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

BEC

Scientific Report
July 2021 - June 2024

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

UNIVERSITÀ DI TRENTO
Dipartimento di Fisica

The Pitaevskii Center on Bose-Einstein Condensation is a joint initiative of

Contents

Overview

This is the final report on the research activities of the Center on Bose-Einstein Condensation (BEC Center) carried out from July 2021 to June 2024 within the Accordo di Programma PAT CNR-INO 2021-2024 funded by the Provincia Autonoma di Trento (PAT).

Since November 2022, the BEC Center in Trento has been renamed as Pitaevskii Center on Bose-Einstein Condensation in honour of Lev Pitaevskii, a celebrated member of our Center who passed away the morning of August 23, 2022.

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 aim of the agreement with PAT is to support both the experimental and the theoretical research on the physics of ultracold atoms and quantum gases and further reinforce the capacity of the BEC Center to work on cutting-edge research topics. The activities of the experimental laboratory have included the characterization of the formation dynamics of the Bose condensate when crossing the phase transition on a finite time scale, the investigation of spin excitations in superfluid mixtures, and the study of the ferromagnetic properties of a coherently coupled spin mixture. As usual, the experimental activities are developed in close connection with the theory group who provides continuous 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 scientists during the period 2019-21, namely, a UniTrento professor (Philipp Hauke) and three CNR researchers (Alessandro Zenesini, Gianluca Rastelli and Alberto Biella). Their strong involvement in the activities of the Center has significantly broadened our spectrum of scientific expertise: the reinforced manpower and the new competences on theoretical quantum science and technology, solid-state physics and superconductors, non-equilibrium quantum many-body physics, together with the collaborative spirit which has got back to the traditional pre-Covid-19 levels, have allowed to explore new directions of theoretical as well as experimental research. The main axes of research and their most remarkable achievements will be presented in detail in the following of this report.

In quantitative terms, since July 2021 to June 2024, the researchers of the BEC Center have published about 180 articles in peer reviewed journals, including 23 Physical Review Letters, 7 Nature Physics, 6 PRX Quantum, 5 Quantum, 2 Physical Review X, 2 Nature Review Physics, 1 Nature, 1 Science.

The activities of the BEC Center have involved 13 master students, 25 graduate students and 23 postdocs, of whom about 40% coming from abroad, namely from Belgium, Brasil, Canada, China, Colombia, Germany, Great Britain, India, Lebanon, Namibia, Poland, Serbia, Switzerland, and USA. In addition, 10 undergraduate and graduate students, coming from Belgium, Denmark, France, UK, Spain, and Mexico, have spent a few months in Trento for internships and stages.

In the period July 2021 - June 2024, the Pitaevskii BEC Center has organized and co-organized about 100 seminars and colloquia with international speakers, most of which in presence thanks to the relaxation of the Covid-19 restrictions. The BEC Center has also hosted or organized 10 international meetings, including two Varenna International Schools of Physics “Enrico Fermi”, the first one on Quantum Mixtures with Ultra-cold Atoms and the second one on Quantum Fluids of Light and Matter, and the celebration for the 20th anniversary of the BEC Center.

In this report, a detailed description of the achievements in the period July 2021 – June 2024 is provided.

Trento, July 30, 2024

Lev Petrovich Pitaevskii

Lev Petrovich Pitaevskii was a Russian-born physicist who had been a member of the Department of Physics of University of Trento since 1998. Lev came from the Russian school founded by Lev Landau around the middle of the last century, and was one of the most prominent theoretical physicists in the world in the field of statistical physics and the physics of matter.

He co-authored several books of the prestigious Landau-Lifshitz series and made a fundamental contribution to the development of Bose-Einstein condensation theory, which is now the subject of studies and experiments in hundreds of laboratories around the world. He was professor at the Faculty of Mathematical, Physical and Natural Sciences of the University of Trento from 1998 to 2008 and, after his retirement, collaborated with the Department of Physics and in particular with the BEC Center. On 6 July 2013, the University of Trento celebrated Lev Pitaevskii's 80th birthday with a ceremony attended by three Nobel Laureates and about a hundred researchers from all over the world.

Lev Pitaevskii received numerous awards during his lifetime including, among the most recent ones, the Enrico Fermi Prize in 2018, the Isaak Pomeranchuk Prize in 2018, the Senior BEC Prize in 2019 and the Lars Onsager Prize in 2021. For his contributions to physical sciences in general and the BEC Center in particular, the staff of the BEC Center has decided unanimously to rename the center in his honor.

Obituaries written to commemorate the memory of Lev Pitaevskii:
S. Stringari and M. Inguscio, Il Nuovo Saggiatore, **38**, 5-6 p.81 (2022)
M.A. Liberman, V.L. Pokrovsky, and S. Stringari, Physics Today, **76**, 3, 61 (2023)
A.F. Andreev, S.S. Gershtein, A.V. Gurevich, V.V. Dmitriev, N.M. Kreines, M.A. Liberman, B.E. Meierovich, V.L. Pokrovsky, V.I. Ritus, M.P. Ryutova, A.A. Starobinskii, M.V. Feigel'man, I.A. Fomin and A.V. Chaplik, Physics-Uspekhi **66** (2) 213 (2023)

Staff, researchers, scientific board

Principal investigators

Alberto Biella (CNR)
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)
Alessio Recati (CNR)
Sandro Stringari (UniTrento)
Alessandro Zenesini (CNR)

Postdocs

Soumik Bandyopadhyay
Cosetta Baroni
Carlos L. Benavides
Anna Berti
Victor Colussi
Riccardo Cominotti
Ricardo Costa de Almeida
Daniele De Bernardis
Arturo Farolfi
Luca Giacomelli
Kevin T. Geier
Jad C. Halimeh
Christian H. Johansen
Haifeng Lang
Andrea Legramandi
Jeffrey A. Maki
Stephanie Matern
Julius Mildenberger
Carmelo Mordini

Alberto Nardin
Luca Parisi
Santo Maria Roccuzzo
Arko Roy
Sudipto Singha Roy
Gabriele Spada
Emanuele Tirrito
Matteo Michele Wauters

PhD Students and Young Researchers

Diego Andreoni
Edoardo Ballini
Anna Berti
Alberto Bottarelli
Sebastiano Bresolin
Chiara Capecci
Leon Carl
Riccardo Cominotti
Daniele Contessi
Ricardo Costa de Almeida
Kevin Geier
Nick Keepfer
Haifeng Lang
Julius Mildenberger
Alberto Muñoz de las Heras
Alberto Nardin
Sebastian Nagies
Pietro Oreglia
Veronica Panizza
Nicola Paracone
David Pascual Solis
Francesco Piccioli
Chiara Rogora
Gopal Chandra Santra
Matteo Sighinolfi
Marija Sindik
Philipp Uhrich

Alex Windey
Louise Wolswijk
Tomasz Zawislak

Master Students

Simon Kochsiek (cotutela UniTN e Università di Tuebingen)
Francesco Musso (now internship at Pasqal, Paris)
Diego Andreoni (now PhD in Trento)
Zeno Bacciconi (co-supervision with M. Capone in SISSA; now PhD at SISSA)
Martina Scrinzi (now working at LEOS, Rovereto)
Greta Villa (co-supervision with Tomoki Ozawa, Tohoku Univ., Japan; now PhD in Konstanz)
Veronica Panizza (now PhD in Trento)
Alessio Paviglianiti (Trento-SISSA program, co-supervision with Erik Tonni, SISSA, now PhD at SISSA)
Chiara Rogora (now PhD in Trento)
Claudio Iacovelli (co-supervision with M. Lewenstein and V. Kasper, ICFO, now PhD at ICFO)
Antonio Anna Mele (Trento-SISSA program, co-supervision with Mario Collura, SISSA, now PHD at FU Berlin)
Ludwig Schmid (co-supervision with Davide Pastorello (DISI), now PhD at TU Munich)
Janabi Hazarika (co-supervision with Prof. Hartmut Roskos, Goethe University, Germany)
Jacopo Coccomello (co-supervision with Prof. Faccioli, Physics Department, Trento)
Alessandro Gioffredi (co-supervision with Prof. Faccioli, Physics Department, Trento)

International student internships and stages

Jason Barckicke (ENS, Paris), 28 February - 28 July 2022
Mattheus Burkhard (ENS Cachan, France) (Master student in stage): 20 April -10 July 2022
Esben Rohan Christensen (Univ. Aarhus, Danmark) (PhD Stage): September 2021 - February 2022
Bosco d'Aligny (École Polytechnique, Paris) (Master student in stage): March - July 2024
Clement Dulin (École Normale Supérieure, Paris, France): February - July 2022
Lennart Fernandes (Univ. Antwerp, Belgio) (Ph.D stage): February- July 2022
Mikel Garcia-de-Andoin (University of the Basque Country UPV/EHU, Spain) (PhD Stage): January - February 2023
Chris Oliver (Univ. Birmingham, UK) (PhD Stage): September - November 2022
Gerardo Ortiz-Ugalde (CINVESTAV Querétaro, Mexico): September - November 2023

Administration

Beatrice Ricci (CNR)
Monica Cosi (UniTrento, until July 2022)
Sara Rebecchi (UniTrento, since April 2023)

Scientific board

Jean Dalibard (Collège de France and Kaster Brossel Laboratory, ENS, Paris)
Anna Minguzzi (LPMMC, CNRS, Grenoble)
William D. Phillips (UMD Physics - University of Maryland)

Visiting scientists and scientific collaborations

Long visits

Naga Dileep Varikuti (Indian Institute of Technology Madras), 25/02/2024 - 02/03/2024
Michele Burrello (Niels Bohr Institute, University of Copenhagen), 25/02/2024 - 02/03/2024
Tomasz Wasak (Nicolaus Copernicus University in Toruń, Poland), 20/02/2024 - 27/02/2024
Berta Ros Blanco (UPC Barcelona, Spain), 05/02/2024 - 15/07/2024
Shunji Tsuchiya (Chuo University, Japan), 05/02/2024 - 09/02/2024
Luis Colmenarez (RTWH Aachen University, Germany), 20/11/2023 - 24/11/2023
Sebastiano Peotta (Aalto University, Finland), 01/08/2023 - 31/07/2024
Matteo Rizzi (Univ. Cologne, Germany) Feb. 06th-17th 2023; July 18th-25th Jul 2023.
Alonso Viladomat, Technische Universitaet Muenchen (TUM) 25 June - 1 July 2023
Arko Roy IIT Mandi, India June 9 - July 9 2023
Tomasz Wasak (Univ. Torun, Poland) Mar. 26 - Apr. 03 2023
Paolo Ghiggini (CNRS Nantes, France), April 26 - May 27, 2022
Grigori Astrakharchik (Universitat Politecnica de Catalunya, Barcelona) Aug. 25 - Sept. 7 2022

Short visits

Rocío Sáez-Blázquez (TU Wien), 21/05/2024 - 25/05/2024
Ivan Amelio (Université Libre de Bruxelles, Belgium), 28/05/2024 - 31/05/2024
Carlo Di Castro (La Sapienza, Roma), 20/05/2024 - 22/05/2024
Roberto Balbinot (Università di Bologna) , 2024-04-04
Nicolas Pavloff (IPTMS, Université Paris-Saclay), 2024-04-04
Greta Villa (Universität Konstanz, Germany), 2024-02-28
Ragheed Al Hyder (University of Vienna), 28/02/2024 - 01/03/2024

Nicola Grani (LENS, University of Florence), 31/01/2024 - 01/02/2024
Diego Hernandez-Rajkov (LENS, University of Florence), 31/01/2024 - 01/02/2024
Giulia Del Pace (LENS, University of Florence), 31/01/2024 - 01/02/2024
Giacomo Roati (LENS, INO-CNR Florence), 31/01/2024 - 02/02/2024
Raffaele Borrelli (University of Torino), 24/01/2024 - 26/01/2024
Pietro Brighi (University of Vienna, Austria), 10/01/2024 - 12/01/2024
Francesco Riboli (INO-CNR, Firenze), 19/12/2023 - 20/12/2023
Tomoki Ozawa (Tohoku University, Japan), 18/12/2023 - 21/12/2023
Esben Rohan Christenssen (Aarhus University, Denmark), 27/11/2023 - 29/11/2023
Paolo Stornati (ICFO Barcelona, Spain), 20/11/2023 - 21/11/2023
Sebastian Schmitt (Honda Research Institute, Germany), 24/10/2023 - 27/10/2023
Kevin Mato (Technical Univ. of Munich, Germany), 24/10/2023 - 25/10/2023
Linus Ekstrøm (Honda Research Institute, Germany), 23/10/2023 - 27/10/2023
Greta Villa (Universität Konstanz, Germany), 16/10/2023 - 20/10/2023
Cosetta Baroni (IBK University, Austria), 11/10/2023 - 13/10/2023
Stephanie Matern (Lund University, Sweden), 05/10/2023 - 06/10/2023
Christian Johansen (Torun, Poland - Dresden, Germany) , 02/10/2023 - 06/10/2023
Grigori Astrakharchik (UPC Barcelona, Spain), 14/08/2023 - 01/09/2023
Chiara Capecci Univerisità dell'Aquila July 19-20 2023
Davide Nigro Università di Pavia July 17-21 2023
Michele Governale (Victoria Wellington University, New Zealad) June 12-16 2023
Mark Oliver Goerbig LPS - Université Paris Saclay July 12-13 2023
Michail Skoteiniotis (Universidad de Granada) Jun. 25th - July 1th 2023
Giuseppe Clemente (DESY Berlin) Jun. 24-25th 2023
Lorenzo Rosso LPTMS - Université Paris Saclay 23-25 May 2023
Alvise Bastianello (TU Munich) May. 18th-19th, 2023
Jacopo Catani (Lens Florence, Italy) Apr. 20th 2023
Lennart Fernandes University of Antwerp 11-14 April 2023
Philipp Heinen (Kirkhhoff Inst. Hedelberg University, Germany) Feb. 28-Mar. 2 2023
Chris Oliver (Univ. Birmingham, UK) 13-17 Feb. 2023
Fabrizio Minganti (EPFL, Losanna, Svizzera) 13-17 Feb. 2023
Luca Gravina (EPFL, Losanna, Svizzera) 13-17 Feb. 2023
Nicolas Roch Institut Néel, CNRS, Grenoble (France) Jan. 25 2023
Paolo Stornati (ICFO, Barcelona) Jan. 10-13, 2023
Pavel Popov (ICFO, Barcelona) Jan. 10-13, 2023
Emanuele Tirrito (SISSA - ICTP, Trieste) Jan. 10-13, 2023
Pasquale Scarlino (EPFL, Lausanne), December 2 - 6, 2022

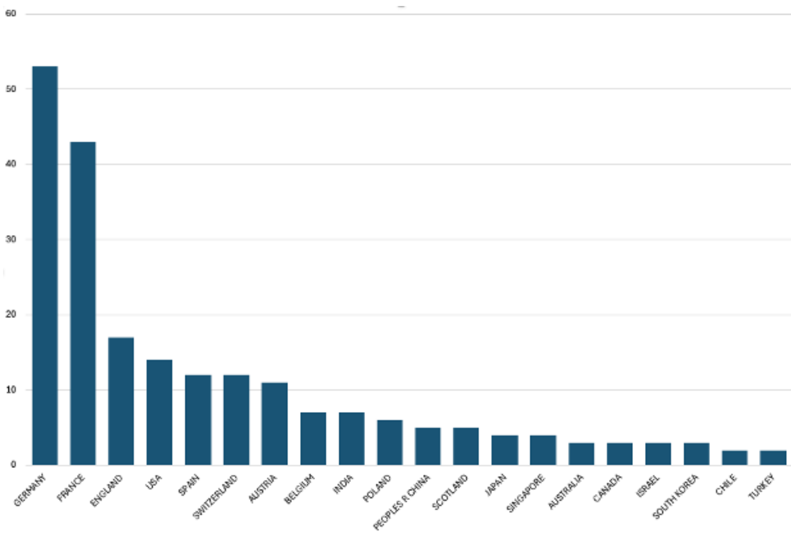
Michele Governale (Victoria Univ. Wellington, New Zealand), November 28 - 29, 2022
Stefan Lannig (Kirchhoff-Institut für Physik, Univ. of Heidelberg), September 22 - 23, 2022
Robert Ott (Ruprecht Karls Universität Heidelberg), August 8 - 12, 2022
Michiel Wouters (Univ. Antwerp, Belgo), March 14 - 18, 2022
Carlos Ballestro (Univ. Innsbruck), May 11 2022
Salvatore G. Butera (Univ. Glasgow), May 24 - June 1, 2022
Andrea Richaud (SISSA, Trieste), March 14 - 16, 2022
Elettra Neri (ICFO, Barcelona), November 18 - 19, 2021

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 (now at University Milano-Bicocca), Leonardo Ricci, Francesco Pederiva and Massimiliano Rinaldi. In the last couple of years, an intense collaboration was established with experimental colleagues at FBK and at IFN-CNR on different topics related to superconducting quantum devices and on nanomechanical systems. Finally, the interdisciplinary scientific exchanges with other Departments of the University of Trento, ECT*, and FBK are being boosted by the Q@TN initiative with a number of 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 in Innsbruck, with several groups in different institutions in the Paris area such as ENS, Université Paris Sorbonne, Collège de France, Université Paris Saclay, Université Paris Cité, Laboratoire C2N; in Munich at LMU, TUM and MPI; in Barcelona such as UPC and ICFO; and with the University of Antwerp. More recent collaborations are in place with Konstanz, Dresden, Tohoku (Japan), Newcastle (UK), Birmingham, Heidelberg, EPFL Lausanne, Hefei (China), and Toruń (Poland).

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 165 peer-reviewed published articles in the period 2021-2024, 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.

38. CENTRE NATIONAL DE LA RECHERCHE SCIENTIFIQUE CNRS
26. UNIVERSITE PARIS CITE
23. UNIVERSITE PARIS SACLAY
18. RUPRECHT KARLS UNIVERSITY HEIDELBERG
17. UNIVERSITE PSL
16. FONDAZIONE BRUNO KESSLER
15. COLLEGE DE FRANCE, ECOLE NORMALE SUPERIEURE ENS
14. SORBONNE UNIVERSITE
13. INTERNATIONAL SCHOOL FOR ADVANCED STUDIES SISSA, UNIVERSITY OF MILANO BICOCCA
12. UNIVERSITY OF SALERNO
11. ISTITUTO NAZIONALE DI RICERCA METROLOGICA INRIM, UNIVERSITY OF SALENTO, UNIVERSITY OF SANNIO
10. ECOLE POLYTECHNIQUE, INSTITUT POLYTECHNIQUE DE PARIS, SWISS FEDERAL INSTITUTES OF TECHNOLOGY DOMAIN,
9. ISTITUTO DI FOTONICA E NANOTECNOLOGIE IFN CNR
8. ETH ZURICH, ISTITUTO OFFICINA DEI MATERIALI IOM CNR, POLYTECHNIC UNIVERSITY OF TURIN
7. MUNICH CTR QUANTUM SCI TECHNOL MCQST, UNIVERSITAT POLITECNICA DE CATALUNYA, UNIVERSITY OF INNSBRUCK, UNIVERSITY OF MUNICH
6. AUSTRIAN ACADEMY OF SCIENCES, MAX PLANCK SOCIETY, NEWCASTLE UNIVERSITY UK, UNIVERSITY OF COLOGNE
5. CNRS INSTITUTE OF PHYSICS INP, ECOLE NORMALE SUPERIEURE DE LYON, GHENT UNIVERSITY, HARVARD UNIVERSITY, HELMHOLTZ ASSOCIATION, UNIVERSITY OF CAMERINO, BARCELONA INSTITUTE OF SCIENCE TECHNOLOGY
4. HOMI BHABHA NATIONAL INSTITUTE, INSTITUT DE CIENCIES FOTONIQUES ICFO, ISTITUTO DI NANOTECNOLOGIA NANOTEC CNR, LEIBNIZ UNIVERSITY HANNOVER, RESEARCH CENTER JULICH, SAHA INSTITUTE OF NUCLEAR PHYSICS, TECHNICAL UNIVERSITY OF MUNICH, UNIVERSITY OF BIRMINGHAM, UNIVERSITY OF KONSTANZ
3. CNR SPIN SALERNO SECT, COMMUNAUTE UNIVERSITE GRENOBLE ALPES, ECOLE POLYTECHNIQUE FEDERALE DE LAUSANNE, ICREA, INSTITUTE FOR BASIC SCIENCE KOREA IBS, KOREA ADVANCED INSTITUTE OF SCIENCE TECHNOLOGY KAIST, NANYANG TECHNOLOGICAL UNIVERSITY, NATIONAL UNIVERSITY OF SINGAPORE, POLISH ACADEMY OF SCIENCES, TOHOKU UNIVERSITY, UNIVERSITE COTE D AZUR, UNIVERSITE GRENOBLE ALPES UGA, UNIVERSITY OF GLASGOW, UNIVERSITY OF

MARYLAND COLLEGE PARK, UNIVERSITY OF QUEENSLAND, UNIVERSITY OF ROSTOCK, UNIVERSITY OF SOUTHAMPTON, UNIVERSITY SYSTEM OF MARYLAND

2. BASQUE FOUNDATION FOR SCIENCE, BICOCCA QUANTUM TECHNOL BIQUTE CTR, CAS CENTER FOR EXCELLENCE IN QUANTUM INFORMATION QUANTUM PHYSICS, CHINESE ACADEMY OF SCIENCES, CITY COLLEGE OF NEW YORK CUNY, CITY UNIVERSITY OF NEW YORK CUNY SYSTEM, CNRS UCA SU NUS NTU INT JOINT RES UNIT, DORTMUND UNIVERSITY OF TECHNOLOGY, FRIEDRICH SCHILLER UNIVERSITY OF JENA, HEBREW UNIVERSITY OF JERUSALEM, IMPERIAL COLLEGE LONDON, INDIAN INSTITUTE OF TECHNOLOGY IIT MANDI, INDIAN INSTITUTE OF TECHNOLOGY SYSTEM IIT SYSTEM, INSTITUT NATIONAL POLYTECHNIQUE DE GRENOBLE, INSTITUT UNIVERSITAIRE DE FRANCE, INSTITUTE OF PHYSICAL CHEMISTRY OF THE POLISH ACADEMY OF SCIENCES, ISTITUTO NANOSCIENZE NANO CNR , MIMAR SINAN GUZEL SANATLAR UNIVERSITY, NICOLAUS COPERNICUS UNIVERSITY, PURDUE UNIVERSITY, ROMA TRE UNIVERSITY, SMITHSONIAN ASTROPHYSICAL OBSERVATORY, SOUTHERN UNIVERSITY OF SCIENCE TECHNOLOGY, TECHNISCHE UNIVERSITAT WIEN, UNIVERSITE CLAUDE BERNARD LYON, UNIVERSITE DE BOURGOGNE, UNIVERSITE DE LILLE, UNIVERSITE DE MONTREAL, UNIVERSITE DE TECHNOLOGIE DE BELFORT MONTBELIARD UTBM, UNIVERSITY COLLEGE LONDON, UNIVERSITY OF AUGSBURG, UNIVERSITY OF GENEVA, UNIVERSITY OF LONDON, UNIVERSITY OF MASSACHUSETTS SYSTEM, UNIVERSITY OF PALERMO, UNIVERSITY OF PISA, UNIVERSITY OF REGENSBURG, UNIVERSITY OF SCIENCE TECHNOLOGY OF CHINA CAS, UNIVERSITY OF STRATHCLYDE, UNIVERSITY OF WURZBURG

Research activity: Experiments

During the funding period, the experimental activities of the BEC Center continued on the two experimental apparatus available in Trento and in close and profitable collaboration with the theoreticians from the BEC Center.

In the BEC1 lab, historically the first apparatus where Bose-Einstein condenstion was first produced in Trento, we pursued the investigations on the process of condensation and the many aspects that characterise the crossing of the phase transition and the emergence of the condensate. Thanks to the experience accumulated in the recent years on the characterization of defects in superfluids and on the measurement of temperature and of the equation of state, we turned our attention to the understanding of how the condensate emerges from an ultracold but still thermal atomic gas as a function of the cooling rate across the transition crossing. Many theoretical and numerical works in the last decade have addressed the topic, discovering universal connections with statistical physics and cosmology. However, the comparison with these works is complicated by their use of evaporation protocols which differ considerably from the ones generally used in experiments with ultracold atomic gases. Our article published in the Physical Review A describes a systematic experimental study on the formation dynamics of the Bose-Einstein condensate both in terms of the growth of population of the superfluid fraction, and of the relaxation of the defects which are typically generated in the turbulent regime which is expected to dominate at the onset of condensation. By varying the evaporation sequences and changing the size of the atomic sample we could highlight the relations of the cooling rate to both the observed time scales for the relaxation of defects, and the condensation latency time, hence allowing a clear and more direct comparison between existing theoretical models and experiments.

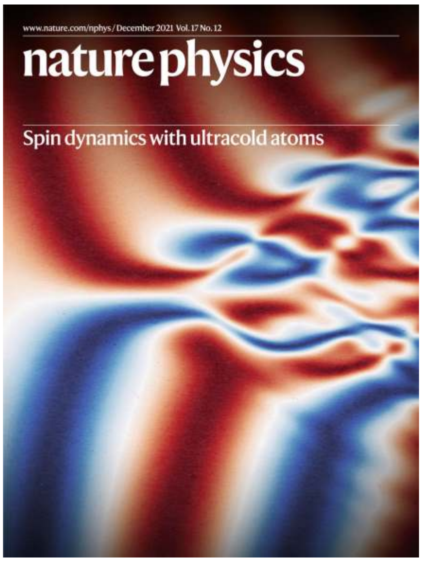


Figure 1: Nature Physics cover of the issue December 2021 builds on Trento's data about the breaking of magnetic interfaces under the action of a coherent coupling and inhomogeinity.

The second apparatus features unique conditions of magnetic field stability thanks to the integration in the experimental setup of a magnetic field shield, and it allows to perform experiments with unprecedented conditions of simultaneous long coherence time and relatively strong interactions at the manybody level. During the present funding period we unfold for the first time the full capacity of the system by investigating spinor phenomena in the novel experimental setting. The first results where already submitted at the end of the previous funding period and they focused on magnetic dynamics induced by coherent coupling an atomic sodium hyperfine mixture which features miscibility in the absence of coherent coupling. As explained in the following pages, this work was pushed forward in the present funding period with further investigation on this line. The novelty and the importance of these results were recognised with several publications on prestigious journals such as Nature Physics and Physical Review X.

By maintaining the same combination of miscible hyperfine states, we pursued the experimental investigation by measuring the dispersion relation of the total and relative population in the two states. With this set of measurements we provided a novel tool to the characterisation of the dispersion relation in spin mixtures, both with and without the action of coherent coupling between the constituents of the mixture. In the presence of coherent coupling, in particular, we verified that the excitation spectrum acquires a gap which remarkably introduces an effective massive character to many-body excitations. The results, which were published in Physical Review Letters, pave the way to the use of coherently coupled atomic gases as analog models of gravitational phenomena.

In the second part of the reporting period the measurements were extended to a different choice of hyperfine states featuring an immiscible character. Here, the action of coherent coupling in the mixture develops static and dynamic properties in close relation to ferromagnetism which, for the first time, is obtained simultaneously to the presence of superfluidity. We characterized the quantum phase transition fro para- to ferromagnet with the possibility to tune several experimental parameters and used such a tunability to prepare an extended system in a metastable state and study its relaxation to the ground state through the formation of spin bubbles, in connection to the false vacuum decay of quantum field theory.

Research activity: 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.

Cold atoms

Collaborations with the experimental team

An important part of the theory activity has consisted in a direct collaboration with the experimental group of the BEC Center. The cross-fertilisation between theory and experiment allowed to envision, realise and analyse new protocols for the characterisation of both ground state, excitations and out-of equilibrium properties of coherently coupled Bose-Einstein condensates. In particular we explored Faraday waves to extract the spectra of the system, the possibility of having a non-homogeneous internal Josephson junction as well as the role of the critical slowing down dynamics at the bifurcation point in the breaking of the local Josephson dynamics. The results have been published in Physical Review Letters, Physical Review A and Nature Physics, respectively. In the last part of the funded period we concluded the theoretical analysis of the temperature dependence of the ferromagnetic transition in coherently coupled Bose gases, with first evidence for a new scaling law. Moreover we also submitted a paper concerning the magnetic solitons in the ferromagnetic phase of the system, showing that our system can simulate Landau-Lifhsitz soliton perfectly and that solitons are well defined beyond the Landau-Lifshtz regime, and providing an explanation of the well known, but never explained, oscillating behaviour of solitons under the action of a constant force.

Finally we exploited the theory-experiment synergy to carry out an ambitious project aiming at the experimental measurement of the so-called false vacuum decay rate. The theoretical activity along this line has started in collaboration with quantum field theory specialists like Ian Moss in Newcastle (UK) and is now extending its scope to a variety of different configurations, from spinor atomic gases to spin chains: in particular, we have started investigating how the false vacuum decay is modified in the presence of a continuous measurement process acting on the system.

Bose gases and mixtures at finite temperature

The Stochastic Gross-Pitaevskii Equation (SGPE) is a reliable tool to predict relevant properties of dilute Bose gases at finite temperature. In collaboration with a group of Newcastle University, we have explored the 2D- 3D dimensional crossover for a single component Bose gas confined in a planar rectangular box with harmonic confinement in the orthogonal direction and we have characterized the transition from a 2D behavior, with the BKT phase transition, to a 3D behavior with the BEC phase transition. We have also used SGPE to study two-component mixtures in 2D. In particular, we have investigated the role of thermal fluctuations in the miscible-immiscible phase transition and the spin dynamics in a binary condensate, comparing the results with the predictions of a mean-field Hartree-Fock theory. When the mixture is subject to coherent coupling the system exhibits a paramagnetic-ferromagnetic quantum phase transition and we have found an interesting power-law scaling of the key quantities describing the critical behavior across the transition.

Quantum mixtures using Monte Carlo methods

During this year the subunit of the CNR-INO group composed by Stefano Giorgini (staff member) and Gabriele Spada (postdoc) has been working on the study of quantum mixtures of Bose gases using path-integral Monte Carlo (PIMC) simulations. First, a very efficient code has been developed which is fully compatible with periodic boundary conditions and allows for precise simulations of systems in the thermodynamic limit reducing significantly the impact of finite-size effects (G. Spada, S. Pilati and S. Giorgini, Condensed Matter 7, 30 (2022)). Then we applied this tool to investigate in detail the thermodynamic properties of a single-component Bose gas and in particular the effects of interaction on the temperature dependence of pressure and compressibility (G. Spada, S. Pilati and S. Giorgini, Phys. Rev. A 105, 013325 (2022)). Once the capabilities of the new simulation tool have been established, we addressed the topic of repulsively interacting Bose mixtures close to the threshold of phase separation, and in particular the possibility of a ferromagnetic transition occurring at finite temperature. To investigate this we developed a new way of calculating the chemical potentials in the mixture and, for the first time in PIMC simulations, the global free energy whose minima correspond to the equilibrium states (G. Spada, L. Parisi, G. Pascual, N.G. Parker, T.P. Billam, S. Pilati and S. Giorgini, SciPost Phys. **15**, 171 (2023).

Furthermore, we investigated the local structure of repulsive Bose mixtures finding two remarkably different behaviors as a function of temperature. For phase-separated states at $T = 0$, thermal effects induce a diffusion process which reduces the local population imbalance whereas, while for miscible states at $T = 0$, a maximum in the local population imbalance appears at a certain temperature, below the critical one (G. Pascual, G. Spada, S. Pilati, S. Giorgini and J. Boronat, Phys. Rev. Res. **5**, L032041 (2023)).

We also investigated attractive Bose mixtures in the regime where at zero temperature quantum droplets have been observed. These are produced by a combination of mean-field attractive and beyond mean-field repulsive contributions to the energy functional. At finite temperature we calculate the liquid-vapour coexistence line and we locate the critical point in the phase diagram. We also discuss possible experimental signatures of the first-order phase transition (G. Spada, S. Pilati and S. Giorgini, Phys. Rev. Lett. **131**, 173404 (2023)).

Equilibrium and dynamics of non uniform BECs at zero temperature

In collaboration with the team of Jean Dalibard at the Collège de France we have investigated the cross-over from Townes solitons to droplets in a 2D Bose mixture, which has been recently the object of experimental work at the Collège de France. We have in particular studied how the equilibrium state of the system critically depends on the miscibility criterion between the two components and exploited the critical dependence of the atom number of atoms of the minority component immersed in an infinite bath formed by the majority component. In collaboration with the same team we have also explored the behavior of the superfluid density of periodically modulated Bose-Einstein condensates, comparing the Leggett's bound and the exact solution of the Gross-Pitaevskii equation, based on the phase twist method, with the experimental results based on the integral of the in-situ density profile and on the propagation of sound.

Supersolidity of Bose-Einstein condensed atomic gases

In the last five 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. Such a state – which breaks simultaneously and independently the $U(1)$ and the translational symmetry – resembles the long sought supersolid state. While the first experiments produced very small samples with only 2-to-5 droplets in a row, experimentalists have been finally able to obtain two-dimensional configurations, with more droplets. The Trento team on dipolar gases – after the first relevant contributions on vortices and moment of inertia – has kept working on characterising the supersolid phase of two dimensional dipolar supersolids.

In the period of the report the team developed a new protocol for vortex generation and detection in such a system in collaboration with Luis Santos. Moreover dipolar gases in box potentials have been thoroughly analysed, leading to the discovery of novel density distributions, due to an accumulation of atoms near the walls, well separated from the bulk. As a byproduct, with respect to contact interacting gases, the box potentials is not to be the proper choice for the study of bulk properties of dipolar gases in the Lee-Huang-Yang regime. More recently the Trento team has started studying the details of the hydrodynamic description of the supersolid phase and possible ways to extract experimentally its parameters. The quality of the research of the Trento team has also been recognized by the request for a review by Nature publishing (Recati and Stringari, Nature Reviews Physics 5, 735 (2023)). 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, through the identification of a novel Goldstone mode associated with the spontaneous breaking of translational invariance and taking the characteristic form of a spin dipole mode in the presence of harmonic trapping. We have also explicitly identified the crystal nature of this mode, which is characterized by a typical oscillation of the relative distance between the stripes forming the supersolid. The understanding of the nature of the supersolid phase of these spin-orbit coupled configurations has been also investigated by carrying out a rigorous perturbation approach in infinite matter as a function of the Raman coupling strength, responsible for the appearance of the superstripes.

Quantum Gutzwiller approach

We have generalized the Quantum Gutzwiller approach introduced previously in [Phys. Rev. Research 2, 033276 (2020)] to investigate the effects of quantum fluctuations in the two-component Bose-Hubbard model and to study the physics of a mobile impurity confined in a two-dimensional lattice moving within a Bose-Hubbard bath at zero temperature.

We studied the two-component Bose-Hubbard model analysing the mean-field ground-state phase diagram and the spectrum of the elementary excitations, with particular attention on their different behaviours at the quantum phase transitions. Within the quantum critical regimes, we addressed both the superfluid transport properties and the linear response dynamics to density and spin probes of direct experimental relevance. Interestingly, we found that quantum fluctuations have a dramatic effect on the drag between the superfluid species of the system, particularly in the vicinity of the paired and antipaired phases which are absent in the usual one-component Bose-Hubbard model. We also provided results for the few-body correlations in all the regions of the phase diagram; in the quantum corrections to the one-body coherence and density/spin fluctuations, we highlighted the role of the collective modes of the system,

To describe the properties of the polaronic quasiparticle created by the dressing of the impurity by quantum fluctuations of the bath, we used the quantum Gutzwiller formalism to develop a beyond-Fröhlich model of the bath-impurity interaction. We have shown that the polaron properties are highly sensitive to the different universality classes of the quantum phase transition between the superfluid and Mott insulating phases, providing an unambiguous probe of correlations and collective modes in a quantum critical many-body environment.

Two-body losses in cold atomic gases

Despite the tremendous technological progresses in the isolation of quantum systems, a finite coupling with the surrounding environment is unavoidable and certainly play a crucial role in implementation of quantum technologies as well as in the dynamics of quantum simulators based on AMO systems. Losses are not only detrimental for the build up and preservation of quantum coherence but certain classes of dissipative processes can play a role in stabilizing correlated quantum states despite the presence of a noisy environment. We investigate the effect of two-body losses (typically induced by photoassociation processes) on cold atomic (bosonic and fermionic) gases in one dimension. In this class of system the dynamics of the system density matrix is faithfully described by the a markovian Lindblad master equation which accounts for both the unitary (particle hopping and coherent density-density interactions) dynamics and the effect of two-body losses (which are intrinsically incoherent and decrease the purity of the system). To this aim we developed theoretical tools (extensions of the time-dependent generalized Gibbs ensamble) and numerical methods (based on tensor networks techniques and

Monte Carlo wavefunction) to study the many-body dynamics ruled by the master equation. Our studies shows how the interplay between coherent and incoherent dynamics lead to peculiar features in the dynamics (showing signatures of the quantum Zeno effect in the large dissipation regime) as well as in the steady state. In particular when fermionic particles are considered, we show that dark subspaces composed by generalized Dicke states are stabilized in the long time limit.

Solid state and optical systems

Quantum Fluids of Light

Our theoretical activity on quantum fluids of light has been focused on the study of the collective modes of non-equilibrium fluids of light and on their excitation by quantum fluctuations.

On one hand, we have generalized the Gutzwiller approach to the driven-dissipative context to explore the collective excitations of both superfluid and insulating states of a strongly interacting fluid of light under a non-Markovian pumping.

On the other hand, in the wake of our previous studies of the coherence of topological laser operation, we have made use of the theory of weakly interacting quantum gases concepts to develop a general picture of the ultimate limits to the linewidth of a lasing device and we have connected this phenomenology to celebrated models of non-equilibrium statistical mechanics, such as the Kardar-Parisi-Zhang model of interface growth. On the experimental side, we have provided theoretical support to the experimental groups at LKB in Paris (A. Bramati and Q. Glorieux) and at C2N in Palaiseau (J. Bloch) in their measurements of the dispersion of the collective excitations of quantum fluids of light and of the statistical fluctuations of a one-dimensional quasi-condensate.

In parallel to the research activity, we have continued the BEC Center tradition of writing long review articles, by summarizing our point of view on non-equilibrium Bose-Einstein condensation in photonic systems for the prestigious journal Nature Reviews in Physics.

Topological photonics

We have investigated novel configurations to explore topological effects in photonics and realize specific topological models of interest for different applications in fundamental and/or applied science. Chiral quantum optics effects have been theoretically investigated in a configuration with crossed synthetic magnetic and electric fields. A novel configuration based on an inhomogeneous array of waveguides has been theoretically proposed to realize a quantum Hall coupled wire model in a mixed spatial-j/temporal-t plane, with exciting perspectives towards strongly correlated fluids of light.

In parallel to this theoretical investigations, collaborative efforts with experimental groups have been pursued. On one hand, we have collaborated with the group of Alexander Szameit in Rostock to a preliminary study of new configurations to obtain synthetic gauge fields and synthetic dimensions in temporally modulated arrays of laser-written waveguides. Within this same collaboration, a joint theoretical-experimental effort has explored a new class of interface states that may be of interest as an inter-connection between topological edge states. On the other hand, we have knotted an experimental collaboration with the Université de Montréal in Canada to use fiber-loop devices to realize different models of interest and, then, explicitly measure their topological properties

Fractional Quantum Hall fluids

With an eye to both photonic and atomic realizations of fractional quantum Hall fluids, we have theoretically studied the linear and nonlinear dynamics of the edge modes of a spatially confined quantum Hall cloud. Stimulated by the rich phenomenology found for the Integer quantum Hall case, we have set up a new numerical method that is able to describe strongly interacting fluids. This allowed us to successfully attack the fractional case and identify the first corrections to the traditional chiral Luttinger liquid theory of the edge dynamics. These can be summarized in group velocity dispersion and nonlinear terms in a Korteweg-de Vries form. Based on the physical insight offered by these numerical results, we then built a fully quantum theory that turns out to quantitatively capture the physics of the system. In the last period of the project, we have made use of fermionization techniques to shine additional light on this complex dynamics and we have started extending the theory to lattice configurations.

Circuit QED with quantum dots

Hybrid quantum devices combine different physical components with complementary functionalities. In this domain, our research concerns quantum electron transport in nanoscale conductors coupled to microwave photon cavities. Specifically, quantum dots can now be coupled to microwave photon cavities, providing a novel family of coherent quantum devices that combine electronic with photonic degrees of freedom on-chip. Our activity contributes to this new field of solid-state quantum electrodynamics (QED). In the work Physical Review B 105 L241407 (2022), we suggest a realistic setup to generate entanglement between two spatially separated microwave cavities using quantum delocalized electrons that flow through a parallel double quantum dot, connected between two electrodes. In another work (to be submitted soon) we analyze a proposal to transfer entanglement from electrons in a superconducting nanocontact to microwave photons within a waveguide circuit QED architecture. Our studies demonstrate that such hybrid devices based on semiconducting quantum circuits with integrated microwave photonics are promising for implementing quantum transducers, in which single electrons control photonic quantum states.

Nanomechanical systems: nonlinear dynamics and nonequilibrium fluctuations

Emblematic examples of nanoscale devices include low-dimensional mechanical resonators as membranes and nanowires, which have applications as ultra-sensitive detectors and high-quality resonators in hybrid quantum systems. Our research in this field deals with the study of nonlinear dynamics and fluctuations in classical and quantum low-dimensional mechanical resonators. With the experimental group of Prof. E. Weig (University of Munich) - Phys. Rev. X 12, 041019 (2022) - we demonstrated that a frequency comb can be generated by a single resonantly driven nanomechanical mode. The occurrence of a frequency comb in a single-mode system provides new insight into the nature of the combs and opens a qualitatively new route to generating them.

Quantum dissipation in superconducting nanodevices

Energy dissipation or, more generally, the unavoidable interaction with the surrounding environment results in the decoherence of quantum states. Remarkably, a custom-built engineered interaction with designed environments can actually become a resource for the generation and stabilization of quantum states. It can also drastically enhance the rate of some processes leading to a dramatic speedup when compared to the classical case. We showed this principle in a simple model formed by a particle in a one-dimensional potential affected by a suitably designed dissipative interaction. We also demonstrated that our theoretical proposal can be realized in a superconducting Josephson circuit with an extremely simple scheme.
The results of this research line have been published in Phys. Rev. B **106**, 045408 (2022), Physical Review Research **3**, 033019 (2021), Physical Review Research **3**, 033122 (2021).

Measurement-induced physics in quantum many-body systems

How an observer influences the fate of a quantum system is a fundamental longstanding question in quantum theory. Recent advances in the experimental manipulation of large ensembles of particles in the quantum regime made this question relevant also for extended systems coupled to a measurement apparatus. We investigate the the nonequilibrium dynamics arising from the competition between unitary dynamics and measurements in quantum many-body systems. In particular we focused on the paradigmatic quantum Ising chain under variable-strength weak measurement of the local magnetization. We developed analytical (non-Hermitian fermionization) and numerical (Monte Carlo wavefunction) tools to study the trajectory-resolved dynamics of this model. In this framework we characterized how the different kind of measurements can trigger phase transitions in the entanglement properties of the system and we connect such a physics with the emergence of the quantum Zeno effect and subradiance.

Recently, we have analyzed how frequent measurements can be used to stabilize quantum simulations of strongly-correlated many-body systems, thus interlinking two important research lines of the Pitaevskii BEC Center. In this context, we have identified a sharp transition in a lattice gauge theory between a chaotic, error-prone regime and a stable regime, which is induced simply by increasing the measuremerent frequency. This result is available as a preprint [arXiv:2405.18504 (2024)].

Quantum simulations

Analog Models

Our theoretical investigations on analog models of gravity has kept addressing the two cases of quantum fluids of atoms and of light. Most remarkably, these theoretical studies are now starting to address phenomena that had not been yet investigated in the gravitational context.

On the atomic side, we have pushed forward a series of preliminary studies in view of the development of an activity on analog model of gravity in the cold atom experiment of the BEC Center. These have highlighted the advantage of using spinor gases in view of observing Hawking emission and superradiance effects. As a purely theoretical study, we have started investigating back-reaction effects of quantum fluctuations on the underlying metric and we have discovered that the friction effect due to parametric emission processes displays unexpectedly strong quantum fluctuations that may give rise to rapid decoherence effects.

On the optical side, we have collaborated with the experimental group at LKB in Paris (A. Bramati and M. Jacquet) in view of an experimental realization with exciton-polaritons in microcavity devices. Quite unexpectedly, we have unveiled an intrinsic coupling between Hawking radiation and quasi-normal modes of a black hole, which suggests that the space-time in the vicinity of a black hole suffers from an intrinsic mechanism of quantum fluctuations.

Following the tradition, the 2023 edition of the international workshop on analog models was held in Trento at ECT*. This time, the workshop also included a special celebration day in honor of Renaud Parentani, a preminent colleague and friend of the BEC Center that prematurely passed away in 2020.

Holographic quantum matter

Recently, we opened a new research direction in the field of quantum simulation by investigating the possibilities to quantum simulate the Sachdev–Ye–Kitaev model. This model represents a paradigm for so-called holographic matter, i.e., quantum matter that is holographically dual to a gravitational theory. The model further realizes the fastest scrambling of quantum information of any known system. It is characterized by disordered and long-ranged interactions, which make it highly challenging to implement in the laboratory. In collaboration with the experimental group of J.-P. Brantut, Lausanne, we have started working on an implementation using a cloud of fermionic atoms confined in an optical cavity and subjected to a disordered light shift. To better understand the model, theoretically as well as in view of potential experimental imperfections, we have also investigated deformations of it, e.g., if the system is subject to dissipation or has interactions that decrease as a power-law with distance. As our studies are revealing, such modifications of the ideal model can lead to intriguing phase transitions.

On the way towards realizing this challenging physics, we have also investigated—theoretically and experimentally—a disordered spin model in a cavity, where we have found finite-size localization transitions as well as so-called grey states characterized by multifractality. These results are published in Nature Physics.

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 are gauge-theory models from high-energy and nuclear physics, whose simulation is currently one of the main drivers of classical scientific high-performance computing.

A particularly relevant question is whether and how such highly constrained systems attain thermal equilibrium if they are isolated from any thermal bath. We have investigated this question theoretically for a simple lattice gauge theory, which was implemented in an optical superlattice by the group of Jian-Wei Pan, Hefei/Heidelberg, continuing our fruitful collaboration. In several theory works, we have also derived and benchmarked extensions of the basic setup, including with a so-called topological theta angle that permits the study of such important phenomena as confinement or the strong CP problem.

Moreover, we have participated in the Early Access Program by Google Quantum AI, which gave us exclusive access to the cutting-edge quantum hardware of Google, as one of only 8 groups worldwide and only group in the EU. Within this program, we have studied a confinement–deconfinement transition a Z2 gauge theory. Moreover, we have performed a thorough investigation of various error-mitigation strategies, among which a gauge-symmetry stabilization method developed by us. The result has recently been accepted in the journal Nature Physics.

To further advance the capabilities of quantum simulators for high-energy physics, we have designed methods to efficiently encode higher-dimensional gauge theories in quantum hardware, to simulate non-Abelian symmetries, and to include multiple flavors. All of these address key challenges for progressing the field of gauge-theory quantum simulation beyond the current state of art. In the context of multiple flavors in particular, we have discovered considerably rich physics, including fractional topological sectors of the gauge fields. We have designed a step-by-step protocol to extract these from experimental data, showing that this subtle phenomenon is well within reach of current quantum-simulator hardware. The studies performed in this reporting period have thus significantly widened the possibilities of quantum simulators for high-energy phenomena.

Entanglement and quantum information

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 groups of P. Faccioli, Trento, and C. Micheletti, SISSA, we have designed quantum algorithms to tackle outstanding problems from computational soft-matter physics. In this reporting period, we have continued working on the dynamics of configurational changes of macromolecules using a quantum computer, in particular on their sampling. We have combined methods from machine learning, quantum field theory, and quantum computing in order to propose an efficient and mathematically rigorous scheme to approximate the continuous transition paths through a grid. Sampling by help of quantum computing results to be significantly more efficient than the current gold standard given by classical Monte Carlo. The latter typically suffers from extremely long autocorrelation times in the Markov chain that quantum computing can avoid. We have further continued work on the problem of sampling from different polymer configurations. Also here we found promising results on performance gain through quantum computing.

Finally, we have initiated and strengthened collaborations with Honda RI and Fraunhofer. Our aim is to solve practical problems from industry sectors such as electrovehicle charging and logistics. We have in particular designed ways to include constraints, characteristic for many optimization problems of practical relevance, into the quantum optimization routine. Moreover, we have studied possibilities to render quantum optimization more efficient by compressing quantum information into qudits, i.e., information carriers with $d > 2$ levels rather than the 2 levels encountered in the common qubits.

The effort in this reporting period is thus continuing to make diverse paradigmatic problems of practical relevance amenable to solution by quantum computing. They also highlight the large potential for obtaining a computational gain through this innovative approach.

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.

To push current possibilities into less explored territories, we have developed a framework for describing entanglement in lattice gauge theories. As these theories are characterized by an extensive number of local constraints, the associated Hilbert space does not present a tensor product structure, posing a major challenge for the characterization of entanglement. To derive a concise and elegant framework, we start in contrast to previous works from the allowed algebra rather than from postulates on states. This then provides an efficient means to define witnesses for entanglement in lattice gauge theories. We have shown that the scaling of the necessary resources is much more benign than what is demanded for previously proposed entanglement measures. This framework thus opens the door to characterizing entanglement in state-of-the-art quantum simulation experiments of lattice gauge theories.

In a second project, we have studied the role of entanglement in quantum-enhanced optimization. We have identified that running quantum algorithms on certain optimization problems naturally generates spin squeezed states. Spin squeezing is a witness for multipartite entanglement, and it is being used in clouds of cold atoms as a resource for quantum-enhanced metrology. Our results thus establish a profound connection between two applications of quantum technologies that were previously thought disparate, the use of quantum computers to solve hard classical optimization problems, and the use of quantum-mechanical sensors to measure more precisely than classical devices. Moreover, the spin squeezing generated by the quantum computer can serve as a application sensitive hardware benchmark; i.e., a device that is able to generate larger squeezing provides better solutions to the optimization problem. Finally, our findings also enable a new way to enhance the efficiency of quantum optimization. Namely, by warmstarting the system in a spin squeezed state, we find the final solution to be better than starting as usual from a product state. These results deepen our theoretical understanding of the role of entanglement in quantum algorithms, and they help us to improve their performance in practical applications.

Recently, we have extended these results to genuinely multipartite entanglement in the form of the so-called geometric measure of entanglement. We find that this entanglement quantifier displays an "entanglement barrier": for a successfull quantum optimization schedule, a sufficient amount of entanglement has first to be built up, but it has to be released again towards the later stages of the schedule in order to faithfully reach the solution state. To make such behavior accessible, we are currently developing an approach to efficiently measure the geometric measure of entanglement in quantum hardware.

Selected articles

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

Physical Review A 105, 033316 (2022)

Measurement of the order parameter and its spatial fluctuations across Bose-Einstein condensation

L. Wolswijk, C. Mordini, A. Farolfi, D. Trypogeorgos, F. Dalfovo, A. Zenesini, G. Ferrari, and G. Lamporesi

This publication completes a series of measurements started about ten years ago and dealing with the effects of the out-of-equilibrium crossing of the Bose–Einstein condensation transition. By cooling a harmonically trapped bosonic gas of Na atoms across T_c at different rates, we studied the growth of the order parameter and the temporal evolution of its spatial fluctuations. We found that the condensate starts forming after a latency time from the critical condition; this latency time inversely depends on the classical collision rate of the gas. If the evaporation is sufficiently fast, the condensate starts forming after the end of the evaporation ramp and the growth of the order parameter follows a universal curve with an intrinsic growth rate independent of the quench time τ_Q. For slower evaporation rates, condensation occurs during the evaporation ramp and the growth curves still manifest a universal behavior, but with a characteristic timescale that linearly scales with τ_Q. We also investigated the amount of spatial fluctuations of the order parameter, formed at the early stage of condensation, and found that they decay exponentially in time and the characteristic time for relaxation obeys a power-law scaling with τ_Q with exponent ≈ 0.6.

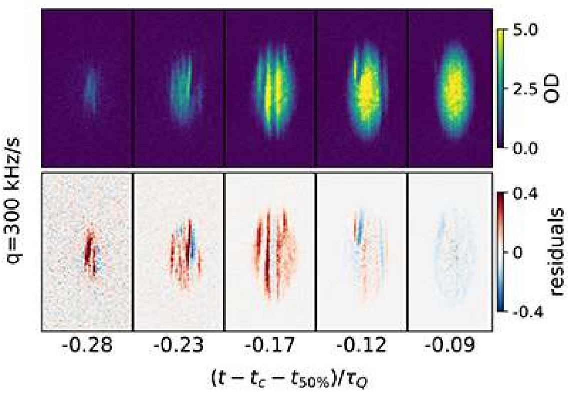


Figure 2: Images of condensing clouds at different waiting time after crossing the critical temperature (waiting time increasing from the left to the right). Atom images in the upper panel show the growth for the BEC fraction along with the growth of defect number in the early stage and then their disappearing at longer times due to the dissipation with thermal fraction, which is substracted in these pictures. The lower panel represents the residual of the images above from a defect-free cloud profile, to highlight the presence of phase defects in the order parameter.

Nature Physics 17, 1359 (2021)

Quantum-torque-induced breaking of magnetic interfaces in ultracold gases

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

Physical Review A 104 023326 (2021)

Manipulation of an elongated internal Josephson junction of bosonic atoms

A. Farolfi, A. Zenesini , D. Trypogeorgos, A. Recati , G. Lamporesi, and G. Ferrari

The two papers describe the very first measurements in which the dynamics of a superfluid mixture is studied in the presence of steady coherent coupling between the two internal states. Both articles were accepted for publication in the early stage of the project object of the report, but they were submitted to the respective journals before the activation of the funding.

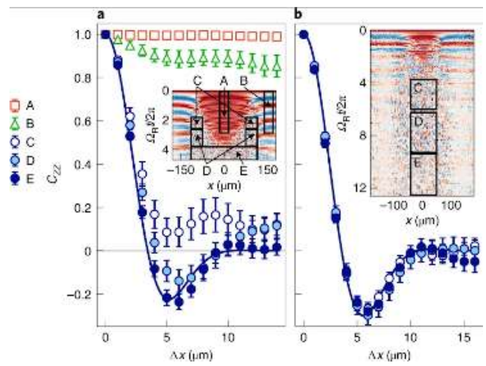


Figure 3: Spatial autocorrelation in a coherently-coupled system dominated by quantum-torque. In the inset, at short times (top) the system remains about homogeneous in the center of the cloud (red state) and in the tails (oscillating red/blue states). At the interfaces it develops spin turbulent features which diffuse inwards and outwards. This behaviour corresponds to the appearance of a negative autocorrelation.

As compared to the previously submitted version, the article published in Nature Physics features an improved analysis and presentation of the experimental data. In particular the paper was enriched by an analysis of the spatial correlation in the "glassy phase" which develops at the boundary between the paramagnetic and ferromagnetic phases. In this analysis we revealed how spatial correlation builds up during the growing of the turbulent region and how it stabilises when the atomic cloud is saturated by defects. Notably, the correlation length in the stationary condition exceeds the spin healing length expected in our system, but it coincides with the one extracted from numerical simulations. Many details of the experimental results of this work, in particular the different calibrations and the techniques used to prepare the atomic cloud, represent by themself novel and notable results. We collected them in the second paper which has been published in Physical Review A. There we show how we chose the trapping parameters which allow us to enter in a one dimensional dynamical regime. Additionally we present four different calibrations of the atomic density which we developed. While the four methods are in principle equivalent, their actual implementation on the experiment results in different features which may turn out favorable or unfavorable depending on the specific conditions or constraints. This paper discuss in detail the topic, providing effective tools to the manipulation of coherently coupled spin superfluids.

Physical Review Letters 128, 210401 (2022)

Observation of Massless and Massive Collective Excitations with Faraday Patterns in a Two-Component Superfluid

R. Cominotti, A. Berti, A. Farolfi, A. Zenesini, G. Lamporesi, I. Carusotto, A. Recati, and G. Ferrari

Faraday were named after the physicist Michael Faraday who in 1831 discussed the appearance of regular patterns on a water surface when the containing bucket was made oscillating along the vertical direction at given frequencies and amplitudes. The formation of the pattern relies on the non-linear part of the equation ruling the motion of surface waves on the liquid, so that the length scales and shape of the pattern reflect the dispersion relations of the surface waves. Faraday waves have been already observed in spin-polarized atomic Bose-condensed gases, in our work we extend to the case of spin mixtures both in the absence and in the presence of a stationary coherent coupling between the internal states. Besides the observation of Faraday waves in spin superfluids, which is a novelty *per se*, in the article we demonstrated how to the generating Faraday waves can be effectivelly applied to perform accurate measurements of the dispersion relations of the medium, in the density as well as in the spin channel. In this proof of principle measurement also showed that, in coherently coupled mixture, the dispersion relation of the spin channel possesses a gap which makes phononic, manybody excitations to acquire an effective mass. The massive character of manybody excitations in superfluids was never reported so far, and it opens to application of Bose-Einstein condensates as emulator of cosmological phenomena and analog gravity models.

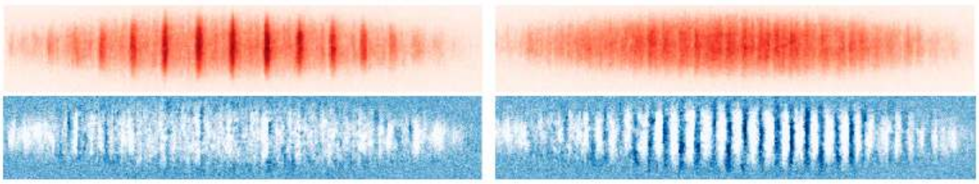


Figure 4: Total density (red clouds) and relative population (blue) for two different driving modulation frequencies (left 400 Hz, rigth 200 Hz). Zero momentum excitations are applied to the system by modulating the radial trapping potential, hence triggering the non-linear processes that ultimately result in the formation of the Faraday time-dependent pattern. In a mixture of two hyperfine states of sodium, Faraday waves can appear both as total density oscillations (on the left) or relative population oscillations (on the right), depending on the driving frequency.

Physical Review X 13, 021037 (2023)

Ferromagnetism in an extended coherently-coupled atomic superfluid

R. Cominotti, A. Berti, C. Dulin, C. Rogora, G. Lamporesi, I. Carusotto, A. Recati, A. Zenesini, and G. Ferrari

In previous recent publications we investigated the excitation spectrum and the static properties of a miscible mixture of sodium hyperfine state, nominally the $|F, m_F\rangle = |1, \pm 1\rangle$, where F is the total angular momentum and m_F its projection on the quantization axis. With the present article we started a novel series of studies based on a different combination of internal states, $|1, -1\rangle$ and $|2, -2\rangle$, which feature an immiscible character in the absence of coherent coupling, making the mixture prone to spatially separate. On the other hand, in the presence of a coherent field coupling the two states the immiscible character partially overcome and mapped onto a magnetism and the para-to-ferromagnetic phase transition. In this publication we characterized the full magnetic phase diagram taking advantage from the nonuniform density of the atomic cloud. Under a weak coherent coupling, the ferromagnetic character of the superfluid in the central, high-density portion of the sample was confirmed by measuring two diverging properties which notoriously mark the transition from the para- to the ferromagnetic phase: the magnetic susceptibility and the magnetization fluctuations.

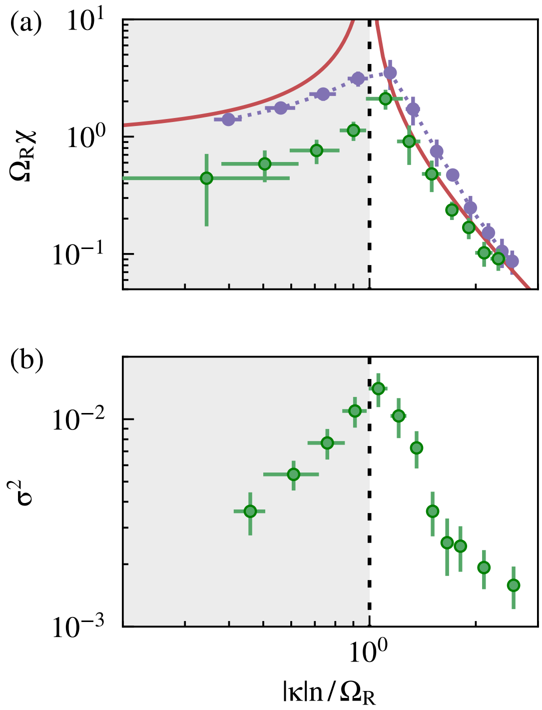


Figure 5: The magnetic susceptibility and the magnetization fluctuations show both an enhancement at the critical value, confirming the presence of a phase transition.

As reported in the figure, both quantities show enhancement at the expected critical value for the normalized coupling strength, which is defined as the ratio between nonlinear ferromagnetic interactions κn and the coherent coupling amplitude Ω_R. This result shows for the first time ferromagnetism in extended superfluid system of ultracold atoms and paves the way to the study of quantum phase transitions in non-dispersive enviroment.

Nature Physics 20, 558 (2024)

False vacuum decay via bubble formation in ferromagnetic superfluids

A. Zenesini, A. Berti, R. Cominotti, C. Rogora, I. G. Moss, T. P. Billam, I. Carusotto, G. Lamporesi, A. Recati, and G. Ferrari

In quantum field theory, quantum fluctuations can trigger the macroscopic tunneling of the field from a metastable state (false vacuum) to the ground state (true vacuum) through a many-body energy barrier. The decay of a false vacuum, which is thought to manifest via the nucleation of spatially localized bubbles of true vacuum, is a fascinating phenomenon for a rich variety of systems, ranging from condensed matter to cosmology. Nevertheless, its experimental verification has been elusive so far, due to the extreme energy scales involved and the lack of tunable parameters. Here, we present the first experimental evidence of false vacuum decay in a metastable ferromagnetic superfluid (see Figure). In this novel platform, realized with ultracold sodium atoms in two coherently-coupled internal states in an ultrastable magnetic field environment, the superfluid acts as the quantum field, and macroscopic tunneling events are observed through the spontaneous nucleation of spin bubbles. Our results find good agreement with numerical simulations and instanton theory, opening the way for the simulation of out-of-equilibrium phenomena in a highly controllable and tunable atomic system.

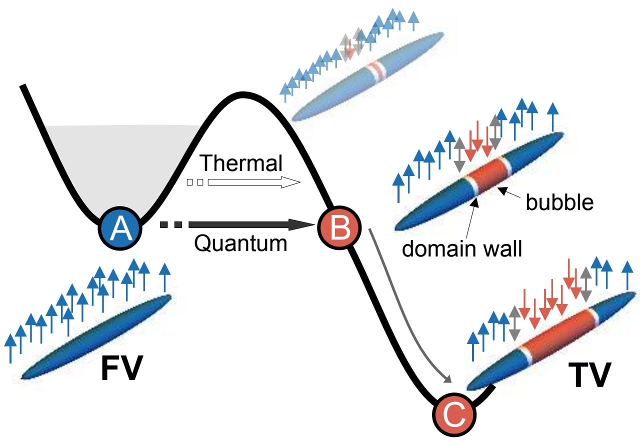


Figure 6: Decay mechanism from an extended metastable with all spins up (false vacuum) to the absolute ground state with spins down (true vacuum) through the formation of macroscopic spin bubbles.

Nature Physics 18, 1453–1458 (2022)

Observation of vortices and vortex stripes in a dipolar Bose-Einstein condensate

L. Klaus, T. Bland, E. Poli, C. Politi, G. Lamporesi, E. Casotti, R.N. Bisset, M.J. Mark, F. Ferlaino

A fruitful new collaboration between G. Lamporesi of the Pitaevskii BEC Center and the experimental team lead by F. Ferlaino in IQOQI (Innsbruck) allowed to merge the expertise on vortex physics in nondipolar gases and the experimental possibility to produce dipolar BECs. The joint collaboration resulted in the first experimental observation of vortices in a dipolar BEC of highly magnetic dysprosium (Dy) atoms. Vortices were introduced through a novel experimental technique called magnetostirring, based on a rotating magnetic field that induces a rotation of the BEC through magnetostriction. At stirring frequencies approaching the radial trap frequency, we observed the generation of dynamically unstable surface excitations, which cause angular momentum to be pumped into the system through vortices. Under continuous rotation, the vortices arrange into a stripe configuration along the field, in close agreement with numerical simulations.

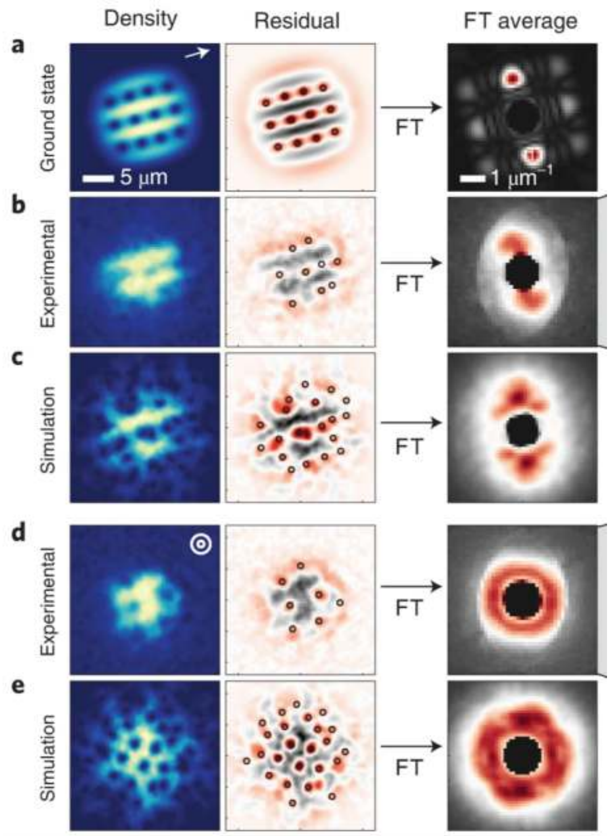


Figure 7: (a) Ground state stripe lattice solution for the parameters in the experiment. b-c) Experiment and simulation found for a dipolar system under continuous magnetostirring. d-e) Experiment and simulation found after letting the B field spiral toward the symmetry axis. The first column shows the density profiles, the second shows the residuals after subtracting the average density profiles and its Fourier transform is shown in the third.

Physical Review Research 4, 033130 (2022)

Phase transition dimensionality crossover from two to three dimensions in a trapped ultracold atomic Bose gas

N. A. Keepfer , I.-K. Liu , F. Dalfovo , and N. P. Proukakis

While dimensionality crossovers have been previously considered both theoretically and experimentally, relevant questions on the effects of dimensionality between the Berezinskii-Kosterlitz-Thouless (BKT) and BEC phase transitions of a dilute Bose gas in experimentally viable geometries are still open. In this paper, we characterize the 2D-3D dimensionality crossover using as a reference case the setting employed in the experiments by the group of J.Dalibard in Paris. The gas is confined in a rectangular box in the xy plane and, at the same time, in a harmonic potential along the transverse z direction. We perform numerical simulations for various values of the transverse frequency on a wide range, from very tight to loose trapping. Our simulations are based on a stochastic projected Gross-Pitaevskii equation (SPGPE). For each set of parameters we average over many SPGPE trajectories in order to extract relevant statistical properties of the gas such as the mean occupation of the lowest energy states, the Binder cumulant, the quasicondensate density, and the condensate fraction. All these quantities are found to interpolate smoothly between the expected behaviors in the 2D and 3D limits. Our findings showcase a continuous shift in the character of the phase transition from BKT to BEC, and a monotonic increase of the identified critical temperature as a function of dimensionality, with the strongest variation exhibited for small chemical potential values up to approximately twice the transverse confining potential.

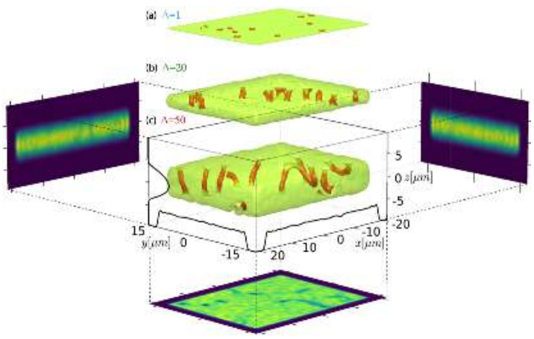


Figure 8: Examples of isosurface rendering (green) of c-field density during a quench from zero-field conditions to equilibrium. The quantity Λ is an input parameter determining the width of the transverse harmonic confinement. The cases for $\Lambda = 1, 20, 50$ as labeled by (a), (b), and (c), respectively. The temperature of the gas in all cases is 20 nK, which is well below the transition temperature where the system is superfluid. In red we plot an isosurface of high velocity regions, indicating vortex structures. In the $\Lambda = 50$ case, integrated line density profiles are overlayed for each axis; the image at the bottom is the column density, i.e., the density integrated along z; the images on the left and right are the column densities in the planar directions.

SciPost Physics 15, 171 (2023)

Phase separation in binary Bose mixtures at finite temperature

G. Spada, L. Parisi, G. Pascual, N. G. Parker, T. P. Billam, S. Pilati, J. Boronat and S. Giorgini

By means of exact path-integral Monte-Carlo simulations we investigate the magnetic behavior of repulsive two-component Bose mixtures as a function of the interspecies coupling strength. At fixed temperature below the Bose-Einstein transition we calculate the chemical potentials in the two components and the dependence of the total free energy upon polarization in the mixture. We find that the magnetic susceptibility and the conditions for phase separation are not modified from the zero temperature case in contrast to predictions using approximate theories. As a result, the intriguing scenario where ferromagnetism can be induced by thermal effects appears to be ruled out. For the value of interspecies coupling corresponding to experimentally relevant balanced mixtures, we calculate the chemical potential and the contact parameters as a function of temperature. In particular, the results for the interspecies contact parameter shows a suppression of correlations at intermediate temperatures due to Bose statistics.

In the figure we show results for the free energy as a function of the polarization p at some fixed temperature and for different values of the interspecies coupling g_{12}. In particular, close to the threshold value $g_{12} = g$ in panel (b) and (c), approximate theories predict a minimum in F/N at a finite polarization which corresponds to the minority species being in the normal phase. This prediction is not verified by our PIMC results which indicate $p = 0$ as the equilibrium polarization in panel (b) and an ever increasing free energy for $p > p_c$ in panel (c). Only for values of g_{12} above threshold (see panel (d)) a minimum in F/N is present for $p > p_c$ indicating that at equilibrium the mixture is in a phase-separated state.

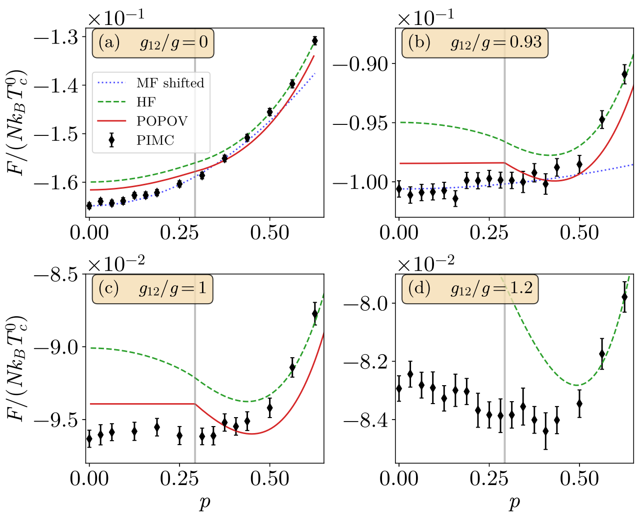


Figure 9: Free energy as a function of the polarization $p = (N_1 - N_2)/N$ for a system with a total of $N = N_1 + N_2 = 128$ particles at temperature $T = 0.794T_c^0$ and with gas parameter $na^3 = 10^{-4}$, for four values of the couplings ratio g_{12}/g. The dotted blue lines in the panels (a) and (b) are the parabolas obtained from the mean-field prediction of the magnetic susceptibility $\chi = 2/(g - g_{12})$, the green dashed lines are the HF predictions, the red solid lines are the Popov predictions. In panel (d) only the HF line is shown. The vertical lines indicate the critical polarization p_c.

Physical Review Letters 131, 173404 (2023)

Attractive Solution of Binary Bose Mixtures: Liquid-Vapor Coexistence and Critical Point

G. Spada, S. Pilati and S. Giorgini

We study the thermodynamic behavior of attractive binary Bose mixtures using exact path-integral Monte Carlo methods. Our focus is on the regime of interspecies interactions where the ground state is in a self-bound liquid phase, stabilized by beyond mean-field effects. We calculate the isothermal curves in the pressure vs density plane for different values of the attraction strength and establish the extent of the coexistence region between liquid and vapor using the Maxwell construction. Notably, within the coexistence region, Bose-Einstein condensation occurs in a discontinuous way as the density jumps from the normal gas to the superfluid liquid phase. Furthermore, we determine the critical point where the line of first-order transition ends and investigate the behavior of the density discontinuity in its vicinity. We also point out that the density discontinuity at the transition could be observed in experiments of mixtures in traps.

In the figure we show the pressure along isothermal lines which, as the system undergoes the first-order gas to liquid transition, feature the typical S-like shape of finite-size systems in the coexistence region. Above the critical point the pressure is instead a monotonically increasing function of the density. The results for the pressure along a given isothermal line are fitted using a cubic curve in the volume per particle $1/n$ and the Maxwell construction is applied to determine the gap parameter $\Delta n = n_L - n_G$ between the densities respectively of the liquid and the gas. These two densities delimit the constant p region corresponding to the coexistence line in the thermodynamic limit.

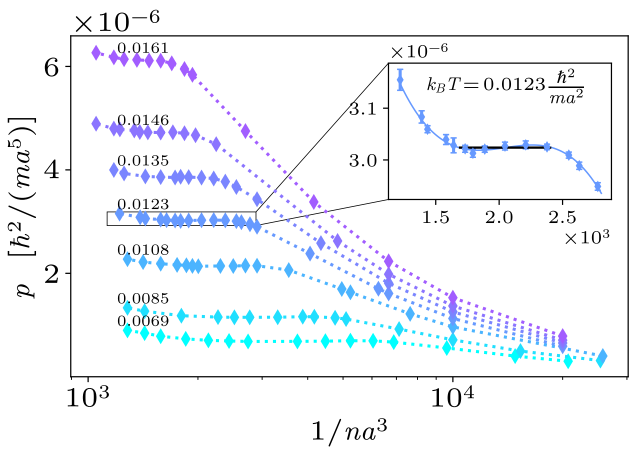


Figure 10: Isothermal curves of pressure as a function of density below and across the critical point. PIMC results refer to systems with $N = 512$ particles and the dotted lines are a guide to the eye. Labels on each curve indicate the value of k_BT in units of $\hbar^2/ma^2$. The inset shows the cubic fit to the points near the phase transition and the Maxwell construction used to determine the density discontinuity.

Physical Review Research 5, L032041 (2023)

Thermal-induced local imbalance in repulsive binary Bose mixtures

G. Pascual, G. Spada, S. Pilati, S. Giorgini and J. Boronat

We study repulsive two-component Bose mixtures with equal populations and confined in a finite-size box through path-integral Monte Carlo simulations. For different values of the s-wave scattering length of the interspecies potential, we calculate the local population imbalance in a region of fixed volume inside the box at different temperatures. We find two different behaviors: for phase-separated states at $T = 0$, thermal effects induce a diffusion process which reduces the local imbalance whereas, for miscible states at $T = 0$, a maximum in the local population imbalance appears at a certain temperature, below the critical one. We show that this intriguing behavior is strongly related to the bunching effect associated with the Bose-Einstein statistics of the particles in the mixture and to an unexpected behavior of the cross pair correlation function not reported before.

In the figure we show the behavior of the local population imbalance $\delta\tilde{N}/\tilde{N}$ as a function of temperature below the transition temperature $T_{\rm BEC}$ of Bose-Einstein condensation. For the ratio of inter-species to intra-species coupling constants $g_{12}/g = 1.50$ the system is fully separated in the limit $T \to 0$ and, by increasing the temperature, the local imbalance decreases monotonously, pointing to a tendency to mix. On the other hand, for values of $g_{12}/g \leq 1$, we see that the slope of $\delta\tilde{N}/\tilde{N}$ is positive at low temperature, showing a maximum imbalance at the characteristic temperature $T^{\star} \simeq 0.7 T_{\rm BEC}$. By further increasing T, the local imbalance starts to decrease and the local separation between species progressively vanishes. This effect is more evident when g_{12}/g approaches the threshold value for phase separation.

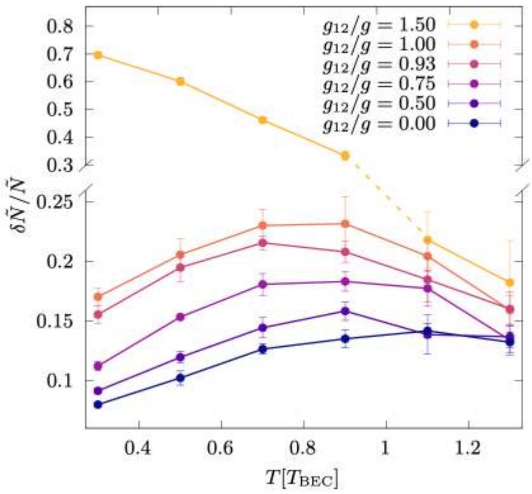


Figure 11: Local population imbalance as a function of temperature for different values of the ratio of inter-species to intra-species coupling constants g_{12}/g with $N = 256$. Note that the vertical axis is broken in order to show the different scale when $g_{12}/g > 1$.

Physical Review A 104, 023301 (2021)

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

F. Carlini and S. Stringari

By applying a sudden perturbation to one of the components of a mixture of two quantum fluids, we explore the effect on the motion of the second component on a short time scale. For very 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 spin drag regimes, which are sensitive to the interaction effects in the Hamiltonian. Special focus is given to the case of coherently coupled Bose-Einstein condensates, interacting Bose mixtures exhibiting the Andreev-Bashkin effect, where the fast spin drag effect is caused by beyond mean field effects not accounted for by Gross-Pitaevskii theory, normal Fermi systems described by Landau theory of 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.

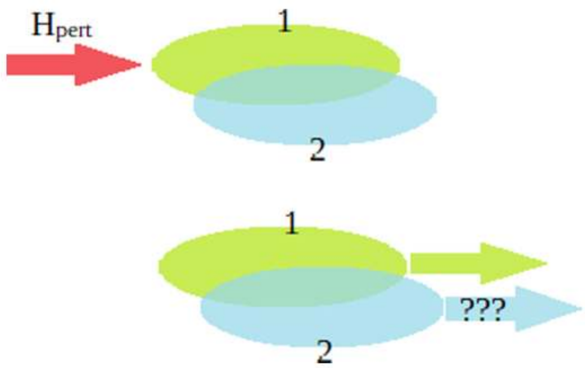


Figure 12: Schematic visualization of fast spin drag. A fast kick, applied to component 1 of a mixture, can drag the motion of component 2.

Scipost Physics 12, 111 (2022)

Quantum Gutzwiller approach for the two-component Bose-Hubbard model

Victor Colussi, Fabio Caleffi, Chiara Menotti, and Alessio Recati

In this work, we studied the effects of quantum fluctuations in the two-component Bose-Hubbard model generalizing to mixtures the quantum Gutzwiller approach introduced previously in [Phys. Rev. Research 2, 033276 (2020)]. We first analyzed the mean-field ground-state phase diagram and spectrum of elementary excitations, with particular emphasis on the quantum phase transitions of the model. Within the quantum critical regimes, we addressed both the superfluid transport properties and the linear response dynamics to density and spin probes of direct experimental relevance. Crucially, we found that quantum fluctuations have a dramatic effect on the drag between the superfluid species of the system, particularly in the vicinity of the paired and antipaired phases absent in the usual one-component Bose-Hubbard model. We compared our results for the drag with previous Bogoliubov and Quantum Monte Carlo simulations (see Figure 13). Additionally, we analysed the contributions of quantum corrections to the one-body coherence and density/spin fluctuations from the perspective of the collective modes of the system, providing results for the few-body correlations in all the regimes of the phase diagram.

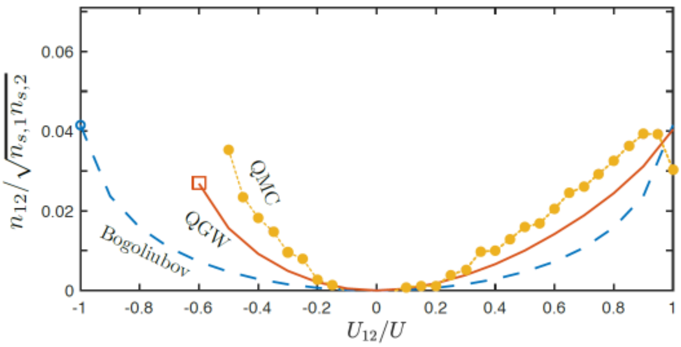


Figure 13: Collisionless drag versus the interspecies coupling strength U_{12}/U for fixed total density $n_d \approx 0.5$ and $2dJ/U = 0.4$ in two dimensions. Here, we compare the QGW prediction (orange solid line) with the Bogoliubov result from [J. Linder et al., Phys. Rev. A 79, 063610 (2009), D. Romito et al., Phys. Rev. Res. 3, 023196 (2021)] (light-blue dashed line) and the QMC data (yellow dotted line) from [K. Sellin et al., Phys. Rev. B 97, 094517 (2018)], evaluated on a lattice of 10^2 sites. The hollow square and circle for the QGW and Bogoliubov results, respectively, indicate the point of the collapse.

Physical Review Letters 127, 203402 (2021)

Beyond-Mean-Field Effects in Rabi-Coupled Two-Component Bose-Einstein Condensate

L. Lavoine, A. Hammond, A. Recati, D. S. Petrov, and T. Bourdel

The present work is the result of a collaboration of the BEC Center with the Institut d'Optique (Palaiseau, Paris, F).

We theoretically calculate and experimentally measure the beyond-mean-field (BMF) equation of state in a coherently coupled two-component Bose-Einstein condensate (BEC) in the regime where averaging of the interspecies and intraspecies coupling constants over the hyperfine composition of the single-particle dressed state predicts the exact cancellation of the two-body interaction. It is shown that with increasing the Rabi-coupling frequency Ω , the BMF energy density crosses over from the non-analytic Lee-Huang-Yang scaling $\propto n^{5/2}$ to an expansion in integer powers of density, where, remarkably, in addition to a two-body BMF term, there emerges a repulsive three-body contribution $\propto n^3/\sqrt{\Omega}$. Thanks to a different energy scaling it has been possible to obtain experimental evidence of both the two terms in the expansion of a Rabi-coupled two-component ^{39} K condensate in a waveguide. The experimental results are further supported (Figure 14) by using the analytical expression for the BMF effect in a time-dependent energy functional theory with the inclusion of the magnetic noise which is present in the experiment (known as extended Gross-Pitaevskii).

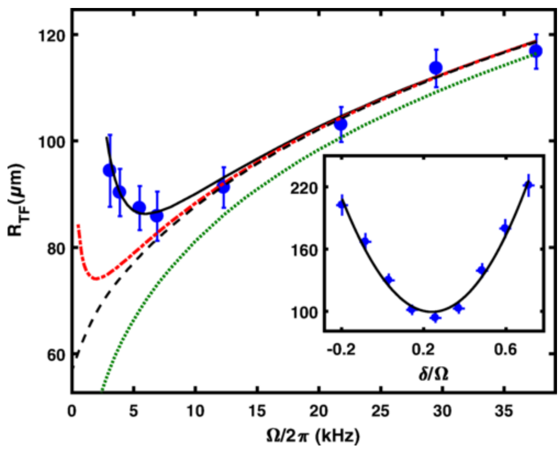


Figure 14: Minimal Thomas-Fermi radius of the condensate after expansion (75 ms) as a function of the Rabi coupling strength Ω. Blue points: experimental outcomes. The curves correspond to quasi-1D extended Gross-Pitaevskii simulations with or without magnetic field noise and assuming different forms of the BMF term. Black solid curve: full BMF term with noise; black dashed curve: full BMF without noise; green dotted curve: two-body BMF term without noise; red dash-dotted curve: two-body plus three-body BMF term without noise. Inset: Experimental Thomas-Fermi radius of the condensate as a function of δ/Ω – with δ the detuning from the resonant atomic transition – for a Rabi frequency $\Omega/2\pi = 12.29$kHz. The curve is a parabolic guide to the eye.

Physical Review A 104, L011302 (2021)

Bragg scattering of an ultracold dipolar gas across the phase transition from Bose-Einstein condensate to supersolid in the free-particle regime

D. Petter, A. Patscheider, G. Natale, M. J. Mark, M. A. Baranov, R. van Bijnen, S. M. Roccuzzo, A. Recati, B. Blakie, D. Baillie, L. Chomaz, and F. Ferlaino

This work is the result of the long-standing and fruitful collaboration with the experimental group led by Prof. Ferlaino at IQOQI/University of Innsbruck (A). In the present paper we perform an experimental and theoretical study of the response of a dipolar supersolid to a Bragg excitation at high-energy defined by the impulse approximation regime. We experimentally observe a continuous reduction of the response $\mathcal{F}$, when tuning the contact interaction from an ordinary Bose-Einstein condensate to a supersolid state and ultimately to an incoherent array of droplets. Already in the supersolid regime, the observed reduction is faster than the one theoretically predicted by the Bogoliubov–de Gennes theory. By comparing experiments and theories, we are able to attribute this discrepancy to the presence of coherent phase dynamics induced by the crossing of the phase transition. The phase variations are found to change character along the phase diagram and become predominantly incoherent only when reaching the incoherent-droplet regime. The role of phase fluctuations by crossing the supersolid phase transition is also taken into account by including them – as obtained in the real-time simulation – on top of the ground state and calculating the linear response to a Bragg pulse. We obtain in this way a reasonable agreement with the experimental outcome (blue line in Fig. 15).

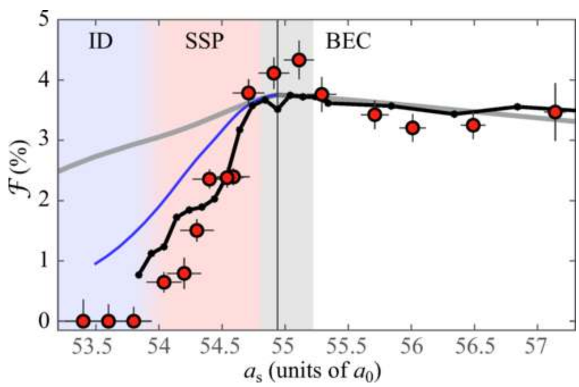


Figure 15: Experimental $\mathcal{F}$ (circles) versus a_s by going from a Bose-Einstein condensate, to a supersolid phase to an independent droplet phase. Horizontal error bars correspond to uncertainties of the magnetic field. The theory lines are from linear response Bogoliubov theory on the system's ground state (grey), from the real-time simulations following the experimental protocol (black), and from a rescaled Bogoliubov calculations (see text). The gray shading corresponds to the uncertainty in a_s of the experimental phase transition (vertical line).

SciPost Physics 11, 092 (2021)

Supersolid phase of a spin-orbit-coupled Bose-Einstein condensate: A perturbation approach

G.I. Martone and S. Stringari

In this work we develop a perturbation approach to study the ground state and the Bogoliubov modes of the supersolid phase of a Bose-Einstein condensate with Raman-induced spin-orbit coupling, holding for small values of the Raman coupling. We obtain analytical predictions for the most relevant observables (including the periodicity of stripes, their contrast, sound velocities, compressibility, and magnetic susceptibility) which are in excellent agreement with the exact (non perturbative) numerical results, obtained for significantly large values of the Raman coupling. We further unveil the nature of the two gapless Bogoliubov modes in the long-wavelength limit and in particular the crystal nature of the spin branch of the spectrum. Finally, using sum-rule arguments, we show that the superfluid density can be experimentally accessed by measuring the ratio of the sound velocities parallel and perpendicular to the direction of the spin-orbit coupling. We also show that the Leggett's upper bound to the superfluid density, given by a proper integral depending on the in situ density, is not adequate for the actual calculation of the superfluid density. Important deviations are in fact found not only in the plane wave and zero momentum phases, but also in the stripe (supersolid) phase, as illustrated by the comparison with the exact calculation (see the figure), based on the solution of the Gross-Pitaevskii equation.

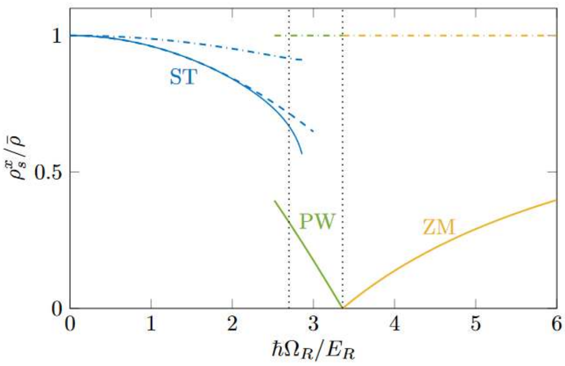


Figure 16: Superfluid density estimated through the ratio of the sound velocities parallel and perpendicular to the direction of the spin-orbit coupling. The figure points out the peculiar behavior at the first-order transition between the stripe (ST) and the plane wave (PW) phases, as well as at the second-order transition between the PW and the zero-momentum (ZM) phases. It also points out the inadequacy of the Leggett criterion (dash-dot curves) to account for the superfluid density, as a consequence of the violation of Galilean invariance of the spin-orbit Hamiltonian.

Physical Review Letters 127, 115301 (2021)

Exciting the Goldstone Modes of a Supersolid Spin-Orbit-Coupled Bose Gas

K. T.Geier, M.I. Martone. P. Hauke and S. Stringari

Supersolids are peculiar quantum many-body systems characterized by the simultaneous spontaneous breaking of two continuous symmetries: the phase symmetry, which is peculiar of superfluid systems, and the translational invariance, which is peculiar of crystals. In this paper we propose accessible signatures of the novel Goldstone modes appearing in a spin-orbit-coupled Bose-Einstein condensate, where supersolidity appears in the form of stripes. By suddenly changing the trapping frequency of the confining harmonic potential, 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, while below it, we predict a beating effect signaling the excitation of a Goldstone spin-dipole mode. In the paper we also show that a sudden modification of the external effective magnetic field, obtained through a proper detuning of the laser beams, gives rise to the excitation of the so called zero frequency crystal Goldstone mode, corresponding to the rigid motion of stripes at constant velocity. Our results open up new perspectives for probing supersolid properties in experimentally relevant configurations with both symmetric as well as highly asymmetric intraspecies interactions.

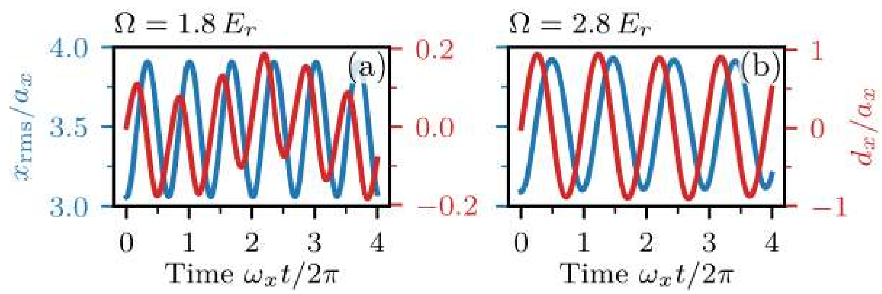


Figure 17: Collective modes of a harmonically trapped spin-orbit BEC gas, excited after suddenly changing the trap frequency along the x-direction. In the stripe phase (Fig. a) a clear beating of two frequencies is observable in the average value of the spin dipole operator (red curve), which is absent in the plane wave phase (Fig. b), where a single frequency is observed.

Physical Review A 106, L061303 (2022)

Creation and robustness of quantized vortices in a dipolar supersolid when crossing the superfluid-to-supersolid transition

Marija Šindik, Alessio Recati, Santo Maria Roccuzzo, Luis Santos, and Sandro Stringari

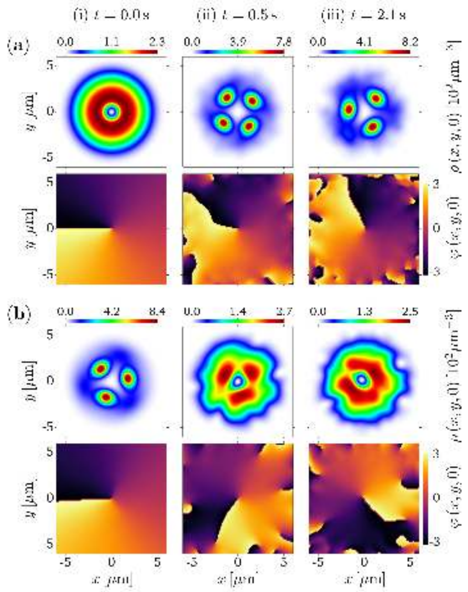


Figure 18: Density and phase profiles in the $z = 0$ plane. (a) Vortex through the superfluid-to-supersolid crossing at $t = 0$, 0.5, and 2.1 s. The vortex is initially created in the superfluid regime ($\Omega/\omega_\perp = 0.22$, $a = 105\,a_0$), and a is then linearly ramped in 100 ms down to $94\,a_0$, within the supersolid phase. (b) Vortex through the supersolid-to-superfluid crossing for the same times. At $t = 0$, the vortex is in the supersolid phase ($\Omega/\omega_\perp = 0.16$, $a = 94\,a_0$). Then a is ramped in 100 ms up to $105\,a_0$, within the superfluid regime. In all cases, $\omega_\perp = 2\pi \times 60\,$Hz, $\lambda = 2$, and $\varepsilon = 0$.

This work is based on our previous experience on the study of vortical configurations in the supersolid phase of dipoalr gases. Quantized vortices constitute a key hallmark of superfluidity. They are topological defects of the order parameter, and therefore robust with respect to perturbations in the U(1) broken symmetry phase. Ultra-cold gases are an ideal platform for the study of vortices. In these gases, vortices are typically created either by stirring the cloud with a laser, or by rotating a slightly deformed trap. In this work we study quantized vortices in dipolar supersolids at the transition between the superfluid and the supersolid phase. The transition is obtained by changing the s-wave scatteriung length a. We present an approach to the nucleation of vortices and their observation, based on the quenching of the s-wave scattering length across the phase transition. Starting from a slowly rotating, vortex-free configuration in the superfluid phase, we predict vortex nucleation as the system enters the supersolid phase, due to the strong reduction of the critical angular velocity in the supersolid. Once a vortex is created, we show that it is robustly preserved when the condensate is brought back to the superfluid phase, where it may be readily observed. These results may have a significant impact on ongoing experiments, given that the observation of quantized vortices would constitute a key probe of the superfluid character of dipolar supersolids.

Physical Review Research 4, 013086 (2022)

Supersolid edge and bulk phases of a dipolar quantum gas in a box

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

We investigate the novel density distributions acquired by a dipolar Bose-Einstein condensed gas confined in a box potential, with special focus on the effects of supersolidity. Different from the case of harmonic trapping, the ground-state density reveals a strong depletion in the bulk region and an accumulation of atoms near the walls, well separated from the bulk, as a consequence of the competition between the attractive and the repulsive nature of the dipolar force. In a quasi-two-dimensional geometry characterized by cylindrical box trapping, we observe the emergence of a ring-like configuration near the boundary of the box (Fig. 19 upper panel), revealing peculiar supersolid and crystal effects in a useful range of parameters. In the case of square box trapping, the density oscillations along the edges, caused by the enhanced accumulation of atoms near the vertices, exhibit interesting analogies with the case of box-trapped quasi-one-dimensional configurations (Fig. 19 middle panel). For sufficiently large values of the atom number, the bulk region can also exhibit supersolidity. In these cases the resulting geometry reflecting the symmetry of the confining potential even for large systems and in these cases the edges are high-density superfluids (no modulation) (Fig. 19 lower panel).

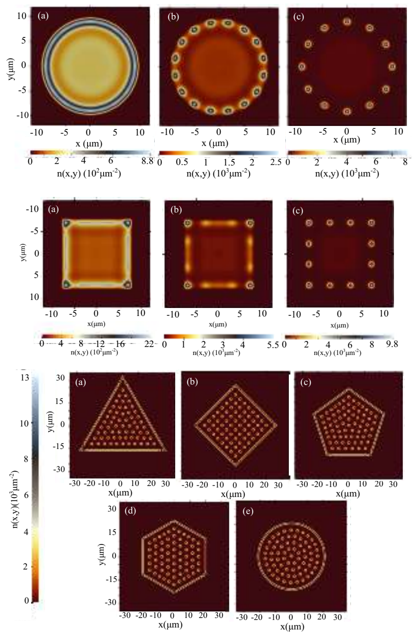


Figure 19: Representative density profiles for a dipolar supersolid in box potentials. Ground state for experimentally available atomic densities: cylindrical box (upper panel); square box (middle panel). For larger density a bulk supersolid is obtained whose geometry is however fixed by the box. The edges are high-density superfluids.

Physical Review Letters 132, 146001 (2024)

Sound, Superfluidity, and Layer Compressibility in a Ring Dipolar Supersolid

Marija Šindik, Tomasz Zawiślak, Alessio Recati, and Sandro Stringari

We propose a protocol to excite the two Goldstone modes of a supersolid dipolar Bose-Einstein condensed gas confined in a ring geometry (see upper panel Fig.20).

By abruptly removing an applied periodic modulation proportional to $\cos(\phi)$,where ϕ is the azimuthal angle, the system starts oscillating. We explore the resulting oscillations of the gas by solving the extended Gross-Pitaevskii equation. The value of the two longitudinal sound velocities exhibited in the supersolid phase are analyzed using the hydrodynamic theory of supersolids at zero temperature, which explicitly takes into account both the superfluid and the crystal nature of the system. This approach allows for the determination of the layer compressibility modulus as well as of the superfluid fraction, f_s. The latter turns out to be in almost perfect agreement with the Leggett estimate of the nonclassical moment of inertia.

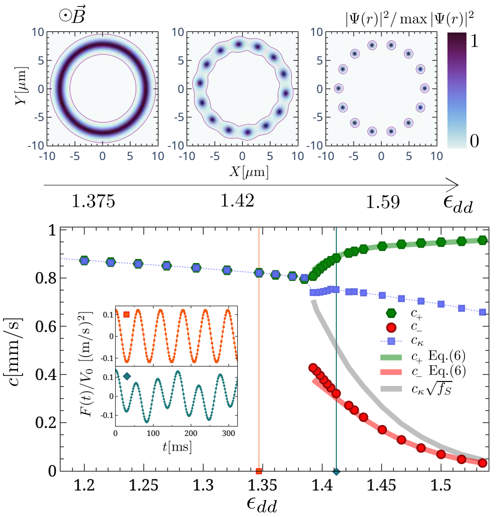


Figure 20: Upper panel: Representative density profiles for a dipolar superfluid, supersolid and incoherent droplet state in a ring potential. Lower panel: the extracted speed of sound using our protocol.

Annual Review of Condensed Matter Physics 13, 407 (2022)
Coherently Coupled Mixtures of Ultracold Atomic Gases
Alessio Recati and Sandro Stringari

After more than ten years studying binary mixtures of Bose–Einstein condensates in the presence of coherent coupling, we have been asked to write a review papers on the topic. This article summarizes some of the relevant features exhibited by such a system at zero temperature. The coupling, which is experimentally produced by proper photon transitions, can involve either negligible momentum transfer from the electromagnetic radiation (Rabi coupling) or large momentum transfer (Raman coupling) associated with spin–orbit effects. The nature of the quantum phases exhibited by coherently coupled mixtures is discussed in detail, including their paramagnetic, ferromagnetic, and, in the case of spin–orbit coupling, supersolid phases. The behavior of the corresponding elementary excitations is discussed, with explicit emphasis on the novel features caused by the spin-like degree of freedom. Focus is further given to the topological excitations (solitons, vortices) in presence of Rabi coupling and in particular to the relative phase domain wall, which generates confinement between half-quantum vortices (Fig. 21). This review also points out relevant open questions that deserve more systematic theoretical and experimental investigations.

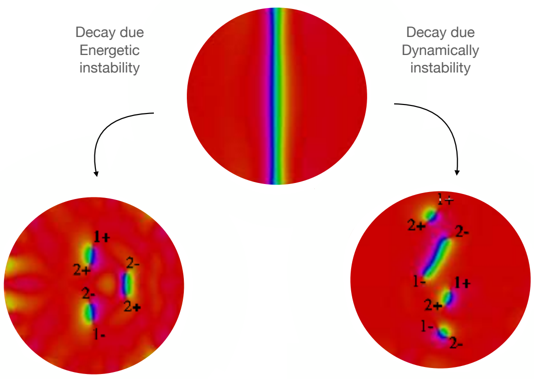


Figure 21: Phase profile of a long domain wall created at $t = 0$ (upper panel) across a two-dimensional Rabi coupled gas trapped by an harmonic potential $V(x, y) = 1/2m\omega_{\text{ho}}^2(x^2 + y^2)$. The circle contour correspond to the radius of the cloud where the Thomas-Fermi density is zero. The domain wall decays (left) via energetic instability, after bending, into three composite objects or (right) via snake dynamic instability into four composite objects. The pairs are either made of vortices with the same circulation ($\pm$ in the figure) in two different components 1 and 2 or with opposite circulation in the same component.

New Journal of Physics 25, 013007 (2023)

The cross-over from Townes solitons to droplets in a 2D Bose mixture

B. Bakkali-Hassani, C. Maury, S. Stringari, S. Nascimbene, J. Dalibard, J. Beugnon

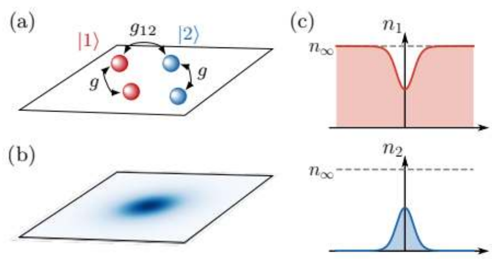


Figure 22: Equilibrium state of a 2D minority superfluid component immersed in a bath. (a) Sketch of the interactions in the mixture, with the intra-component couplings $g_{11} = g_{22} \equiv g$ and the inter-component coupling g_{12}. Here, we consider the immiscible regime $g_{12} > g$. (b) Two-dimensional density profile of the minority component for $N/N_T = 1, 5$, where $N_T = 5 : 85/|g_e|$ is the atom number at which the Townes soliton exists and $g_e = g - g_{12}^2/g$. (c) Density cuts through the center for both components for $N/N_T = 1.5$. At a large distance from the center, the bath density takes the asymptotic value n_∞.

When two Bose-Einstein condensates-labelled 1 and 2-overlap spatially, the equilibrium state of the system depends on the miscibility criterion for the two fluids. Here, we theoretically focus on the non-miscible regime in two spatial dimensions and explore the properties of the localized wave packet formed by the minority component 2 when immersed in an infinite bath formed by component 1. We address the zero-temperature regime and describe the two-fluid system by coupled classical field equations. We show that such a wave packet exists only for an atom number $N(2)$ above a threshold value corresponding to the Townes soliton state. We identify the regimes where this localized state can be described by an effective single-field equation up to the droplet case, where component 2 behaves like an incompressible fluid. We study the near-equilibrium dynamics of the coupled fluids, which reveals specific parameter ranges for the existence of localized excitation modes.

Physical Review A 105, 043308 (2022)

Stochastic dynamics and bound states of heavy impurities in a Fermi bath

Matteo Sighinolfi, Davide De Boni, Alessandro Roggero, Giovanni Garberoglio, Pietro Faccioli, and Alessio Recati

One of the most active topic in the field of ultra cold Fermi gases of the last 10 years has been the study of the so-called Fermi (and Bose) polaron problem, i.e., the problem of a single or very few impurities in a quantum degenerate bath. Cold gases platforms indeed represent an almost ideal platform to study a very long standing problem.

While the polaron static properties have been theoretically and experimentally studied in some detail, the dynamical properties are still far from be fully understood.

The present work is the result of a collaboration with members of the nuclear physics group of the Trento university, within the Q@TN initiative.

We investigate the dynamics of heavy impurities embedded in an ultracold Fermi gas by using a generalized Langevin equation. The latter – derived by means of influence functional theory – describes how the stochastic classical dynamics of the impurities and the quantum nature of the fermionic bath manifests in the emergent interaction between the impurities and in the viscosity tensor. By focusing on the two-impurity case, we predict the existence of bound states, in different conditions of coupling and temperature, whose lifetime can be analytically estimated. Our predictions should be testable using cold-gases platforms within current technology. Moreover this work shows once more how fruitful cross-fertilisation is by applying techniques typically used in nuclear matter to cold gases.

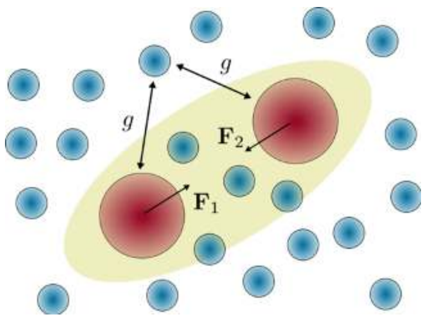


Figure 23: Two heavy impurities (red) in a bath of degenerate Fermi atoms (cyan). The bare impurity-bath interaction g is responsible for the induced forces $\mathbf{F}_{1,2}$ between impurities and for the low friction region (yellow).

SciPost Physics 12, 107 (2022)

Detection of Berezinskii-Kosterlitz-Thouless (BKT) transition via Generative Adversarial Networks

Daniele Contessi, Elisa Ricci, Alessio Recati, Matteo Rizzi

The detection of phase transitions in quantum many-body systems with lowest possible prior knowledge of their details is among the most rousing goals of the flourishing application of machine-learning techniques to physical questions. In the present work, we combine state of the art machine learning techniques and numerical many-body techniques (Tensor Network) for phase recognition.

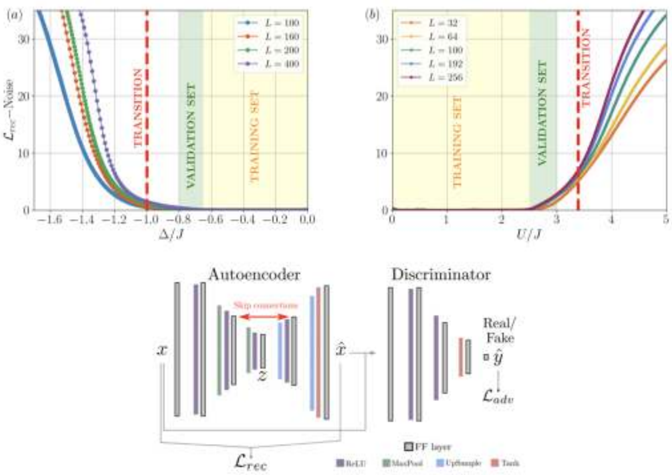


Figure 24: Bottom panel: scheme of the used architecture for anomalous detection applied to data from many-body calculation. The machine is in particular trained by passing bi-partite entanglement spectra. Upper panel: result of the "losses" in data reconstruction by changing the microscopic parameters of a one-dimensional XXZ model (left) and of a one-dimensional Bose-Hubbard model (right). Dashed vertical red lines are state-of-the-art phase transition critical points.

In particular we train a Generative Adversarial Network (GAN) with the Entanglement Spectrum of a system bipartition, as extracted by means of Matrix Product States ansätze. We are able to identify gapless-to-gapped phase transitions in different one-dimensional models by looking at the machine inability (losses $\mathcal{L}_{rec}$) to reconstruct outsider data with respect to the training set. We select models with BKT phase transitions, to check whether the architecture is efficient even against such subtle transitions.

We foresee that GAN-based methods will become instrumental in anomaly detection schemes applied to the determination of phase-diagrams. This work it is the result of a collaboration within the Q@TN initiative among members of the Pitaevskii BEC Center, of the machine learning group of the department of informatics of the Trento University and of the quantum information group at the Forschungszentrum Jülich.

Quantum 5, 528 (2021)

Many-body quantum Zeno effect and measurement-induced subradiance transition

A. Biella and M. Schiró

It is well known that by repeatedly measuring a quantum system it is possible to completely freeze its dynamics into a well defined state, a signature of the quantum Zeno effect. Here we show that for a many-body system evolving under competing unitary evolution and variable-strength measurements the onset of the Zeno effect takes the form of a sharp phase transition. Using the Quantum Ising chain with continuous monitoring of the transverse magnetization as paradigmatic example we show that for weak measurements the entanglement produced by the unitary dynamics remains protected, and actually enhanced by the monitoring, while only above a certain threshold the system is sharply brought into an uncorrelated Zeno state. We show that this transition is invisible to the average dynamics, but encoded in the rare fluctuations of the stochastic measurement process, which we show to be perfectly captured by a non-Hermitian Hamiltonian which takes the form of a Quantum Ising model in an imaginary valued transverse field. We provide analytical results based on the fermionization of the non-Hermitian Hamiltonian in supports of our exact numerical calculations.

These results establish a rather general important connection between many body quantum Zeno physics, subradiance transition in non-hermitian systems and rare fluctuations of the stochastic dynamics of a measured quantum many-body system. Future directions include the investigation of the role of spatially inhomogeneous measurements leading to dilute disorder, different initial conditions and higher dimensionality. The study of a model where the unmeasured dynamics is governed by an interacting system represents a further intriguing research direction.

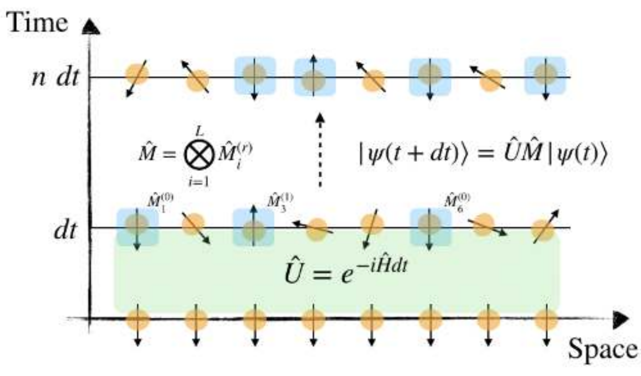


Figure 25: Cartoon of the hybrid quantum dynamics considered in this work where in addition to the unitary evolution ruled by $\hat{U}$ (in our example generated by the Quantum Ising Model) there is a stochastic measurement process on each site $\hat{M} = \bigotimes_{i=1}^{L} \hat{M}_i^{(r)}$.

Physical Review A 105, L051302 (2022)

Eightfold way to dark states in SU(3) cold gases with two-body losses

L. Rosso, L. Mazza and A. Biella

Cold-atom experiments usually feature a high degree of control over system parameters and allow for an almost perfect decoupling from the surrounding environment. However, despite the tremendous experimental progresses, a perfect isolation has never been reached, for instance because of particle losses, causing energy relaxation and decoherence phenomena. On one hand, this fact introduces a typical timescale determining for how long a system can be regarded as closed. On the other hand, on a longer timescale, the interplay between the coherent unitary evolution and the coupling to the environment can lead to a non-trivial dynamics and to stationary states featuring strong quantum correlations and critical behaviors.

In this work we study the quantum dynamics of a one-dimensional SU(3)-symmetric system of cold atoms in the presence of two-body losses. We exploit the representation theory of SU(3), the so-called eightfold way, as a scheme to organize the dark states of the dissipative dynamics in terms of generalized Dicke states and show how they are dynamically approached, both in the weakly and strongly interacting and dissipative regimes. Our results are relevant for a wide class of alkaline-earth (-like) gas experiments, paving the way to the dissipative preparation and exploitation of generalized Dicke states.

This work also paves the way to future intriguing research directions. Among them we mention the study of inhomogeneous situations where the interactions between the internal degrees of freedom acquires a spatial dependence allowing the exploration of analogies with general relativity and the implementation of experimentally friendly protocols for the certification and exploitation of generalized Dicke states.

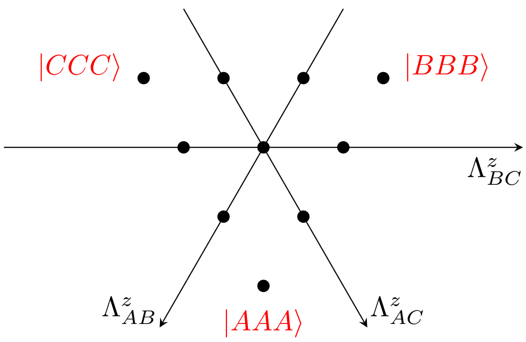


Figure 26: The eightfold way in a dark state. Triangular irreducible representation with labels $(3, 0)$, which is composed of ten states. The three arrows allow one to identify each state through the quantum numbers $\lambda^z_{\mu\mu'}$, where μ, μ' take values in the three components of the gas, A, B and C. Note that only two of them are linearly independent.

SciPost Physics 12, 044 (2022)

The one-dimensional Bose gas with strong two-body losses: the effect of the harmonic confinement

L. Rosso, A. Biella and L. Mazza

In this article we have studied the effect of a harmonic confinement on the dynamics of a one-dimensional Bose gas subject to strong two-body losses. Thanks to the fermionisation that takes place in the regime of strong dissipation, the so-called quantum Zeno regime, we have developed a set of rate equations that describe the depopulation of each fermionic mode. In the homogeneous case we have predicted both the dynamics of the density of the gas, displaying an anomalous $t^{-1/2}$ decay, and the time-dependence of the fermionic momentum distribution function. This latter quantity, which is often called distribution of rapidities, is a measurable quantity, via an expansion in a one-dimensional setting. The main result of the article is that the presence of a harmonic confinement leads to a drastic modification of the dynamics of the gas; in particular, when the trap is strong, the density of the gas decreases as t^{-1}. We have shown the existence of a crossover time that signals the passage from the behaviour of a homogeneous-gas at short times to that of a strongly-confined gas at long times. Several of our predictions can be tested in state-of-the-art experiments.

Two directions of further study can be devised. The first one concerns the fact that during the dynamics the gas might leave the purely one-dimensional situation, and start to populate excited levels of the transverse confinement. A second investigation direction concerns the study of strong and finite elastic interactions, which could be responsible for the scattering of the fermionic momenta in phase space.

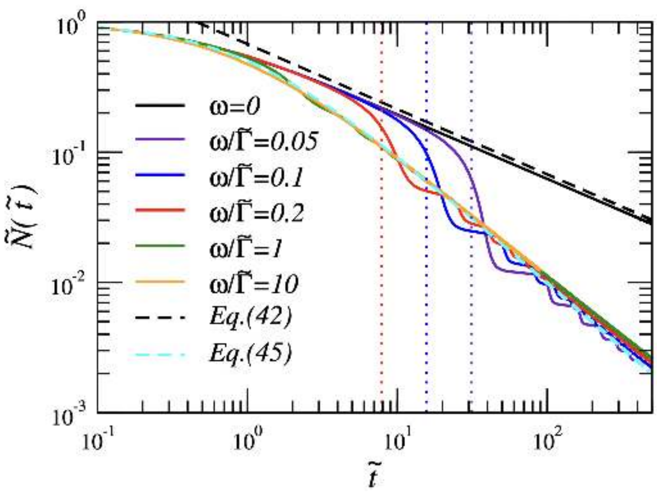


Figure 27: Time-evolution of the normalized density for different values of the ratio $\omega/\tilde{\Gamma}$. Black and cyan dashed lines are theoretical prediction for the weak and strong confinement case.

SciPost Physics 15, 152 (2023)

Monte Carlo matrix-product-state approach to the false vacuum decay in the monitored quantum Ising chain

J. Maki, A. Berti, I. Carusotto and A. Biella

With the aim to extend our theoretical understanding of false vacuum decay physics we studied the effect of quantum measurements on the metastable dynamics in quantum spin chains. Specifically, in this work we characterized the false vacuum decay in the ferromagnetic quantum Ising chain with a weak longitudinal field subject to continuous monitoring of the local magnetization. Initializing the system in a metastable state, the false vacuum, we study the competition between coherent dynamics, which tends to create resonant bubbles of the true vacuum, and measurements which induce heating and reduce the amount of quantum correlations. To this end we exploit a numerical approach based on the combination of matrix product states with stochastic quantum trajectories which allows for the simulation of the trajectory-resolved non-equilibrium dynamics of interacting many-body systems in the presence of continuous measurements. We show how the presence of measurements affects the false vacuum decay: At short times the departure from the local minimum is accelerated while at long times the system thermalizes to an infinite-temperature incoherent mixture. For large measurement rates the system enters a quantum Zeno regime. The false vacuum decay and the thermalization physics are characterized in terms of the magnetization, connected correlation function, and the trajectory-resolved entanglement entropy. This work paves the way to future intriguing research directions. Specifically, on a general ground, it is not clear how the presence of a coupling to an external environment affects the metastable dynamics. How is the false vacuum decay timescale affected by the opening? What is the fate of the nucleated bubbles in such a setting?

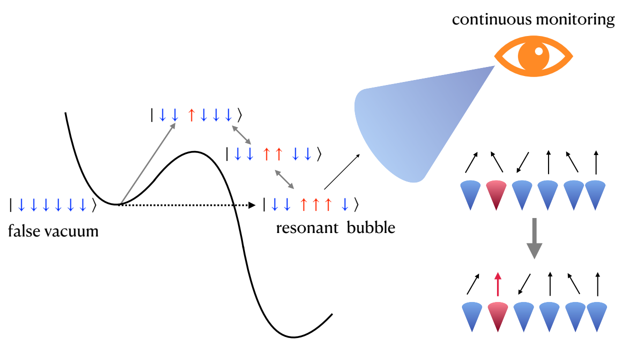


Figure 28: A sketch of the system under consideration. The decay of the false vacuum of the quantum Ising chain takes place through the virtual occupation of $\mathcal{O}(\tilde{l})$ off-resonant states ($\tilde{l}$ being the size of the bubble). This metastable dynamics is continuously monitored by measuring the local magnetization. This process induces incoherent spin flips in random positions (denoted by red spins) and affects the closed system dynamics.

Physical Review A 107, 033320 (2023)

Linear and nonlinear edge dynamics of trapped fractional quantum Hall droplets

Alberto Nardin and Iacopo Carusotto

The fractional quantum Hall (FQH) effect is one of the most fascinating concepts of modern quantum condensed matter physics. One of the most exciting features is the possibility of observing fractional statistics effects both in the bulk and on the edge. Many of these features are theoretically captured by the chiral Luttinger liquid (χLL) theory of gapless edge excitations which is expected to be an accurate description in the long-wavelength and weak excitation limits.

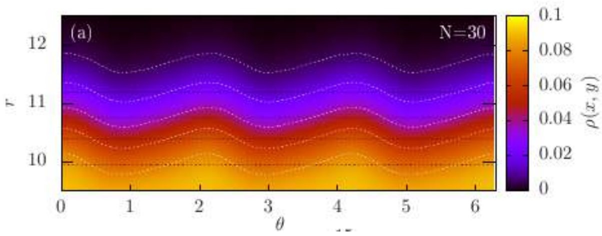


Figure 29: Colorplot of the density of a FQH liquid in response to a strong perturbation; white (black) lines are isodensity contours for the perturbed (unperturbed) system.

In this theoretical work, we investigate the physics beyond the the regime of validity of the χLL description and perform numerical studies of the linear and nonlinear edge dynamics of a fractional QH liquid trapped by a generic, non-harmonic external potential.

Using a novel numerical method, we carry out a numerical study of the linear and nonlinear edge dynamics of a fractional quantum Hall cloud of macroscopic size. Signatures of the quantized transverse conductivity of the bulk in the edge physics are first discussed within the χLL picture. Effects beyond the χLL description are then highlighted by looking at the dynamical structure factor of a anharmonically confined droplet, at the group velocity dispersion of the edge excitations, and at their nonlinear features at stronger excitation levels. The numerical observations are then used to write a minimal non-linear χLL Hamiltonian whose classical limit gives a Kortweg-de Vries equation for the edge-density dynamics. In particular, we show how this generalized χLL Hamiltonian is able to reproduce all the microscopic calculations in a quantitative way.

Once supplemented with tunneling processes between FQH edges, this formalism holds great promise in view of using FQH fluids as a novel platform for nonlinear quantum optics of edge excitations with exotic statistics.

Physical Review A 105, 023527 (2022)

Bogoliubov theory of the laser linewidth and application to polariton condensates

Ivan Amelio and Iacopo Carusotto

The emission spectrum of a laser device reflects the complex dynamics of spatial and temporal fluctuations. For a single mode laser, Schawlow and Townes predicted the linewidth of the Lorentzian spectral peak to scale as the inverse of the emitted power. However, corrections to this simple formula have been first proposed by Petermann, who noticed that deviations of the shape of the lasing mode from the eigenmode of a lossless cold cavity determine a broadening of the laser linewidth. Then, the crucial role of the fluctuations of the intensity, hence of the nonlinear refractive index, was first considered by Henry. As a further broadening mechanism, we have recently shown that in low dimensions the lack of long-range order can determine a dramatic broadening of the linewidth. In particular, in one dimension the scaling is determined by universal Kardar-Parisi-Zhang exponents.

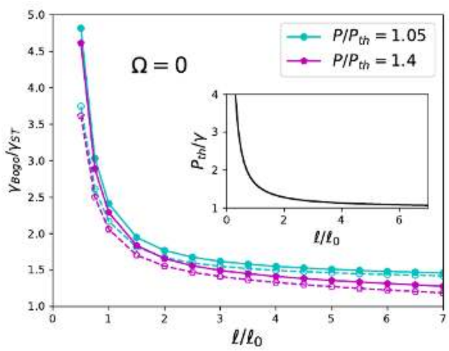


Figure 30: Plot of the Petermann-like broadening as a function of the pump-spot width for a laser device with no photon-photon interactions.

In this work we develop a new theoretical framework for the computation of the linewidth of a generic semi-classical laser dynamics via the solution of a Bogoliubov eigenproblem. The Bogoliubov method has been originally developed for the computation of the collective modes of quantum fluids. Here we give a general presentation of its application to the seemingly completely distinct problem of the laser linewidth, and we show how it provides a very convenient treatment when spatial inhomogeneities and refractive index nonlinearities interplay. One main insight is that the Petermann and Henry factors can be explained in a unifying perspective as both arising from the non-orthogonality of the Bogoliubov modes, which live in a space with doubled degrees of freedom.

Physical Review A 105, 053519 (2022)

Topologically protected frequency control of broadband signals in dynamically modulated waveguide arrays

F. S. Piccioli, Alexander Szameit, Iacopo Carusotto

In many technological applications, the ability of manipulating the spectrum of generic signals is a fundamental basic block in the direction of building complex networks. To this purpose, a most intriguing process is the dynamical modulation in time of the optical properties of a medium. Such mechanism has been recently exploited to realize synthetic dimensions in which the frequency degree of freedom plays the role of an extra physical dimension.

Most of the so far proposed synthetic frequency dimension schemes rely on resonating structures like multimode cavities. This restricts the signals to be manipulated to quasimonochromatic light beams or frequency combs with a spacing commensurate to the free spectral range of the resonators. This limitation can be overcome by replacing resonating configurations with propagating ones such as optical waveguides.

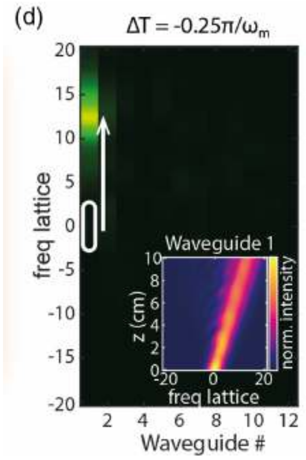


Figure 31: Light propagation in a chiral edge state of a frequency-space synthetic lattice.

In this article, we propose the use of propagating sound waves to dynamically modulate a uniformly spaced coupled waveguide array via the acousto-optic effect. This provides a hybrid frequency-space synthetic lattice subject to a synthetic magnetic field, whose strength is controlled by the wave vector of the sound wave and, in turn, determines the topological properties of the lattice. Selectively excitation of the chiral edge states can be obtained by tuning the arrival time of the incident pulse with respect to the modulation period.

The proposed scheme paves the way to the use of the standard photonic technology of laser-written waveguides for the spectral manipulation of broadband signals. The coherent nature of the proposed scheme permits its application both to classical waves and to single- or few-photon quantum wave packets, e.g., to manipulate their entanglement between time, frequency, and spatial variables. This opens the way to various applications in telecommunications and quantum science and technology.

Physical Review Letters 130, 241501 (2023)

Numerical studies of back-reaction effects in an analog model of cosmological pre-heating

Salvatore G. Butera and I. Carusotto

Since Unruh's pioneering proposal, analog models of gravity represent a promising platform where a wide range of effects of quantum fields in curved spacetime can be studied from first principles and potentially find experimental confirmation. A most celebrated achievement was the observation of the analog of Hawking radiation emanating from the acoustic horizon in a trans-sonically flowing Bose-Einstein condensates (BECs) of ultra-cold atoms. All these advances deal with a kinematic, test-field effects of a non-interacting quantum field theory on a pre-determined curved space-time background. The next challenge is to attack the so-called back-reaction phenomena, where the background has its own dynamics and interplays with the quantum field. An outstanding problem in this class is black hole evaporation under the effect of Hawking emission.

In this Letter, we consider an analog model of the pre-heating stage of the early Universe. Here, the periodic oscillations of the inflaton parametrically excite the vacuum fluctuations of the matter fields, resulting in an explosive production of matter and a corresponding decay of the inflaton oscillations. In our analog model, we simulate this dynamics by using a two-dimensional ring-shaped BEC configuration: the oscillations of the inflaton field are implemented by exciting a breathing mode along the transverse direction. These oscillations then lead to the parametric amplification of zero-point fluctuations in the longitudinal modes, which provide an analog for the matter fields.

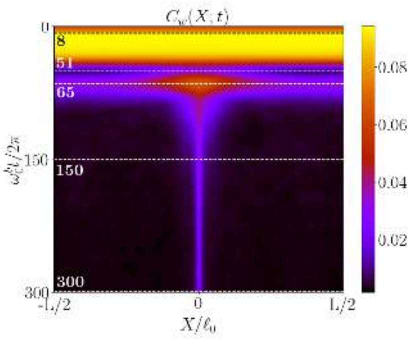


Figure 32: Colorplot of the spatial correlation function of the transverse size of the condensate, showing the decay and the decoherence of the transverse breathing mode under the effect of the back-reaction.

Contrary to the standard semiclassical model, our numerical results predict a crucial role of quantum fluctuations: not only does the emission of longitudinal excitations lead to an effective damping of the breathing mode, but is also responsible for its quick decoherence.

Nature Reviews Physics 4, 470-488 (2022)

Non-equilibrium Bose–Einstein condensation in photonic systems

Jacqueline Bloch, Iacopo Carusotto, Michiel Wouters

Since its original prediction in 1924, Bose–Einstein condensation (BEC) has been a major focus of interest for theoretical and experimental research. In parallel to the impressive achievements in ultracold atomic gases, exciting new phenomena have been uncovered by the study of condensation effects in photonic systems, which are typically non-conservative systems. As a consequence of this driven-dissipative condition, condensation displays dramatically new features in its static, dynamical, superfluid and coherence properties, from condensation in excited states possibly displaying outward flows, to diffusive Goldstone modes and generalized Landau criteria for superfluidity, to Kardar–Parisi–Zhang (KPZ) spatiotemporal scalings in the coherence properties.

This Review continues the tradition of celebrated review papers by the BEC Center. In particular, we offer an overview of non-equilibrium condensation in photonic systems and give a comparative account of the main platforms on which landmark experiments have been performed. Our main focus is on the identification of universal phenomena that stem from the non-equilibrium condition, rather than from the specific properties of each system. Our interdisciplinary point of view involves fundamental concepts from quantum optics, non-equilibrium statistical mechanics, quantum condensed matter and quantum field theories, and opens promising perspectives towards new developments in fundamental science, as well as towards applications in optoelectronics, analogue computation and quantum technologies.

System	Mass	Temperature	Interparticle interactions	Thermalization mechanism	Properties
Cold atoms	$\sim 10^5 m_e$	nK	Atomic collisions. Fully tunable from mean field to strongly interacting	Collisions and evaporation	Conservative. Full thermal equilibrium
Laser	$\sim 10^{-5} m_e$	Not relevant	Gain saturation and intensity-dependent refractive index. Mean field, weak	None	Driven-dissipative. Non-equilibrium distribution
Photon BEC	$\sim 10^{-5} m_e$	Room	Thermo-optic effects. Mean field, weak, non-local	Absorption/ emission by dye	Driven-dissipative. Thermal distribution
Exciton BEC	$\sim m_e$	1 K	Dipolar interactions. Typically strong	Collisions, phonons	Driven-dissipative. Thermal
Polariton BEC	$\sim 10^{-5} m_e$	10–300 K	Exciton collisions. Mean field, strong	Collisions, phonons, exciton reservoir	Driven-dissipative. Tunable: non-equilibrium or thermal distribution
Classical condensation of light waves	Not relevant; $t \leftrightarrow z$ mapping	Not relevant; $t \leftrightarrow z$ mapping	Intensity-dependent refractive index. Mean field, moderate	Collisions	Conservative. Thermalizes to Rayleigh–Jeans distribution

Figure 33: Comparative summary of the characteristic parameters of different physical realizations of BEC

Physical Review Letters 129, 103601 (2022)

High-Resolution Coherent Probe Spectroscopy of a Polariton Quantum Fluid

F. Claude, M. J. Jacquet, R. Usciati, I. Carusotto, E. Giacobino, A. Bramati, and Q. Glorieux

From liquid helium to ultracold atoms, these hydrodynamic properties of superfluids depend on the dispersion of the collective excitation modes in the quantum fluid, which, in the dilute regime, are described by the Bogoliubov theory. Quantum fluids may also be made of photons in nonlinear media, but the precise detection of the Bogoliubov dispersion in such quantum fluids of light has so far remained a challenging goal.

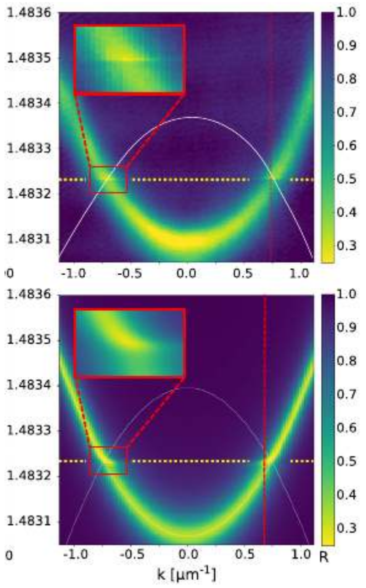


Figure 34: Experimental (top) and theoretical (bottom) colorplots of the probe reflectivity, showing the Bogoliubov dispersion of a quantum fluid of light in a regime that strongly departs from equilibrium.

In this Letter, we report a joint theoretical-experimental work on the dispersion of collective excitations in a quantum fluid of exciton polaritons within a semiconductor microcavity. The high resolution of our novel coherent probe spectroscopy method enables the accurate study of the Bogoliubov dispersion in all regimes of interactions.

In this way, we are able to highlight the influence of the polariton fluid local density on the dispersion at low wave number and the presence of a dark excitonic reservoir that modifies the effective speed of sound in the fluid. The versatility of our method is further illustrated by the resolution of narrow spectral features that specifically stem from nonequilibrium effects such as the controlled opening of an energy gap and the appearance of horizontal plateaus precursory of dynamical instabilities.

The follow-up of this work [F. Claude, M. J. Jacquet, I. Carusotto, Q. Glorieux, E. Giacobino, and A. Bramati, *Spectrum of collective excitations of a quantum fluid of polaritons*, Phys. Rev. B 107, 174507 (2023)] was highlighted by a viewpoint in Physics [C. Michel, M. Bellec, *Quantum Fluids of Light Come into Sharper View*, Physics **16**, 74 (2023)].

Physical Review Letters 132, 183802 (2024)

Wave-Function Tomography of Topological Dimer Chains with Long-Range Couplings

F. Pellerin, R. Houvenaghel, W. A. Coish, I. Carusotto, and P. St-Jean

Engineering materials with specific topological properties requires an acute control over the hybridization of electronic orbitals. As was pioneered by the Haldane model, introducing next-nearest-neighbor coupling terms with arbitrary phases strongly enriches the variety of phenomena that can be observed in topological band models.

In this work, started during I. Carusotto's visit at the Université de Montréal, we use the frequency of the photon modes in an optical fiber loop as a synthetic dimension to engineer one-dimensional dimerized lattices with full control over the range, magnitude, and phase of the hopping terms. When only nearest-neighbor couplings are present, our lattice realizes the well-known Su-Schrieffer- Heeger (SSH) model, which displays two topologically distinct phases associated with the integer-valued winding number $\mathcal{W} = 0, 1$. A wider variety of phases with $\mathcal{W}$ ranging from -1 to 2 is realized by adding 3rd-nearest- neighbor hopping terms with specific amplitudes.

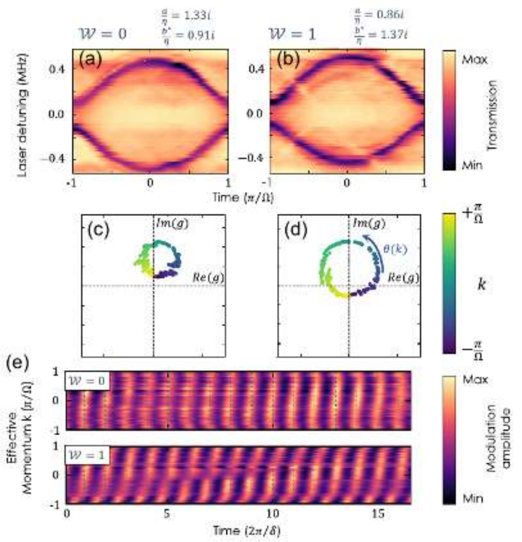


Figure 35: Experimental characterization of a SSH model: band structure (top); topological winding number (middle); experimentally observed transmission signal (bottom).

The entire topological phase diagram of this Hamiltonian is reconstructed using a wave-function tomography technique for the Bloch modes. Finally, we report the generation of a time-reversal-breaking synthetic gauge field, which allows to change the band topology without modifying the relative strength of the couplings.

The natural next step will be to relate this microscopic characterization of the topology to macroscopic observables such as a driven-dissipative version of the mean chiral displacement and edge states in the presence of frequency-space potentials. Setting up these tools will be instrumental in enabling investigations of more complex Hamiltonians in synthetic dimensions, involving non-Hermiticity, higher dimensions, many- body quantum states of light, non-Markovian dynamics, and/or optical nonlinearities.

This work was highlighted as a PRL Editors' suggestion and featured by a Synopsis *A Photonic Emulator of Topological Matter* in Physics.

Physical Review Letters 131, 193604 (2023)

Collective Excitations of a Strongly Correlated Nonequilibrium Photon Fluid across the Insulator-Superfluid Phase Transition

Fabio Caleffi, Massimo Capone, Iacopo Carusotto

Quantum fluids of light are rapidly growing as a new branch of many-body physics. Right after the observation of Bose-Einstein condensation and superfluidityin weakly interacting polariton fluids in semiconductor microcavities, exciting advances in circuit- QED engineering are preparing the ground for the realization of strongly interacting fluids in bosonic lattice models, so to explore the insulator-superfluid quantum phase transition in a novel out-of-equilibrium context. Extending the theoretical investigations to scenarios with non-Markovian incoherent pumping provide us with a whole new direction, as non-Markovian features proved crucial for the experimental creation of genuine insulating states in strongly interacting regimes.

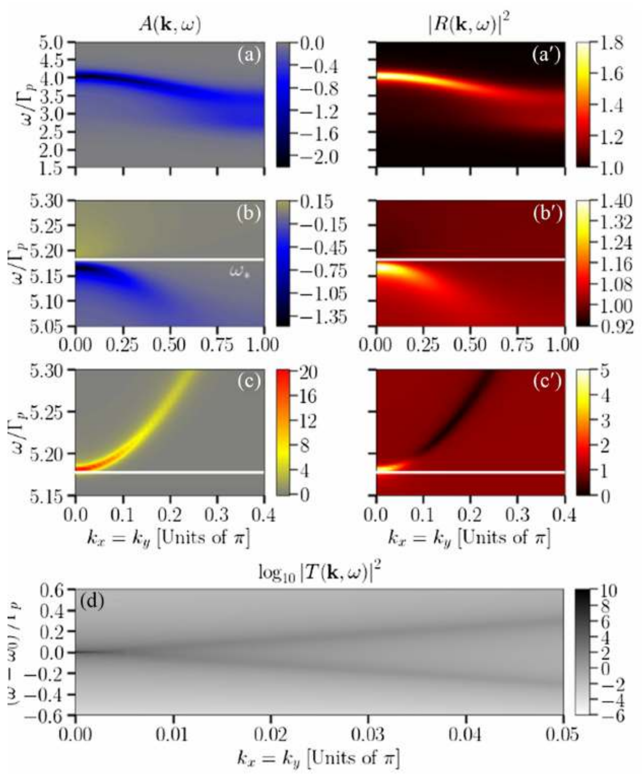


Figure 36: Examples of optical spectra in the different phases: density-of-states in the insulating phase (a-c) and transmission spectra in the superfluid phase (d).

In this Letter, we make use of the Gutzwiller ansatz and we extend it to the nonequilibrium context of strongly interacting photons in a cavity array under a non-Markovian and incoherent pump. The properties of the collective excitation spectrum across the insulating and superfluid phases are characterized, and novel, experimentally accessible features stemming from the non-equilibrium condition are highlighted. Observable fingerprints are identified in the response of the system to additional weak probes, e.g. a light amplification in a pump-and-probe configuration and a rich inter- play between coherence and dissipation underlying the diffusive nature of the Goldstone mode.

Thanks to its flexibility, our theory paves the way to a more general understanding of the exotic quantum phases that emerge in lattice systems driven out of equilibrium and can find experimental realization in the next generation of circuit- QED experiments.

Science Advances 9, eadj0360 (2023)

Artificial gauge fields in the $t-z$ mapping for optical pulses: Spatiotemporal wave packet control and quantum Hall physics

C. Oliver, S. Mukherjee, M. C. Rechstman, I. Carusotto, H. M. Price

Propagating geometries have proven to be a very fruitful platform for topological photonics, with a major early achievement being the investigation of Floquet topological insulators in which a honeycomb array of waveguides acquires a nontrivial topology when a helical patterning of the waveguides is introduced. So far, most, if not all, works on topological photonic effects using propagating geometries have used monochromatic light and so do not make substantial use of the temporal dynamics associated with an optical pulse propagating in a dispersive medium: within a so-called $t-z$ mapping, time t can be interpreted as an additional spatial dimension in addition to the transverse x, y ones, while the coordinate z along the propagation direction plays the role of a time.

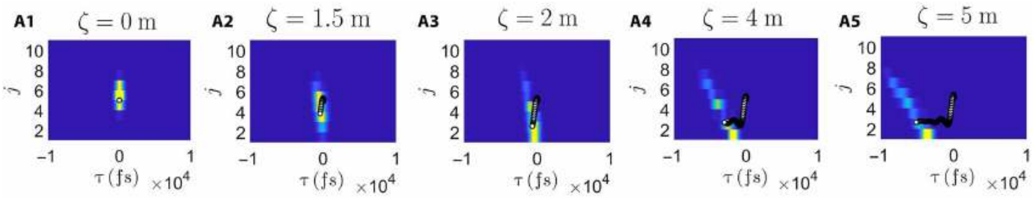


Figure 37: Effect of the anomalous Hall effect (A1-A3) and of the edge propagation (A3-A5) on the spatio-temporal dynamics of a light wavepacket in an inhomogeneous array of optical waveguides.

In this work, we propose a novel configuration based on an inhomogeneous array of coupled optical waveguides with slightly different properties where a synthetic gauge field naturally appears when the temporal dynamics of an optical pulse is taken into account under the $t-z$ mapping. We show that the 2D wave equation for the classical optical field propagation in a mixed spatial-j/temporal-t plane has the form of a Schrödinger equation including a synthetic vector potential term as in the coupled wire model of quantum Hall physics. A realistic configuration resulting in a sizable synthetic magnetic field and a nontrivial band topology is put forward, and experimentally accessible signatures of the magnetic effects are pointed out. These include a cyclotron motion of light wave packets in the spatiotemporal $j-t$ plane, a Hall drift in response to additional synthetic electric fields in either the spatial or the temporal direction, and unidirectional propagation in chiral edge states.

As compared to previous schemes for synthetic magnetic fields and synthetic dimensions in arrays of microcavities or waveguides, our proposal has the crucial advantage that it does not require a dynamical modulation of the system and provides a new tool for the manipulation of the spatiotemporal shape of optical wave packets. Moreover, the local interactions in our system suggest exciting prospects for strongly correlated fluids of photons if the interaction strength can be scaled up.

Physical Review Letters 127, 163901 (2021)

Superfluidity of Light and Its Breakdown in Optical Mesh Lattices

M. Wimmer, M. Monika, I. Carusotto, U. Peschel, and H. M. Price

The last decades have witnessed an impressive develop- ment of new conceptual links between the apparently disconnected fields of nonlinear optics and many-body physics of quantum gases. In this work, we introduce a new platform for studying fluids of light by using classical light in a so-called optical mesh lattice. The idea is to encode one (or even more) discrete synthetic spatial dimensions in the arrival time of optical pulses that propagate along coupled optical fiber loops. This allows for the application of arbitrary dynamical potentials to the fluid of light and for the measurement of its evolution in real time with key advantages over traditional systems. In contrast to semiconductor microcavities, our system provides great flexibility in the design of different lattice geometries with no fabrication effort and naturally offers site-resolved access to the temporal dynamics of the fluid without the need for sophisticated ultrafast optics tools. In contrast to bulk nonlinear systems, the nonlinearity stems from the power dependent propagation constant of optical fibers and is thus fully controllable with standard opto-electronic tools.

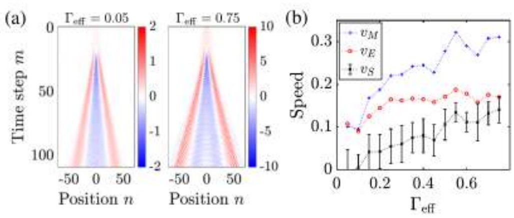


Figure 38: Direct experimental measurement of the sound speed in a fluid of light.

Here we report the first use of an optical mesh lattice as a platform to investigate fluids of light. In particular, we report a direct measurement of the speed of sound by looking at the response of the fluid to a temporally short and spatially localized perturbation. The conservative dynamics of our fluid of light then allows for a quantitative measurement of the friction force felt by a moving defect and of the consequent heating effect, providing unambiguous signature of superfluidity.

Taking advantage of the flexibility of the setup in designing different geometries, ongoing work is extending the investigation to fluids of light in lattices with nontrivial geometrical and topological properties in two or even higher $d > 3$ dimensions . From a more applicative perspective, the nonlinear optical mesh platform opens exciting new avenues to exploit the interplay of interference and nonlinear optical processes for manipulations of the quantum states of optical pulses in fibers.

This work was highlighted as a PRL Editors' suggestion and featured by a viewpoint *Photons Get Slippery* in Physics [K. hazzard, Physics **14**, 139 (2021)]. The long follow-up work *Theory of hydrodynamic phenomena in optical mesh lattices* by H. M. Price, M. Wimmer, M. Monika, U. Peschel, and I. Carusotto, Phys. Rev. A 108, 063517 (2023) was also selected as a PRA Editors' suggestion.

Physical Review X 12, 041019 (2022)

Frequency comb from a single driven nonlinear manomechanical mode

J.S. Ochs, D.K.J. Boneß, G. Rastelli, M. Seitner, W. Belzig, M.I. Dykman, E.M. Weig

The occurrence of frequency combs is a fascinating effect that plays an important role in several areas of science and technology. All frequency combs reported to date emerge from two or more nonlinearly coupled modes. Our experiment shows that, contrary to the conventional paradigm, a frequency comb can be generated by a single nanomechanical mode resonantly driven into a nonlinear regime. The theory is based on the mechanism of comb generation that differs qualitatively from the standard mechanisms.

Specifically, we show that the comb results from the modulation of the forced vibrations at the drive frequency by the low-frequency oscillations of the mode amplitude and phase. Such oscillations are strongly nonlinear, with multiple overtones, which are seen as a frequency comb in the laboratory frame. The demonstrated onset of a frequency comb in a single-mode system opens a qualitatively new route to the comb generation. The phenomenon is not limited to nanomechanics, which deserves further exploration and can lead to new technological applications.

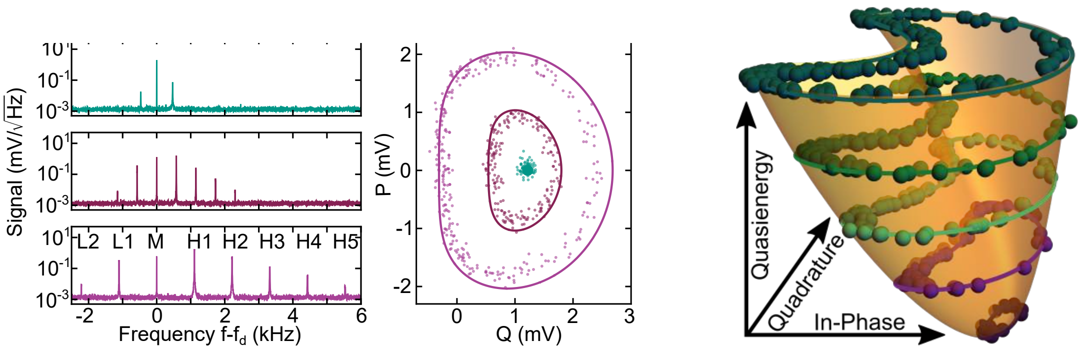


Figure 39: Left panel: Frequency combs in the power spectrum of a driven nonlinear mechanical resonator (a suspended nanowire) for different strength of the applied drive. The frequency comb corresponds to the modulation of the amplitude of the oscillatory mode at frequency smaller than the frequency of the drive. In the rotating frame the motion of the amplitude is described by close trajectory of an effective Hamiltonian in term of the two quadratures.

Physical Review B 106, 045408 (2022)

Engineering the speedup of quantum tunneling in Josephson systems via dissipation

D. Maile, J. Ankerhold, S. Andergassen, W. Belzig, G. Rastelli

It is common sense that when a quantum coherent system is not perfectly isolated from the environment, quantum effects are destroyed and the system fundamentally follows the classical mechanics' rules. This is not always the case. Indeed, the dissipative interaction, namely the interaction between a quantum system and its external bath, can lead to an enhancement of quantum effects.

We show that such a situation can occur when a particle in a metastable potential is coupled to a dissipative bath via its momentum. We find that the escape rate is exponentially enhanced. This theoretical model can be realized in a superconducting Josephson circuit with an extremely simple scheme to achieve the suitable dissipation. We demonstrate that the engineered electromagnetic environment formed by the external impedances and coupled to a current bias Josephson junction can enhance the quantum tunneling of the superconducting phase from a metastable state. A such environmentally assisted quantum tunneling can therefore speed up the relaxation dynamics of the phase towards the absolute energy minimum. This provides a proof of concept opening the route for the promising perspective of using quantum dissipative Josephson circuits as quantum simulators for optimization problems.

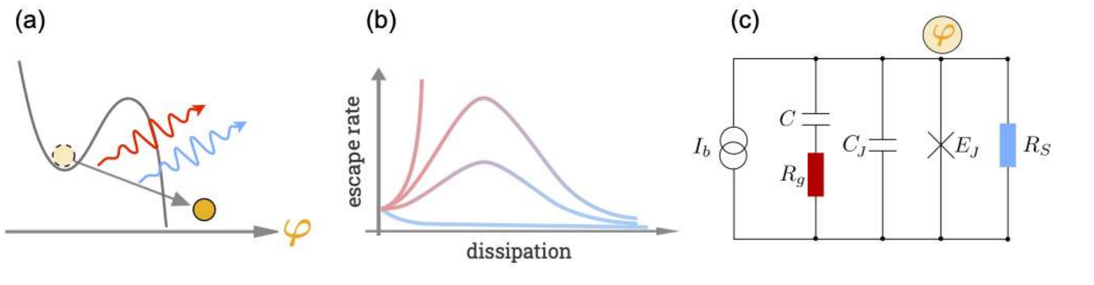


Figure 40: In an open quantum system, the quantum tunneling becomes inelastic as part of the energy is emitted into the environment (environmentally assisted quantum tunneling). Using engineered dissipation, the escape rate cab be enhanced by increasing the dissipative coupling strength. A such situation can be implemented in a current bias Josephson junctions in a controlled electromagnetic environment.

Physical Review X Quantum 3, 030308 (2022)

From non-Hermitian linear response to dynamical correlations and fluctuation–dissipation relations in quantum many-body systems

K. T. Geier and P. Hauke

The famous fluctuation–dissipation relation (FDR) establishes a deep connection between the intrinsic fluctuations of a system in thermal equilibrium and the energy dissipated in response to external perturbations. Despite being fundamental in statistical physics, it has to date only been measured in a classical context. For quantum systems, testing the FDR requires independent measurements of both commutators and anti-commutators of observables at unequal times, but a straightforward readout of such temporal correlations is hindered by the collapse of the wave function. While the two-time *commutator* can be probed in standard linear response experiments, a measurement of the two-time *anti-commutator* has been elusive so far.

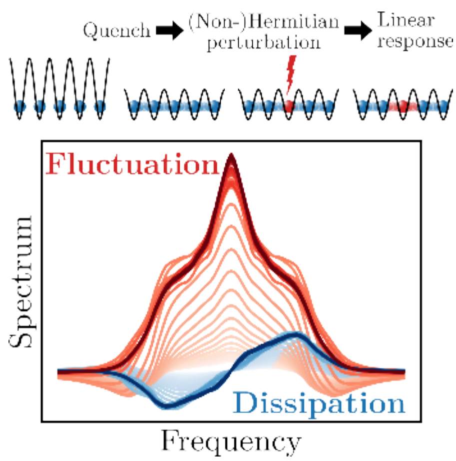


Figure 41: (Non-)Hermitian linear response protocol for measuring fluctuation–dissipation relations, illustrated for a Bose–Hubbard chain that undergoes thermalization following a quench from the Mott-insulating to the superfluid regime.

In our work, we show that the two-time anti-commutator can be measured by probing the linear response to a non-Hermitian perturbation and we propose experimentally feasible realizations of this scenario. The protocol relies on weakly coupling the system to an ancilla, which induces a loss of probability to a complementary state space that can be described by an effective non-Hermitian Hamiltonian. We illustrate the scheme through extensive numerical simulations at the example of measuring the FDR in a Bose–Hubbard system undergoing thermalization after a quantum quench (see Fig. 1).

Our approach opens up new avenues to characterize quantum many-body systems via dynamical correlations with manifold potential applications in quantum technologies. In addition, testing the FDR may help answering outstanding fundamental questions like whether and how isolated quantum systems locally evolve to thermal equilibrium.

J. High Energy Phys. 2022, 196 (2022)

Entanglement Witnessing for Lattice Gauge Theories

Veronica Panizza, Ricardo Costa de Almeida, and Philipp Hauke

Best poster award IQIS 2022 for V. Panizza

Quantum simulation will enable researchers to explore currently inaccessible features of crucial physical models. One specially interesting prospect is to realize lattice gauge theories and thus to study the role of entanglement in fundamental phenomena of elementary particles. To bring this prospect to fruition, it is necessary to develop tools to detect and characterize entanglement that factor in the presence of a gauge symmetry. Most importantly, gauge theories do not present a tensor-network structure of the Hilbert space, invalidating many conventional approaches to entanglement. In this work, we address this challenge and introduce entanglement witnesses as a tool for certifying the presence of entanglement in lattice gauge theories.

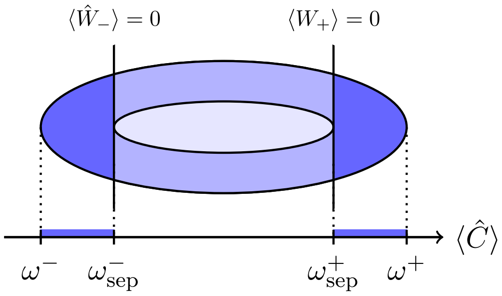


Figure 42: Schematics of the entanglement witnessing techniques. The observable $\hat{C}$ is taken in accordance with the underlying gauge symmetry to avoid false positives, and a subsequent optimization procedure allows us to construct witnesses $\hat{W}_{\pm}$. In the figure, we depict the space of states of the gauge theory. The lighter shade of blue corresponds to the set of separable states, the darker shade to those entangled states that can be certified with our method, and the intermediary shade to entangled states that cannot be identified

Quantum simulation will enable researchers to explore currently inaccessible features of crucial physical models. One specially interesting prospect is to realize lattice gauge theories and thus to explore fundamental phenomena of elementary particles with tabletop experiments. Particularly fascinating is the possibility of using such quantum simulation platforms to controllably study entanglement in gauge theories. To bring this prospect to fruition, it is necessary to develop tools to detect and characterize entanglement that factor in the presence of a gauge symmetry. Most importantly, due to this local symmetry constraint the system does not present a tensor-network structure of the many-body Hilbert space, invalidating many conventional approaches to entanglement. In this work, we address this challenge and introduce entanglement witnesses as a tool for certifying the presence of entanglement in lattice gauge theories.

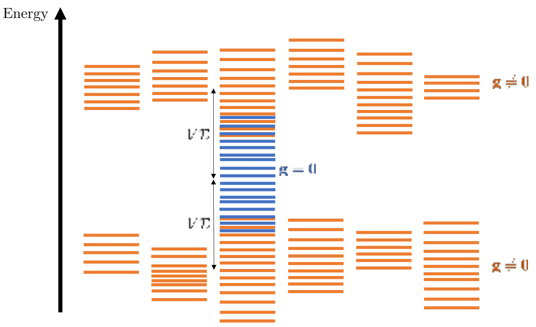
Physical Review X Quantum 2, 040311 (2021)

Gauge-Symmetry Protection Using Single-Body Terms

J. C. Halimeh, H. Lang, J. Mildenberger, Z. Jiang, P. Hauke

Quantum simulations of lattice gauge theories (LGTs) promise new avenues to address problems from particle, nuclear, and condensed-matter physics. A major challenge is to reproduce gauge invariance, since violations of this quintessential property of LGTs can have dramatic consequences, e.g., the generation of a photon mass in quantum electrodynamics.

In this work, we introduce an experimentally feasible method employing only single-body energy-penalty terms to protect gauge invariance in $U(1)$ lattice gauge theories against coherent errors in a controllable way. The gauge invariant subspace is protected by an emergent global symmetry, see figure below (left). We analytically show that some sets of penalty coefficients render undesired gauge sectors inaccessible by unitary dynamics for exponentially long times, and these results are confirmed by numerical calculations (up to $t > 10^{10}/J$, with J the relevant energy scale). For sufficiently large protection strength, gauge violations are suppressed quadratically even for non-local gauge-breaking errors, see figure (right). Moreover, for few-body error terms, we show numerically that this is achieved with resources exhibiting little dependence on system size. These findings constitute an exponential improvement over previously known results from energy-gap protection or perturbative treatments. Crucially, our gauge-protection technique can be readily implemented in current ultracold-atom analog simulators as well as digital noisy intermediate-scale quantum devices.



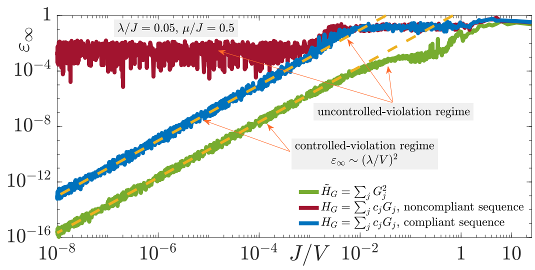


Figure 43: (Left) A lattice gauge theory can be decomposed into symmetry sectors characterized by an extensive number of local conserved quantities, defined by the gauge-symmetry generators G_j with eigenvalues $\mathbf{g} = (\ldots, g_j, \ldots)$. In realistic quantum simulator experiments, coherent error terms can break the gauge symmetry. The gauge protection $VH_G = V\sum_j c_j G_j$ induces an emergent global symmetry that in the sector $\mathbf{g} = \mathbf{0}$ coincides with the local gauge invariance at sufficiently large V when coefficients c_j are compliant sequences. (Right) Infinite-time gauge violation in gauge-theory dynamics with inherent non-local gauge-breaking errors show the two-body energy penalty (green) and a single-body protection with the compliant sequence (blue) to exhibit a controlled suppression of gauge violations at large enough V. The error decreases controllably proportional to $(\lambda/V)^2$.

Physical Review Letters 127, 080501 (2021)

Polymer Physics by Quantum Computing

C. Micheletti, P. Hauke, P. Faccioli

Despite exciting recent progress, present-day quantum computers cannot yet outperform classical ones in solving challenging physics problems of general interest. However, the current growth rate of their performance is triggering a strong effort to design new algorithmic paradigms for tackling problems that are hard for classical computing, and thus understand the implied advantages and disadvantages. With its wealth of problems that are inherently hard computationally, classical statistical mechanics offers an ideal avenue for such endeavors. Yet, while the potential of quantum machines has been extensively explored for quantum many-body systems, thus far there have been very few classical statistical-mechanics applications, mostly in biophysics contexts.

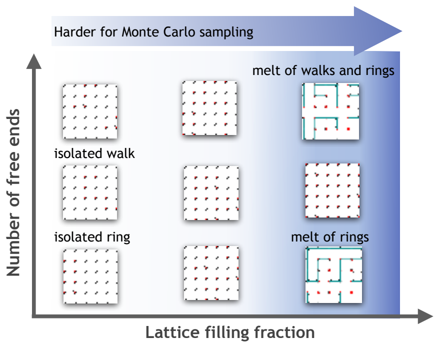


Figure 44: The quadratic unconstrained binary optimization (QUBO) formulation of the sampling problem allows for generating mixtures of polymers with discrete degrees of freedom (here schematised for a square lattice embedding) at fixed number of monomers and free ends. The QUBO problem complexity is set by the size of the embedding space and thus is insensitive to its filling fraction. Without any additional overhead it can thus reach regimes that are intrinsically hard for classical Monte Carlo approaches.

In this work, we discuss the use of quantum annealing machines to tackle a paradigmatic statistical mechanics problem, namely sampling the equilibrium ensemble of self-avoiding walks and rings, from dilute to concentrated solutions. Sampling equilibrium ensembles of dense polymer mixtures is a paradigmatically hard problem in computational physics, even in lattice-based models. Here, we develop a formalism based on interacting binary tensors that allows for tackling this problem using quantum annealing machines. Our approach is general in that properties such as self-avoidance, branching, and looping can all be specified in terms of quadratic interactions of the tensors. Microstates realizations of different lattice polymer ensembles are then seamlessly generated by solving suitable discrete energy-minimization problems. This approach enables us to capitalize on the strengths of quantum annealing machines, as we demonstrate by sampling polymer mixtures from low to high densities, using the D-Wave quantum annealer. Our systematic approach offers a promising avenue to harness the rapid development of quantum machines for sampling discrete models of filamentous soft-matter systems.

Science 377, 311-314 (2022)

Thermalization dynamics of a gauge theory on a quantum simulator

Z.Y. Zhou, G.X. Su, J.C. Halimeh, R. Ott, H. Sun, P. Hauke, B. Yang, Z.S. Yuan, J. Berges, J.-W. Pan

From formation of the early universe to heavy ion collisions, gauge theories that describe non-equilibrium dynamics of quantum fields are fundamental to our understanding of nature. Investigating these dynamics, however, remains theoretically as well as experimentally challenging. In a recent breakthrough experiment with theory support from the Pitaevskii BEC Center [Yang *et al.*, Nature 587, 392-396 (2020)], gauge invariance was first observed with a Bose–Hubbard quantum simulator of 71 lattice sites near equilibrium. Here, we exploit this Bose–Hubbard quantum simulator to investigate non-equilibrium dynamics of a lattice gauge theory after a quench.

We perform quantum simulations of the unitary dynamics of a U(1) symmetric gauge theory. We investigate how the gauge theory equilibrates to a steady state that is well approximated by a thermal ensemble, even though the system is isolated from any thermal bath. This work is thus a first step into the question how highly constrained systems such as gauge theories can thermalize after a perturbation away from equilibrium. It may thus have relevance to questions probed in subatomic systems in extreme conditions, such as the expanding fireball of quarks and gluons in a heavy-ion collision. Our work also opens the way towards the investigation of elusive dynamical phenomena of gauge theories, such as Schwinger pair production and string-breaking.

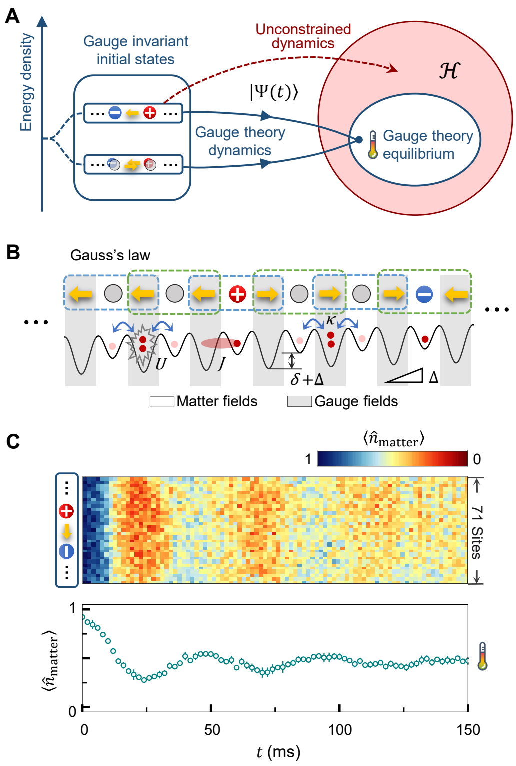


Figure 45: (A) Under the constrained (gauge) condition, different initial states with the same energy density evolve towards a common thermal state of the gauge theory. (B) The target gauge theory, describing electrons and positrons interacting with an electric field, is mapped to a Bose–Hubbard simulator. (C) Equilibration of the matter density following a violent quench. Top: experimental in-situ images. Bottom: spatial average.

Physical Review Research 6, L012052 (2024)

Extracting many-body quantum resources within one-body reduced density matrix functional theory

Carlos L. Benavides-Riveros, Tomasz Wasak, and Alessio Recati

Quantum Fisher information (QFI) is a central concept in quantum sciences used to quantify the ultimate precision limit of parameter estimation, detect quantum phase transitions, witness genuine multipartite entanglement, or probe nonlocality. Despite this widespread range of applications, computing the QFI value of quantum many-body systems is, in general, a very demanding task. Here we combine ideas from functional theories and quantum information to develop a functional framework for the QFI of fermionic and bosonic ground states. By relying upon the constrained-search approach, we demonstrate that the QFI matrix terms can universally be determined by the one-body reduced density matrix (1-RDM), thus avoiding the use of exponentially large wave functions. Furthermore, we show that QFI functionals can be determined from the universal 1-RDM functional by calculating its derivatives with respect to the coupling strengths, thus becoming the generating functional of the QFI. We showcase

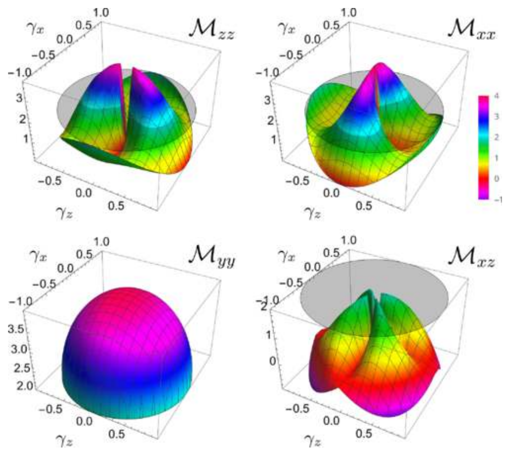
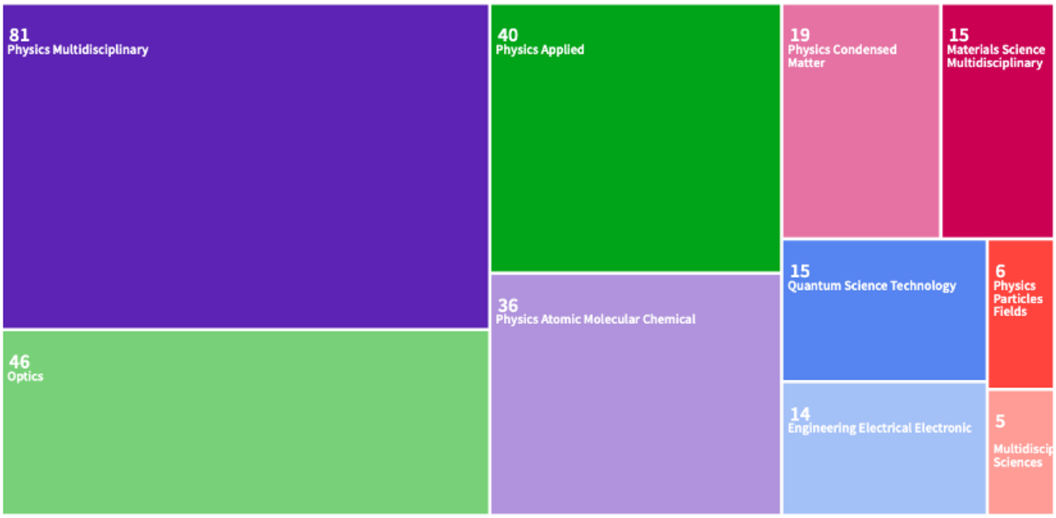


Figure 46: Example of universal functionals of QFIM for the repulsive Bose-Hubbard model (better dimer Hubbard model since the number of sites and particles are $N = 2$). The limit $\mathcal{M}_{\alpha\beta} = 2$ is indicated as a disk in gray.

our approach with the Bose-Hubbard model and present exact analytical and numerical QFI functionals. Our results provide the first connection between the one-body reduced density matrix functional theory and the quantum Fisher information.

Articles, preprints and highlights

Here below we list all publications of the BEC Center from July 2021 to June 2024 and a few highlights. The following figure shows the remarkable interdisciplinarity of the research activities of the BEC Center, quantified by the number of peer-reviewed articles published during the funding period, classified according to the subject classification scheme of ISI - Web of Science.



Published articles

2024

1. *Symmetry-Broken Perturbation Theory to Large Orders in Antiferromagnetic Phases*, Garioud, Renaud; Šimkovic, Fedor; Rossi, Riccardo; Spada, Gabriele; Schäfer, Thomas; Werner, Félix and Ferrero, Michel - Physical Review Letters **132** 246505 (2024)

2. *Development of KI-TWPAs for the DARTWARS project*, Ahrens, Felix; Ferri, Elena; Avallone, Guerino; Barone, Carlo; Borghesi, Matteo; Callegaro, Luca; Carapella, Giovanni; Caricato, Anna Paola; Carusotto, Iacopo; Cian, Alessandro; D'Elia, Alessandro; Di Gioacchino, Daniele; Enrico, Emanuele; Falferi, Paolo; Fasolo, Luca; Faverzani, Marco; Filatrella, Giovanni; Gatti, Claudio; Giachero, Andrea; Giubertoni, Damiano; Granata, Veronica; Guarcello, Claudio; Labranca, Danilo; Leo, Angelo; Ligi, Carlo; Maccarrone, Giovanni; Mantegazzini, Federica; Margesin, Benno; Maruccio, Giuseppe; Mezzena, Renato; Monteduro, Anna Grazia; Moretti, Roberto; Nucciotti, Angelo; Oberto, Luca; Origo, Luca; Pagano, Sergio; Piedjou, Alex Stephane; Piersanti, Luca; Rettaroli, Alessio;

Rizzato, Silvia; Tocci, Simone; Vinante, Andrea and Zannoni, Mario - Ieee Transactions On Applied Superconductivity **34** 1 (2024)

3. *Wave-Function Tomography of Topological Dimer Chains with Long-Range Couplings*, Pellerin, F.; Houvenaghel, R.; Coish, W.A.; Carusotto, I. and St-Jean, P. - Physical Review Letters **132** 183802 (2024)

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147. *Superfluidity of Light and Its Breakdown in Optical Mesh Lattices*, Wimmer, Martin; Monika, Monika; Carusotto, Iacopo; Peschel, Ulf and Price, Hannah M. - Physical Review Letters **127** 163901 (2021)

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149. *Probing Photoinduced Two-Body Loss of Ultracold Nonreactive Bosonic Na 23 Rb 87 and Na 23 K 39 Molecules*, Gersema, Philipp; Voges, Kai K.; Meyer zum Alten Borgloh, Mara; Koch, Leon; Hartmann, Torsten; Zenesini, Alessandro; Ospelkaus, Silke; Lin, Junyu; He, Junyu and Wang, Dajun - Physical Review Letters **127** 163401 (2021)

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Submitted articles

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1. *Topological classification of driven-dissipative nonlinear systems*, Villa, Greta; del Pino, Javier; Dumont, Vincent; Rastelli, Gianluca; Michałek, Mateusz; Eichler, Alexander and Zilberberg, Oded - arxiv.2406.16591.

2. *Quantifying non-Hermiticity using single- and many-particle quantum properties*, Bandyopadhyay, Soumik; Hauke, Philipp and Roy, Sudipto Singha - arxiv.2406.13517.

3. *Quantum Mixtures of Ultracold Atomic Gases*, Baroni, Cosetta; Lamporesi, Giacomo and Zaccanti, Matteo - arxiv.2405.14562.

4. *Symmetry-protection Zeno phase transition in monitored lattice gauge theories*, Wauters, Matteo M.; Ballini, Edoardo; Biella, Alberto and Hauke, Philipp - arxiv.2405.18504.

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7. *Theory of fractional quantum Hall liquids coupled to quantum light and emergent graviton-polaritons*, Bacciconi, Zeno; Xavier, Hernan; Carusotto, Iacopo; Chanda, Titas and Dalmonte, Marcello - arxiv.2405.12292.
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9. *Signatures of Conformal Symmetry in the Dynamics of Quantum Gases: A Cyclic Quantum State and Entanglement Entropy*, Maki, Jeff and Zhou, Fei - arxiv.2404.15827.
10. *Miscibility-Immiscibility transition of strongly interacting bosonic mixtures in optical lattices*, Bai, Rukmani and Bandyopadhyay, Soumik - arxiv.2403.14601.
11. *Quantum nonlinear optics on the edge of small lattice fractional quantum Hall fluids*, Nardin, Alberto; De Bernardis, Daniele; Umucalilar, Rifat Onur; Mazza, Leonardo; Rizzi, Matteo and Carusotto, Iacopo - arxiv.2403.10598.
12. *Loss induced collective mode in one-dimensional Bose gases*, Maki, Jeff; Rosso, Lorenzo; Mazza, Leonardo and Biella, Alberto - arxiv.2402.05824.
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16. *Unveiling Eigenstate Thermalization for Non-Hermitian systems*, Roy, Sudipto Singha; Bandyopadhyay, Soumik; de Almeida, Ricardo Costa and Hauke, Philipp - arxiv.2309.00049.
17. *Observation of the diffusive Nambu-Goldstone mode of a non-equilibrium phase transition*, Claude, Ferdinand; Jacquet, M.J.; Wouters, Michiel; Giacobino, Elisabeth; Glorieux, Quentin; Carusotto, Iacopo and Bramati, Alberto - arxiv.2310.11903.
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19. *Photonic lattices of coaxial cables: flat bands and artificial magnetic fields*, Oliver, Christopher; Nabari, Denis; Price, Hannah M.; Ricci, Leonardo and Carusotto, Iacopo - arxiv.2310.18325.

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21. *Mean-chiral displacement in coherently driven photonic lattices and its application to synthetic frequency dimensions*, Villa, Greta; Carusotto, Iacopo and Ozawa, Tomoki - arxiv.2309.16101.

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28. *Two-component spin mixtures*, Lamporesi, Giacomo - arxiv.2304.03711.

29. *A cavity quantum electrodynamics implementation of the Sachdev–Ye–Kitaev model*, Uhrich, Philipp; Bandyopadhyay, Soumik; Sauerwein, Nick; Sonner, Julian; Brantut, Jean-Philippe and Hauke, Philipp - arxiv.2303.11343.

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30. *Microscopic theory of cavity-enhanced interactions of dipolaritons*, Christensen, Esben R.; Camacho-Guardian, Arturo; Cotlet, Ovidiu; Imamoglu, Atac; Wouters, Michiel; Bruun, Georg M. and Carusotto, Iacopo - arxiv.2212.02597.

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32. *Temperature-Induced Disorder-Free Localization*, Halimeh, Jad C.; Hauke, Philipp; Knolle, Johannes and Grusdt, Fabian - arxiv.2206.11273.

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34. *Probing confinement in a $\mathbb{Z}_2$ lattice gauge theory on a quantum computer*, Mildenberger, Julius; Mruczkiewicz, Wojciech; Halimeh, Jad C.; Jiang, Zhang and Hauke, Philipp - arxiv.2203.08905.

35. *Populating and probing protected edge states through topology-entailed trivial states*, Piccioli, Francesco S.; Kremer, Mark; Ehrhardt, Max; Maczewsky, Lukas J.; Schmitt, Nora; Heinrich, Matthias; Carusotto, Iacopo and Szameit, Alexander - arxiv.2202.03252.

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38. *Suppressing nonperturbative gauge errors in the thermodynamic limit using local pseudogenerators*, Van Damme, Maarten; Mildenberger, Julius; Grusdt, Fabian; Hauke, Philipp and Halimeh, Jad C. - arxiv.2110.08041.

Highlights

The paper *False vacuum decay via bubble formation in ferromagnetic superfluids* by A. Zenesini *et at* is published on Nature Physics **20** 558–563 (2024). Thanks to the connection to other fields of physics, the paper got an outstanding popularity and was subject of tens of press releases, TV reports, social media covers and interviews as can be seen in details on the group website (QR code). The statistics on social media and press release popularity set the paper on the top 40 article published in the last 20 years of Nature Physics.

The paper *Squeezing and quantum approximate optimization* published as Gopal Chandra Santra *et al.*, Phys. Rev. A **109**, 012413 (2024) was selected as a PRA Editors' Suggestion.

The paper *Superfluid Fraction in an Interacting Spatially Modulated Bose-Einstein Condensate* coauthored by S. Stringari and published as G. Chauveau *et al.*, Phys. Rev. Lett. **130**, 226003 (2023) was selected as a PRL Editors' Suggestion.

The paper *Wave-Function Tomography of Topological Dimer Chains with Long-Range Couplings* coauthored by I. Carusotto and published as F. Pellerin *et al.*, Phys. Rev. Lett. **132**, 132, 183802 (2024), was featured by a Synopsis in Physics and was selected as a PRL Editors' Suggestion.

The paper *Disorder-free localization with Stark gauge protection* coauthored by H. Lang and P. Hauke, published as H. Lang *et al.*, Phys. Rev. B 106, 174305 (2022), has been selected as PRB Editors' Suggestion.

PHYSICAL REVIEW X

The paper *Frequency Comb from a Single Driven Nonlinear Nanomechanical Mode* coauthored by G. Rastelli has been published as J. S. Ochs *et al.*, Phys. Rev. X **12**, 041019 (2023) and featured by a synopsis in Physics.

The paper *Observation of vortices and vortex stripes in a dipolar condensate*, L. Klaus et al. coauthored by G. Lamporesi, Nature, **18** 1453 (2022) coauthored by G. Lamporesi has been selected for the Nature Physics News and Views.

The paper *Theory of hydrodynamic phenomena in optical mesh lattices* coauthored by I. Carusotto and published as H. M. Price *et al.*, Phys. Rev. A **108**, 063517 (2023), was selected as a PRA Editors' Suggestion.

The paper *Spectrum of collective excitations of a quantum fluid of polaritons* coauthored by I. Carusotto and published as F. Claude *et al.*, Phys. Rev. B **107**, 174507 (2023), was selected for a viewpoint in Physics.

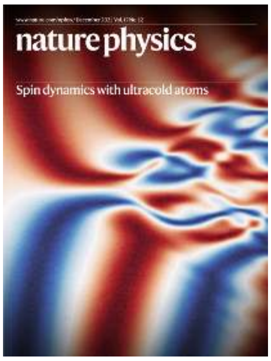
The paper *Excitations of Quantum Many-Body Systems via Purified Ensembles: A Unitary-Coupled-Cluster-based Approach* by C. L. Benavides-Riveros et al., published in Physical Review Letters **129**, 066401 (2022), has been selected as PRL Editors' Suggestion.

The article *Thermalization dynamics of a gauge theory on a quantum simulator*, coauthored by P. Hauke, has been published as Zhou et al., Science **377**, 311 (2022).

The paper *Topologically protected frequency control of broadband signals in dynamically modulated waveguide arrays* by Francesco S. Piccioli, Alexander Szameit, and Iacopo Carusotto, published in Physical Review A **105**, 033361 (2022), has been selected as PRA Editors' Suggestion.

The paper *Superfluidity of Light and Its Breakdown in Optical Mesh Lattices* coauthored by I. Carusotto, published as M. Wimmer *et al.*, Physical Review Letters **127**, 163901 (2021), has been was selected as PRL Editors' Suggestion and highlighted by a viewpoint in Physics.

The paper *Measurement of the order parameter and its spatial fluctuations across Bose-Einstein condensation* by L. Wolswijk, C. Mordini, A. Farolfi, D. Trypogeorgos, F. Dalfovo, A. Zenesini, G. Ferrari, and G. Lamporesi, published in Physical Review A **105**, 033361 (2022), has been selected as PRA Editors' Suggestion.



The paper *Quantum-torque-induced breaking of magnetic interfaces in ultracold gases* by Farolfi et al. has deserved the cover of the December 2021 issue of Nature Physics.
https://www.nature.com/nphys/volumes/17/issues/12
Press releases for the paper *Quantum-torque-induced breaking of magnetic interfaces in ultracold gases* by Farolfi et al, on INFN Website, Le Scienze, INO-CNR webite, CNR Website, CNR Twitter, CNR Facebook, CNR Instagram, CNR Linkedin, UNITN, UNITN Facebook, l'Adige, Nature Physics Facebook, Provincia Autonoma di Trento, TIFPA

The paper *Roadmap to Atomtronics* coauthored by S. Stringari has deserved the cover of the September 2021 issue of AVS Quantum Science.
https://pubs.aip.org/avs/aqs/issue/3/3

Meetings, seminars, conferences, honors, outreach

Group meetings and seminars at the BEC Center

- June 18th 2024 at 9.30 am in Via alla Cascata - BEC Seminar
  Sandro Stringari (Pitaevskii BEC Center)
  "Propagation of Sound in Ultracold Atomic Gases with Broken Symmetries"

- May 28st 2024 at 9.30 am in Via alla Cascata - BEC Seminar
  Ivan Amelio (Université Libre de Bruxelles)
  "Polaron spectroscopy of many-body systems"

- May 24th 2024 at 9.30 am in Via alla Cascata - BEC Seminar
  Rocío Sáez-Blázquez (Vienna Center for Quantum Science and Technology)
  "Detection of Goldstone and Higgs modes in strongly interacting lattice bosons"

- May 21st 2024 at 9.30 am in Via alla Cascata - BEC Seminar
  Carlo Di Castro (La Sapienza Roma)
  "New quantum criticality for the strange metal and Planckian behaviour in high temperature superconductors"

- May 7th 2024 at 9.30 am in Via alla Cascata - BEC Seminar
  Veronica Panizza (Pitaevskii BEC Center)
  "Protein design by integrating machine learning and quantum annealing"

- April 23rd 2024 at 9.30 am in Via alla Cascata - BEC Seminar
  Chiara Capecci (Pitaevskii BEC Center)
  "Quantum Computing Algorithms for Chemical Systems: Variational Approaches with Low Circuit Depth"

- April 9th 2024 at 9.30 am in Via alla Cascata - BEC Seminar
  Franco Dalfovo and Iacopo Carusotto (Pitaevskii BEC Center)
  "Meet the editors"

- April 4th 2024 at 10.30 am in room A218 - PhD defense
  Anna Berti (Pitaevskii BEC Center)
  "Simulation of curved-space quantum field theories with two-component Bose-Einstein condensates: from black hole physics to cosmology"

- April 2nd 2024 at 9.30 am in Via alla Cascata - BEC Seminar
  Johannes Lang (Pitaevskii BEC Center)
  "Open-system Boltzmann equation"

- March 26th 2024 at 9.30 am in Via alla Cascata - BEC Seminar
  Christian Johansen *"Drive and dissipation of a strongly correlated light-matter system"*

- March 19th 2024 at 9.30 am in Via alla Cascata - BEC Seminar
  Chiara Rogora (Pitaevskii BEC Center)
  "Towards a zero magnetic field environment for ultracold atoms experiments"

- March 5th 2024 at 9.30 am in Via alla Cascata BEC Seminar
  Jeff Maki (Pitaevskii BEC Center)
  "Loss induced collective mode in one-dimensional Bose gases"

- February 29th 2024 at 2 pm in Via alla Cascata - BEC Seminar
  Ragheed Al Hyder (Ecole Normale Supérieure de Paris)
  "Polarons in Lead Halide Perovskites"

- February 8th 2024 at 2 pm in Via alla Cascata - BEC Seminar
  Shunji Tsuchiya (Chuo University, Japan)
  "Evolution of entanglement entropy in strongly correlated bosons in an optical lattice"

- February 1st 2024 at 2 pm in Via alla Cascata - BEC Seminar
  Sebastiano Bresolin (Pitaevskii BEC Center)
  "Understanding why magnetic solitons oscillate under a constant force"

- January 31st 2024 at 3 pm in Via alla Cascata - BEC Seminar
  Nicola Grani (LENS-UNIFI)
  "Kelvin-Helmholtz instability by single-vortex tracking in Fermi superfluids"

- January 31st 2024 at 2.30 pm in Via alla Cascata - BEC Seminar
  Diego Hernandez-Raikov (LENS-UNIFI)
  "Dissipative vortex dynamics in a strongly interacting fermionic superfluid"

- January 31st 2024 at 2 pm in Via alla Cascata - BEC Seminar
  Giulia Del Pace (LENS-UNIFI)
  "Supercurrents in atomic superfluid rings"

- January 25th 2024 at 2 pm in Via alla Cascata - BEC Seminar
  Raffaele Borrelli (University of Torino)
  "Finite-Temperature electron-vibrational problems: Tensor-Train methodologies in closed and open system approaches"

- January 18th 2024 at 2 pm in Via alla Cascata - BEC Seminar
  Matteo Michele Wauters (Pitaevskii BEC Center)
  "Hunting for the topological Kondo effect in multiterminal quantum devices"

- January 11th 2024 at 2 pm in Via alla Cascata - BEC Seminar
  Pietro Brighi (University of Vienna)
  "Quantum Hilbert space fragmentation and anomalous transport in particle conserving kinetically constrained models"

- December 21st 2023 at 2 pm in Via alla Cascata - BEC Seminar
  Tomoki Ozawa (AIMR-Tohoku University, Japan)
  "Ultracold atoms with density-difference-dependent hoppings: coexistence of condensate and solitons, emergent SSH physics, and many-body non-Hermitian topology"
- December 20th 2023 at 2 pm in room A208 - PhD defense
  Francesco Piccioli (Pitaevskii BEC Center)
  "Topological photonics in guided wave geometries - A topological toolbox or signal processing"
- December 20th 2023 at 10.30 am in room A110 - BEC Seminar
  Francesco Riboli (CNR-INO, Florence)
  "Physical unclonable functions exploitingdisordered photonics for cryptography"
- December 15th 2023 at 2.30 pm in room A224 - PhD defense
  Julius Mildenberger (Pitaevskii BEC Center)
  "Towards Error-Resilience in Quantum Simulation of Lattice Gauge Theories"
- December 7th 2023 at 2 pm in Via alla Cascata - BEC Seminar
  Sebastiano Peotta (Aalto University, Finland)
  "Superfluidity in a flat band: from the quantum metric to the minimal quantum metric"
- November 30th 2023 at 2 pm in Via alla Cascata - BEC Seminar Gabriele Spada (Pitaevskii BEC Center) *"Attractive solution of binary Bose mixtures: Liquid-vapor coexistence and critical point"*
- November 23rd 2023 at 2 pm in Via alla Cascata - BEC Seminar
  Luis Colmenarez (RTWH Aachen University, Germany)
  "Quantum error correction: introduction, challenges and solutions"
- November 20th 2023 at 2 pm in room A209 (Povo1) - BEC Seminar
  Paolo Stornati (ICFO Barcelona, Spain)
  "Variational quantum simulation using non-Gaussian continuous-variable systems"
- November 16th 2023 at 4 pm in room A105 - PhD defense
  Riccardo Cominotti (Pitaevskii BEC Center)
  "Experiments with Coherently-Coupled Bose-Einstein condensates: from magnetism to cosmology"
- November 9th 2023 at 2 pm in Via alla Cascata - BEC Seminar
  Andrea Legramandi (Pitaevskii BEC Center)
  "Spectral correlations and phase transitions in SYK-like models"
- October 31st 2023 at 2 pm in Via alla Cascata - BEC Seminar
  Servaas Kokkelmans (Eindhoven University, Netherlands)
  "Multichannel nature of the lithium few-body puzzle"

- October 26th 2023 at 2 pm in A108 (Povo1) - BEC Seminar
Sebastian Schmitt (Honda Research Institute, Germany)
"Solving realistic application problems with quantum algorithms"

- October 18th 2023 at 2 pm in Via alla Cascata - BEC Seminar
Greta Villa (Universität Konstanz, Germany)
"Multicriticality in a driven parametric resonator, induced by the competition between a parametric and an external driving force"

- October 12th 2023 at 2 pm in Via alla Cascata - BEC Seminar
Cosetta Baroni (IBK University, Austria)
"Polarons and their mediated interactions in Fermi-Bose and Fermi-Fermi mixtures of Li and K"

- October 5th 2023 at 3 pm in Via alla Cascata - BEC Seminar
Stephanie Matern (Lund University, Sweden)
"Interacting parallel QDs: Metastability and quantum sensing"

- October 5th 2023 at 2 pm in Via alla Cascata - BEC Seminar
Marija Šindik and Tomasz Zawislak (Pitaevskii BEC Center)
"Quantized vortices and sound velocities across the superfluid-supersolid transition in a dipolar Bose gas"

- September 28th 2023 at 2 pm in Via alla Cascata - BEC Seminar
Gianluca Rastelli (Pitaevskii BEC Center)
"Nonlinear effects and dynamical instability in nanomechanical systems"

- Monday, Jul. 24th 2023, at 14h30 in in Aula A224 of Povo 1 Building. - PhD defense
Philipp Johann Uhrich (Pitaevskii BEC Center)
Towards Quantum Simulation of the Sachdev-Ye-Kitaev Model

- Wednesday, Jul. 19th 2023, at 10h30 in in Aula A203 of Povo 1 Building. - PhD defense
Daniele Contessi (Pitaevskii BEC Center)
Data driven approach to detection of quantum phase transitions

- Wednesday, 12th 2023, at 11h30 in in Aula A224 of Povo 1 Building. - PhD defense
Alberto Nardin (Pitaevskii BEC Center)
Linear and nonlinear edge dynamics and quasiparticle excitations in fractional quantum Hall systems

- Wednesday, June 28st 2023, at 14.00, room A221 of the Povo1 building - BEC Seminar
Alonso Viladomat Jasso (Munich)
Counterfactual quantum computation, communication and cryptography

- Tuesday, June 27st 2023, at 17.00, room A221 of the Povo1 building - BEC Seminar
  Michail Skoteiniotis (Universidad de Granada)
  Copying Quantum Channels
- Wednesday, June 21st 2023, at 14.00, room A107 of the Povo1 building - BEC Seminar
  Giuseppe Clemente (DESY Berlin)
  Quantum Algorithms for Lattice QFTs at Finite Temperature and Non-Abelian Gauge Theories
- Friday 19th, May 2023, at 14.00, room A214 of the Povo1 building - BEC Lecture
  Alvise Bastianello (TU Munich)
  Confinement in one-dimensional spin chains out of equilibrium: Lecture 2
- Thursday 18th, May 2023, at 13.30, room A214 of the Povo1 building - BEC Lecture
  Alvise Bastianello (TU Munich)
  Confinement in one-dimensional spin chains out of equilibrium: Lecture 1
- Thursday 13th, April 2023, at 10.30, room A219 of the Povo1 building - BEC Seminar
  Kevin Thomas Geier(INO-CNR Pitaevskii BEC Center)
  Is the Stripe Phase in Spin-Orbit-Coupled Bose-Einstein Condensates Truly Supersolid
- Tuesday 28th, March 2023, at 9.30, room 7 of the Povo0 building - BEC Colloquium
  Tomasz Wasak (Institute of Physics Nicolaus Copernicus University, Torun, Poland)
  Quantum kinetic theory of Fermi polarons
- Wednesday 22th, February 2023, at 14.30, room A209 of the Povo1 building - BEC Colloquium
  Philipp Heinen (University of Heidelberg)
  Universality far from equilibrium and non-thermal fixed points
- Wednesday 15th, February 2023, at 15.00, room 7 of the Povo0 building - BEC Colloquium
  Luca Gravina (EPFL Lausanne)
  A critical cat code
- Tuesday 14th, February 2023, at 15.00, room 7 of the Povo0 building
  - BEC Colloquium
  Fabrizio Minganti (EPFL Lausanne)
  Critical dissipative phenomena
- Wednesday 1st, February 2023, at 11.00, room 7 of the Povo0 building - BEC Colloquium
  Mikel Garcia de Andoin (University of the Basque Country (UPV/EHU) and Tecnalia)
  Digital-Analog Quantum Computation
- Thursday, December 15, 2022, at 10:00, room 7 Povo0, BEC Internal Seminar
  Victor Colussi (BEC Center)
  Lattice polarons, Higgs mode, and the Dolomiti: A recap of my time at the BEC Center

- Tuesday, December 13, 2022, at 10:00, room 7 Povo0, - BEC Seminar
  Matteo Foresti (University of Bergamo, University of Milano-Bicocca)
  Topological effects of vortices in Bose-Einstein Condensates and possible experiments

- Wednsday, December 7, 2022, at 11:00, room 7 Povo0, - BEC Seminar
  Philipp Uhrich (BEC Center)
  Proposal for analog quantum simulation of theSachdev-Ye-Kitaev model in cavity-QED

- Monday, November 9, 2022, at 10:30, A209 Povo1, - BEC Colloquium
  Carlos Leonardo Benavides-Riveros (INO-CNR Pitaevskii BEC Center)
  All quantum spectra in one shot

- Wednesday, October 26, 2022, 10:30, A219 Povo1, - BEC Seminar
  Daniele De Bernardis (BEC Center)
  Magnetic-field-induced cavity protection for intersubband polaritons

- Tuesday, October 25, 2022, at 10:30, room 7 Povo0, - BEC Seminar
  Marius Sparn (Kirchhoff-Institut für Physik-University of Heidelberg)
  Quantum Field Simulator for a relativistic scalar field in curved space time

- Monday, October 17, 2022, at 14:00, A223 Povo1, - BEC Colloquium
  Lin Rui (ETH Zürich)
  Dissipative dynamics and many-body dark states in cavity-BEC systems

- Thursday, September 22, 2022, at 14:30, A220 Povo1 and online meeting, - BEC Colloquium
  Stefan Lannig (Kirchhoff-Institut für Physik-University of Heidelberg)
  Collisions of 3-Component Vector Solitons

- Monday, September 19, 2022, at 14:00, A221 Povo1 and online meeting, - BEC Colloquium
  Dimitri Gangardt (University of Birmingham)
  Relaxation of phonons in the Lieb-Liniger gas by dynamical refermionization

- Wednesday, September 7, 2022, at 11.00, Theory seminar room Povo0 and Online, - BEC Colloquium
  Grigori Astrakharchik (Polytechnic University of Catalonia)
  Formation of liquids in low-dimensional dipolar systemss

- Friday, June 24, 2022, at 9:30, A108 Povo1 and Online, - PhD defence
  Louise Wolswijk (BEC Center)
  Equilibrium and out-of-equilibrium physics of Bose gases at finite temperature

- Friday, June 24, 2022, at 15:30, A222 Povo1 and Online, - BEC Seminar
  Ian Spielman (JQI)
  Dynamically symmetry breaking in a bipartite optical lattice

- Wednesday, May 25, 2022, at 16:30, A222 Povo1 and Online, - BEC Seminar
  Gabriele Spada (BEC Center)
  Phase separation in Bose mixtures at finite temperature

- Wednesday, May 18, 2022, at 16:30, A222 Povo1 and Online, - BEC Seminar
  Anna Berti and Riccardo Cominotti (BEC Center)
  Observing quantum phase transitions and elementary excitations in superfluid spin mixtures

- Wednesday, May 11, 2022, at 15:30, A222 Povo1 and Online, - BEC Seminar
  Carlos Gonzalez-Ballestero (Univ. Innsbruck)
  Levitodynamics: toward new regimes of quantum physics

- Wednesday, April 27, 2022, at 15:30, A222 Povo1 and Online, - BEC Seminar
  Alberto Biella (BEC Center)
  Emergent non-Hermitian dynamics in open many-body systems

- Tuesday, April 12, 2022, at 14:00, A218 Povo1 and Online, - PhD defence
  Matteo Sighinolfi (UNITN)
  Open Quantum Systems and Ultracold Atoms

- Wednesday, March 23, 2022, at 11:00, Online Meeting, - BEC Seminar
  Jeff Maki (HKU) *p-Wave Fermi Gases in Confined Geometries*

- Monday, March 14, 2022, at 15:30, A204 Povo1 and Online, - BEC Seminar
  Andrea Richaud (SISSA)
  Dynamics of massive point vortices in a binary mixture of Bose-Einstein condensates

- Friday, December 10, 2021, at 14:30, A225 Povo1 and Online, - BEC Seminar
  Yuri Minoguchi (TU Wien)
  Measurement induced dynamics: On finding all ways for entanglement to die

- Friday, December 3, 2021, at 14:30, A225 Povo1 and Online, - BEC Seminar
  Benedikt Schneider (LMU)
  Projective symmetry group classification of chiral Z_2 spin liquids on the pyrochlore lattice: Application to the XXZ Model

- Friday, November 26, 2021, at 9:00, Online Seminar, - BEC Seminar
  Joachim Brand (Massey Univ.)
  Putting the universe on the tabletop with coherently coupled superfluids

- Friday, November 19, 2021, at 14:30, A225 Povo1 and Online, - BEC Seminar
  Elettra Neri (ICFO)
  Realizing a 1D topological gauge theory in an optically dressed BEC

- Thurday, November 18, 2021, at 15:00, A218 Povo1 and Online, - PhD defence
  Santo Maria Roccuzzo (UNITN)
  Supersolidity in a Dipolar Bose Gas

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

- May 2, 2024 Q@TN Colloquium
  Lorenzo Scarpelli (TU Delft)
  Quantum acoustic with gigahertz mechanical vibrations

- December 20, 2023 Q@TN Colloquium
  Francesco Riboli (INO-CNR Sesto Fiorentino)
  Physical Unclonable Functions: exploiting disordered photonics for cryptography

- October 23, 2023 Q@TN Colloquium
  Matteo Barbone (Munich, Germany)
  *2*D materials as a platform for (topological?) quantum science & technology

- July 25, 2023 Q@TN Seminar
  Gianluigi Catelani (Abu Dhabi, EAU)
  *M*odelling superconducting qubits: some history and recent advances

- July 13, 2023 Q@TN Colloquium
  Mark Oliver Goerbig (LPS Orsay, France)
  Volkov-Pankratov states in smooth topological interfaces

- January 26, 2023 Q@TN Colloquium
  Nicolas Roch (CNRS Grenoble, France)
  Josephson meta-metarials: a new platform for quantum optics

- December 5, 2022 Q@TN Seminar
  Pasquale Scarlino (EPFL Lausanne, Switzerland)
  High impedance superconducting technology for hybrid devices and analog quantum simulation

- November 29, 2022 Q@TN Seminar
  Michele Governale (Victoria University of Wellington (New Zealand))
  Topological-Insulator nanocylinders

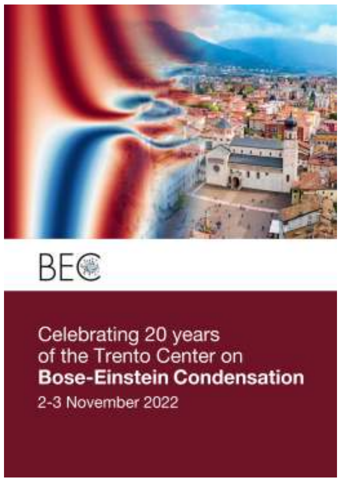
- Friday, September 16, 2022, at 14:30, A210 Povo1, Q@TN Colloquium
  Guglielmo Mazzola (Institute for Computational Science, University of Zurich, Switzerland)
  Quantum computing and Monte Carlo

- Friday, June 7, 2022, at 14:00, A204 Povo1 and Online, Q@TN Colloquium
  Niccolò Crescini (Grenoble)
  Current quantum metrology
- Friday, February 25, 2022, at 14:00, A104 Povo1 and Online, Q@TN Colloquium
  Alberto Amo (CNRS and Univ. Lille, France)
  Engineering optical cavities via drive and dissipation in photonic lattices
- Tuesday, November 16, 2021, at 14:00, Aula Seminari di Fisica Teorica Povo0 and Online, Q@TN Colloquium
  Valerio Scarani (CQT - NUS Singapore)
  Irreversibility as irretrodictability

International meetings organized or co-organized by the BEC Center

Celebrating 20 years of the Trento BEC Center
Trento, November 2-3, 2022

The year 2022 has marked 20 years since the creation of the Trento Center on Bose-Einstein Condensation. This event, kindly hosted by the Department of Humanities and the Bruno Kessler Foundation, has been possible thanks to the support from the University of Trento and the Consiglio Nazionale delle Ricerche (CNR).
After the opening remarks by Flavio Deflorian (UNITN), Maria Chiara Carrozza (CNR, online), Francesco Saverio Cataliotti (CNR-INO), Achille Spinelli (PAT), Monica Baggia (Comune di Trento), Richard Hall-Wilton (FBK) and Eric Cornell (JILA, Nobel Prize Laureate, online), the first day included an overview by Franco Dalfovo on the first 20 years of the BEC center, a memory by Sandro Stringari of Lev Pitaesvkii and a Lectio Magistralis by Wolfgang Ketterle (MIT, Nobel Prize Laureate). During the second day, the present and future research at the BEC Center was presented by the staff members.



https://bec.science.unitn.it/BEC/BEC20/20years_BEC.html

ECT Workshop on*
"Quantum simulation of gravitational problems on condensed matter analog models"
ECT* (Trento), June 19th-23rd, 2023

This interdisciplinary workshop has gathered specialists from theoretical and experimental condensed matter physics, quantum optics, quantum information, and from theoretical cosmology, gravitation and astrophysics. It is the 4th edition of a series of key events that have fostered the transition of analog models from being a scientific curiosity towards being a useful quantum simulation tool to experimentally explore new physics. The specific goal of this edition was to stimulate interdisciplinary studies of condensed matter analog models of gravity as a concrete experimental tool to attack outstanding problems that arise in the context of gravitation, cosmology and astrophysics. The present challenge is to keep extending the range of configurations that can be simulated, and to identify the most important questions to be addressed.

A special event in memory of Renaud Parentani (1962-2020) has taken place on Wed. 21st. In collaboration with SIGRAV, a "Parentani medal" prize has been offered to the best contribution by a young participant.
Financial support was provided by the Q@TN joint laboratory, INFN, SIGRAV, and Trento University.
https://indico.ectstar.eu/event/170/

Quantum Science Generation Workshop
ECT*, May 2nd-5th, 2023

The first aim of the QSG workshop was to offer seminars held by young scientists and leading researchers in theoretical and experimental quantum physics. The talks were divided between senior and junior invited speakers, in addition to further contributions selected among all the participants. Moreover we had special contributed talks from company and startup representatives working in the field of quantum science and technology.
As a second purpose, the QSG workshop tried to promote and facilitate discussions between the students, postdocs, young researchers and experienced professors through suitably designed social activities.
https://indico.ectstar.eu/event/162/overview

Quantum Science Generation Workshop – 2024
ECT*, May 6th-10th, 2024

This is the second edition of the QSG workshop, which aims at becoming a recurring, yearly, appointment gathering together early-stage and experienced researchers in the field of quantum science and technology. The first aim of the QSG workshop was to offer seminars held by young scientists and leading researchers in theoretical and experimental quantum physics. The talks were divided between senior and junior invited speakers, in addition to further contributions selected among all the participants. Moreover, we had special contributed talks from company and startup representatives working in the field of quantum science and technology. As a second purpose, the QSG workshop tried to promote and facilitate discussions between the students, postdocs, young researchers, and experienced professors through suitably designed social activities.

The objective of the Quantum Science Generation Workshop 2024 was to cover some of the most important aspects of those developments and provide an up-to-date overview of the most active areas of research within this field. The workshop's topics included optical and condensed matter platforms for quantum computing; quantum simulation of problems of interest for condensed matter, nuclear, high-energy, or gravitational physics; and hybrid quantum algorithms for optimization problems.
https://indico.ectstar.eu/event/204/

PreDoctoral School on
"Quantum Photonics in Solid State Devices"
Lecce, April 8th-12th, 2024

The school consists of morning theory classes followed by afternoon experimental sessions and aims to be a gateway to the fascinating realm of quantum photonics in solid-state devices. Whether you are an undergraduate or recent graduate, our program is designed to provide you with essential knowledge, laying the foundation for an exciting Ph.D. course in this cutting-edge field. The program is dedicated to exploring light-matter interactions at the quantum scale, covering a wide range of physics concepts from Bose-Einstein condensation to quantum fluids of light, with a focus on the behaviour of atoms, photons, and polaritons.

The peculiarity of this school apart is its interdisciplinary approach. We integrate theoretical understanding with hands-on experimentation and programming, encouraging students to delve into the intricacies of quantum systems. In the state-of-the-art laboratories of CNR-Nanotech, students collaborate with distinguished researchers who are not only experts in their respective fields but also passionate mentors dedicated to nurturing the next generation of quantum scientists.
https://polaritonics.nanotec.cnr.it/photonics-school-2024/

Q@TN Workshop on
"Circuit QED: from Quantum Devices to Analogues on Superconducting Circuits"
FBK (Trento), Oct 3-5, 2022

This workshop aimed at bringing together theorists and experimentalists working in the field of superconducting (SC) circuits to discuss the present status of the research in Circuit QED (cQED), the opportunities for developing new devices suitable for investigating fundamental physics through analogues on SC circuits, and their applications in quantum information, metrology, sensing and, in particular, quantum simulation of quantum field theories on temporally modulated geometries and/or curved space-times.

The workshop hosted a Special Session on Microwave Quantum Detection (MQD) organized on the platform of the SUPERGALAX project funded by the European Union's Horizon 2020 research and innovation programme.
Financial support was provided by the Q@TN joint laboratory, INFN, and FBK.
https://agenda.infn.it/event/31349/


International school of physics "Enrico Fermi" COURSE 211 -
QUANTUM MIXTURES WITH ULTRA-COLD ATOMS
Varenna, July 18-23, 2022

Directed by Rudolf Grimm, Massimo Inguscio and Sandro Stringari and organized by Giacomo Lamporesi, the School covered the following topics: Bose-Bose, Bose-Fermi and Fermi-Fermi mixtures, Solitons and vortices in quantum mixtures, Bose and Fermi polarons, Liquid phase and quantum droplets with ultracold atoms, Quantum mixtures in low dimensions, Coherently-coupled quantum gases, Few-body physics, Quantum simulations of gauge theories, Hybrid

quantum mixtures (atoms and ions), Mixtures for quantum technologies.
https://www.sif.it/corsi/scuola_fermi/mmxxii/211

International school of physics "Enrico Fermi" COURSE 209 - QUANTUM FLUIDS OF LIGHT AND MATTER - QFLM2022
Varenna, July 2-7, 2022

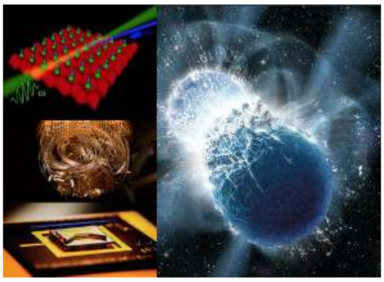
Directed by Alberto Bramati, Iacopo Carusotto and Cristiano Ciuti, the School covered the following topics: Quantum gases, Quantum fluids of light, Topological matter, Topological photonics, Strongly correlated open quantum systems, Quantum trajectories and quantum jumps in quantum optics, Quantum optics with Rydberg atoms, Circuit QED, Optics of strongly correlated electron gases, History of nonlinear optics.
https://www.sif.it/corsi/scuola_fermi/mmxxii/209

SPRING SCHOOL 2022: Quantum Science and Technologies at Trento
Trento, April 19-23, 2022

Organized by Gabriele Ferrari, the School gave a basic introduction into the fascinating research field of quantum sciences and technologies and the related educational offers at the master's level available in Trento, with the aim to motivate people to pursue this topic in their master degree, possibily at UniTn.

Tutorial lectures given by experts from the research institutes active in Trento on quantum sciences and technologies covered the main topics. The lectures were supplemented by lab visits and social events.
https://quantumtrento.eu/spring-school-2022-registration-opened/

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 are 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

Interdisciplinary Workshop on Supersolidity

Trento, September 20-22, 2021

The workshop was first scheduled in 2020, but due to the COVID pandemics has been postponed to September 2021.

The workshop has explored 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/

Tensor Networks: Quantum Physics, Geometry and Applications

Levico Terme, July 26-28, 2021

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 had to be postponed to July 2021 because of the COVID emergency. The goal of the workshop was to develop the connections between the mathematics and physics communities working on tensor network. As a key novelty, it was a hands-on event with a

limited number of talks and several sessions of active work. During these sessions, participants distributed themselves in small groups and actively worked 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

In July 2022, Sandro Stringari became National Associate Member of the Accademia dei Lincei.
https://www.lincei.it/it/news/nuovi-soci-2022

In June 2022, Iacopo Carusotto has been awarded with the Early Career Award of the Messori-Roncaglia/Mari Award of the Accedemia dei Lincei.
https://www.cnr.it/it/news/11191/a-iacopo-carusotto-il-premio-maria-teresa-messori-roncaglia-ed-eugenio-mari-dell-accademia-nazionale-dei-lincei

In December 2022, Alberto Biella has been awarded with the Early Career Award of the ILAMP 2021.
https://secondotempo.cattolicanews.it/news-assegnati-i-premi-ilamp-2021

Outreach

On April 13th, 2023, Franco Dalfovo was invited to give a presentation on “Il mondo dei quanti: intrecci coerenti e altre stranezze” in the framework of the National Competition in Physics, organized by the Associazione per l’Insegnamento della Fisica in Senigallia.

On Feb.21st, 2024, the Associazione Italiana Studenti di Fisica invited Franco Dalfovo to give a presentation in the framework of the Trento-Innsbruck Quantum Information Tour 2024 on “Cosa (non) è la Meccanica Quantistica” at the Fondazione Caritro in Trento.

On May 8th, 2023, in the framework of the Beer & Physics meetings organized by the Associazione Italiana Studenti di Fisica, Sandro Stringari, Franco Dalfovo and Anna Berti have been invited to speak about “Condensazione di Bose-Einstein” in memory of Lev Pitaevskii at the Bookique in Trento.

On June 20th, 2023, in connection with the workshop on “Quantum simulations of gravitational problems in condensed matter analog models” and in collaboration with the Associazione Italiana Studenti di Fisica, I. Carusotto, G. Ferrari, R. Balbinot have coorganized and moderated a Beer & Physics meeting on Modelli Analoghi di Gravità at the Bookique in Trento.

On March 14th, 2024, the MUSE in Trento has invited Alessio Recati e Gianluca Rastelli to contribute with a presentation “QUANTUM SESSION: Viaggio tra atomi, fotoni e superconduttori” in the framework of the MUSE-FUORI-ORARIO event.

Gianluca Rastelli, Alberto Biella, Alessio Recati and Daniele De Bernardis joined with other UNITN and CNR fellows to present the quantum world to a interested audience, within the initiative of the ”Italian Quantum Weeks” which began in 2022 and concluded in 2024. In specific:

ITALIAN QUANTUM WEEKS

- In 2022, two meetings on ”Il mondo dei quanti: Dall’atomo al computer quantistico” have been organized on April 7-8 at the Bookique in Trento.
- In 2023, other two meetings on 14 and 21 April have been organised with title ”Entanglement: intrecci di luce” at the Bookique in Trento.
- In 2024 a meeting has been organised on April 24th in connection with the exhibition “QUANTO. La rivoluzione in un salto” at MUSE-Trento with title “Meccanica quantistica: tra filosofia e tecnologie futuristiche”.