, e.g., the Mott insulating phase in metals and give insights in the existence of high-Tc superconductivity can be emulated by trapping ultra-cold gases in an optical lattice.

In the case when the atoms loaded into the lattice follow the Bose statics, it is well known that the system exhibts a Superfluid-to-Mott insulator transition. In the latter phase the filling is commensurate with the lattice size. Moreover the mechanism of the transition from the superfluid state to the Mott insulator depends on whether the number of particles is kept fix or not. The two kind of transition belong to different universality classes, a fact that strongly affect the spectrum of the system close to the phase transition. For the accurate description of relevant physical quantities and of the response of the system one needs quite sofistaced and/or numerically demanding methods, as, e.g., Quantum-Monte-Carlo methods.

In the present work we devolp a method based on the canonical quantization of the action derived from a Gutzwiller mean-field ansatz. Our theory is a systematic generalization of the Bogoliubov theory of weakly-interacting gases. The control parameter of the theory, defined as the zero point fluctuations on top of the Gutzwiller mean-field state, remains small in all regimes. The approach provides accurate results throughout the whole phase diagram, from the weakly to the strongly interacting superfluid and into the Mott insulating phase. As specific examples of application, we study the off-diagonal single particle correlation functions, the superfluid stiffness, as well as the density-density correlation function, for which quantitative agreement with available quantum Monte Carlo data is found. In particular, the two different universality classes of the superfluid-insulator quantum phase transition at integer and non-integer filling are recovered.

Phys. Rev. A 101, 013610 (2020)

Spin-dipole mode in a trapped Fermi gas near unitarity

Hiroyuki Tajima, Alessio Recati, Yoji Ohashi

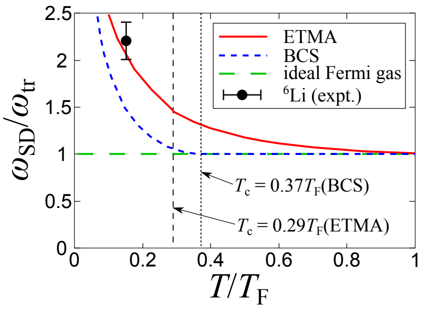


Figure 10: Density-density correlation as a function of the inverse interaction coupling constant $2dJ/U$ across the unity commensurate SF-MI transition. Orange (white) background identifies the MI (SF) region. Panel (a): On-site correlation function. Panel (b): Nearest and next-to-nearest density correlations. The quantum Gutzwiller results (black solid lines) are in good agreemnt with Quantum Monte Carlo simulation [Sci. Rep. 9, 8687 (2019)] and [Phys. Rep. 607, 1 (2016)].

This work is the result of a fruitful collaboration with RIKEN and Keio University in Japan and the BEC Center on strongly interacting Fermio gases, a topic to which the members of the Center gave important contributions.

The first author spent a few months in Trento to discuss the possible application We theoretically investigate the spin-dipole oscillation of a strongly interacting Fermi gas in a harmonic trap. By using a combined diagrammatic strong-coupling theory with a local density approximation and a sum rule approach, we clarify the temperature dependence of the spin-dipole frequency near the unitarity, which is deeply related to the spin susceptibility, as well as pairing correlations. While the spin-dipole frequency exactly coincides with the trap frequency in a non-interacting Fermi gas, it is shown to remarkably be enhanced in the superfluid state, because of the suppression of the spin degree of freedom due to the spin-singlet Cooper-pair formation. In strongly interacting Fermi gases, this enhancement occurs even above the superfluid phase transition temperature, due to the strong pairing correlations.

Phys. Rev. Lett. 124, 045702 (2020)

Rotating a supersolid dipolar gas

S. M. Roccuzzo, A. Gallemí, A. Recati, S. Stringari

This work continue the analysis of the physics of the supersolid phase of dipolar gases, on which the Trento team has already given relevant contributions in the past year. In the present we address the rotational properties a supersolid.

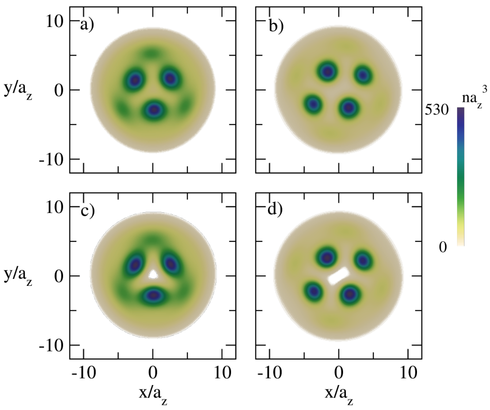


Figure 11: Density plots of a supersolid dipolar gas in its ground state and in presence of a central vortex. The number of peaks depends on the ratio between the strength of the dipolar and the contact (s-wave) interaction, ε_{dd}. In (a) and (c) in the triangular cell structure for $\varepsilon_{dd} = 1.334$; in (b) and (d) we show the case of a two-triangular cells structure obtained for $\varepsilon_{dd} = 1.351$.

In particular we calculate the moment of inertia of a harmonically trapped dipolar Bose-Einstein condensed gas as a function of the tunable scattering length parameter, providing the transition from the (fully) superfluid to the supersolid phase and eventually to an incoherent crystal of self-bound droplets. The transition from the superfluid to the supersolid phase is characterized by a jump in the moment of inertia, revealing its first order nature.

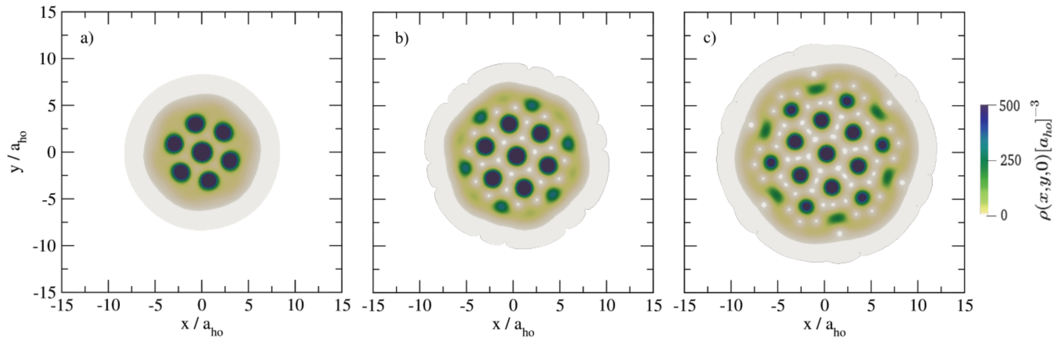
We first study the case of an elongated trapping in the plane of rotation and show that the moment of inertia determines the value of the frequency of the scissors mode, which is significantly affected by the reduction of the superfluid density in the supersolid phase. In the second part of the work we consider the case of an in-plane isotropic trapping which is instead well suited to study the formation of quantized vortices, which are shown to be characterized, in the supersolid phase, by a sizeable deformed core, caused by the presence of the surrounding density peaks.

Phys. Rev. A 102, 023322 (2020)

Quantized vortices in dipolar supersolid Bose-Einstein condensed gases

A. Gallemì, S. M. Roccuzzo, S. Stringari, A. Recati

This work is the second part of the publication Phys. Rev. Lett. 124, 045702 (2020), where first evidence of vorticity in the supersolid phase was obtained. In this paper we investigate the properties of quantized vortices in a dipolar Bose-Einstein condensed gas. Many features differ with respect to the standard condensate with only contact interaction: (I) The size of the vortex core becomes very large by increasing the weight of the dipolar interaction and approaching the transition to the supersolid phase; (II) the critical angular velocity for the existence of an energetically stable vortex decreases in the supersolid, due to the reduced value of the density in the interdroplet region; (III) the angular momentum per particle associated with the vortex line is shown to be smaller than , reflecting the reduction of the superfluid density. The previous results are obtained for an imposed vortical configuration.



Density plots of $N = 110000$ ^{164}Dy atoms in the supersolid phase confined in an harmonic trap with in plane trapping frequency ω_x. Panel a) non-rotating gas, Panel b) $\Omega = 2/5\omega_x$ and Panel c) $\Omega = 5/6\omega_x$.

An important question for superfluid system is how a vortex is generate in real-time. We study the zero temperature case, by rotating a deformed cloud. In this way we have been able to show that the vortex nucletion is triggered – as for a standard condensate – by the softening of the quadrupole mode, whose frequency has to be independently numerically determined. For large angular velocities Ω, when the distance between vortices becomes comparable to the inter-peak distance, the vortices are arranged into a honeycomb structure, which coexists with the triangular geometry of the supersolid lattice and persists during the free expansion of the atomic cloud. At even larger angular velocities new vortex lattice structures appear.

Phys. Rev. Research 3, 013143 (2021)

Supersolidity of cnoidal waves in an ultracold Bose gas

Giovanni I. Martone, Alessio Recati, and Nicolas Pavloff

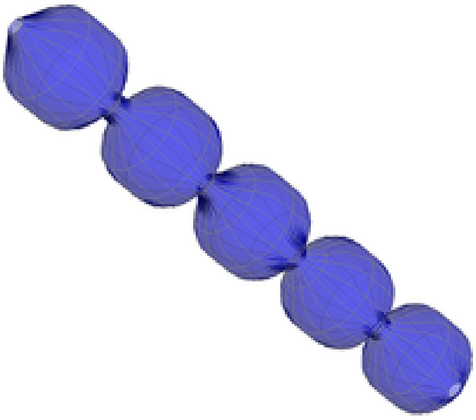


Figure 12: Schematic representation of a cnoidal wave solution in a quasi-one-dimensional condensate. The stationary excited state spontaneously breaks translational invariance resulting in a reduction of the superfluid density. The latter is found analitically to coincide with the well known Leggett's variational result.

A one-dimensional Bose-Einstein condensate may experience nonlinear periodic modulations known as "cnoidal waves". We argue that such structures represent a promising candidate for the study of supersolidity-related phenomena in a non-equilibrium state.

In particular from the solution of the mean-field equations for the condensate we show that it possible to rederive Leggett's formula for the superfluid fraction of the system and to obtain an analytical expression for it. More importantly, given the recent interest in modulated superfluids, we are able to determine the excitation spectrum, for which we obtain analytical results in the two opposite limiting cases of (i) a linearly modulated background and (ii) a train of dark solitons. The presence of two Goldstone (gapless) modes – associated with the spontaneous breaking of $U(1)$ symmetry and of continuous translational invariance – at large wavelength is verified. We also calculate the static structure factor and the compressibility of cnoidal waves, which show a divergent behavior at the edges of each Brillouin zone.

New J. Phys. 23, 033018 (2021)

Impurity dephasing in a Bose–Hubbard model

Fabio Caleffi, Massimo Capone, Inés de Vega, Alessio Recati

In this work we exploit the flexibility of the method we recently developed in Phys. Rev. Res.2 033276 (2020) to study time dependent phenomena in a Bose-Hubbard model, which plays the role of a non-trivial bath for another (small) quantum system. For the latter we consider the simplest possible case of a two-level impurity, which is embedded in a two-dimensional Bose–Hubbard model at zero temperature. Our analysis uses an open quantum system perspective. We obtain results for the decoherence across the phase diagram, with a focus on the critical region close to the transition between the superfluid and Mott insulating phase. In particular we show that the decoherence and the deviation from a Markovian behaviour are sensitive to whether the transition is crossed at commensurate or incommensurate densities, i.e., on the universality class of the phase transition.

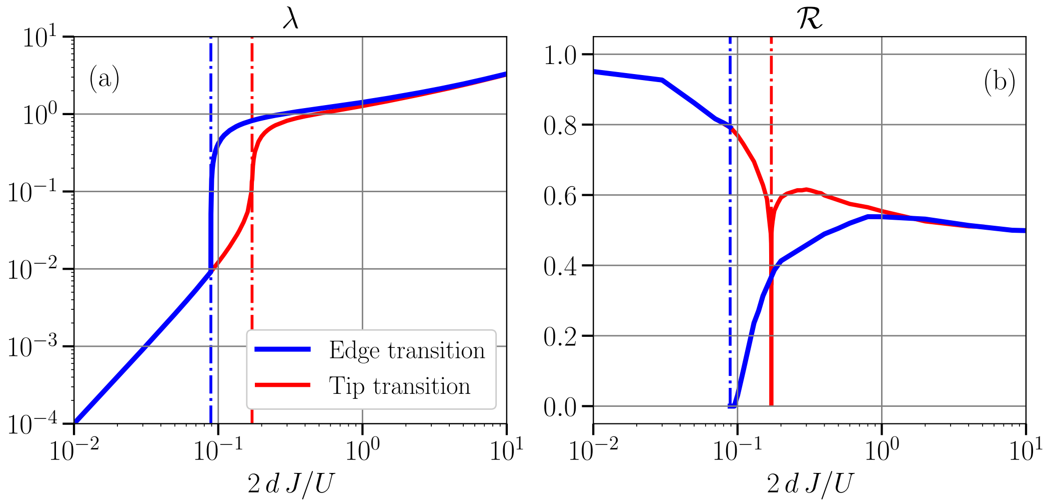


Figure 13: Panel (a): short-time decoherence rate as a function of the rescaled hopping energy $2dJ/U$ across the edge (blue line) – so-called Commensurate-Incommensurate phase transition – and tip (red line) – corresponding to a $O(2)$ phase transition – transition points. Panel (b): normalized information back-flow R for the same parameters. In both panels, the Commensurate-Incommensurate and the $O(2)$ critical points are indicated by the blue and the red dashed–dotted line, respectively.

The role of the spectrum of the BH environment and its non-Gaussian statistics, beyond the standard independent boson model, is highlighted. Our results are possible thanks to the the method which enables us to capture properly the quantum correlations across the phase diagram, beyond the standard Gutzwiller approach. Moreover, since the method is semi-analytical, we can provide a detailed insight into the physics of the spin decoherence in the superfluid and Mott phases as well as close to the phase transitions.

Phys. Rev. Research 3, L022017 (2021)

Collisionless drag for a one-dimensional two-component Bose-Hubbard model

Daniele Contessi, Donato Romito, Matteo Rizzi, and Alessio Recati

Andreev and Bashkin 45 years ago predicted that two superfluids experience a collisionless drag, due to the breaking of Galilean invariance for the single component. Such an effect although believed to be quite ubiquitous has never been directly measured. Cold-gases mixtures are considered good candidates to study such an effect. Unfortunately in the standard configuration the drag is simply too small to give rise to any measurable effect. In this work, we theoretically investigate the elusive Andreev-Bashkin collisionless drag for a two-component one-dimensional Bose-Hubbard model on a ring.

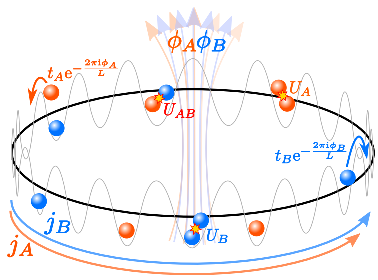


Figure 14: Sketch of the 2-component Bose-Hubbard ring with hopping parameters $\tilde{t}_\alpha = t_\alpha e^{-i2\pi\phi_\alpha/L}$, on-site intra-species interactions U_α and inter-species interaction U_{AB}. The two fluxes ϕ_α pierce the ring and give rise to bosonic currents j_α in the ground state.

By means of Tensor Network algorithms, we calculate superfluid stiffness matrix as a function of intra- and inter-species interactions and of the lattice filling. We then focus on the most promising region close to the so-called pair-superfluid phase, where we observe that the drag can become comparable with the total superfluid density.We elucidate the importance of the drag in determining the long-range behavior of the correlation functions and the spin speed of sound. In this way we are able to provide an expression for the spin Luttinger parameterin terms of drag and the spin susceptibility. Our results are promising in view of implementing the system by using ultra-cold Bose mixtures trapped in deep optical lattices, where the size of the sample is of the same order of the number of particle we simulate. Importantly the mesoscopicity of the system far from being detrimental appears to favour a large drag, avoiding the Berezinskii-Kosterlitz-Thouless jump at the transition to the pair superfluid phase which would reduce the region where a large drag can be observed.

Phys. Rev. Research 3, 023196 (2021)

Linear Response Study of Collisionless Spin Drag

Donato Romito, Carlos Lobo, and Alessio Recati

In this work we are concerned with the understanding of the collisionless drag or entrainment between two superfluids, also called Andreev-Bashkin effect, in terms of current response functions. The drag density is shown to be proportional to the cross transverse current-current response function, playing the role of a normal component for the single-species superfluid density. We can in this way link

the existence of finite entrainment with the exhaustion of the energy-weighted sum rule in the spin channel. The formalism is then used to reproduce some known results for a weakly interacting Bose-Bose mixture. We include the drag effect to determine the beyond mean-field correction on the speed of sound and on the spin dipole excitations for a homogeneous and a trapped weakly interacting gas, respectively. Finally, we show that the response to a quick dipole perturbation on one of the species induces a dipole moment on the other species which is proportional to the drag at short times.

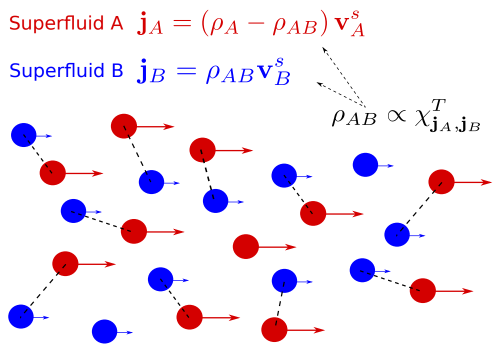


Figure 15: Sketch of the Andreev-Bashkin effect, or superfluid entrainment: a superfluid velocity field $\mathbf{v}_A^s$ in the component A, induces a current in both components. The current in component A is smaller than in absence of the collisionless drag, which plays the role of a normal part. The same quantity corresponds to the off-diagonal superfluid density of the current in B, which would be simply zero without the entrainment.

Nature Physics 17, 770 (2021)

Second sound seen

Sandro Stringari

Sandro Stringari has been invited by Nature Physics to write a News & Views article about an experiment performed by the team of Zoran Hadzibabic in Cambridge (P. Christodoulou et al, Nature 594, 191.194 (2021)). The experiment provides the first observation of second sound in a two-dimensional Bose Gas, a key phenomenon for the characterization of the superfluid behavior of the gas. In two-dimensional systems, Bose–Einstein condensation is ruled out by thermal fluctuations, but superfluidity can still be achieved at sufficiently low temperature, thanks to the occurrence of the infinite order Berezinskii–Kosterlitz–Thouless (BKT) transition. The Cambridge team has recently observed (P. Christodoulou et al, Nature 594, 191.194 (2021)) two different kinds of sound propagation in a two-dimensional quantum gas, verifying the predictions of BKT superfluidity and confirming the universal jump of the superfluid density at the transition predicted by Nelson and Kosterlitz in 1977. Using a Bose gas of potassium atoms, The Cambridge team reached a regime with strong interactions that made it possible to verify the applicability of the two-fluid hydrodynamic theory. The gas was confined in a box potential at very low temperatures and subject to a periodic drive that excited density modulations. In the superfluid phase, the density response of the system exhibited a characteristic two-peak structure, which is a clear signature of the two (first and second) sound velocities exhibiting clear discontinuities at the transition, as previously predicted by the Trento team (Ozawa and Stringari 2014). By a careful analysis based on the measurement of the sound speeds and on the knowledge of the thermodynamic functions entering Landau's two-fluid theory, the superfluid density could be extracted, exhibiting the predicted jump at the transition.

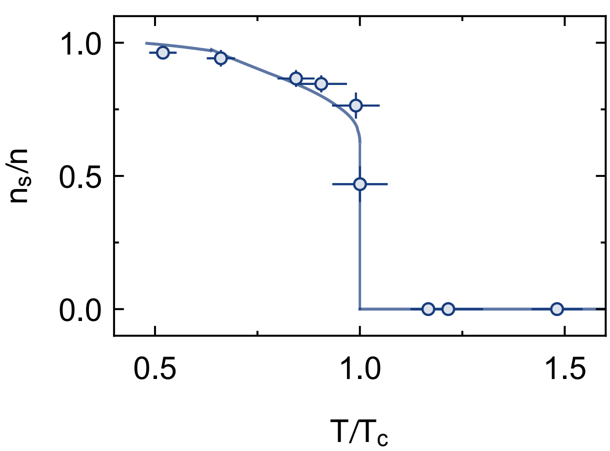


Figure 16: Superfluid density versus temperature The data were measured in the experiment of Christodoulou and co-workers. The superfluid density approaches the total density as $T \to 0$. At the BKT transition transition temperature T_c the superfluid density exhibits the predicted universal jump. The continuous line is the theoretical prediction by Prokof'ev and Svistunov (2002). Credit: Image courtesy of Panagiotis Christodoulou and Zoran Hadzibabic, University of Cambridge.

arXiv:2103.00918

Spin drag and fast response in a quantum mixture of atomic gases

Federico Carlini and Sandro Stringari

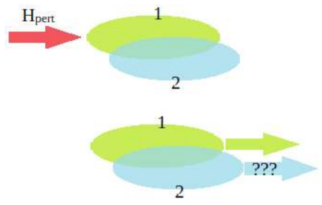


Figure 17: Schematic visualization of fast spin drag. A fast kick, applied to the component 1 of the mixture, can drag the motion of the component 2.

Spin drag is an ubiquitous concept in many branches of physics. It is usually associated with the presence collisional effects in the equation for the spin current, giving rise to spin diffusion. In this work we investigate spin drag effects of collisionless nature. By applying a sudden perturbation to one of the components of a mixture of two quantum fuids, we explore the effect on the motion of the second component on a short time scale (see Figure). By implementing perturbation theory, we show that for short times the response of the second component is fixed by the energy weighted moment of the crossed dynamic structure factor (crossed f-sum rule). We also show that by properly monitoring the time duration of the perturbation it is possible to identify peculiar fast spin drag regimes, which are sensitive to the interaction effects in the Hamitonian of the system. Special focus is given to coherently coupled Bose-Einstein condensates (with and without spin-orbit coupling), interacting Bose mixtures exhibiting the Andreev-Bashkin effect, normal Fermi liquids and the polaron problem. The relevant excitations of the system contributing to the spin drag effect are identified and the contribution of the low frequency gapless excitations to the f-sum rule in the density and spin channels is explicitly calculated employing the proper macroscopic dynamic theories. Both spatially periodic and Galilean boost perturbations are considered.

arXiv:2102.02221

Exciting the Goldstone modes of a supersolid spin-orbit-coupled Bose gas

Kevin T. Geier, Giovanni I. Martone, Philipp Hauke and Sandro Stringari

Supersolidity is deeply connected with the emergence of Goldstone modes, reflecting the spontaneous breaking of both phase and translational symmetry. Recent experiments have provided evidence for these Goldstone mode in atomic gases interacting with long range dipolar force. Here, we propose accessible signatures of these modes in harmonically trapped spin–orbit-coupled Bose–Einstein condensates, where supersolidity appears in the form of stripes. With respect to dipolar gases spin-orbit coupled BECs exhibit the crucial spin degree of freedom, whose effect on the nature of the novel Goldstone modes, caused by the breaking of translational invariance, is main purpose of the paper. By suddenly changing the trapping frequency, an axial breathing oscillation is generated, whose behavior changes drastically at the critical Raman coupling. Above the transition, a single mode of hybridized density and spin nature is excited (see Figure(b)), while below it, we predict a beating effect (see Figure(a)) signaling the excitation of a Goldstone a mode of clear spin-dipole nature. The dispersion of the spin-dipole mode, together with the frequencies of the other relevant collective modes, is shown in Figure(c). We further provide evidence for the spin nature of the "zero frequency" Goldstone mode, associated with the translational motion of stripes. We in fact observe that the sudden release of a uniform spin perturbation has the effect of applying a boost to the stripes, causing their translation at a constant velocity, proportional to the perturbation strength. Our results open up new perspectives for probing supersolid properties in experimentally relevant configurations with both symmetric as well as highly asymmetric intraspecies interactions.

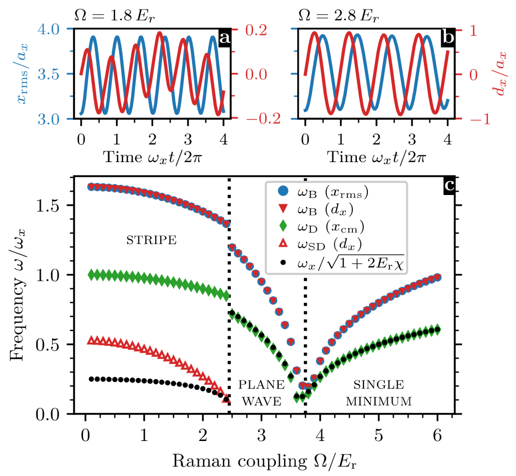


Figure 18: (a, b) Oscillations $x_{\rm rms} = \sqrt{x^2}$ and $d_x = x - x$ after suddenly removing the perturbation $H_{\rm pert} = \lambda m\omega_x^2 x^2$ with $\lambda = 0.2$. In the stripe phase (a), a clear beating of two frequencies $\omega_{\rm B} \approx 1.49\,\omega_x$ and $\omega_{\rm SD} \approx 0.32\,\omega_x$ is visible in the observable d_x, which is absent in the plane-wave phase (b), where d_x oscillates only at a single frequency $\omega_{\rm B} \approx 1.02\,\omega_x$. (c) Dispersion $\omega(\Omega)$ of the breathing mode (B), the spin-dipole mode (SD), and the center-of-mass (dipole) mode (D), calculated for $\lambda \ll 1$. The breathing and the spin-dipole modes are fully hybridized above the critical coupling $\Omega_c \approx 2.5\,E_r$, while below Ω_c, a new Goldstone mode of spin nature appears. The dipole frequencies $\omega_{\rm D}$ have been obtained from the center-of-mass oscillation $x_{\rm cm} = x$ after a sudden shift of the trap center. For $\Omega >$, they practically coincide with the bound $\omega_x/\sqrt{1+k_0^2\chi}$. The violation of this upper bound by $\omega_{\rm D}$ for $\Omega <$ implies the emergence of a new low-energy mode.

Phys. Rev. X 10, 041060 (2020)

Theory of the Coherence of Topological Lasers

Ivan Amelio and Iacopo Carusotto

The first generation of topological photonics experiments have focused on demonstrating the topologically protected chiral propagation of light along the edges of passive photonic lattices displaying topologically nontrivial band structures. In the past years, a major direction research has concerned the study of laser operation in topological edge modes. Such topological lasing appear as a very promising strategy in order to combine high power emission and highly coherent single-mode emission in semiconductor laser devices.

The goal of our work was to make use of advanced concepts of nonequilibrium statistical mechanics to investigate how spatial fluctuations affect temporal coherence in topological laser devices. Here, we make an important step in the direction by analyzing in full detail a simplest model of topological laser.

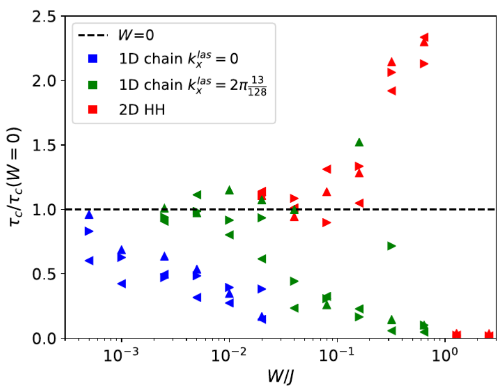


Figure 19: Coherence time normalized to the clean system value, as a function of the strength W of the disorder. Blue and green markers are for a nontopological one-dimensional laser array. Red markers are for the topological laser.

As a common feature of both nontopological and topological laser arrays, we have highlighted the crossover for growing observation times from a Kardar-Parisi-Zhang scaling of the temporal coherence to a Schawlow-Townes-like phase-diffusion regime. Furthermore, for growing system sizes the long-time phase diffusion rate displays a crossover from the standard Bogoliubov-Schawlow-Townes linewidth to a faster decoherence determined by the nonlinear dynamics of spatial fluctuations encoded in the KPZ dynamics.

Crucial consequences of topology have instead been identified in disordered systems, where the chiral motion of the lasing mode entails a much larger resilience to fabrication imperfections. For the nontopological arrays, disorder is, in fact, able to spatially localize the lasing mode and/or break it into several disconnected and incoherent pieces. On the other hand, the topological protected chiral motion of the edge state of a topological laser device is able to phase lock the different sites and, thus, maintain the spatial and temporal coherence across the whole sample.

These results confirm the strong promise that topological lasers hold for practical optoelectronic applications where one needs to make an array of many lasers to phase lock and emit as a single laser. Also, on the fundamental science side, topological laser are extremely promising to suppress undesired spatial inhomogeneities and boundary effects in experimental studies of the critical properties of different nonequilibrium statistical models.

Phys. Rev. X 10, 041058 (2020)

Anyonic Molecules in Atomic Fractional Quantum Hall Liquids: A Quantitative Probe of Fractional Charge and Anyonic Statistics

Alberto Muñoz de las Heras, Elia Macaluso, and Iacopo Carusotto

The discovery of the fractional quantum Hall effect in two-dimensional electron gases under a strong transverse magnetic field changed the paradigm of the boson-fermion dichotomy highlighting the possibility of observing quasiparticles with fractional charge and statistics, the so-called anyons, with a strong potential towards the development of fault-tolerant quantum computers. While the existence of fractionally charged quasi-particles was confirmed by shot-noise experiments, clear and direct signatures of fractional statistics are still somehow elusive. In the last years, the impressive developments in the experimental study of ultracold atomic gases and quantum fluids of light are opening the door to the exploration of fractional quantum Hall physics in novel highly controllable quantum platforms.

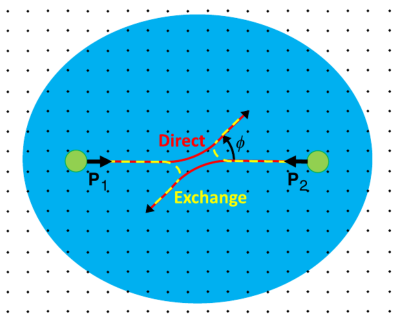


Figure 20: We consider the scattering of two anyonic molecules (green circles) formed by the binding of the same number of quasiholes to a pair of identical impurities in the bulk of a FQH fluid (blue region). Because of their indistinguishability, two scattering channels contribute to the differential scattering cross section, the "direct" (red) and the "exchange" (yellow) ones, whose relative phase is determined by the anyonic statistics.

In analogy with polarons arising from the many-body dressing of an impurity immersed in a cloud of quantum degenerate particles, a series of works have anticipated the possibility of using impurity particles immersed in a FQH liquid to generate anyonic molecules that inherit the fractional statistics of the quasi-hole. Here theoretically propose configurations where fractional statistics can be experimentally highlighted with state-of-the-art technology.

If a single anyonic molecule is prepared inside the FQH fluid, the values of the renormalized mass and of the fractional charge can be extracted from the experimentally accessible cyclotron orbit. In the case of two anyonic molecules, the fractional statistics of the quasiholes provides a long-range Aharonov-Bohm-like interaction between the molecules, with dramatic consequences on two-body scattering processes. For sufficiently large values of the relative incident momentum, the differential cross section displays a clear oscillatory pattern due to the interference of direct and exchange processes, and the nontrivial fractional statistical phase that the quasiholes acquire upon exchange is directly observable as a rigid shift of the angular interference pattern.

Further work will address the extension to more subtle FQH fluids supporting non-Abelian excitations and explore the consequences of the topological degeneracy on the quantum dynamics of the non-Abelian anyonic molecules.

Phys. Rev. Lett. 125, 165301 (2020)

Hanbury-Brown and Twiss bunching of phonons and of the quantum depletion in a strongly-interacting Bose gas

Hugo Cayla, Salvatore Butera, Cécile Carcy, Antoine Tenart, Gaétan Hercé, Marco Mancini, Alain Aspect, Iacopo Carusotto, and David Clément

In systems of non-interacting and indistinguishable quantum particles, correlations are rooted in quantum statistics. A paradigmatic example is the Hanbury-Brown and Twiss bunching of photons from a chaotic source. This approach was successfully extended to various other situations, from high-energy physics and solid-state devices to cold atoms. In non-interacting atomic gases at thermal equilibrium, the bunching (for bosons) and anti-bunching (for fermions) is set by the quantum statistics and the thermal occupation of single-particle states, whereas orrelations are absent in a fully coherent Bose-Einstein Condensate (BEC), in analogy to single-mode laser beams. HBT-like measurements with interacting particles are instead scarce.

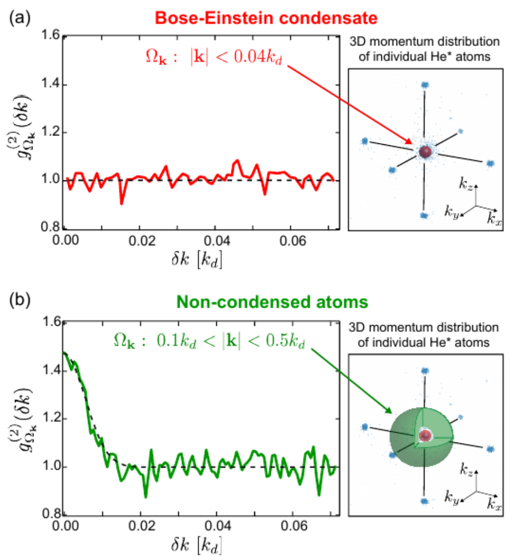


Figure 21: Experimental measurement of the momentum-space two-body correlations in the condensate (top) and in the thermal cloud (bottom).

The goal of this work is to experimentally and theoretically investigate the interplay between quantum statistics and interactions in the opposite regime where interactions dominate. Momentum-momentum correlations are measured in an ensemble of interacting atoms in the low-temperature regime dominated by interactions. We characterize the amplitude and width of the HBT bump and we highlight the differences with previous findings in non-interacting ensembles.

The observed bunching phenomenon directly reflects the interplay of interactions and quantum statistics, through the properties of the phononic collective excitation modes and of the quantum depletion. Our results thus demonstrate that momentum-momentum correlations provide information about the quantum state of strongly interacting bosons. Future work will make use of this same method to characterize the opposite-momenta two-body correlations in the quantum depletion and in other many-body phenomena.

An extensive presentation of the theoretical analysis was published in the companion work [S. Butera, D. Clément, I Carusotto, *Position-and momentum-space two-body correlations in a weakly interacting trapped condensate*, Phys. Rev. A **103**, 013302 (2020)].

Phys. Rev. A 103, 043309 (2020)

Understanding superradiant phenomena with synthetic vector potentials in atomic Bose-Einstein condensates

Luca Giacomelli, Iacopo Carusotto

Superradiance a very general phenomenon appearing in many different physical systems, from the bosonic Klein paradox for charged fields, to the Zel'dovich amplification of electromagnetic waves by a fast spinning absorbing body, to the superradiant scattering of electromagnetic or gravitational waves from rotating black holes. These amplification processes are often associated to different instabilities mechanisms that are important in the search of physics beyond the standard model. Superradiance in the gravitational context can be directly translated to condensed matter systems through the so-called gravitational analogy that maps the propagation of a scalar field in a curved space-time onto the one of sound in a non-uniformly moving fluid. In this framework, it has been extensively studied in vortex configurations and has been recently observed using gravity waves on water.

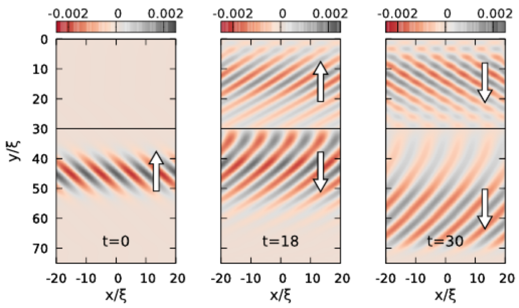


Figure 22: Snapshots of the superradiant amplified reflection of a sound wavepacket from an analog ergosurface ($t = 18$) and precursor of the ergoregion instability at a later time ($t = 30$).

The goal of the present work is to propose a new concept of analog model based on synthethic gauge potentials. Our proposed set-up allows to break the irrotationality constraint of superfluid flows and offers a wider flexibility in the design of the analog space-time to be studied. Here, superradiance can be understood in terms of the scattering of a plane wave on a planar interface playing the role of the analogue of a black hole ergosurface. By changing the boundary conditions, transitions from a stable superradiant amplification to dynamical instability behaviours can occur, analogously to the instabilities of rotating black holes in an anti-de Sitter space-time (black hole bomb) and of horizonless rotating stars (ergoregion instability).

While our work has focused on the linearized dynamics in a small excitation regime, a natural next step is to extend our investigation to large amplitude perturbations and to the quantum emission of excitation pairs by superradiant processes. The long-term perspective will be to explore the interplay between these two phenomena so to identify novel paths to black hole evaporation.

Phys. Rev. A 103, 043309 (2020)

Photonic materials in circuit quantum electrodynamics

Iacopo Carusotto, Andrew A. Houck, Alicia J. Kollár, Pedram Roushan, David I. Schuster and Jonathan Simon

Historically, most experiments with photons have explored elementary processes involving the generation, manipulation, and detection of a few only of such particles. In the last decade, the situation changed with the advent of the so-called quantum fluids of light: under suitable conditions, photons inherit an effective mass from the structure confining them, and collide with one another due to the nonlinear optical response of the structure. Together, these properties enable macroscopic ensembles of photons to exhibit collective behaviours akin to ordinary fluids.

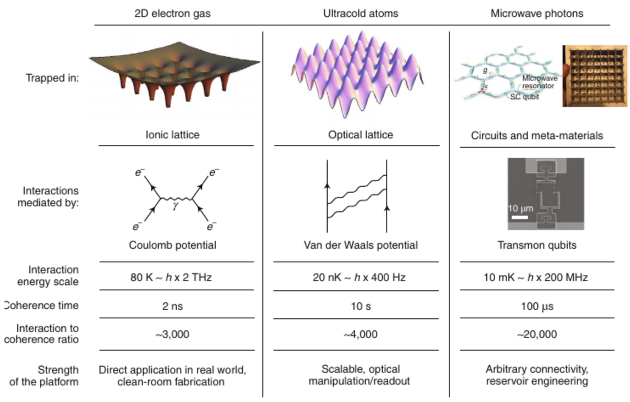


Figure 23: Comparative summary of the parameters of some among the most promising platforms for quantum matter.

While this adventure had its first breakthroughs in the infrared and visible domains using exciton polaritons in semiconductor microcavities and Rydberg polaritons in atomic gases, exciting new possibilities have recently emerged from microwave photons in superconducting quantum circuits, a platform presently of great interest for quantum computing applications.

This review article was written by a team involving some among the main international actors of this field from the academic and industrial world. It summarizes the main recent achievements of this novel field of research, including the realization of Mott insulators of light and complex non-Euclidean lattices and the first steps towards fractional quantum Hall liquids of light. Several among such advances have seen the active involvement of theoretical researchers from the BEC Center and/or have been inspired from our works.

It furthermore sketches our point of view on what we believe are the most promising avenues for its development from both the fundamental science and the quantum technology points of view, including dissipative stabilization of complex many-body states, novel phases of matter in digital quantum computer platforms, the realization of topological states displaying non-Abelian anyons of interest for topological quantum computing, the extension of many-body physics to non-Euclidean geometries.

Science 367, 1128 (2020)

A scalable realization of local U(1) gauge invariance in cold atomic mixtures

Alexander Mil, Torsten V Zache, Apoorva Hegde, Andy Xia, Rohit P Bhatt, Markus K Oberthaler, Philipp Hauke, Jürgen Berges, Fred Jendrzejewski

The fundamental laws of physics at a subatomic level are described by gauge theories, which govern the interaction between charged particles. An example is quantum electrodynamics, the theory of electrons and positrons interacting with the electromagnetic field. Solving such gauge theories is in general a hard problem for classical computational techniques. While quantum computers suggest a way forward, large-scale digital quantum devices required for complex simulations are still lacking.

In this work, we propose a fully scalable analog quantum simulator of a gauge theory, using a cold atomic mixture and employing a mechanism that has not yet been demonstrated experimentally, which is based on inter-species spin-changing collisions. We demonstrate the experimental realization of the elementary building block. We analyse the quantum dynamics following a perturbation that brings the system far from equilibrium, and find good agreement with benchmark numerics using Gross–Pitaevskii equations.

This platform permits the quantum simulation of large values of the electric field, and thus avoids a truncation that is typically done in similar setups. We also discuss how the system can be scaled up to extended systems, also in higher dimensions. This work thus presents a key step towards a platform for large-scale quantum simulations of continuous gauge theories.

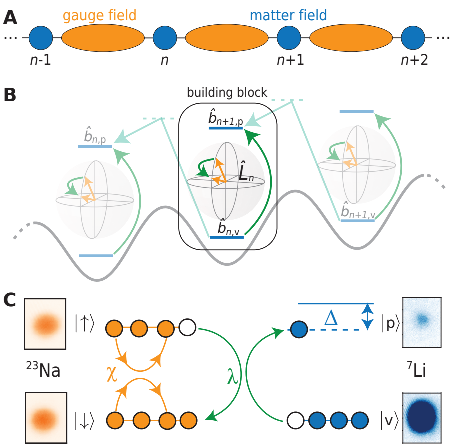


Figure 24: Engineering a gauge theory in a cold atomic mixture. (A) Structure of a lattice gauge theory. Electrons and positrons reside on lattice sites, the electric field generated by these charges on links in-between. (B) Proposed implementation of the extended system. An array of building blocks, each hosting small BECs in an optical lattice, is connected via laser-assisted tunneling. (C) Experimental realization of the elementary building block. Electric field (simulated by sodium atoms) and electrons/positrons (simulated by lithium atoms) generate the target model by heteronuclear spin-changing collisions.

Nature 587, 392 (2020)

Observation of gauge invariance in a 71-site Bose–Hubbard quantum simulator

Bing Yang, Hui Sun, Robert Ott, Han-Yi Wang, Torsten V Zache, Jad C Halimeh, Zhen-Sheng Yuan, Philipp Hauke, Jian-Wei Pan

The modern description of elementary particles is built on gauge theories, whose defining property are local constraints. For example, in quantum electrodynamics, Gauss's law introduces an intrinsic relation between charged matter (electrons and positrons) and electromagnetic fields. Solving gauge theories by classical computers is an extremely arduous task, which has stimulated a vigorous effort to simulate gauge-theory dynamics in microscopically engineered quantum devices. Previous achievements employed mappings onto effective models or were limited to very small systems. The essential Gauss's law has never been observed experimentally.

In this work, we report the quantum simulation of an extended lattice gauge theory, and experimentally quantify Gauss's law. This achievement has become possible thanks to the development of a novel implementation scheme employing a simple optical superlattice. We demonstrate full tunability of the model parameters, benchmark the matter–field interactions, and achieve the first measurement of Gauss's law in a quantum simulator. The system of 71 lattice sites is the largest such quantum simulation to date. Having such a mesoscopic system at hand opens the door towards controlled studies into many-body effects in gauge theories fundamental particles.

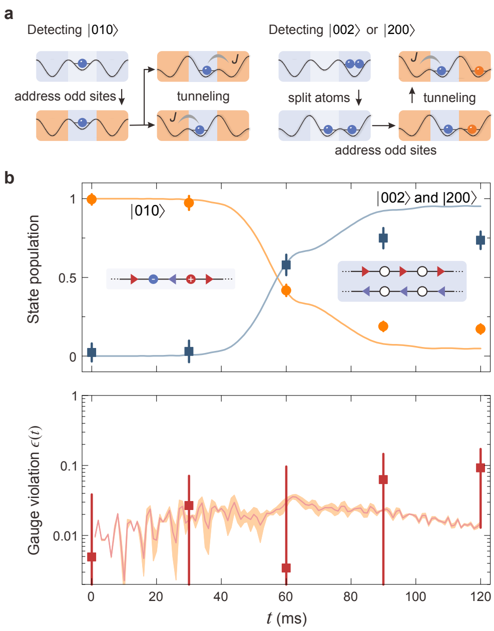


Figure 25: Certifying a gauge-theory quantum simulator. (a) Various configurations of cold atoms can be measured by tracking small subsystems. (b) As the system is driven through a phase transition, the probability of configurations change. Inset: Mapping back to the simulated gauge theory, this corresponds to an annihilation of electron and positron particles (+ and − signs). (c) These measurements enable to extract violations of Gauss's law, making this experiment the first quantum simulation to certify the defining property of a gauge theory.

Reports on Progress in Physics 83 (5), 054401 (2020)

Perspectives of quantum annealing: Methods and implementations

Philipp Hauke, Helmut G. Katzgraber, Wolfgang Lechner, Hidetoshi Nishimori, and William D. Oliver

Quantum devices open the exciting possibility to solve computational problems that are hard for classical computers. A particularly appealing quantum computing paradigm is quantum annealing, which has the ambitious goal of using quantum tunnelling to efficiently solve large-scale combinatorial optimization problems of practical importance. Such problems find application in many fields of science and industry, including computer science problems, classification, quantum chemistry, machine learning, search engine ranking, protein folding, compressive sensing, molecular similarity in chemistry, optimal trading trajectory, circuit fault diagnosis, planning, job-shop scheduling, variational autoencoders, and data processing in high-energy physics. However, many challenges have yet to be overcome before the goal of solving such problems beyond the capacities of classical computers can be reached in realistic devices.

This perspectives article first gives a brief introduction to the concept of quantum annealing. It then highlights new pathways that may clear the way towards feasible and large scale quantum annealing. Since this field of research is to a strong degree driven by a synergy between experiment and theory, we discuss both in this work. An important focus in this article is on future perspectives, which complements other review articles. This review article will thus hopefully stimulate further research and provide the community with a blueprint for future stepping stones to make further progress.

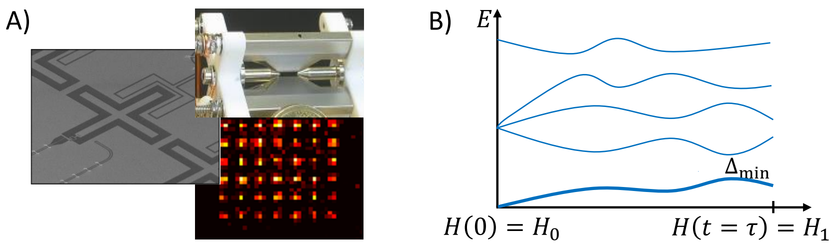


Figure 26: (A) Recent years have seen exciting developments on quantum-technology platforms, exemplified here by superconducting qubits, trapped ions, Rydberg atoms. These enable the implementation of quantum annealing protocols, which aim at solving hard optimization problems. (B) Sketch of time-dependent energy spectrum of the quantum system. The solution to the optimization problem is encoded in the ground state of a problem Hamiltonian H_0. It is reached at the end time τ of a slow sweep starting from the ground state of a Hamiltonian H_1 that is simple to prepare. If the sweep is sufficiently adiabatic (i.e., slow as compared to an inverse polynomial of the minimum energy gap $\Delta_{\min}$), the system remains in the instantaneous eigenstate throughout (thick line). This article discusses experimental as well as theoretical prospects to boost the performance of such quantum annealers. Picture credits panel A (clockwise from left): MIT Lincoln Laboratory; Blatt group, University of Innsbruck; LCF, Institut d'Optique, CNRS.

Physical Review Letters 126, 028104 (2021)

Dominant Reaction Pathways by Quantum Computing

Philipp Hauke, Giovanni Mattiotti, and Pietro Faccioli

One extremely hard computational task for classical computers is the characterization of thermally activated transitions in high-dimensional rugged energy surfaces, a problem that is of large relevance to computational biophysics, chemistry, and affine areas including pharmaceutics.

Here, we develop a quantum annealing scheme to solve this problem. First, the task of finding the most probable transition paths in configuration space is reduced to a shortest-path problem defined on a suitable weighted graph. Next, this optimization problem is mapped into finding the ground state of a generalized Ising model. A finite-size scaling analysis suggests this task may be solvable efficiently by a quantum annealing machine. Our approach leverages on the quantized nature of qubits to describe transitions between different system's configurations. By avoiding any lattice space discretization, our approach circumvents a major bottleneck in the scaling that haunted previous related proposals due to insufficient resolution. Thus, it paves the way towards future biophysical applications of quantum computing based on realistic all-atom models.

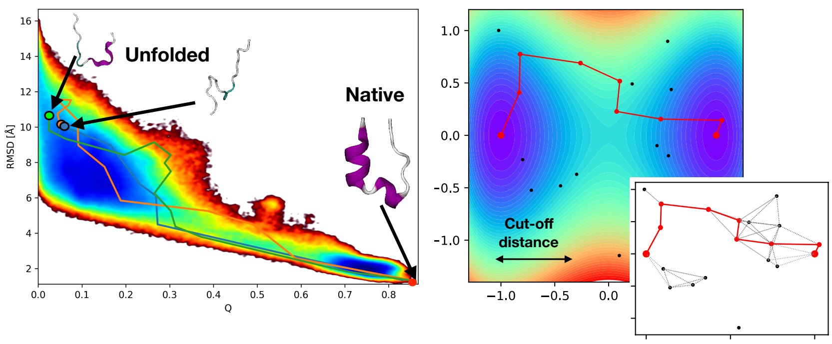


Figure 27: Illustrative applications of our reaction pathway calculations in prototypical systems. Left panel: The initial (unfolded) and final (folded) configurations of a protein (here: Trp-Csage) are known. The challenging task is to find the path of intermediate configurations that the system takes during the chemical reaction. The solid lines correspond to a classical benchmark calculation of the dominant reaction pathways, computed using the Dijkstra algorithm from three different unfolded configurations in a graph with 2180 vertices and 4×10^4 directed edges. The heat-map in the background shows the potential of mean-force estimated from standard molecular dynamics of the protein. Each dominant trajectory consists of about 20 configurations. Right Panel: Calculation of the dominant reaction path in a two-dimensional double-well potential that serves as a simple benchmark model, computed using a hybrid classical/quantum annealing approach on a D-Wave quantum annealing machine.

arXiv:2005.03049, accepted in Phys. Rev. Research

From entanglement certification with quench dynamics to multipartite entanglement of interacting fermions

Ricardo Costa de Almeida and Philipp Hauke

Multipartite entanglement is a crucial resource for quantum technologies. Yet, its experimental certification is highly challenging, often requiring resources that scale forbiddingly steeply with size of the quantum system. Here, we propose an experimentally friendly protocol to measure the quantum Fisher information (QFI), an important witness for multipartite entanglement and a central quantity for quantum enhanced sensing.

Our protocol relies on recording the short-time dynamics of simple observables after a perturbation of the system from a thermal state. It works for spins, bosons, and fermions, and can be implemented in standard cold-atom experiments and other platforms with temporal control over the system Hamiltonian. To showcase the protocol, we simulate it for the one-dimensional Fermi–Hubbard model. Further, we establish a family of bounds connecting the QFI to multipartite mode entanglement for fermionic systems, which provide a novel framework for entanglement in fermionic systmes and enable the detection of multipartite entanglement at sizable temperatures. Our work paves a flexible, general, and experimentally straightforward way to accessing entanglement as a resource for quantum enhanced metrology.

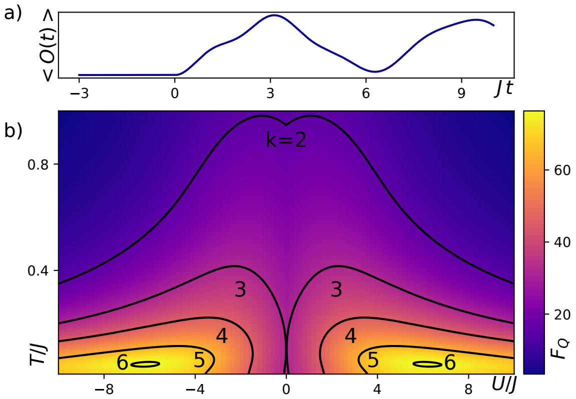


Figure 28: Certification of multipartite entanglement. (a) A many-body quantum system is abruptly perturbed by an operator O. Subsequently, the evolution of the same observable $\langle O(t)\rangle$ is measured, from which the quantum Fisher information, $F_Q[\rho, O]$, is extracted, yielding an experimentally extremely straightforward protocol. (b) $F_Q[\rho, O]$, computed by simulating the protocol for the Fermi–Hubbard model in 1D, a paradigm model for cold-atoms in optical lattices. The solid lines mark entanglement bounds derived in this work, which delimit different strengths of multipartite entanglement as well as the value of quantum enhancement in a sensing protocol. Many-body entanglement that can lead to a quantum enhancement is certified up to large temperatures and can thus be generated in realistic devices based on cold atoms.

PRX Quantum 2, 010310 (2021)

Second Chern number and non-Abelian Berry phase in topological superconducting systems

H. Weisbrich, R. L. Klees, G. Rastelli, and W. Belzig

Interestingly, topology is not restricted to low-dimensional systems, but it can also emerge in higher-dimensional spaces in which control parameters play the role of synthetic dimensions. Unfortunately, current theories in the area of condensed matter rarely enable implementations of higher-dimensional topological systems. Therefore, only a very small number of such implementations have been experimentally realized, thus, making the progress in this field rather slow.

Our models are based on two quantum dots with two spin levels, see Fig.29. A local Zeeman field B_z is externally applied with opposing direction on each dot. Such a simple double-dot system is coupled to a network composed by different superconducting contacts. The superconducting phases associated with the environment provide the synthetic gauge fields composed by four independent parameters λ_n from which we define topological properties. After integrating out the superconducting contacts, the tunnel coupling of the dots with the superconducting environment results in an effective phase-dependent Hamiltonian acting solely on the double-dot system which defines the energy spectrum of the lowest discrete states inside the superconducting gap.

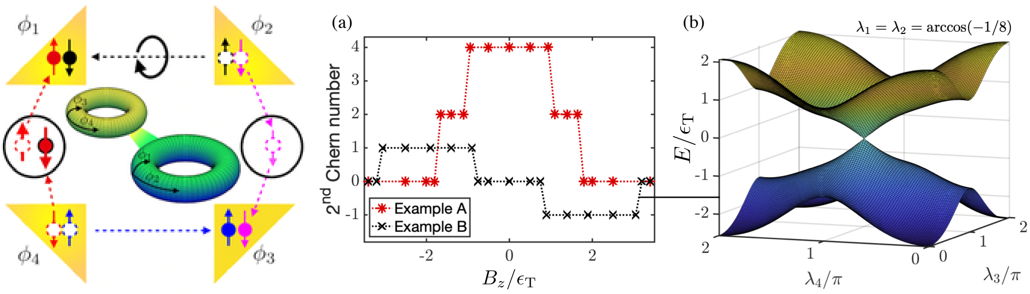


Figure 29: A cartoon of the theoretical models. The presence of two superconducting contacts between the two quantum dots leads to an effective electron tunneling with synthetic phases. A such tunneling is the result, for example, of two crossed Andreev reflections in which one Cooper pair is broken and another one is re-combined. Examples of results: (a) Second Chern number in four dimensions; (b) Energy band as a function of only two parameters with a crossing point.

Phys. Rev. B 103, 014516 (2021)

Ground-state quantum geometry in superconductor-quantum dot chains

R L. Klees, J. C. Cuevas, W. Belzig, and G. Rastelli

The concrete systems for MMJs proposed so far have the common disadvantage that the superconducting leads are arranged around a central non-superconducting region in a circular way. Such circular arrangements of the terminals will eventually have an adverse effect on the scalability of these systems. We proposed a new system, see Fig. 30, namely a linear chain of multiple quantum dots coupled to multiple superconducting leads, in which we show that topologically nontrivial Andreev bound states appear. Such a system represents an ideal platform for an experimental implementation as all the necessary ingredients are already available. Indeed, due to the linear arrangement of the terminals, the total number of terminals of such systems can be easily extended at will. As the dimension D in which the topology of the system is studied scales directly with the number of superconducting terminals D+1, our proposed system represents also a suitable system to experimentally study higher-dimensional topology.

We extended the developed sub-gap microwave spectroscopy to characterize the topology of single Andreev bound states to the case of multiple Andreev bound states. We demonstrate how to apply microwave spectroscopy to eventually measure the fundamental local quantity, namely the quantum geometric tensor of the multiband ground state. An important result is that the nontrivial topology in a linear chain appears beyond a threshold value of the nonlocal proximity-induced pairing potential which represents the novel theoretical key ingredient of this work. Moreover, we generalize the microwave spectroscopy scheme to the multiband case and show that the elements of the quantum geometric tensor of the noninteracting ground state can be experimentally accessed from the measurable oscillator strengths at low temperature.

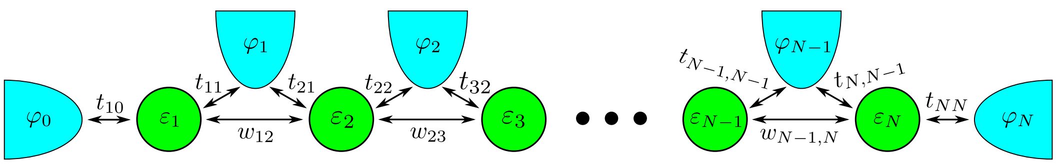
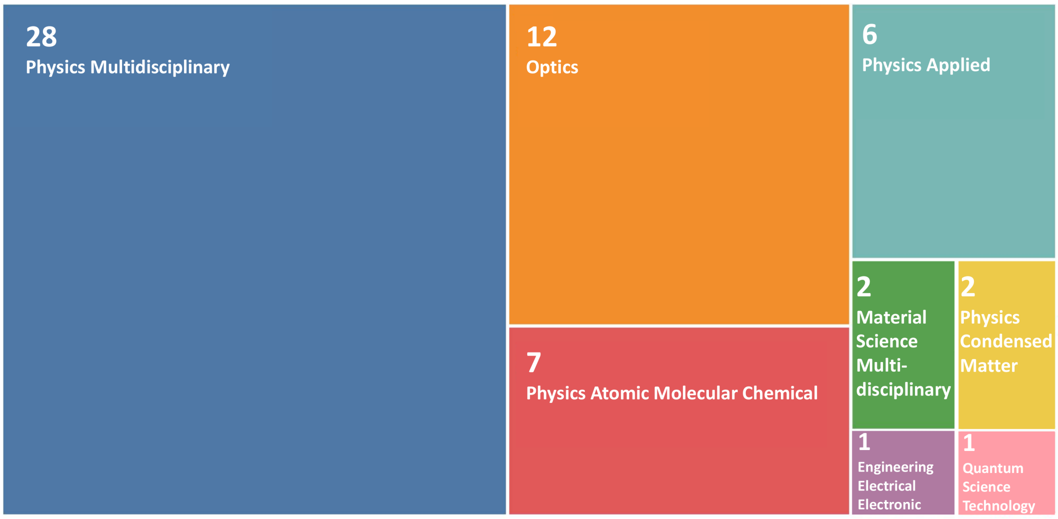


Figure 30: Model of the superconductor-quantum dot chain. The chain consists of N quantum dots (each with onsite energy) which are connected to N+1 s-wave superconducting leads (each with a pairing phase). Nearest neighbor's quantum dots are tunneling coupled between them as well as to common superconducting leads.

Articles, preprints and highlights

Here below we list all publications of the BEC Center since January 2020 to June 2021: first the articles that have already appeared in peer-reviewed journals, then the preprints that have been submitted to journals and posted on the arXiv, and finally a few highlights. The following figure shows the remarkable interdisciplinarity of the research activities of the BEC Center, quantified by the number of articles falling into the subject classification scheme of ISI - Web of Science.



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State of the art and perspective on Atomtronics, L. Amico, M. Boshier, G. Birkl, A. Minguzzi, C. Miniatura, L.-C. Kwek, D. Aghamalyan, V. Ahufinger, D. Anderson, N. Andrei, A.S. Arnold, M. Baker, T.A. Bell, T. Bland, J.P. Brantut, D. Cassettari, W.J. Chetcuti, F. Chevy, R. Citro, S. De Palo, R. Dumke, M. Edwards, R. Folman, J. Fortagh, S.A. Gardiner, B.M. Garraway, G. Gauthier, A. Günther, T. Haug, C. Hufnagel, M. Keil, W. von Klitzing, P. Ireland, M. Lebrat, W. Li, L. Longchambon, J. Mompart, O. Morsch, P. Naldesi, T.W. Neely, M. Olshanii, E. Orignac, S. Pandey, A. Pérez-Obiol, H. Perrin, L. Piroli, J. Polo, A.L. Pritchard, N.P. Proukakis, C. Rylands, H. Rubinsztein-Dunlop, F. Scazza, S. Stringari, F. Tosto, A. Trombettoni, N. Victorin, D. Wilkowski, K. Xhani, A. Yakimenko, A., arXiv:2008.04439c, to be publisehd in AVS Quantum Science

Analog reheating of the early universe in the laboratory, Aleksandr Chatrchyan, Kevin Geier, Markus K. Oberthaler, Jürgen Berges, Philipp Hauke, arXiv:2008.02290

Gauge-Symmetry Protection Using Single-Body Terms, Jad C. Halimeh, Haifeng Lang, Julius Mildenberger, Zhang Jiang, Philipp Hauke, arXiv:2007.00668

Unconventional critical exponents at dynamical quantum phase transitions in a random Ising chain, Daniele Trapin, Jad C. Halimeh, Markus Heyl, arXiv:2005.06481.

From entanglement certification with quench dynamics to multipartite entanglement of interacting fermions, Ricardo Costa de Almeida, Philipp Hauke, arXiv:2005.03049, accepted for publication in Physical Review Research

High-energy Bragg scattering measurements of a dipolar supersolid, D. Petter, A. Patscheider, G. Natale, M.J. Mark, M.A. Baranov, R. v. Bijnen, S.M. Roccuzzo, A. Recati, B. Blakie, D. Baillie, L. Chomaz, F. Ferlaino, arXiv:2005.02213

Staircase Prethermalization and Constrained Dynamics in Lattice Gauge Theories, Jad C. Halimeh, Philipp Hauke, arXiv:2004.07248

Origin of staircase prethermalization in lattice gauge theories, Jad C. Halimeh, Philipp Hauke, arXiv:2004.07254

Persistent response in ultra-strongly driven mechanical membrane resonators, Fan Yang, Felicitas Hellbach, Felix Rochau, wolfgang Belzig, Eva M. Weig, Gianluca Rastelli, Elke Scheer, arXiv:2003.14207, published in Physical Review Lett. on July 2, 2021

Linear Response Study of Collisionless Spin Drag, Donato Romito, Carlos Lobo, Alessio Recati, arXiv:2002.03955

Highlights

Sandro Stringari has been invited by Nature Physics to write the News & Views article *Second sound seen* published on June 9, 2021

The article *Robustness of gauge-invariant dynamics against defects in ultracold-atom gauge theories* by Jad C. Halimeh et al., published in Physical Review Research **2**, 033361 (2020), has been selected as PRR Editors' Suggestion.

The article *Observation of Magnetic Solitons in Two-Component Bose-Einstein Condensates* by A. Farolfi et al., published in Physical Review Letters 125, 030401 (2020), has been selected as PRL Editors' Suggestion and has been highlighted with a Synopsis by the on-line journal Physics.

The article *Observation of gauge invariance in a 71-site Bose-Hubbard quantum simulator*, by Bing Yang, Hui Sun, Robert Ott, Han-Yi Wang, Torsten V. Zache, Jad C. Halimeh, Zhen-Sheng Yuan, Philipp Hauke, and Jian-Wei Pan has been published in Nature **587**, 392 (2020).

The article *A scalable realization of local U(1) gauge invariance in cold atomic mixtures*, by Alexander Mil, Torsten V. Zache, Apoorva Hegde, Andy Xia, Rohit P. Bhatt, Markus K. Oberthaler, Philipp Hauke, Jürgen Berges, Fred Jendrzejewski, has been published in Science **367**, 1128 (2020).

The review article *Photonic materials in circuit quantum electrodynamics* by Iacopo Carusotto, Andrew A. Houck, Alicia J. Kollár, Pedram Roushan, David I. Schuster, and Jonathan Simon, has been published in Nature Physics **16**, 268 (2020).

Meetings, seminars, conferences, honors, outreach

Group meetings and seminars at the BEC Center

- Tuesday, June 1, 2021, at 11.00, Online Meeting BEC Seminar
  Hélène Perrin (LPL, CNRS, Sorbonne Paris Nord Univ.)
  Physics in a bubble: from supersonic rotation to the effects of dimensional reduction

- Tuesday, May 18th, 2021, at 11.00, Online Meeting BEC Seminar
  Daniele de Bernardis (TU Wien)
  Light-matter interaction in the ultra-strong coupling regime

- Friday, May 7th, 2021, at 14.00, Online Meeting BEC Colloquium
  Amir Boag (Tel Aviv University)
  Modeling Electromagnetic Phenomena in Large Quantum Systems

- Tuesday, May 3rd, 2021, at 11.00, Online Meeting BEC Seminar
  Thomas Bourdel (Institut d'Optique)
  Beyond-mean field effects in Rabi-coupled two-component Bose-Einstein condensate

- Tuesday, April 27th, 2021, at 11.00, Online Meeting BEC Seminar
  Leticia Tarruell (ICFO)
  Realizing a one-dimensional topological gauge theory in an optically dressed Bose-Einstein condensate

- Tuesday, April 20, 2021, at 11.00, Online Meeting BEC Colloquium
  Wolfgang Belzig (Univ. Konstanz)
  Quantum Properties of Squeezed Magnons in Ferro- and Antiferromagnets

- Wednesday, April 14th, 2021, at 10.00, Online Meeting PhD Defense
  Arturo Farolfi (BEC Center)
  Spin dynamics in two-component Bose-Einstein condensates

- Tuesday, April 13, 2021, at 11.00, Online Meeting BEC seminar
  Haifeng Lang (BEC Center)
  Generalized Discrete Truncated Wigner Approximation for Nonadiabatic Quantum-Classical Dynamics

- Monday, March 22, 2021, at 11.00, Online Meeting BEC seminar
  Markus Oberthaler (Heidelberg University)
  Recent and latest results from Heidelberg

- Monday, March 15, 2021, at 11.00, Online Meeting BEC seminar
  Soumik Bandyopadhyay (BEC Center)
  Universal dynamics of Sachdev-Ye-Kitaev model

- Monday, March 8th, 2021, at 11.00, Online Meeting BEC Seminar
  Alessandro Zenesini (BEC Center)
  Quantum-torque in ultracold gases

- Thursday, March 4th, 2021, at 14.00, Online Meeting PhD Defense
  Luca Giacomelli (BEC Center)
  Superradiant phenomena - Lessons from and for Bose-Einstein condensates

- Monday, February 22th, 2021, at 11.00, Online Meeting BEC seminar
  Tommaso Comparin (ENS Lyon)
  Quench Spectroscopy and Tower of States: Low-energy excitations from real-time quantum dynamics

- Monday, January 18th, 2021, at 11.00, Online Meeting Journal Club
  Sandro Stringari (BEC Center)
  Two recent experimental works on the Berezinskii-Kosterlitz-Thouless transition

- Monday, January 11th, 2021, at 11.00, Online Meeting BEC seminar
  Antonio Picozzi (Univ. Bourgogne)
  Rayleigh-Jeans condensation of classical light waves propagating in multimode fibers

- Monday, December 21st, 2020, at 11.00, Online Meeting BEC seminar
  Alberto Biella (Collège de France)
  Measurement-induced entanglement phase transitions and the Quantum Zeno Effect

- Monday, December 14th, 2020, at 11.00, Online Meeting BEC seminar
  David Clément (Institut d'Optique) and Salvatore Butera (University of Glasgow)
  Momentum-space correlations in a trapped weakly-interacting Bose gas

- Monday, December 7th, 2020, at 11.00, Online Meeting BEC seminar
  Kevin Geier (BEC Center and Univ. Heidelberg)
  Goldstone modes as a probe of supersolidity in spin-orbit-coupled Bose-Einstein condensates

- Friday, December 4th, 2020, at 17.00, Online Meeting PhD Defense
  Ivan Amelio (BEC Center)
  Coherent Dynamics of Low Dimensional Quantum Fluids of Light and Matter

- Monday, November 30th, 2020, at 11.00, Online Meeting BEC seminar
  Lauriane Chomaz (Univ. Innsbruck and Univ. Heidelberg)
  Dipolar many-body states in ultracold quantum Bose gases of highly magnetic atoms: from rotons to supersolids

- Tuesday, July 7th, 2020, at 10.00, Online Meeting BEC seminar
  Claudio Benzoni (Technical University Munich)
  Rayleigh edge waves in two-dimensional chiral crystals

- Tuesday, June 16th, 2020, at 10.00, Online Meeting BEC seminar
  Arturo Camacho Guardián (Aarhus University)
  Strongly interacting polaron-polaritons

- Tuesday, June 9, 2020, at 10.00, Online Meeting BEC seminar
  Victor Colussi (Eindhoven University of Technology)
  Bose-Einstein Condensation at the Limits of Interaction

- Tuesday, May 26, 2020, at 10.00, Online Meeting BEC Internal Report
  Santo Maria Roccuzzo (BEC Center)
  Quantized vortices in dipolar supersolid Bose-Einstein condensed gases

- Tuesday, May 6, 2020, at 10.00, Online Meeting BEC seminar
  Carlos Lobo (Univ. Southampton and BEC Center)
  Quasithermalisation of atoms in quadrupole traps

- Wednesday, April 15, 2020, at 10.00, Online Meeting BEC Internal Report
  Alberto Muñoz de las Heras (BEC Center)
  Anyonic molecules in atomic fractional quantum Hall liquids: a quantitative probe of fractional charge and anyonic statistics

- Wednesday, April 8, 2020, at 10.00, Online Meeting BEC Internal Report
  Carmelo Mordini (BEC Center)
  Equations of State of a weakly interacting 3D Bose gas

- Wednesday, February 12th 2020, at 10:30, A206, Povo 1, BEC Internal Report
  Jad Halimeh (BEC Center)
  Reliability and thermalization dynamics in lattice gauge theories

- Tuesday, February 4th 2020, at 10:30, A106, Povo 1, BEC Internal Report
  Ivan Amelio (BEC Center)
  Theory of the coherence of extended and topological lasers in low dimensions

- Monday, February 3rd 2020, at 10:30, A106, Povo 1, BEC Seminar
  Michele Modugno (Euskal Herriko Unibertsitatea)
  A new look at 'old' BEC topics: bosonic Josephson junctions and self-similar expansion

- Friday, January 31st 2020, at 11:00, A107, Povo 1, PhD Defense
  Miki Ota (BEC Center)
  Sound propagation in dilute Bose gases

- Monday, January 27th 2020, at 14:00, A203, Povo 1, PhD Defense
  Elia Macaluso (BEC Center)
  Probing Quasihole and Edge Excitations of Atomic and Photonic Fractional Quantum Hall Systems

- Wednesday, January 22nd 2020, at 14:00, A204, Povo 1, BEC Colloquium
Giovanni Modugno (LENS and Dipartimento di Fisica e Astronomia, Università di Firenze; CNR-INO, sezione di Pisa)
Exploring the supersolid phase of matter with a dipolar quantum gas

- Wednesday, January 15th 2020, at 14:30, Physics seminar room, 2nd floor, BEC Seminar
Gregory Astrakharchik (Universitat Politècnica de Catalunya)
Spontaneous formation of Kagomé lattice in two-dimensional Rydberg atoms

- Tuesday, January 14th 2020, at 10:30, A108, Povo 1, BEC Internal Report
Ricardo Costa de Almeida (BEC Center)
Multipartite entanglement certification in quantum many body systems using quench dynamics

- Wednesday, January 8th 2020, at 10:30, Physics seminar room, 2nd floor, BEC Seminar
Nicolas Pavloff (LPTMS, Université Paris-Saclay and CNRS)
Recent experimental and theoretical advances in analogue gravity

Q@TN Colloquia and Seminars (co-organized by the BEC Center)

- Friday, May21 st, 2021, at 14.00, Online Meeting Q@TN Lab Seminar
Silvano De Franceschi (Univ. Grenoble Alpes CEA, IRIG/PHELIQS, Grenoble, France)
Semiconductor technology for quantum computing

- Friday, April 9th, 2021, at 14.00, Online Meeting Q@TN Lab Seminar
Matteo Lostaglio (TU Delft)
Error mitigation and quantum assisted simulation in the error corrected regime

- Tuesday, March 9th, 2021, at 14.00, Online Meeting Q@TN Seminar
Yannick Dumeige (Université de Rennes 1 and Institut FOTON, CNRS)
Optical micro-resonators: application to laser micro sources, nonlinear optics and magnetometry

- Friday, March 5th, 2021, at 16.00, Online Meeting Q@TN Colloquium
Ivan Deutsch (Univ. New Mexico (USA))
Quantum Computing with Neutral Atoms

- Friday, February 26th, 2021, at 14.00, Online Meeting Q@TN Colloquium
Markus Oberthaler (Kirchhoff-Institut fuer Physik, Ruprecht-Karls-Universitaet Heidelberg, Germany)
Quantum technology and Environmental Physics

- Friday, February 19th, 2021, at 14.00, Online Meeting Q@TN Colloquium
Giacomo De Palma (MIT, USA)
Optimal mass transport: a new approach to quantum machine learning

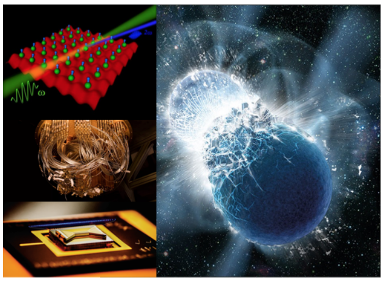
- Friday, January 15th, 2021, at 14.00, Online Meeting Q@TN Colloquium
  Marcos Rigol (Penn State, USA)
  Prethermalization and thermalization in isolated quantum systems

- Tuesday, December 15th, 2020, at 14.00, Online Meeting Q@TN Seminar
  Dr. Gianluca Aiello (Laboratoire de Physique des Solides, CNRS, Université Paris Saclay, Orsay, France)
  Quantum dynamics of a high impedance cavity coupled to a Josephson junction

- Friday, November 27th, 2020, at 14.00, Online Meeting Q@TN Colloquium
  Gianluca Rastelli (BEC Center)
  Electron-vibration and electron-photon interaction in quantum dots: towards a mesoscopic QED

- Thursday, February 13th 2020, at 14:30, B105, Povo 2 Q@TN Seminar
  Michael Hartmann (Erlangen University and Google Al Quantum, Germany)
  Quantum supremacy and noisy intermediate scale quantum computers

International meetings organized or co-organized by the BEC Center

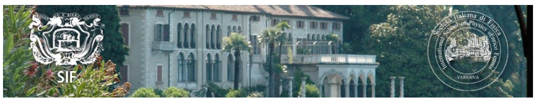


Quantum Simulation for Nuclear Physics
an online seminar series
A seminar series focused on the emerging area of quantum simulation for nuclear physics research. Theoretical and experimental progress, ideas, visions and plans will be discussed by experts at the cutting-edge of quantum information science, quantum many-body systems, quantum field theory and nuclear physics.
https://sites.google.com/uw.edu/seminars-qs4np/home

International events postponed due to the COVID pandemics

Interdisciplinary Workshop on Supersolidity
The workshop was first scheduled in 2020, but due to the COVID pandemics has been postponed to 2021 and will take place in Trento, Italy from Monday 20th to Wednesday 22nd September, 2021.
The workshop will explore in an interdisciplinary fashion various aspects of supersolidity, focusing on different mechanisms and experimental platforms, including dipolar and spin-orbit-coupled quantum gases, Rydberg atoms, light-induced dipoles, as well as solid Helium and nuclear systems. http://www.erbium.at/workshopTN/

Quantum Fluids of Light and Matter



This 208th Course of the Enrico Fermi School was scheduled in Varenna for July 2020. Because of the COVID emergency it was postponed first to July 2021, then to 2022. It is co-organized with two long-standing collaborators of the BEC Center, namely C. Ciuti and A. Bramati. It continues a series of leading events on the physics of quantum fluids of light and aims at giving students a interdisciplinary overview on this rapidly growing field of research.
https://www.sif.it/corsi/scuola$_fermi/mmxxi/$208

Tensor Networks: Quantum Physics, Geometry and Applications

This small interdisciplinary workshop, organized by CIRM-FBK and directed by BEC researchers in collaboration with the Mathematics department of UniTrento, was originally scheduled for July 2020 and postponed to July 2021 because of the COVID emergency.
The goal of the workshop is to develop the connections between the mathematics and physics communities working on tensor network. As a key novelty, it will be a hands-on event with a limited number of talks and several sessions of active work. During these sessions, participants will distribute themselves in small groups and will actively work on a specific cutting-edge research problem under the supervision of a world expert.
https://sites.google.com/unitn.it/tensor-networks-quantum-geo

Honors

On April 7, 2021, Philipp Hauke (University of Trento) was awarded a Google Research Scholar for the proposal *P*roGauge: Protecting Gauge Symmetry in Quantum Hardware.
https://ai.googleblog.com/2021/04/announcing-2021-research-scholar.html

On February 15, 2021, Philipp Hauke (University of Trento) was nominated for the IOP International Quantum Technology Young Scientist Award, "Highly Commended Nominee".
https://ioppublishing.org/news/iop-publishings-international-quantum-technology-award-winners-are-announced/

Lev Pitaevskii has been selected to receive the American Physical Society's 2021 Lars Onsager Prize, which recognizes outstanding work in atomic physics or surface physics.
The citation for the award reads: "For originating the Gross-Pitaevskii theory of non-uniform Bose-Einstein condensates and subsequent extensive contributions to the theory of quantum fluids, especially as applied to ultracold atomic gases."
https://www.aps.org/programs/honors/prizes/onsager.cfm

Philipp Hauke was awarded the Young Scientist Prize in Atomic, Molecular and Optical Physics of IUPAP, the International Union of Pure and Applied Physics ”For his outstanding contributions to the development of quantum technologies based on Atomic, Molecular and Optical systems, ranging from quantum annealing, over quantum metrology, to quantum simulations of strongly-correlated condensed-matter systems and lattice gauge theories.”
https://iupap.org/who-we-are/internal-organization/commissions/c15-atomic-molecular-and-optical-physics/c15-news/

Arko Roy as been awarded as Outstanding reviewer of the year 2020 for J. Phys. A.
https://publishingsupport.iopscience.iop.org/questions/journal-of-physics-a-mathematical-theoretical-2020-reviewer-awards/

Outreach

Public conferences

On October 27, 2020, Franco Dalfovo has been invited to hold the talk *Alcuni buoni motivi per fidarsi della scienza* at the Associazione Culturale Antonio Rosmini in Trento, in the framework of a series of seminars devoted to ”Come combattere le fake news. Educare alla razionalità e alla dimostrazione”.

Activities for schools and kids

Within the thematic seminars for high school students organized by the University of Trento, Franco Dalfovo held the seminar *1900-1925: Stories of atoms and scientists* at Liceo Lioy in Vicenza on February 11th, 2021 and Liceo Rosmini in Rovereto on May 5, 2021.