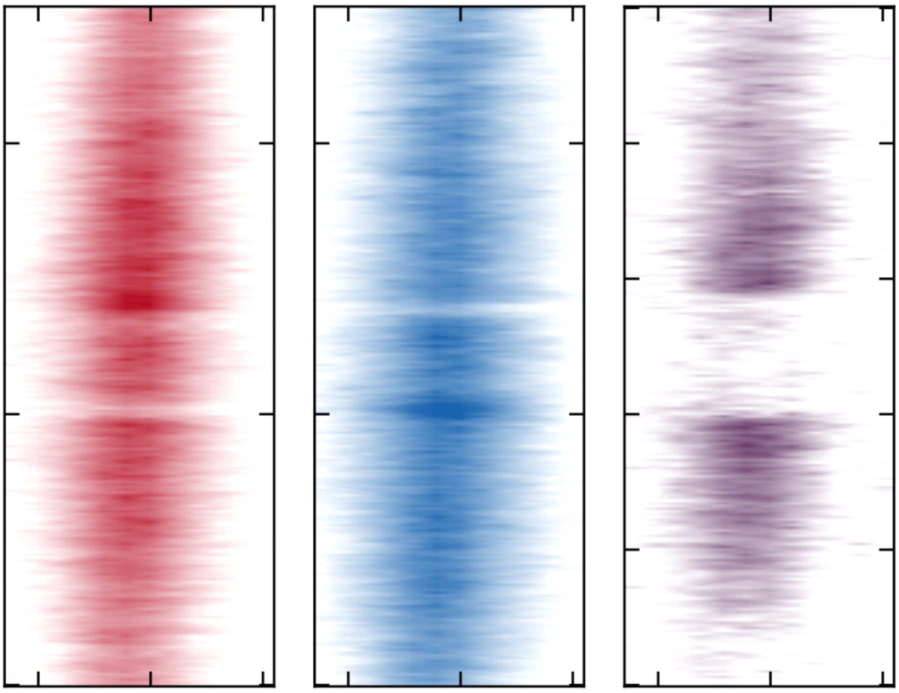
Center on **Bose-Einstein Condensation**, Trento, Italy

BEC

Scientific Report
July 2016 - December 2019



The BEC Center is a joint initiative of

CNR-INO
ISTITUTO NAZIONALE DI OTTICA
CONSIGLIO NAZIONALE DELLE RICERCHE

UNIVERSITÀ DEGLI STUDI
DI TRENTO
Dipartimento di Fisica

Contents

Overview

This is the final report on the research activities of the Center on Bose-Einstein Condensation (BEC Center) within the program funded by the Provincia Autonoma di Trento (PAT) from July 2016 to December 2019. The agreement with PAT is aimed at supporting the experimental and theoretical research on the physics of ultracold atoms and quantum gases. The main objective of the project is to consolidate the experimental laboratory of the BEC Center in terms of its capacity of working on frontier research topics. The experimental laboratory workflow includes: Kibble-Zurek mechanism for the spontaneous generation of quantum vortices and the study of the mechanisms of mutual interaction between vortices; measurement of the equation of state of weakly interacting Bose gases; observation of collective motions in multicomponent superfluid gases; study of condensates in the presence of resonant coupling between internal degrees of freedom. The experimental activities are developed in close connection with the theory group of the BEC Center. The spectrum of theoretical activities also includes broader topics on quantum gases and fluids, on superfluidity and coherence phenomena, analogies between properties of atomic gases and those of other systems in condensed matter, in quantum optics and, more generally, in systems where quantum mechanics manifests itself at a macroscopic level.

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 CNR researchers are regularly involved in education and training programs. In this sense, the BEC Center in Trento can be considered as a good example of close collaboration between CNR and University in the Italian context, where the links between these two institutions are often quite weak.

Since July 2016 the researchers of the BEC Center have published more than 110 articles in peer reviewed journals, including 22 Physical Review Letters, 1 Physical Review X, 2 Nature, 2 Nature Physics and 1 Nature Photonics. The activities of the BEC Center have involved 37 graduate students and postdocs, 14 of them coming from abroad, namely from China, India, Japan, France, Belgium, Poland, Spain, Great Britain, Greece, and New Zealand. In addition, 12 undergraduate and graduate students, coming from other universities in Italy and abroad, have spent a few months in Trento for internships and stages. More than 160 scientists have visited the Center, giving talks and discussing with local researchers about projects of common interest. The Center has co-organized 10 international meetings and 4 national meetings.

In the last months of 2019, two new scientists joined the BEC Center with a permanent position. Philipp Hauke, coming from the University of Heidelberg, is now associate professor at UniTrento; he is a theorist, expert in quantum optics, quantum information and synthetic quantum systems. He is currently setting up his own group in the the framework of the ERC Starting Grant StrEnQTh devoted to the study of entanglement in quantum many-body systems as well as quantum simulation of lattice gauge theories. Alessandro Zenesini, coming from the Leibniz University of Hannover, is now researcher at CNR-INO in Trento; he is an experimentalist, expert in trapping and manipulating ultracold atomic gases; he will soon join the experimental laboratory of the BEC Center.

A detailed description of these achievements is given in this report. Additional information can be found on the website of the BEC Center (**http://bec.science.unitn.it**), which is regularly updated.

Trento, February 5th, 2020

Staff, researchers, scientific board

Principal investigators

Iacopo Carusotto (CNR)
Franco Dalfovo (UniTrento)
Gabriele Ferrari (CNR and UniTrento)
Stefano Giorgini (UniTrento)
Philipp Hauke (UniTrento, since November 1st, 2019)
Giacomo Lamporesi (CNR)
Chiara Menotti (CNR)
Lev P. Pitaevskii (UniTrento)
Alessio Recati (CNR)
Sandro Stringari (UniTrento)

Postdocs

Tomoki Ozawa
Marek Tylutki
Pierre-Élie Larré
Hannah M. Price
Tom Bienaimé
Russell N. Bisset
Marco Di Liberto
Chunlei Qu
Grazia Salerno
Tommaso Comparin
Albert Gallemí
Salvatore Giulio Butera
Jacopo Nespolo
Dimitrios Trypogeorgos
Arko Roy
Luca Parisi
Carmelo Mordini

PhD Students

Simone Serafini (Thesis defense on March 15, 2017)
Giulia De Rosi (Thesis defense on April 27, 2017)
José Lebreuilly (Thesis defense on December 7, 2017)
Fabrizio Larcher (Thesis defense on April 23, 2018)
Eleonora Fava (Thesis defense on February 22, 2018)
Giacomo Colzi (Thesis defense on April 20, 2018)
Carmelo Mordini (Thesis defense on June 21, 2019)
Luca Parisi (Thesis defense on May 10, 2019)
Miki Ota
Elia Macaluso
Arturo Farolfi
Ivan Amelio
Matteo Barbiero (Politecnico di Torino e INRIM)
Donato Romito
Luca Giacomelli
Santo Maria Roccuzzo
Matteo Sighinolfi
Louise Wolswijk
Alberto Muñoz de las Heras
Nick Keepfer (joint program with Newcastle University)

Student internships and stages

Jules Givois (École Normale Supérieure de Cachan, France), Nov 2019 - Aug 2020
Wataru Kohno (Hokkaido University, Japan), May - July 2019
Rocío Sáez-Blázquez (Universidad Autónoma Madrid), Feb - May 2019
Anna Fancelli (Univ. Milano), November 2018
Raul Bombin (Univ. Politecnica Catalunya, Barcelona), Sep 10 - Dec 15, 2018
Aurelian Loirette-Pelous (École Normale Sup. de Cachan, France), Oct 2018 - Jun 2019
Marin Tharrault (École Normale Supérieure, Paris), Feb - Jul 2018
Alexis Amouretti (École Normale Supérieure de Cachan, France), Apr - Jul 2016
Francesco Rosati (Univ. Pisa), Apr - Sep 2016
Mathieu Isoard (École Normale Supérieure de Cachan), Sep 2015 - Jul 2016
Mathias Van Regemortel (Univ. Antwerp), Nov 2015 - Apr 2016, Dec 2017
Salvatore Giulio Butera (Heriot-Watt, Edinburgh), Apr - Jun 2017

Secretariat

Beatrice Ricci (CNR)
Rachele Zanchetta (UniTrento)

Technical Staff

Giuseppe Froner (UniTrento)

Scientific board

Jean Dalibard
Rudolf Grimm
Christopher J. Pethick
William D. Phillips
Gora Shlyapnikov

Visiting scientists and scientific collaborations

Long visits

Matteo Rizzi (Universität zu Köln, Germany), starting from October 2019
Luca Galantucci (Newcastle University, UK), May - July 2019
Marco Giacinto Tarallo (INRIM, Torino), October 9 - December 22, 2017
Alexander L. Fetter (Stanford University), October 2017
Nick Proukakis (Newcastle University, UK), April 2017
Sebastian Will (Columbia Univ. and MIT, USA), September - November 2016

Short visits

Andreas Haller (Johannes Gutenberg Universität Mainz), December 19, 2019
Pierre Fromholz (ICTP Trieste), December 18-20, 2019
Guido Pupillo (Univ. Strasbourg, France), December 17, 2019
Barak Hirschberga (Inst. Comput. Sciences, USI, Lugano), December 17, 2019
Valerio Rizzi (Inst. Comput. Sciences, USI, Lugano), December 17, 2019
Alonso Viladomat (Heidelberg University), December 10-13, 2019
Murray Holland (University of Colorado, Boulder), December 4, 2019
Johannes Lang (MPIPKS, Dresden), December 1-5, 2019
Grazia Salerno (Univ. Libre de Bruxelles), December 3-6, 2019
Manel Bosch Aguilera (LKB-ENS, Paris), November 27-29, 2019
Florent Michel (Durham University), November 18-23, 2019

Vijay Singh (Universität Hamburg), November 20-23, 2019

Antoine Browaeys (Inst. d'Optique, Palaiseau, France), November 13-15, 2019

Martin Kroner (ETH Zurich), November 7-8, 2019

Robert Ott (Heidelberg University), October 16, 2019

Davide Squizzato (University Grenoble-Alpes), September 23, 2019

Alessio Chiocchetta (University of Cologne), September 11, 2019

Rıfat Onur Umucalılar (Mimar Sinan Fine Arts Univ., Istanbul), September 2-6, 2019

Hayder Salman (University of East Anglia), July 10-26, 2019

Grazia Salerno (Univ. Libre de Bruxelles), July 18-19, 2019

Nick Proukakis (Newcastle University, UK), July 15-26, 2019

Dmitry Petrov (CNRS and University Paris-Sud), July 18-19, 2019

Riccardo Rota (EPFL Lausanne), July 18, 2019

Maria Luisa Chiofalo (Univ. Pisa), July 18-19, 2019

Hannah Price (Univ. Birmingham), July 18, 2019

Markus Oberthaler (Univ. Heidelberg), July 18, 2019

Shunji Tsuchiya (Chuo University, Tokyo), July 11-17, 2019

Matteo Rizzi (Univ. Cologne, Germany), July 8-26, 2019

Grigory Astrakharchik (Univ.Politecnica de Catalunya, Barcelona), July 8-29, 2019

Giacomo Roati (CNR-INO and LENS, Florence), June 21, 2019

Paolo Ochner (Osserv. Astronomico e Univ. di Padova), June 18, 2019

Matteo Soriente (ETH Zurich, Switzerland), May 31, 2019

Federico Becca (Univ. Trieste), May 9-10, 2019

Serge Haroche (Collège de France, Paris), March 21-22, 2019

Paolo Comaron (Univ. Newcastle), March 21, 2019

Philipp Hauke (Univ. of Heidelberg), February 6-8, 2019

Ines de Vega (LMU Munich), February 19-20, 2019

Léonie Canet (Université Grenoble Alpes), February 19-20, 2019

Quentin Glorieux (LKB Sorbonne Université, Paris), February 6-8, 2019

Egor Babaev (Royal Institute of Technology Stockholm), February 5, 2019

Alberto Biella (MPQ, Paris Diderot), December 3, 2018

Alejandro Yacomotti (Centre Nanosciences et Nanotech. C2N-CNRS) November 8-9, 2018

Luca Galantucci (Joint Quantum Centre Durham-Newcastle), October 17-24, 2018

Giacomo Mazza (Ecole Polytechnique, Paris), October 1-3, 2018

Dimitri Gangardt (University of Birmingham), September 24-28, 2018

Gregori E. Astrakharchik (UPC Barcelona), September 3-7, 2018

Guido Pupillo (University of Strasbourg), July 11 and 13, 2018

I-Kang Liu (Nat. Changhua Univ. of Education, Taiwan), July 9-13, 2018

Alberto Muñoz (UAM Madrid), July 9-11, 2018
Leonardo Mazza (ENS, Paris), June 27-29, 2018
Doerte Blume (University of Oklahoma), June 13-15, 2018
Federico Tonielli (University of Cologne, Germany), June 11-14, 2018
Elio Koenig (Rutgers University), May 24, 2018
Manfred Mark (University of Innsbruck and IQOQI, Austria), May 15, 2018
Lauriane Chomaz (University of Innsbruck and IQOQI, Austria), May 15, 2018
Francesca Ferlaino (University of Innsbruck and IQOQI, Austria), May 15, 2018
Alexander Patscheider (University of Innsbruck and IQOQI, Austria), May 15, 2018
Daniel Petter (University of Innsbruck and IQOQI, Austria), May 15, 2018
Grigori E. Astrakharchik (UPC, Barcelona), April 24 - May 8, 2018
Stefan Wabnitz (Univ. Brescia), April 26, 2018
Katarzyna Krupa (Univ. Brescia), April 26, 2018
Leticia Cugliandolo (LPTHE, Paris), April 23-24, 2018
Carlos Lobo (Univ. Southampton, UK), April 23-24, 2018
Thomas Billam (Univ. Newcastle, UK), April 23, 2018
Thomas Bourdel (Institut d'Optique, Palaiseau), April 20, 2018
Leonardo Fallani (LENS and Univ. Firenze), April 20, 2018
Nick Proukakis (Univ. Newcastle, UK), April 13-23, 2018
Manuele Tettamanti (Univ. Insubria, Como), April 12-13, 2018
Alberto Parola (Univ. Insubria, Como), April 12-13, 2018
Renaud Parentani (LPT Orsay, France), April 12-13, 2018
Munir Al-Hashimi (University of Bern, Switzerland), March 12-13, 2018
Leonardo Mazza (École Normale Supérieure, Paris), March 9, 2018
Hiroyuki Tajima (QHPL, RIKEN Nishina Center, Japan), March 5-8, 2018
Sylvain Nascimbene (LKB-ENS, Paris), February 22-23, 2018
Marco Fattori (LENS and Univ. Firenze), February 22, 2018
Federico Corberi (Univ. Salerno), February 8-9, 2018
Roberta Citro (Univ. Salerno), February 8-9, 2018
Francesco Romeo (Univ. Salerno), February 8-9, 2018
Maria Luisa Chiofalo (Univ. Pisa), February 8-9, 2018
Andrey Turlapov (RAS, Nizhniy Novgorod, Russia), January 30, 2018
Daniel Benedicto-Orenes (Univ. Birmingham), January 26, 2018
Florian Christaller (IQST and University of Stuttgart), January 17-19, 2018
Hao Zhang (IQST and University of Stuttgart), January 17-19, 2018
Giovanni Modugno (LENS and Univ. Firenze), January 16, 2018
Marco Fattori (LENS and Univ. Firenze), January 16, 2018

Alessio Ciamei (Institute of Physics, Univ. Amsterdam), January 12, 2018

Giulio Cerullo (Politecnico di Milano), January 11-12, 2018

Massimo Capone (SISSA Trieste), January 11-12, 2018

Angelo Valli (SISSA Trieste), January 11-12, 2018

Giacomo Roati (INO-CNR and LENS Firenze), January 11-12, 2018

Francesco Scazza (INO-CNR and LENS Firenze), January 11-12, 2018

Matteo Zaccanti (INO-CNR and LENS Firenze), January 11-12, 2018

Claudio Giannetti (Università Cattolica, Brescia), January 11-12, 2018

Fausto Borgonovi (Università Cattolica, Brescia), January 11-12, 2018

Chahan Kropf (Università Cattolica, Brescia), January 11-12, 2018

Paolo Franceschini (Università Cattolica, Brescia), January 11-12, 2018

Daniele De Bernardis (IQST Vienna, Austria), December 21, 2017

Cristiano Simonelli (Univ. Pisa, Italy), December 20, 2017

Nicola Poli (LENS Firenze), December 15, 2017

Jean Dalibard (Collège de France and LKB, Paris), December 11-14, 2017

Mathias Van Regemortel (Universiteit Antwerpen, Belgium), December 4-15, 2017

Sebastian Diehl (Univ. Köln), December 7, 2017

Raul Bombin (Univ. Politecnica de Catalunya, Barcelona), December 4-6, 2017

Matt Visser (Victoria Univ. Wellington, NZ), November 22, 2017

Roberto Balbinot (Univ. Bologna), November 14, 2017

Alessandro Fabbri (LPT Orsay, France), November 14, 2017

Marco Giacinto Tarallo (INRIM, Torino), October 9 - December 22, 2017

Alexander L. Fetter (Stanford University), October 2017

David Bruschi (University of York, UK), October 26-27, 2017

Claudio Giannetti (Univ. Cattolica, Brescia), October 26-27, 2017

Danny Baillie (University of Otago, New Zealand), October 18-23, 2017

Rıfat Onur Umucalılar (Mimar Sinan Fine Arts Univ., Istanbul), October 9-20, 2017

Wolfgang Ketterle (MIT Boston), September 29 - October 3, 2017

John Michael Kosterlitz (Brown Univ., USA), August 23, 2017

Themis Mavrogordatos (UCL London), June 19-20, 2017

Manuele Tettamanti (Univ. Insubria, Como), June 19-21, 2017

Ajit Srivastava (Emory Univ. Atlanta USA), May 16-19, 2017

Maxim Gorlach (ITMO University, Saint Petersburg, Russia), May 2-5, 2017

Klejdja Xhani (LENS Firenze), April 27-28, 2017

Luca Galantucci (Newcastle University, UK), April 28, 2017

Roberta Citro (Univ. Salerno), April 27, 2017

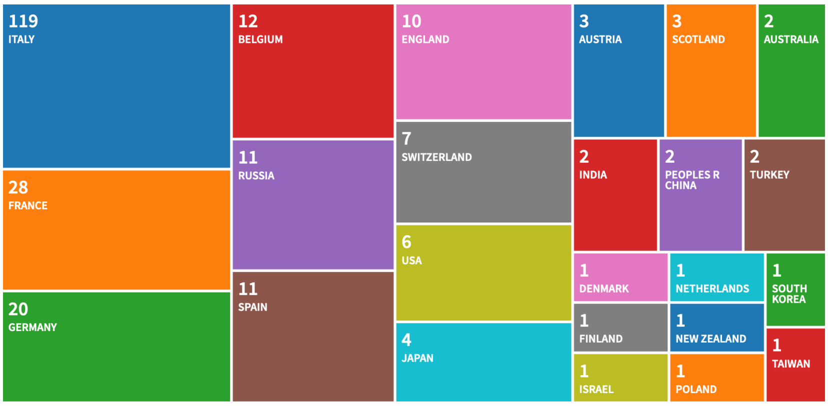
Anna Minguzzi (LPMMC CNRS Grenoble), April 27, 2017

Luca Salasnich (Univ. Padova), April 26, 2017
Paolo Comaron (Newcastle University, UK), April 19 and 26-28, 2017
Davide Dreon (Collège de France, Paris), April 19, 2017
Nick Proukakis (Newcastle University, UK), April 1-30, 2017
Luca Salasnich (Univ. Padova), March 16, 2017
Frederic Chevy (LBK, ENS Paris), March 15-16, 2017
Nick Parker (Newcastle University), March 14-16, 2017
Tommaso Comparin (ENS Paris, France), March 1, 2017
Sergej Moroz (TU Munich, Germany), February 19-21, 2017
Thomas Bland (Newcastle Univ., UK), January 23-27, 2017
Maxime Richard (Institut Néel, Grenoble), January 16-18, 2017
Jonathan Keeling (Univ. St Andrews, UK), January 10-11, 2017
Grigori E. Astrakharchik (UPC, Barcelona), January 7-23, 2017
Roberto Onofrio (Univ. Padova and Dartmouth College), December 22, 2016
Markus Heyl (Max Planck Institute, Dresden, Germany), October 25-26, 2016
Jogundas Armaitis (Vilnius, Lithuania), October 18 - December 15, 2016
Antonio Negretti (Univ. Hamburg, Germany), October 17, 2016
Francesca Ferlaino (IQOQI and Univ. Innsbruck), September 27-28, 2016
Leonardo Mazza (ENS Paris, France), September - October, 2016
Jamir Marino (ITP, Univ. Cologne, Germany), September 29, 2016
Peter Schuck (Institut de Physique Nucleaire, Orsay, France), September 21, 2016
Li Yun (Swinburne Univ. of Technology, Australia), September 12-30, 2016
Sebastian Will (Columbia Univ. and MIT, USA), September - November 2016
Jan Carl Budich (Univ. Innsbruck, Austria), July 19, 2016
Christophe Salomon (LKB-ENS, Paris, France), July 13-15, 2016

Scientific collaborations

The BEC Center operates within a wide network of scientific collaborations. More than half of the papers published by the BEC Center have been the result of joint projects with many groups around the world. Among them, long and fruitful collaborations have been established with the groups at LENS-Florence, the experimental and theory groups at Innsbruck, and with several groups in Paris, in Munich, and Barcelona.

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 119 publications having at least one of the 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. Then we also list the research institutions involved in the co-authorship with the BEC Center with more than two joint articles. In addition, about 65 institutions are involved in single joint articles.



UNIV PARIS SACLAY	14
TECH UNIV MUNICH	7
UNIV POLITECN CATALUNA	7
LUDWIG MAX UNIV MUNCHEN	7
ECOLE NORMALE SUPER	6
UNIV FIRENZE	6
FOND BRUNO KESSLER	5
NEWCASTLE UNIV	5
UNIV ANTWERP	5
UNIV LIBRE BRUXELLES	5
M PLANCK INST PHYS KOMPL SYST	4
SWISS FED INST TECHNOL	4
HERIOT WATT UNIV	3
IST NAZL RIC METROL	3
RIKEN JAPAN	3
POLITECN TORINO	3
SCUOLA NORMALE SUPER PISA	3
UNIV PARIS DIDEROT	3
ABDUS SALAAM INT CTR THEORET PHYS	2
ECOLE POLYTECH	2
ETH ZURICH	2
MIMAR SINAN FINE ARTS UNIV	2
UL BRUXELLES	2
UNIV ARIZONA	2
UNIV AUTONOMA MADRID	2
UNIV BARI	2
UNIV CERGY PONTOISE	2
UNIV COLOGNE	2
UNIV GRENOBLE ALPES	2
UNIV LILLE	2
UNIV MARYLAND	2
UNIV PISA	2
UNIV SOUTHAMPTON	2

Experiments with ultracold atoms

The first condensate of Sodium atoms in Trento was produced in the late December 2012. Since then, the laboratory has been fully operative. The activity of the last years has been focused on the following lines:

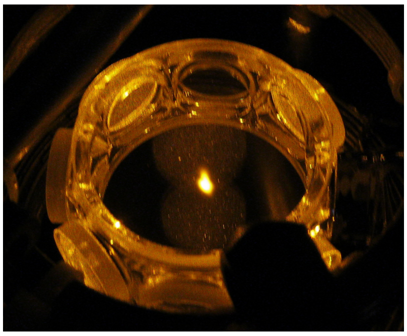
i) Kibble-Zurek mechanism, post-quench dynamics, and vortex dynamics in quenched condensates;

ii) dynamics and excitations in two-component miscible mixtures;

iii) development of novel atomic sources for applications in next-generation atomic clocks.

The campaign of measurements in the first laboratory (BEC1), carried out in previous years, highlighted the possibility of studying the dynamics of solitonic vortices, produced *via* the Kibble-Zurek mechanism, employing quasi-non-destructive imaging techniques. Our experimental results, in addition to being in good agreement with the theoretical predictions of hydrodynamic models, provided some preliminary evidence of interaction mechanisms between vortices in the form of variation of short-distance trajectories, or variation of visibility of the vortex at the intersection of trajectories. These indications, which are of great importance for example in the context of quantum turbulence, did not allow to draw definite conclusions due to the limited temporal and spatial resolution and the lack of information related to the vortex alignment. In the last years we have developed an innovative imaging method that, by offering better spatial and temporal resolution, together with information regarding the alignment of the vortices, has allowed us to distinguish for the first time different fundamental mechanisms of interaction between vortices. In addition to processes associated with the known reconnection mechanism, we have shown that in non-homogeneous condensates such as those produced in the harmonic trap available in the laboratory, vortex pairs may give rise to "rebounds", or to the expulsion of one or both vortices from the condensate. These results have been published in Physical Review X, Physical Review A, Journal of Experimental and Theoretical Physics, and Communication Physics. The study of the system across the phase transition following a quench is also subject of an ongoing international collaboration through the European Quantera project NAQUAS.

Meanwhile, we have completed the setting-up of a new laboratory (BEC2). The strategy of the new laboratory requires the use of multi-component superfluids with the possibility of controlling the coherent coupling between them. The lack of sample polarization increases the complexity of the system adding the spin degree of freedom on top of the density one. A long-term objective of the new BEC2 apparatus consists in the quantum simulation of processes associated with fundamental interactions, such as the confinement of quarks in QCD, and the study of superfluid gases in the presence of spin-orbit coupling. These works are also financially supported by Istituto Nazionale di Fisica Nucleare (INFN) through the FISh project and by the EU Horizon 2020 program through the FET QUIC project. The realization of such a system requires to trap atoms in an optical potential and in a low-magnetic-field noise environment. For this reason we realized a magnetic shield around the science chamber and succeeded in creating a two-component condensate with a few million atoms in an optical trap using a grey molasses pre-cooling technique and a hybrid opto-magnetic final trap. These technical results were published in Physical Review A and Review of Scientific Instruments. We also characterized the static and dynamical properties of a balanced miscible mixture of Sodium atoms at very low and at finite temperature demonstrating spin superfluidity. These results have been published in Physical Review A and Physical Review Letters. Recently we succeeded in producing spin excitations, also known as magnetic solitons, and their dynamics and collisional mechanisms have been reported in a paper currently under review.



Finally, in an ongoing collaborative effort with the Italian Institute of Metrological Research (INRIM), the laboratory is currently involved in the realization of novel optical atomic clock which is expected to outperform the current state of the art in the field by applying advanced quantum protocols based on spin-squeezing and quantum non-demolition measurements. Along this line, in the last years, we have installed a novel source of Strontium atoms, consisting of a collimated source of hot atoms from a Strontium oven, trapped and pre-cooled by a compact 2D-MOT and then sent to a 3D-MOT. This work was reported in IEEE International Frequency Control Symposium. Bosonic Strontium-88 atoms have been recently trapped in our blue 3D-MOT and further cooling techniques are now being explored. A novel cooling technique based on a 2DMOT with additional sidebands was realized and its performances were published in Physical Review Applied.

In the following we give a brief summary of the main publications of the group.

Physical Review X 7, 021031 (2017)

Vortex Reconnections and Rebounds in Trapped Atomic Bose-Einstein Condensates

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

The interaction and reconnection of filaments are key aspects in the description of the dynamics of fluids, plasmas, and many other systems. In quantum fluids, vortices are topological defects of the system's order parameter, around which the circulation of the velocity field is quantized. Their discrete filamentary nature makes quantum fluids an ideal setting for the study of vortex interactions and reconnections. In particular, reconnections trigger a turbulent energy cascade in which vortex lines self-organize in bundles, creating the same Kolmogorov distribution of kinetic energy over the length scales, a signature of a cascade mechanism that is observed in ordinary turbulence. Reconnection events also impact the evolution of the flow's topology, redistributing helicity among length scales, and in the dissipation of superfluid kinetic energy through Kelvin wave cascade.

In this work, we focused on elongated Bose-Einstein condensates of ultracold atoms confined by magnetic harmonic potentials, ideal systems that allow for different regimes of three-dimensional vortex-vortex interactions in the close presence of boundaries. Anisotropic boundaries induce vortical filaments to preferentially align along the shortest direction, minimizing energy. Vortices in cylindrically symmetric, cigar-shaped condensates are the shortest when they lie on radial planes, and the boundaries affect the structure of the vortical flow in such a way that two vortices interact only when their minimum distance is within a range of the order of the transverse size of the condensate.

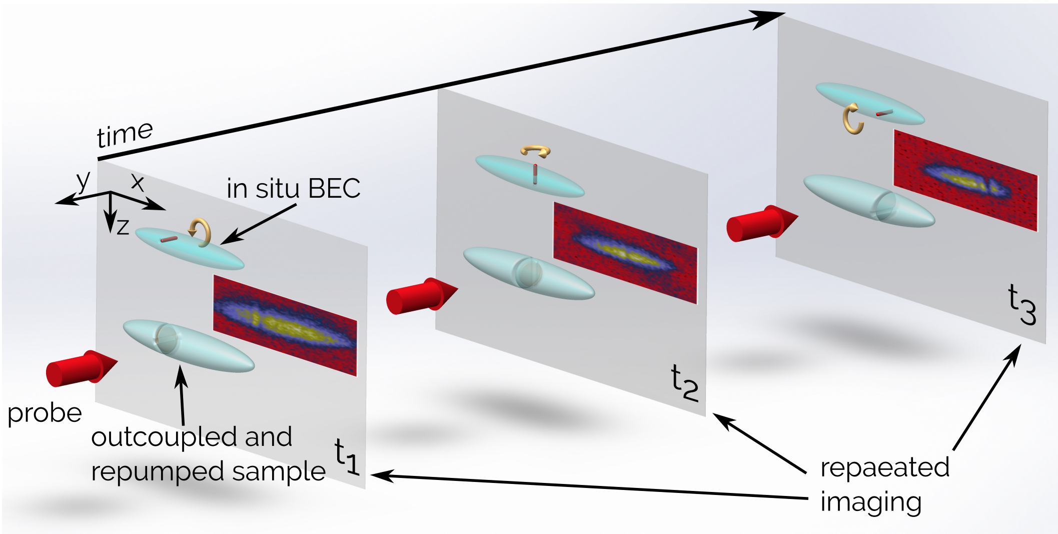


Figure 1: Sketch of an imaging sequence. A trapped condensate (smaller, light blue ellipsoid) contains a transverse vortex line that moves and rotates around the trap center; the direction of the atomic flow around the vortex filament is indicated by the yellow arrow. A small fraction of atoms is repeatedly extracted, typically every 12 ms; these atoms expand and fall in the gravity field, and are imaged in absorption by a probe laser beam after they are spatially separated from the trapped condensate. Each absorption image contains the essential features associated with the vortex lines.

We developed an innovative imaging technique, exploiting self-interference effects of out-coupled atoms, in order to extract both the position and orientation of 3D vortex lines from a temporal sequence of absorption images. We then combine experiments and numerical Gross-Pitaevskii simulations to study the interaction between two vortex lines approaching at various relative speeds and angles. Our experiments and simulations show that the interaction between vortex lines in a finite system is rather different from the one in infinite uniform superfluids. Novel types of vortex interaction regimes are unambiguously identified beyond standard reconnections already observed in superfluid helium. While in uniform, unbounded, and nonrotating superfluids reconnections of vortex lines moving towards each other are unavoidable, and their effects have been extensively investigated, here we showed that in a confined and inhomogeneous superfluid, depending on the relative velocity and orientation, two vortex lines can also rebound, perform double reconnections, maintain their orbits with negligible interaction, and undergo ejections. These processes should play even more important roles when the BEC contains more than two vortices, for example, in the case of turbulence. The processes that we identify could be a key starting point for better understanding the behavior of superfluids near their boundaries.

This work is the result of a fruitful collaboration with Carlo Barenghi and Luca Galantucci at the University of Newcastle, who performed the numerical GP simulations of the in-situ dynamics of vortices. The simulations of the expansion and interference of the outcoupled atoms were instead performed by Russell Bisset in Trento.

Physical Review A 96, 053605 (2017)

Observation of a Spinning Top in a Bose-Einstein Condensate

R.N. Bisset, S. Serafini, E. Iseni, M. Barbiero, T. Bienaimé, G. Lamporesi, G. Ferrari and F. Dalfovo

Boundaries strongly affect the behavior of quantized vortices in Bose-Einstein condensates, a phenomenon particularly evident in elongated cigar-shaped traps where the most stable defect is the so-called solitonic vortex, a short vortex line that pierces the condensate through its side. While they are indeed vortices, solitonic vortices possess some solitonic characteristics such as being more localized and, on the coarse-grain scale, causing a π phase jump between each end of the cigar, which results in a planar density depletion after expansion. Solitonic vortices, which were recently realized in experiments with both bosons and fermions, tend to be long lived and orbit about the condensate center on an elliptical path, along which the core remains surrounded by a roughly constant density.

We experimentally produce solitonic vortices in cigar-shaped traps that are inherited from the condensate formation process, due to the Kibble-Zurek mechanism. With an appropriate imaging technique, we track the axial position and the orientation of the vortex lines that remain in our condensates, after the post-quench dynamics. Some of these vortices exhibit a peculiar rotation of their core around the long axis of the trap. In this article, we showed that such a rotation is caused by a tilt of the vortex line out of the radial plane and towards the symmetry axis; the tilt implies an increase of the vortex line length, with a consequent energy cost and an induced torque. The torque produces the precession of the vortex around the axial direction, in a manner analogous to a classical spinning top. The analogy works well because the solitonic vortex is a localized object, in terms of both its energy and angular momentum densities, in contrast to regular 3D vortices.

We verified this spinning-top behavior by performing numerical simulations, using the Gross-

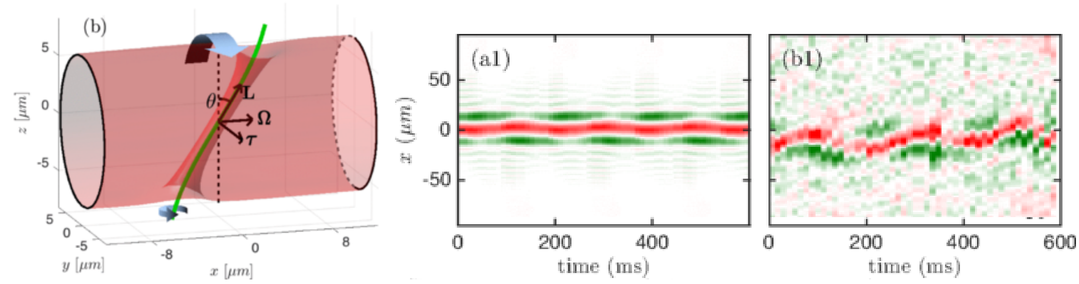


Figure 2: Left: Condensate segment containing a tilted solitonic vortex whose core lies in the $y = 0$ plane with a tilt angle θ into the long x-axis of the trap. The dashed line is a vertical reference. The vortex experiences a torque τ that acts to reduce the core length, i.e., by attempting to reduce θ. An arrow indicating the direction of τ and arrows for the directions of the angular momentum of the vortex $\mathbf{L}$ and precession $\mathbf{\Omega}$ are shown. The senses of the vortex and the precession are indicated by the bottom and top blue arrows, respectively. Right: Comparison between the theoretical (a1) and experimental (b1) signature in the doubly integrated 1D residual densities of a vortex precessing with $\Omega/2\pi = 5.5$ Hz.

Pitaevskii equation (GPE). We find that a solution of the GPE exists corresponding to a tilted vortex, which is stationary in a reference frame rotating around the long axis of the trap. We then used such a stationary state as an input of real-time Gross-Pitaevskii simulations in the nonrotating BEC and we observed that the vortex line keeps rotating at a constant angular velocity. We used the GPE also to simulate the extraction and expansion of atoms as performed in the experiments, in order to reproduce our minimally destructive imaging scheme that is able to track the orientation and position of the spinning vortices in real time.

This article has been highlighted by Physical Review A as an Editors' Suggestion and by the online journal Physics in the form of a Synopsis entitled "Quantum Vortex Twirls Like a Spinning Top".

Commun. Physics 1, 24 (2018)

Dynamical Equilibration Across a Quenched Phase Transition in a Trapped Quantum Gas

I.-K. Liu, S. Donadello, G. Lamporesi, G. Ferrari, S.-C. Gou, F. Dalfovo, N P Proukakis

This is a follow-up article of the previous experimental papers that we published on the spontaneous formation of defects in a rapid quench through the BEC transition. The formation of an equilibrium quantum state from an uncorrelated thermal one through the dynamical crossing of a phase transition is a central question of non-equilibrium many-body physics. During such crossing, the system breaks its symmetry by establishing numerous uncorrelated regions separated by spontaneously-generated defects, whose emergence obeys a universal scaling law with the quench duration. Much less is known about the ensuing re-equilibrating or "coarse-graining" stage, which is governed by the evolution and interactions of such defects under system-specific and external constraints.

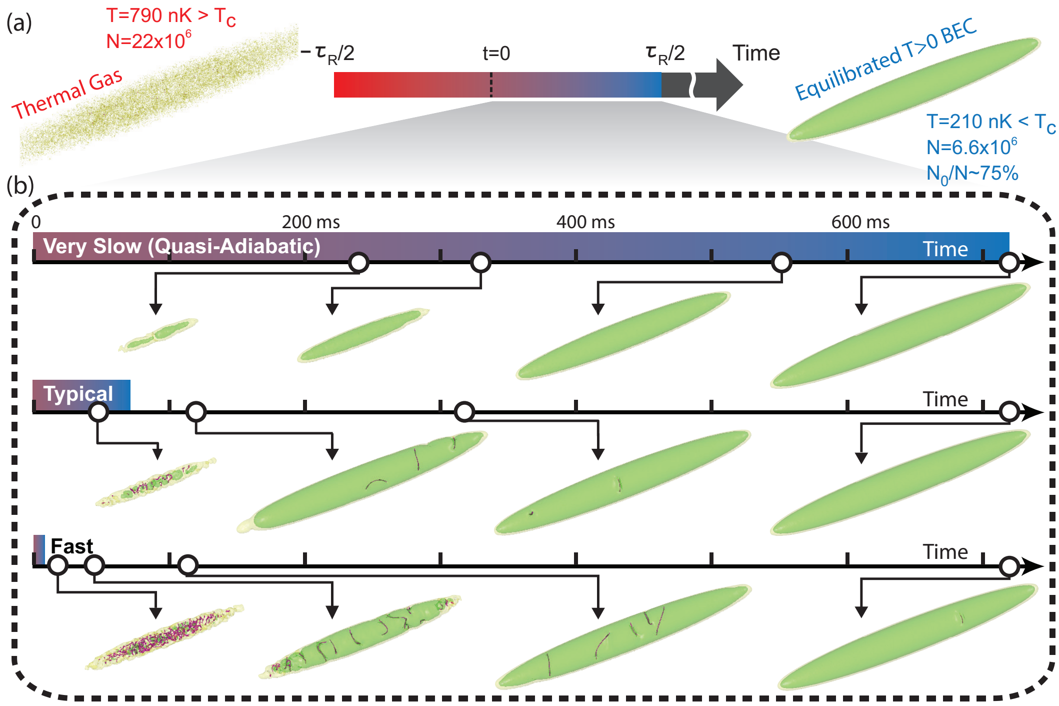


Figure 3: Simulation of quench-induced dynamical equilibration. a) Quench protocol: Starting from a purely thermal state, with a given atom number, we linearly quench temperature to lower values and chemical potential to positive values over a ramp duration τ_R, to mimic experimental conditions. b) Dynamical response of an equilibrium thermal gas subjected to different cooling quench rates ($\tau_R = 1440, 144, 18$ ms, from top to bottom), demonstrating the equilibration route towards a finite temperature phase-coherent BEC.

In order to compare the experimental observations with theory, we involved the group of Nick Proukakis in a joint theory-experiment collaboration. The outcome of such a collaboration is this article, where we offer a unified analysis of quenched condensate growth dynamics in a finite elongated 3D inhomogeneous system, incorporating into a single study the dynamical evolution, for different induced quench rates, from an equilibrium thermal state above the Bose-Einstein condensation transition temperature to a near-equilibrated, low-temperature phase-coherent Bose-Einstein condensate. By demonstrating the natural emergence of symmetry-breaking in our simulations, we perform a detailed parallel analysis of both the spontaneous emergence and complex nonlinear dynamics of defects, and the related evolution of coherence. Addressing subtle open questions in the condensate formation process, we show that coherence and number growth dynamics are in general decoupled, due to competing growth mechanisms following a quench, except for cases of adiabatically-slow growth which exhibit broadly similar timescales.

The unique insight provided by our numerical visualizations, which extend also beyond experimentally-accessible time intervals, provides a natural framework for addressing the still unresolved interplay between Kibble-Zurek defect generation and coarse-graining dynamics. In this regard, our simulations demonstrate that the anticipated power-law defect scaling with quench rate (characteristic of Kibble-Zurek) is not significantly affected over a prolonged evolution period, despite the fact that both the number and type of defects changes considerably during this period. Specifically, the initial randomly-oriented and -shaped spontaneously-generated defects gradually relax to the canonical excitations in the given system geometry (here solitonic vortices), with their number exhibiting a rapid decrease at very early stages, followed by a more gradual decay process as the size of the condensate grows further. These findings are consistent with late-time experimental measurements performed within our group, which further validate our analysis.

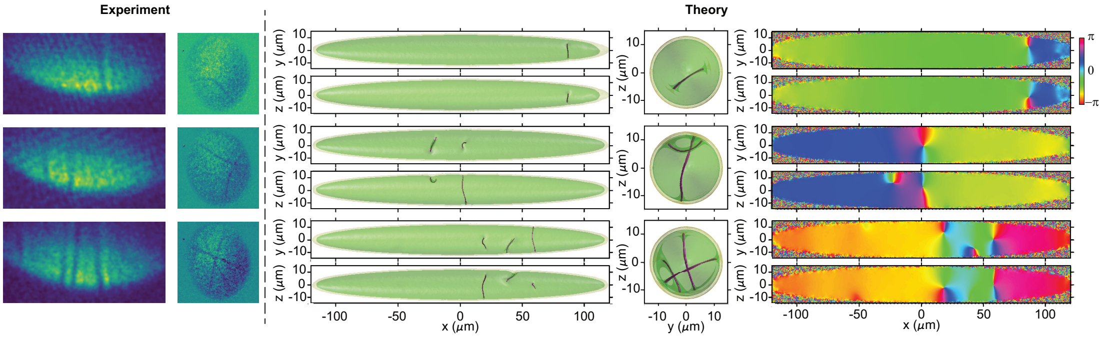


Figure 4: Defect visualization at late evolution times. Shown here are representative density side views containing respectively (top to bottom) 1, 2 and 3 vortices in the condensate. Left: experimental densities following condensate expansion, integrated along a transverse (1st column) or longitudinal (2nd column) axis; Right: numerical simulations showing corresponding characteristic density and phase plots: simulations offer both a view of two different planar cuts (so at $z = 0$, or $y = 0$), and the corresponding planar phase profiles, which clearly highlight the solitonic-vortex nature of the defects at late evolution times.

This work is expected to be of relevance to a broad range of future investigations with quantum-degenerate systems, and could also have technological implications for dynamical control and state-engineering of a quantum system. Given that our numerical scheme has demonstrated good qualitative description also of the much-harder-to-model approach to the phase transition, our method could in the future offer further insight into delicate features of non-equilibrium condensate dynamics, including a critical assessment and extension of the inhomogeneous Kibble-Zurek phenomenon.

Phys. Rev. A 97, 053625 (2018)

Production of large Bose-Einstein condensates in a magnetic-shield-compatible hybrid trap

G. Colzi, E. Fava, M. Barbiero, C. Mordini, G. Lamporesi and G. Ferrari

Production of BECs in traps that combine the advantages of both optical and magnetic potentials was demonstrated to be a viable strategy since the first BEC realizations, where a repulsive "optical plug" was used to suppress Majorana spin flips in a simple quadrupole magnetic trap (QMT). Another recently demonstrated approach consists in combining a tightly focused red-detuned single beam or a crossed dipole trap with a QMT. For the reasons discussed above, the adiabatic compression of the QMT remains a fundamental strategy with this second approach in order to improve the ODT loading conditions, by applying an RF evaporation stage to the magnetically trapped sample. The combined magnetic and optical potential also shows enhanced confinement along the ODT trap axis, compared to the pure optical counterpart, allowing us to reach quantum degeneracy in single-beam configurations even in the absence of magnetic compression. Weak magnetic field gradients can also be used to enhance all-optical production techniques, for instance, to spin polarize the sample or to compensate for gravity during optical evaporation.

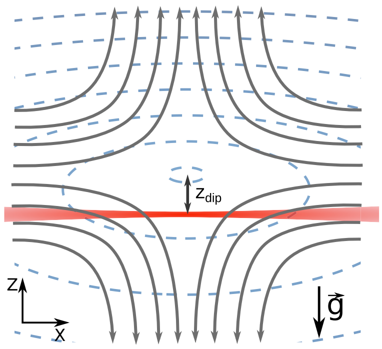


Figure 5: Sketch of the hybrid trap configuration.

In this work we describe the production of 23Na BECs in a hybrid trap composed of a low magnetic field gradient QMT and a single-beam ODT, where the compression of the QMT is avoided for magnetic shield compatibility. Compared to similar realizations, here we also take advantage of gray molasses cooling to efficiently load the atoms into the QMT, where they act as a reservoir during the loading of the deep (compared to the sample temperature) ODT. With such a protocol we produce condensates composed of as many as 7 million atoms in a spin-polarized state, ensuring well-controlled starting conditions for the production of internal atomic state mixtures.

Rev. Sci. Instrum. 90, 115114 (2019)

Design and characterization of a compact magnetic shield for ultracold atomic gas experiments

A. Farolfi, D. Trypogeorgos, G. Colzi, E. Fava, G. Lamporesi and G. Ferrari

In this work we report on the design, construction, and performance of a compact magnetic shield that facilitates a controlled, low-noise environment for experiments with ultracold atomic gases. The shield was designed to passively attenuate external slowly varying magnetic fields while allowing for ample optical access. The geometry, number of layers, and choice of materials were optimized using extensive finite-element numerical simulations. The measured performance of the four-layer shield is in good agreement with the simulations. From measurements of the spin coherence of an ultracold atomic ensemble, we demonstrate a residual field noise of 2.6 μG and a suppression of external dc magnetic fields by more than five orders of magnitude.

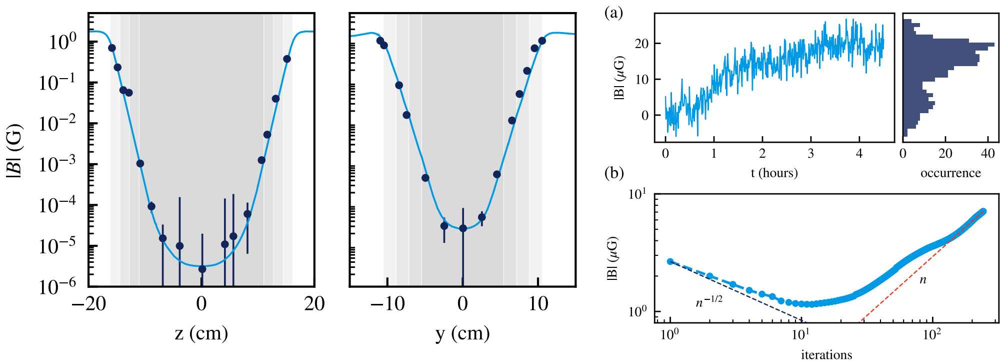


Figure 6: (left) Measurement of the magnetic field suppression along the axial and radial directions (points) compared to the simulated data (lines). (right) Calculated magnetic field from atomic spectroscopy measurements over a period of 4.5 h and the Allan deviation of the field over the number of experimental iterations n.

Spectroscopic measurements on the atomic sample contained in the shield show that the field drifts by about 20 μG on timescales of a few hours, while the shot-to-shot fluctuations are of about 2.6 μG. The magnetic field stability is as low as 1.1 μG after 500 s. At short times, the noise is dominated by shot-to-shot fluctuations $\propto n^{-1/2}$, while at long times, the drift term $\propto n$ is larger.

This work was also selected by the editor of Review of Scientific Instruments and highlighted with a dedicated article on SciLight entitled "Magnetic shield provides field stability for ultracold atomic gas experiments".

Physical Review A 94, 023628 (2016)

Spin-Dipole Oscillation and Polarizability of a Binary Bose-Einstein Condensate near the Miscible-Immiscible Phase Transition

T. Bienaimé, E. Fava, G. Colzi, C. Mordini, S. Serafini, C. Qu, S. Stringari, G. Lamporesi and G. Ferrari

Mixtures of ultracold atoms offer great flexibility thanks to the variety of atomic species and the additional degree of freedom related to the hyperfine structure. For a weakly interacting mixture of two BECs, the ground state of the system can either be a miscible mixture of the two components or a phase-separated configuration. The stability of mixtures very close to the critical region is sensitive to other effects, such as asymmetries in the trapping potential; moreover, for systems in which the intra-component coupling constants do not exactly coincide, one of the two components will experience a positive buoyancy and will "float" on the other. Previous experiments involving two internal states of rubidium were affected by both of these problems, hence setting strong limits to explore the many-body properties of miscible binary BECs. In particular, such conditions prevent the study of the static and dynamic response of an unpolarized system close to the transition between the miscible and immiscible phases, where interaction effects are particularly important despite the weakly interacting nature of the gas.

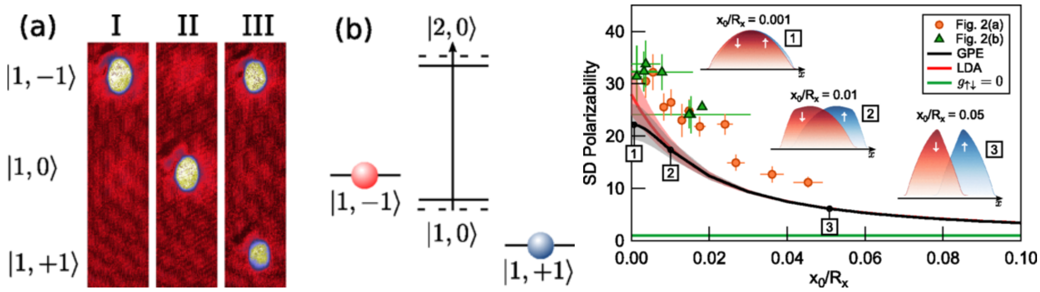


Figure 7: (a) Absorption images taken after a Stern-Gerlach expansion for (I) the dipole loading, (II) the Landau-Zener transition, and (III) the Rabi pulse leading to the creation of the binary mixture. (b) Stabilization of the two components by shifting the $|0\rangle$ state using microwave dressing on the transition to $|F = 2, m_F = 0\rangle$. Spin dipole polarizability extracted from the experimental data. The black (red) solid line is the prediction of the Gross-Pitaesvkii equation (GPE) in local density approximation. The shaded regions give the uncertainties taking into account error bars on the value of the coupling constants. The green solid line corresponds to the situation of no inter-component interaction. We also provide three examples of the density profiles of the spin-up and spin-down components from the GPE.

In this work, we reported on the measurement of the spin dipole polarizability of a two-component BEC, as well as the frequency of the spin dipole oscillation, by using an ultracold mixture of the $|3^2S_{1/2}, F = 1, m_F = +1\rangle \equiv |\uparrow\rangle$ and $|3^2S_{1/2}, F = 1, m_F = -1\rangle \equiv |\downarrow\rangle$ states of atomic Sodium. The polarizability characterizes in a fundamental way the thermodynamic behavior of binary ultracold gases and exhibits a divergent behavior at the transition between the miscible and immiscible phases with the occurrence of important spin fluctuations. On the other hand, the spin dipole oscillation is the simplest collective excitation supported by the system in the presence of harmonic trapping and is characterized by the motion of the two components with opposite phase around equilibrium. The spin dipole oscillation is the analog of the famous giant dipole resonance of nuclear physics, where neutrons and protons oscillate with opposite phase. Actually, collective modes are a popular subject of research in quantum many-body systems where experiments are able to determine the corresponding frequencies with high precision, providing a good testbed for detailed comparison with theory and an accurate determination of the relevant interaction parameters. In the case of Bose-Bose mixtures both the polarization and the spin dipole oscillation frequency are predicted to be crucially sensitive to the difference between the value of the intra- and inter-component interactions, which is particularly small in our case. The dramatic change of the density profile of the trapped gas, caused by a small displacement of the minima of the trapping potentials of the two species near the miscible-immiscible phase transition, was already investigated theoretically. Our mixture is not subject to buoyancy as $g_{\uparrow\uparrow} = g_{\downarrow\downarrow} = g$ and is on the miscible side $g_{\uparrow\downarrow} < g$ near the boundary of the phase transition (g and $g_{\uparrow\downarrow}$ are respectively the intra- and inter-component coupling constants). The mixture is stable and, together with the absence of buoyancy, allows us to overcome the ultimate limits to measure both the polarizability and spin dipole oscillation frequency.

Our experimental measurements of the polarizability and of the frequency of the spin dipole oscillation showed that, due to the vicinity to the miscible-immiscible quantum phase transition, both quantities are very sensitive to the value of the inter-component interaction and their behavior deviates by large factors from the values predicted in the absence of inter-component interaction. This represents a major difference with respect to other available superfluid quantum mixtures, like the Bose-Fermi mixtures of lithium gases, where the role played by the inter-component interaction is much less crucial. Our mixture is characterized by two interacting superfluids oscillating with opposite phase and the observed spin dipole oscillation is undamped for small amplitude as a consequence of superfluidity. For large-amplitude motion the Landau's critical velocity will, however, behave very differently, being very sensitive to the value of the inter-component interaction. The Bose mixtures realized and investigated here represent an ideal platform to explore important equilibrium and dynamic properties of binary superfluids.

Physical Review Letters 120, 170401 (2018)

Observation of Spin Superfluidity in a Bose Gas Mixture

E. Fava, T. Bienaimé, C. Mordini, G. Colzi, C. Qu, S. Stringari, G. Lamporesi and G. Ferrari

This paper is the sequel to the previous one on spin dipole oscillations. Here we extended the experiments and the theoretical analysis to finite temperature, where both the condensed and thermal components of the gas are important. Even in systems where spin is a conserved quantity, like ultracold atomic gases in the absence of spin-orbit coupling, the behavior of spin transport is highly nontrivial since, at finite temperature, collisions between different spin species yield relaxation of the spin current, a phenomenon known as spin drag. So far the study of superfluidity at finite temperature has mainly concerned the density channel, where both the number of particles and the total current are conserved quantities. A major consequence is that in the collisional regime sound can propagate both in the superfluid phase, where it takes the form of first and second sound, as well as in the normal phase (ordinary sound). In the presence of collisions spin sound can instead propagate only in the superfluid phase, so that its observation, in this case, can be considered an ultimate proof of spin superfluidity. Actually the equations of hydrodynamics, applied to a uniform superfluid mixture, predict the propagation of three sounds: pressure, temperature and spin sound.

As in the previous paper, we studied the spin dipole oscillation in a symmetric BEC mixture of the $|m_F = +1\rangle \equiv |\uparrow\rangle$ and $|m_F = -1\rangle \equiv |\downarrow\rangle$ components of the $F = 1$ hyperfine ground

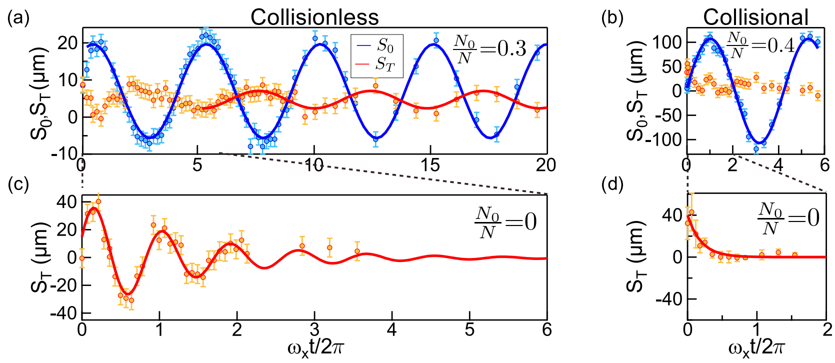


Figure 8: (a) Spin oscillations for the thermal S_T (red) condensed S_0 (blue) parts of the mixture with $N_0/N = 0.3$ ($T/T_c \simeq 0.85$). for configuration (A). After a small transient period, S_T oscillates at $\omega_T = 0.207(2)\omega_x$ which turns out to be equal, within errorbars, to the oscillation frequency of S_0, $\omega_{SD} = 0.205(2)\omega_x$. The ratio of the oscillation amplitude of S_T and S_0 is 0.18(2). (b) Spin oscillations for the condensed and the thermal S_0, S_T parts for a mixture with $N_0/N = 0.4$ ($T/T_c \simeq 0.75$) in configuration (B). The condensed component oscillates at $\omega_{SD} = 0.233(5)\omega_x$. We measure an exponential decay of S_T corresponding to $\omega_x\tau = 1.5(6)$. (c) Thermal spin current S_T for a non-superfluid mixture (above T_c) in configuration (A) where we observe a few damped oscillations at the trap frequency ω_x with an exponentially decaying envelope from which we extract the decay lifetime, and obtain $\omega_x\tau = 15(7)$. (d) Same measurement for configuration (B) where we observe a purely exponential decay and extract $\omega_x\tau = 1.2(4)$, compatible with the measurement of τ below T_c. To maintain a roughly constant condensed fraction during the measurement, we limit the observation time to the first 500 ms after excitation. This explains why, due to the different trapping frequency ω_x, more oscillations are shown for configuration (A) than for (B).

state of Sodium atoms, confined in a harmonic trap. Here, we worked at finite temperature, both in the collisonless and collisional regimes, which are experimentally realized by varying the frequencies of the trapping potential. We use two different configurations: (A) a crossed optical trap with frequencies $[\omega_x, \omega_y, \omega_z]/2\pi = [87, 330, 250]$ Hz, and (B) a single-beam optical trap with frequencies $[\omega_x, \omega_y, \omega_z]/2\pi = [12, 1350, 1350]$ Hz. A major difference between the two configurations is that, in the long axial direction, configuration (A) is basically characterized by a collisionless regime, while configuration (B) by a more collisional one. The spin oscillation is excited by applying a magnetic field gradient for a few ms.

A key result of this work is that the occurrence of oscillating spin supercurrents is observed not only in the collisionless regime, where the mean field drives a counter-phase oscillation of the thermal part, but also in the presence of strong collisions, which are responsible for the relaxation of the thermal component, because of spin drag. The absence of friction of the spin motion in the collisional regime provides a direct proof of the spin superfluid nature of the system. We also showed that, thanks to the vicinity to the miscible-immiscible phase transition, the interaction between the two spin clouds causes, at finite temperature, a large increase of the polarizability of the condensate with respect to the $T = 0$ value. Natural generalizations of this work concern the study of persistent spin currents in ring geometries and the propagation of spin sound waves and magnetic solitons.

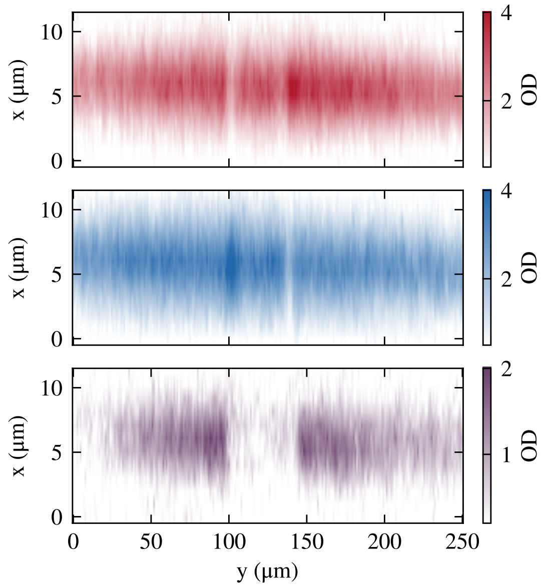
preprint arXiv:1912.10513

Observation of magnetic solitons in two-component Bose-Einstein condensates

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

A two-component superfluid mixture of ultracold atoms can be perturbed from its ground state by creating either excitations in the total density, with an in-phase response of the two components, or excitations in the relative density (magnetization), with an out-of-phase response. Using a state-sensitive optical potential we imprint a relative phase a quasi-1D balanced superfluid spin mixture of ultracold sodium atoms in the $|F = 1, m_F = \pm 1\rangle$ states. Pairs of magnetic solitons, long-living spin solitary waves, are produced.

We characterize the magnetic solitons in-situ using a fully tomographic method with quasi-concurrent density and phase measurements. These solitary spin waves are stable, not dispersive and relatively long-lived. Their oscillatory dynamics in a harmonically confined BEC shows only minimal dispersion and dissipation for times as long as 1 sec. In that time the magnetic solitons reflect multiple times from the edges of the BEC and cross at its centre allowing us to study collisions of MSs with opposite magnetisation ↑↓. In addition, we engineer ↑↑ collisions and show how they are quantitatively different. In the Figure we show in-situ density profiles and relative phase in a two-component mixture with two magnetic solitons with opposite magnetization.



Phys. Rev. Appl. 13, 014013 (2020)

Sideband-Enhanced Cold Atomic Source for Optical Clocks

M. Barbiero, M.G. Tarallo, D. Calonico, F. Levi, G. Lamporesi and G. Ferrari

Optical atomic clocks represent the current state-of-the-art in metrology. In this work, we present an atomic source using a 2D MOT source of Sr atoms for metrological application. The mechanical implementation of the atomic source is similar to other setups built to generate

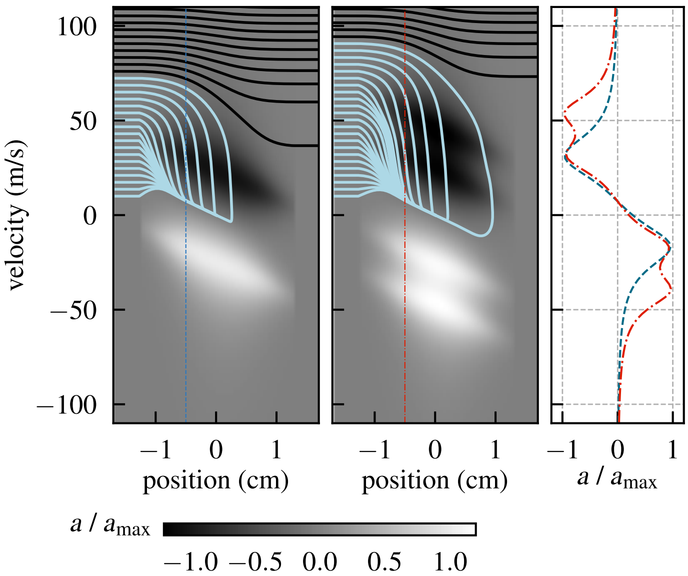


Figure 9: Numerical simulation illustrating the enhanced performance given by the sidebands in the 2D-MOT beams.

lithium, sodium, and strontium atomic beams. Our system is further characterized by a collimated atomic beam transmitted by a bundle of capillaries directly toward the 2D MOT region, and a two-frequency optical molasses to enhance the atomic flux toward the trapping region. The design, engineering, and characterization of the sideband-enhanced 2D MOT strontium source is the main result of this work. The characterization is done in terms of the loading performances of a 3D MOT typically used as the first cooling and trapping stage for an optical lattice clock. Monte Carlo numerical simulations are used to find the optimal optical configuration and are then compared with the experimental results.

We obtain a 2.3 times larger total atomic flux and a brightness increase of a factor 4 compared with a conventional, single-frequency 2D MOT for a given total laser power of 200 mW. We show that the sideband- enhanced 2D MOT can reach the loading-rate performances of space-demanding Zeeman-slower-based systems, while it can overcome systematic effects due to thermal-beam collisions and hot-black-body- radiation shift, making it suitable for both transportable and accurate optical lattice clocks. Finally, we numerically study possible extensions of the sideband-enhanced 2D MOT to other alkaline-earth species.

Theory of quantum gases

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

Collaborations with the experimental team

A significant part of the theory activity is carried on in direct collaboration with the experimental group of the BEC Center. In particular, models have been developed for the dynamics of the vortices in the condensates during the cooling phase through the BEC transition and in the limit of long evolution times, when the thermal part becomes negligible. In a first paper, we included the effect of the post-quench dynamics on the number of defects observed at the end of a temperature quench and the corresponding deviations from the predictions of the Kibble-Zurek mechanism by using a simple heuristic model which accounts for the observed lifetime of vortices. In a subsequent work, we performed numerical simulations of the interaction between vortices and the out-coupling procedure used in the laboratory to observe the dynamics in real time; the simulations were done partly in Trento and partly in Newcastle, and were aimed at highlighting the various stages of creation of defects at the transition, their initial turbulent evolution, and the slower evolution of the vortices in the final condensate. The theory group has also been involved in modeling the dynamics of two-component condensates, for the study of spin dipole oscillations and polarizability at zero and finite temperature, which have been the object of two joint theory-experiment articles. More details about these research lines are given in the previous section.

Supersolidity and dipolar gases

The recent experimental availability of the rotonic nature of the excitation spectrum in quasi 2D dipolar gases and the consequent observation of modulated arrays of coherently coupled array of droplets, have stimulated a significant interest in the community towards the realization of the supersolid phase in these systems. The Trento group has been involved in a significant way in this challenging direction of research. The study of the static response of the system to a periodically modulated perturbation in space has been the object of a theoretical investigation, which has revealed the amplified response of the system for wave vectors of the external perturbation close to the roton minimum. A successful collaboration with the Florence-Pisa team of Giovanni Modugno has permitted to investigate, within a joint experimental and theoretical effort, the nature of the Goldstone modes associated to the supersolid phase, as a consequence of the simultaneous spontaneous breaking of the gauge and translational symmetries. More recently we have started a novel investigation of the rotational properties of supersolids. We have explored the effects of crystallization on the frequency of the scissors mode and on the consequent increase of the moment of inertia. Furthermore we have explored the structure of quantized vortices and their co-existence with the crystalline structure of the supersolid.

Thermodynamics of quantum mixtures

We have developed a systematic investigation of the thermodynamic behavior of quantum mixtures of Bose-Einstein condensates with the aim of exploring the emergence of novel magnetic configurations at finite temperature. We have found that a miscible mixture at zero temperature can undergo a phase transition to a phase separated configuration at finite temperature as a consequence of non trivial interaction effects in the presence of Bose-Einstein condensation. We have shown that mean field many-body approaches, based on Hartree-Fock theory, are inadequate to describe theoretically the new phase and that the inclusion of beyond mean field effects, accounting for quantum and thermal fluctuations in the spin channel is a crucial step for a proper description of thermodynamics.

Coherently coupled Bose gases

When two BECs occupying different hyperfine states are coupled by radio-frequency or microwave radiation (Rabi coupling) the solitonic solutions exhibit novel challenging features. The Trento team has investigated the interplay between the domain wall solution corresponding to a magnetic soliton, and the physics of quantized vortices. In fact a single vortex in one of the components cannot exist as an isolated object, but is always linked to another vortex by the domain wall as a consequence of the topological constraints imposed by the presence of the vortex to the relative phase of the two condensates. The domain wall eventually causes an attraction between vortices in analogy with the confinement mechanism of quarks predicted by QCD. We have systematically investigated the decay mechanism of these vortex molecular-like configurations as a function of the intensity of the Rabi coupling. Our predictions are expected to stimulate future experiments hopefully realized also in the Trento BEC laboratory.

Equilibrium and dynamics of uniform Bose gases at finite temperature

We investigated the properties of a 2D Bose gas confined in a rectangular box as in the case of experiments performed by the group of J.Dalibard in Paris and the group of Z.Hadzibabic in Cambridge. Using the Stochastic Gross-Pitaevskii (SGPE) theory we calculated equilibrium properties of the gas at different temperatures and we simulated temperature and interaction quenches across the BKT transition in order to find signature of universality in the behavior of coherence and correlations. We have also studied the propagation of collective density waves at different temperatures both with SGPE and within a linear response theory in Random Phase Approximation for the case of sound wave propagating in a collisionless regime. We found a good agreement between the two theories and also with the experimental results obtained in Paris. The propagation of second sound has been also investigated by employing the two-fluid Landau hydrodynamic equations in various regimes of interaction.

Strongly interacting fermionic systems and itinerant ferromagnetism

For several years the BEC Center has been dealing with the understanding of strongly interacting fermionic systems. In the last months, in collaboration with an experimental group of LENS in Florence, two important results have been obtained. In a first series of experiments the stability and the coherence of a new quasi-particle called repulsive polaron was studied. The existence itself of such repulsive polarons has been a matter of discussion in previous theoretical works. The experiment, with the theoretical support of the BEC Center, represents a benchmark for microscopic theories and opens the way to the study of new systems. Based on the previous experiment, we proposed a new set of measures to verify the possibility that a diluted Fermi gas shows ferromagnetic behavior. The results obtained at LENS and the theory developed at the BEC Center in collaborations with other European Institutions are in good agreement and have had a remarkable impact in the scientific community. New results have also been obtained on the front of low-dimensional systems and in particular the renormalization of the tunneling and oscillation frequencies of attractive and repulsive polarons by combining exact solutions, exact diagonalization algorithms and sum rules.

Bosonic polarons

We have studied the properties of an impurity immersed in a Bose condensate (bosonic polaron). This problem, which presents interesting analogies with fundamental themes in condensed matter, is a subject of great theoretical and experimental attention in the field of ultracold atoms. The study was carried out using quantum Monte Carlo numerical techniques that allow to analyze strong interaction regimes that can not be tackled with perturbative or mean-field methods. At zero temperature, we calculated the binding energy and the effective mass of the impurity coupled to a three-dimensional condensate as a function of the intensity of the interaction inside the bath and between the impurity and the bath, analyzing in detail both the attractive branch of the polaron and the repulsive one. We studied the effects of the mass ratio between impurity and the particles of the bath, focusing the analysis, in particular, on the values relevant for the experiments carried out in Boulder and Aarhus. Finally, we studied the problem of the polaron in one-dimensional systems, where it is possible to analyze situations in which the bath is strongly interacting and reaches the so-called Tonks-Girardeau regime, in which it acts as a fermionic gas. For this system we have found that the effective mass of the impurity can become much larger than its bare mass if the repulsion between impurity and bath becomes sufficiently strong.

Andreev-Bashkin effect

In the last months, we explored the physics of the so-called Andreev-Bashkin effect. The latter, proposed over 40 years ago, has never been observed in experiments. It should play a fundamental role in the description of coupled superfluids and neutron stars, where however observations are difficult and experiments are obviously impossible. The Andreev-Bashkin effect is based on the coupling between two superfluids that give rise to a superfluid order parameter with matrix structure: due to quantum effects of mass renormalisation, the velocity in a superfluid induces a current in the other superfluid, producing a transport without dissipation. The work of the BEC Center has led to the identification of the systems and the regimes in which this effect is relevant and the quantities that are most affected by the presence of the reciprocal transport of the two superfluids. In particular, for dipolar systems or systems in one dimension, the Andreev-Bashkin effect is dominant. The form of the superfluid matrix was obtained using Monte Carlo numerical methods, confirming the general relationships predicted by the hydrodynamic theory.

Interplay of topology and interactions in two-body systems

Although interactions are responsible for important topological phases, such as fractional quantum Hall effect, the effect of interactions in topological systems is still largely unknown. As a first step in this direction, we have considered two interacting particles in a one-dimensional Su-Schrieffer-Heeger lattice, characterized by alternating strong and weak tunneling couplings. We have shown that two-particle edge states exist despite the lack of symmetries that protect them. The origin of the edge states is due in a non-trivial manner to the combined effect of the lattice, the topology and the interactions. We have extended our study to the case of interactions with nearest neighbors, showing the existence of two-particle edge states with increased localization properties. One of the most attractive perspectives is the observation of such phenomena by us using coupled optical fiber systems, where the physics of two interacting particles in one dimension can be conveniently transferred into the physics of a single particle in two dimensions, allowing the visualization in real time. Further work has addressed the two-particle bound states in a two dimensional Haldane model where topologically protected two-body edge states exist but may have a different chirality compared to the single particle states.

Goldstone and Higgs excitations in the Bose-Hubbard model

We have deepened the study of the excitations in the Bose-Hubbard model using a time-dependent Gutzwiller ansatz. The Mott phase is characterized by excitations of one or more particles and one or more holes. At the superfluid transition, such excitations give rise, in addition to the well-known phononic Goldstone mode, to higher energy modes which present a gap even at small momenta. The first of these modes is often identified as a Higgs mode. In particular we have focused our attention on the particle-hole symmetry of the different modes in the spectrum. The particle-hole symmetry of the Goldstone mode corresponds to the boundary between particle superfluid and hole superfluid. In the particle-hole symmetry points of the Higgs mode, on the other hand, the excitation corresponds to an oscillation of pure amplitude of the order parameter. First steps towards building a quantum theory of the dynamics of the

Bose-Hubbard model were made using a quantized version of the Gutzwiller theory.

Fluids of light

The study of quantum fluids of light was mainly focused on the problem of generating and then characterizing strongly correlated states of a photon gas. In particular, new pumping schemes based on a non-Markovian, frequency-dependent incoherent pumping have been shown to be capable of selecting the fundamental state and/or specific excitations of a strongly non-linear system. This allows the creation, for example, of a light Mott insulator and its use for quantum simulations of more complex systems. From the weakly interacting fluids side, we have provided theoretical support to experimental colleagues in Grenoble and in Palaiseau (France) for studies of the effect of the incoherent reservoir on the dynamical stability and on the collective excitation modes of exciton-polariton condensates in different pumping regimes. Other important studies that we have undertaken in this context were the theoretical characterization of Beliaev-Landau scattering processes between Bogoliubov quasi-particles and of the consequent thermalization phenomena, the possibility of exploiting nonlinearities to engineer complex Gaussian states.

Topological and Quantum Hall effects with light and atoms

We have applied our theoretical understanding on the frequency-dependent incoherent pumping scheme to the generation of fractional Hall states in liquids of light. To this purpose we have studied in detail the ground state and the quasi-hole and edge excitations of fractional quantum Hall liquids under a hard wall confinement potential. Then, we have proposed a scheme to extract microscopic information on quantum Hall fluids from the emitted light. Starting from a mathematical link between the expectation value of angular momentum and the braiding phase of two anyons, we have proposed a protocol to extract the anyonic (that is, in between bosonic and fermionic) statistics of quasi-hole excitations in a fractional quantum Hall fluid from the density profile of the cloud. Our theoretical predictions were validated using state-of-the-art numerical tree-tensor-network calculations. A short proposal summarizing our suggestion was awarded a Google Quantum Innovation Award. A crucial step towards the simulation of interacting models was the identification of a new scheme to combine synthetic dimensions with local interactions. In collaboration with experimentalists at Jena, we presented the first experimental mapping of Berry curvature in a 1+1 dimensional lattice. Together with colleagues of French CNRS, we have studied wave propagation effects in honeycomb lattices and demonstrated a first example of topological lasing device in a SSH chain. Triggered by this advance, we have begun a comprehensive study of laser operation on the chiral edge modes of two-dimensional topological lattices: first, at the mean-field level, we have unveiled convective vs. absolute instability features in the lasing threshold. Including fluctuations, we have characterized a Kardar-Parisi-Zhang physics in the spatio-temporal phase correlations as well as nonlinear corrections to the Schawlow-Townes laser linewidth. A potentially interesting development of these ideas is the application of these concepts to classical mechanics systems, that we have experimentally investigated in collaboration with colleagues at Engineering Department of UniTN using a chain of coupled pendula. Finally, we gave theoretical support to the experimental work done by Immanuel Bloch and his group in Munich on the generalization of the quantum Hall effect to four-dimensional systems. Using cold gases in optical superlattices, a dynamical version of the 4D integer quantum Hall effect has been realized and reported on Nature. The BEC Trento team has coordinated an international team to write a first complete review of topological effects in optics and photonics, which has quickly become the reference text for the field.

Analogue models of gravity

On the front of quantum effects in analogous models of gravity based on cold atoms and light fluids, we undertook a study of quantum fluctuations in spinor gases. These systems allow to decouple the effective metric from the quantum field and widen the spectrum of obtainable configurations, especially in view of studies of back-reaction and evaporation of black holes. In the meanwhile, we have made use of the analogy to deepen our conceptual understanding of the energetic and dynamical instabilities of multiply charged vortices in rotating fluids. We have then carried out a critical study of the recent experimental observation of black hole lasing by J. Steinhauer in Haifa, and we have continued the preliminary study of similar Hawking radiation in fluids of light.

Field theories and zero-point effects for atomic systems

We have investigated the possibility of including quantum emitters in the quantum simulation of quantum field theories in curved space-times using atomic systems. In particular, an important step forward was made by developing the theory to obtain Ginzburg-like radiation from super-luminally moving neutral objects and static Casimir effects using a two-level atomic impurity interacting with a Bose-Einstein condensate. From the dynamical Casimir point of view, we have investigated the mechanical back-reaction effect of the emitted photons on the moving mirror: first, the average value of the force was computed using a mean-field approach; once quantum fluctuations are introduced, peculiar decoherence phenomena are identified. A circuit-QED configuration able to serve as an analog model for this physics was proposed. Its experimental implementation at FBK is presently under study.

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

Nature 574, 382 (2019)

Supersolid symmetry breaking from compressional oscillations in a dipolar quantum gas

L. Tanzi, S. M. Roccuzzo, E. Lucioni, F. Famà, A. Fioretti, C. Gabbanini, G. Modugno, A. Recati, and S. Stringari

Supersolids are exotic materials combining the frictionless flow of a superfluid with the periodic density modulation of a solid. The supersolid phase of matter was predicted about 50 years ago as a possible phase of solid ^{4}He, but despite decades of investigation, supersolidity in solid helium has not yet been revealed. Quantum gases with spin-orbit coupling, cavity-mediated interactions and long-range dipolar interactions are emerging as interesting alternatives. A major difference with respect to solid ^{4}He is that the lattice structure of these configurations is built by clusters rather than by single atoms, thereby allowing for the emergence of coherence - via sort of Josephson links - effects typical of a superfluid. The recently observed supersolid stripe phase in elongated dipolar Bose-Einstein condensates, reported in three different experimental groups (Pisa, Stuttgart and Innsbruck), is particularly appealing, since the lattice-like structure is determined directly by the interatomic interactions and not by light-mediated interactions, allowing the lattice to be deformable. Indeed a crucial feature of a D-dimensional supersolid is the occurrence of D + 1 gapless excitations, reflecting the Goldstone modes associated with the spontaneous breaking of two continuous symmetries: the breaking of phase invariance, corresponding to the locking of the phase of the atomic wave functions at the origin of superfluid phenomena, and the breaking of translational invariance due to the lattice structure of the system. Such modes have been the object of intense theoretical investigations, but they have not yet been observed

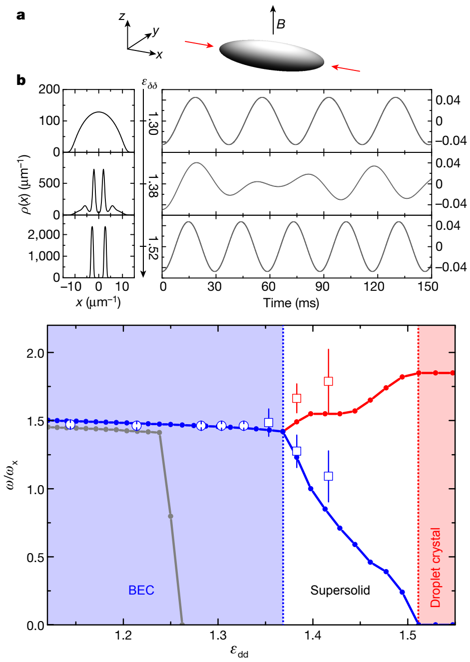


Figure 10: a. Excitation of the axial (arrows) breathing mode of the BEC. b. Density distributions along the x direction (left) and time-dependent oscillations. The 3 regimes are shown: standard BEC (top row), the supersolid regime (middle row) and the droplet crystal regime (bottom row). The BEC and the crystal feature one oscillation frequency, the supersolid clearly shows the beating of two frequencies, corresponding to a new compressional mode. Last panel: theory vs. experiment comparison of the compressional mode frequency.

experimentally. In this work we have demonstrated supersolid symmetry breaking through the appearance of two distinct compressional oscillation modes in a harmonically trapped dipolar Bose-Einstein condensate, reflecting the gapless Goldstone excitations of the homogeneous system. In particular we have observed that the higher-frequency mode is associated with an oscillation of the periodicity of the emergent lattice and the lower-frequency mode characterizes the superfluid oscillations. Our work also suggests the presence of two separate quantum phase transitions between the superfluid, supersolid and solid-like configurations. The work is the outcome of a fruitful collaboration between the BEC Center (Recati, Roccuzzo, Stringari), which developped the theory and performed the numerical simulations of the system, and the experimental group led by Prof. Modugno in Pisa, which following the theory suggestions has been able to properly implement the protocol which led to the frequency measurement of the compressional modes in the supersolid state.

Phys. Rev. Lett. 122, 105302 (2019)

Liquid state of one-dimensional Bose mixtures: a quantum Monte-Carlo study

L. Parisi, G. E. Astrakharchik, and S. Giorgini

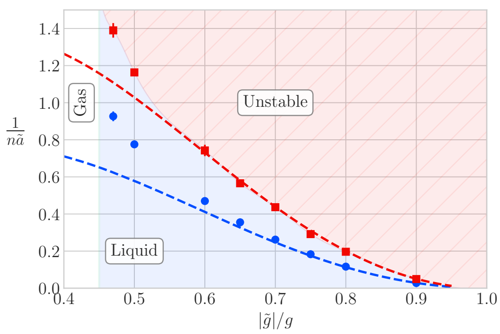


Figure 11: Phase diagram of the homogeneous liquid phase: (blue) circles correspond to the equilibrium density of the liquid and (red) squares to the spinodal point where the compressibility diverges. Dashed lines refer to the predictions of the GGP theory.

By using exact quantum Monte-Carlo methods we calculated the ground-state properties of the liquid phase in one-dimensional Bose mixtures with contact interactions. We found that the liquid state can be formed if the ratio of coupling strengths between inter-species attractive and intra-species repulsive interactions exceeds a critical value. As a function of this ratio we determined the density where the energy per particle has a minimum and the one where the compressibility diverges, thereby identifying the equilibrium density and the spinodal point in the phase diagram of the homogeneous liquid. Furthermore, in the stable liquid state, we calculated the chemical potential, the speed of sound, as well as structural and coherence properties such as the pair correlation function, the static structure factor and the one-body density matrix, thus providing a detailed description of the bulk region in self-bound droplets.

Phys. Rev. Lett. 122, 090401 (2019)

Collisions of self-bound quantum droplets

Giovanni Ferioli, Giulia Semeghini, Leonardo Masi, Giovanni Giusti, Giovanni Modugno, Massimo Inguscio, Albert Gallemì, Alessio Recati, Marco Fattori

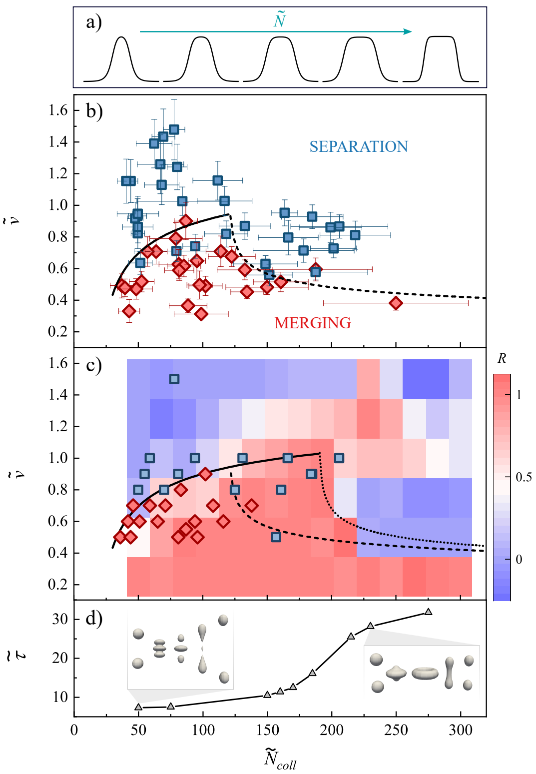


Figure 12: a) Formation of a liquid-like state in the numerical density profile by increasing N. b) Red rhombus (Blue squares) correspond to collisions whose outcome have been a single droplet (two droplets). Lines correspond to a naive energetic estimate of the critical velocity. c) Comparison between experiment and theory. d) The two regimes are characterised by very different collisional time scales.

This work is the result of a collaboration between members of the BEC Center (A.G. and A.R.) with the experimental group lead by Prof. Fattori at LENS (Florence). A few years ago for the first time, experimentalists were able to realize self bound droplets in mixtures of ultra cold Bose gases. The droplets are the result of a competition between the attractive interspecies mean-field interaction and the repulsive Lee-Huang-Yang correction to the equation of state. In this work we reported on the study of binary collisions between quantum droplets in order to understand their liquid nature. We were able to distinguish two main outcomes of the collision, i.e., merging and separation, at small and large velocity, respectively.

The critical velocity v_c that discriminates between the two cases displays a different dependence on the atom number N for small and large droplets as shown in Fig. 12. By comparing our experimental results with numerical simulations, we showed that the non-monotonic behavior of $v_c(N)$ is due to the crossover from a compressible to an incompressible regime. The collisional dynamics is governed by the droplet binding energy in the first, compressible, regime, while is governed by the droplet surface tension in the second, incompressible, regime. Our results provide the first evidence of the liquid-like nature of quantum droplets in the large N limit, where their behavior closely resembles that of classical liquid droplets. The BEC Center team carried out the numerical simulations and figured out the proper interpretation of the outcomes. The interpretation has been confirmed by simple theoretical models concerning inelastic collisions. The theoretical work has been particularly important to quantity the role of three-body losses, which are present in real droplets: we numerically proved that such losses do not change the dynamical nature of the collisions but only reduce the liquid regime.

Phys. Rev. Lett. 121, 025302 (2018)

Spin dynamics and Andreev-Bashkin effect in mixtures of 1D Bose gases

L. Parisi, G. E. Astrakharchik, and S. Giorgini

In this paper, we investigated the propagation of spin waves in two-component mixtures of one-dimensional Bose gases interacting through repulsive contact potentials. By using quantum Monte Carlo methods we calculated static ground-state properties, such as the spin susceptibility and the spin structure factor, as a function of both the intra-species and inter-species coupling strength and we determined the critical parameters for phase separation. In homogeneous mixtures, results of the velocity of spin waves and of its softening close to the critical point of phase separation were obtained by means of a sum-rule approach. We quantified the non-dissipative drag effect, resulting from the Andreev-Bashkin current-current interaction between the two components of the gas, and we showed that in the regime of strong coupling it causes a significant suppression of the spin-wave velocity.

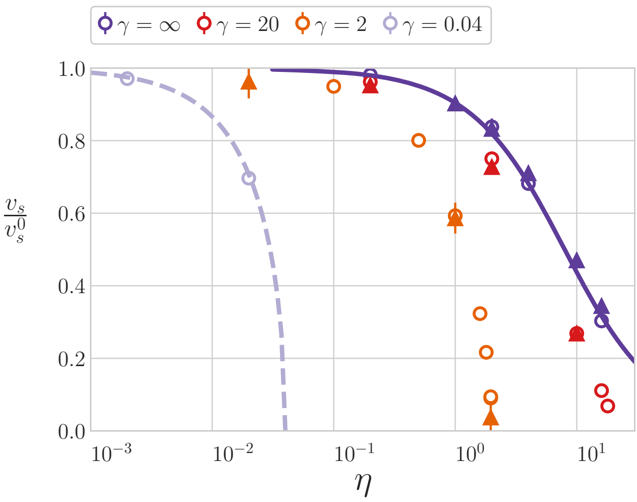


Figure 13: Spin-wave velocity v_s as a function of η for different values of γ, where η and γ are the two relevant coupling parameters proportional to the inter-species and intra-species interaction strengths. The units are provided by the spin-wave velocity in the absence of inter-species interactions, v_s^0. Open symbols refer to the sum rule ratio $\sqrt{(m_1)_{\text{sw}}/m_{-1}}$ and solid symbols to m_0/m_{-1}. The dashed line corresponds to the mean-field prediction and the solid line to the exact solution in the Yang-Gaudin model.

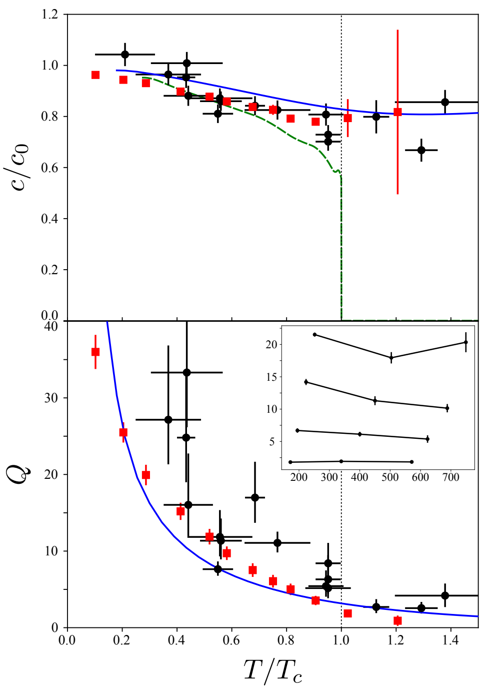
Phys. Rev. Lett. 121, 145302 (2018)

Collisionless Sound in a Uniform Two-Dimensional Bose Gas

Miki Ota, Fabrizio Larcher, Franco Dalfovo, Lev Pitaevskii, Nick P. Proukakis, and Sandro Stringari

Using linear response theory within the random phase approximation (RPA), we investigated the propagation of sound in a uniform two dimensional Bose gas in the collisionless regime. We showed that the sudden removal of a static density perturbation produces a damped oscillatory behavior revealing that sound can propagate also in the absence of collisions, due to mean-field interaction effects. We provided explicit results for the sound velocity and damping as a function of temperature, pointing out the crucial role played by Landau damping. We supported the predictions of the RPA theory by performing numerical simulations with the stochastic (projected) Gross-Pitaevskii equation (SGPE). We found results which were consistent with the experimental observations of sound in a weakly interacting 2D Bose gas both below and above the superfluid Berezinskii-Kosterlitz-Thouless transition, performed by the group of J.Dalibard in Paris. The theory work in Trento and the experiments in Paris were carried on in parallel, with frequent discussions between the two groups, and the two papers appeared back-to-back in the same issue of Physical Review Letters, both highlighted with a joint Synopsis in the online journal Physics.

In the figure we show the main results of our paper. The upper panel shows the sound velocity as a function of temperature, normalized to the Bogoliubov sound speed at $T = 0$; the black circles are experimental data; the blue solid line is the RPA prediction while the red squares are the results of SGPE simulations; the green dashed line represents the speed of second sound predicted by Landau's two-fluids hydrodynamics. The lower panel shows the quality factor (i.e., twice the ratio between the frequency of the wave and its damping rate); as before, the black circles are experimental data, the blue solid line is Q evaluated with RPA and the red squares are the results of SGPE simulations. The inset shows Q as a function of frequency, obtained with from SGPE at different values of T (from top to bottom: $T/T_c = 0.29, 0.52, 0.75, 1.02$). The error bars of the SGPE data in both panels represent the statistical deviations due to different noise.



Physical Review Letters 118, 145302 (2017)

Diffused vorticity and moment of inertia of a spin-orbit coupled Bose-Einstein condensate

S. Stringari

Irrotationality is one of the most important features exhibited by superfluids. It is at the origin of phenomena of fundamental relevance that have been confirmed experimentally both in superfluid helium and in ultracold atomic gases, like the quenching of the moment of inertia and the occurrence of quantized vortices. At small angular velocities the formation of quantized vortices is energetically inhibited and the moment of inertia of a superfluid, in the presence of isotropic confinement, vanishes at zero temperature as a consequence of the irrotationality of the velocity field. In Bose-Einstein condensates the condition of irrotationality is usually associated with the phase ϕ of the order parameter, whose gradient fixes the superfluid velocity. However, even at $T = 0$, the above irrotationality condition is violated in the presence of spin-orbit coupling, causing the violation of irrotationality and the appearance of rigid flow.

In this work, we showed that this effect is the consequence of the breaking of the current-phase relationship $\mathbf{j} = (\hbar/m)n\nabla\phi$, characterizing usual superfluids, and follows from the violation of Galilean invariance. We described the dynamic behavior of spinor condensates using a spinor hydrodynamic formalism based on a variational formulation of the Gross-Pitaevskii equation in terms of the densities and the phases of the two components of the spinor wave function. This theory allows for analytic solutions in the presence of harmonic trapping potentials and is applicable to both Raman-induced and Rashba spin-orbit coupled condensates. Spin-orbit coupling has been shown to give rise to a finite value of the moment of inertia (which can even take the classical rigid value) in isotropic traps at zero temperature, and to cause the reduction of the quantum of circulation in toroidal configurations.

The hydrodynamic results presented in this article provide a natural basis to investigate the role of phase and spin fluctuations in the presence of spin-orbit coupling and to better understand the conceptual distinction between superfluidity and Bose-Einstein condensation. The understanding of the connection between the disappearance of superfluidity in the hydrodynamic behavior, here predicted for isotropic Rashba coupling, and the absence of the Berezinskii-Kosterlitz-Thouless transition, recently investigated in two dimensions using the same isotropic spin-orbit configuration, is also expected to provide further insight into the problem of the superfluid properties of spin-orbit coupled Bose gases and on the role of dimensionality.

This article was selected by Physical Review Letter as Editors' Suggestion.

Physical Review A 95, 033614 (2017)

Magnetic solitons in Rabi-coupled Bose-Einstein condensates

Chunlei Qu, Marek Tylutki, Sandro Stringari, and Lev P. Pitaevskii

Solitary waves are nontrivial collective excitations that appear in a wide variety of systems in different physical branches including classical fluids, cosmology, condensed matter, optics, and cold atoms. Despite the fact that they do not correspond to the ground states of the systems, these solitary waves can be stable and live for a long time under certain physical conditions, which may have important applications. Because of the tunability of the interaction coupling constants and the absence of disorder, ultracold atomic gases provide an ideal playground for the observation of these excitations.

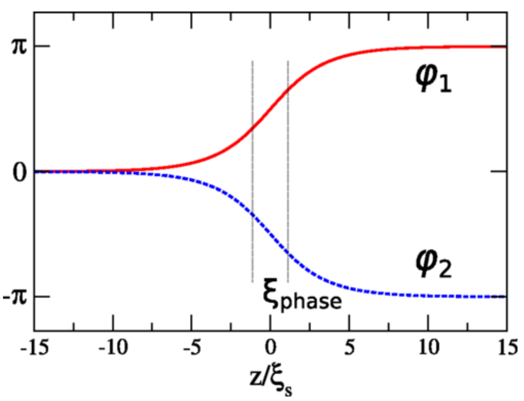


Figure 14: Phase structure of the static Son-Stephanov domain wall. The relative phase $\varphi_A = \varphi_1 - \varphi_2$ of the two spin states exhibits a 2π jump when one moves from $-\infty$ to $+\infty$. The width of the domain wall is fixed by the characteristic length of the relative phase $\xi_{\text{phase}} = [\hbar/(2m\Omega)]^{1/2}$, where Ω is the Rabi coupling frequency.

In this article, we investigated the main properties of moving magnetic solitons in Rabi-coupled binary Bose-Einstein condensates. Two types of magnetic solitons have been identified and characterized: (i) 2π-solitons, which are connected to the unmagnetized static Son-Stephanov domain wall and exhibit a 2π relative phase jump; and (ii) 0π-solitons, which are connected to 2π-solitons at a critical velocity, where the density of one component vanishes, and which do not exhibit a net jump of the relative phase. The complete phase diagram, the energy, and the magnetic properties of these solitons were obtained in a uniform matter, and their dynamical evolution was calculated in a 1D and 2D harmonic trap. A peculiar feature emerging from our calculations is that 2π-solitons evolve into 0π-solitons, and vice-versa, during their oscillatory motion in a harmonic trap. Results for the effective mass, the Landau critical velocity, and the role of the transverse confinement were also given.

We expect that these novel examples of solitons can be observed experimentally in the near-future, for example by using a mixture of the $|F = 1, m_F = +1\rangle$ and $|F = 1, m_F = -1\rangle$ hyperfine components of sodium atoms, where the exact miscibility of the atomic states can be reached. Although our discussion of magnetic solitons was focused on the context of binary Bose-Einstein condensates, similar physics can be easily generalized to and investigated in other physical systems which are governed by coupled Gross-Pitaevskii equations, such as in fiber optics and with exciton-polaritons.

Nature Physics 13, 704 (2017)

Exploring the ferromagnetic behaviour of a repulsive Fermi gas through spin dynamics

G. Valtolina, F. Scazza, A. Amico, A. Burchianti, A. Recati, T. Enss, M. Inguscio, M. Zaccanti, G. Roati

Ferromagnetism is a manifestation of strong repulsive interactions between itinerant fermions in condensed matter. Whether short-ranged repulsion alone is sufficient to stabilize ferromagnetic correlations in the absence of other effects, such as peculiar band dispersions or orbital couplings, is, however, unclear. In this article, we investigated ferromagnetism in the minimal framework of an ultracold Fermi gas with short-range repulsive interactions tuned via a Feshbach resonance. Whereas fermion pairing characterizes the ground state, our experiments provide signatures suggestive of a metastable Stoner-like ferromagnetic phase supported by strong repulsion in excited scattering states. We probed the collective spin response of a two-spin mixture engineered in a magnetic domain-wall-like configuration, and revealed a substantial increase of spin susceptibility while approaching a critical repulsion strength. Beyond this value, we observed the emergence of a time window of domain immiscibility, indicating the metastability of the initial ferromagnetic state. Our findings establish an important connection between dynamical and equilibrium properties of strongly correlated Fermi gases, pointing to the existence of a ferromagnetic instability.

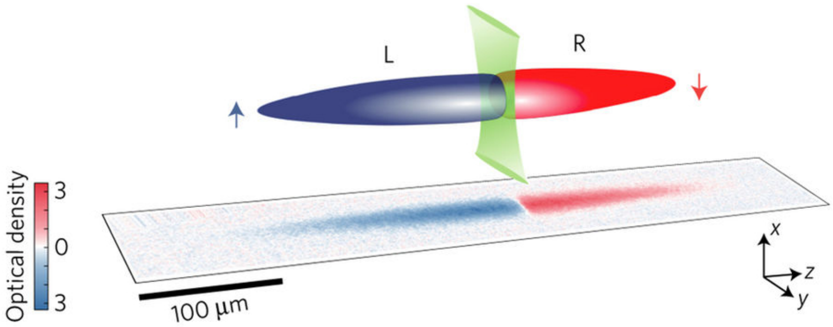


Figure 15: In the experiment at LENS, an atomic Fermi mixture is prepared in a ferromagnetic domain-wall structure. Such initial state is obtained by segregating the two spin components into two initially disconnected reservoirs at equilibrium by means of a thin optical barrier with a waist of about 2μm (in green). The subsequent dynamics is probed via spin-selective in situ imaging (lower image).

These experiments were performed at LENS in Florence. Alessio Recati, of the BEC Center, contributed to the theoretical analysis. The work provides an important link between the dynamic response and the static properties of the repulsive Fermi gas, thereby pointing to a Stoner-like ferromagnetic instability. The techniques demonstrated for realizing and probing a spin-domain interface could be extended to different systems, opening new routes towards the investigation of dynamics in strongly correlated quantum mixtures, also in reduced dimensionality or in the presence of weak optical lattices and controlled disorder.

Physical Review A 94, 063640 (2016)

Bose polaron problem: Effect of mass imbalance on binding energy

Luis A. Peña Ardila and Stefano Giorgini

In this work, by means of Quantum Monte Carlo methods we calculated the binding energy of an impurity immersed in a Bose-Einstein condensate at $T = 0$. The focus was on the attractive branch of the Bose polaron and on the role played by the mass imbalance between the impurity and the surrounding particles.

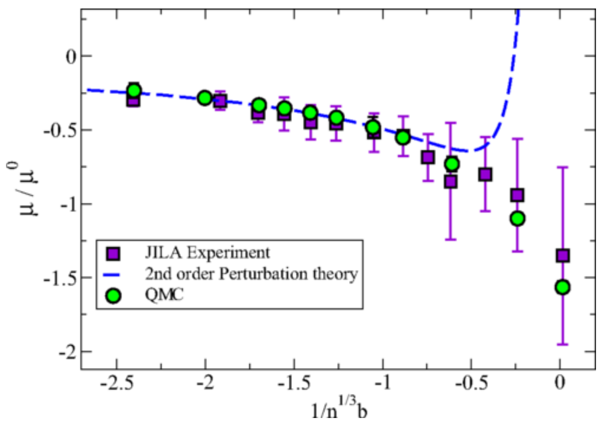


Figure 16: Binding energy of the impurity along the attractive branch as a function of the impurity-bath coupling $1/(bn^{1/3})$. The mass ratio is $m_B/m_I = 2$ and is close to the case of ^{40}K impurities in a BEC of ^{87}Rb atoms as in the JILA experiment. The gas parameter has also been chosen to reproduce the experimental value $na^3 = 2.66 \times 10^{?5}$. The blue dashed line corresponds to the prediction of perturbation theory including first- and second-order terms.

In two recent experiments, the energy of an impurity immersed in a Bose-Einstein condensate was measured using radio frequency spectroscopy and a Feshbach resonance to tune the impurity-bath interaction strength. The most striking result is the existence of a well-defined quasiparticle peak which, on the attractive branch of the Bose polaron, extends up to the unitary point where the impurity is resonantly interacting with the medium. In the experiment carried out at JILA, a low-density gas of fermionic ^{40}K impurities was superimposed onto a condensate of ^{87}Rb atoms, whereas researchers in Aarhus used two different hyperfine states of bosonic ^{39}K atoms. The fermionic analog, i.e., an impurity immersed in a Fermi sea, has already been the object of many experimental and theoretical studies.

In a previous work, we characterized the properties of the Bose polaron using Quantum Monte Carlo methods in the case where the impurity and the particles in the condensate have the same mass, and we determined the dependence of the binding energy of the impurity resonantly interacting with the bath by varying the gas parameter of the condensate. In this article, we extended the calculations by analyzing how this energy changes also as a function of the mass ratio m_B/m_I. We determined the equation of state in the case of a static (infinite mass) impurity, where three-body correlations are irrelevant and the result is expected to be a universal function of the gas parameter. Then we showed that, for the mass ratio corresponding to ^{40}K impurities in a gas of ^{87}Rb atoms, the numerical results for the polaron energy along the attractive branch agree with the experimental findings at JILA.

New Journal of Physics 18, 113044 (2016)

Dynamic structure factor of a strongly correlated Fermi superfluid within a density functional theory approach

Peng Zou, Franco Dalfovo, Rishi Sharma, Xia-Ji Liu, Hui Hu

The dynamic structure factor is a key quantity in the description of a many-body system. In a superfluid Fermi gas, by tuning the momentum and energy transferred to the system by an external probe from low to high values, the dynamic structure factor reveals the typical features associated with low-lying collective phonon excitations, Cooper-pair excitations and single-particle atomic excitations, as well as possible indications of the existence of pseudo-gap pairing or pre-pairing states.

In this article, we presented some new results for the dynamic structure factor of a strongly interacting Fermi gas at the crossover from Bardeen-Cooper-Schrieffer superfluids to Bose-Einstein condensates. We developed an improved random phase approximation (RPA) within the framework of a density functional theory, the so-called superfluid local density approximation (SLDA). We showed that, compared with previous random-phase-approximation calculations based on the standard Bogoliubov-de Gennes equations, the use of the SLDA greatly improves the accuracy of the equation of state at the crossover, and leads to a better description of both collective Bogoliubov-Anderson-Goldstone phonon mode and single-particle fermionic excitations at small transferred momentum. Near unitarity, where the s-wave scattering length diverges, we show that the single-particle excitations start to significantly contribute to the spectrum of dynamic structure factor once the frequency is above a threshold of the energy gap at 2Δ. The sharp rise in the spectrum at this threshold can be utilized to measure the pairing gap Δ. Together with the sound velocity determined from the phonon branch, the dynamic structure factor provides us some key information of the crossover Fermi superfluid. The theory is expected to be quantitatively reliable at low transferred momentum (i.e., $q < k_F$) and at low temperature (i.e., $T \ll T_c$), where the predicted static structure factor agrees excellently well with the result of the most recent ab initio Quantum Monte Carlo results. Our predictions might be tested in experiments with ^{6}Li or ^{40}K atoms using Bragg spectroscopy.

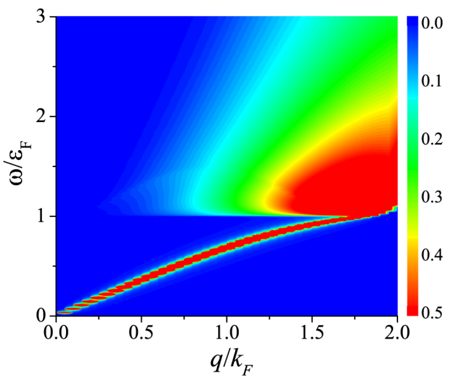


Figure 17: Contour plot of the dynamic structure factor of a unitary Fermi gas at zero temperature, obtained by using SLDA-RPA. The slope of the low-energy branch is given by the sound speed $c_s \simeq 0.354 v_F$, while the horizontal threshold at $\omega \simeq \varepsilon_F$ is equal to the minimum energy 2Δ to break a Cooper-pair. The color bar indicates the value of the dynamic structure factor, which is measured in units of N/ε_F and changes from 0 (blue) to 0.5 (red).

Physical Review A 94, 021602(R) (2016)

Self-bound dipolar droplet: A localized matter wave in free space

D. Baillie, R. M. Wilson, R. N. Bisset, and P. B. Blakie

In this article (selected by the journal as Editors' Suggestion), we showed that it is possible to realize a localized matter wave state in current experiments with dipolar condensates. Such condensates consist of atoms with appreciable magnetic dipole moments and have been experimentally realized with Chromium, Dysprosium, and Erbium. The two-body interaction in this system includes a long-ranged and anisotropic dipole-dipole interaction in addition to a short-ranged s-wave interaction. For sufficiently strong dipoles the two-body interaction is partially attractive and the system is susceptible to local collapse instabilities. However, recent experiments exploring this regime with trapped dipolar condensates have observed the formation of droplet arrays, i.e., the atoms coalesce into a set of small and dense droplets that have long lifetimes. Theoretical works demonstrated that quantum fluctuations are most likely responsible for stabilizing these droplets, as they contribute a local energy proportional to $n^{5/2}$, where n is the density that arrests the two-body driven collapse (proportional to n^2) at sufficiently high n.

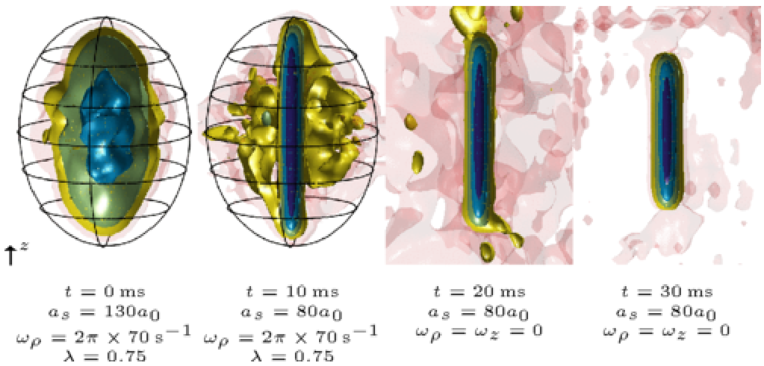


Figure 18: Density iso-surfaces illustrating the dynamical production of a self-bound droplet starting from a ^{164}Dy condensate with $a_s = 130a_0$ and 104 atoms. In the dynamics, as is quenched to $80a_0$ over 10 ms, and then the trapping potential is turned off over 10 ms. Contours are for a density slice in the $y = 0$ plane. Each adjacent contour has a density differing by a factor of 10.

Here we developed a general theory of self-bound dipolar condensates based on the generalized nonlocal Gross-Pitaevskii equation that includes corrections due to quantum fluctuations. We obtained self-bound states directly using numerical methods and by an approximate variational approach. This allowed us to construct a phase diagram for the regime of interaction parameters and atom number N where self-bound states exist, and to explore the typical properties of these states. Finally, we discussed how these states can be produced in experiments beginning from a trapped dipolar condensate by dynamically adjusting the trapping potential and s-wave scattering length. These results show that the lifetimes of the self-bound states are ultimately set by the three-body loss rate, which eventually reduces the atom number to the point when the wave packet is no longer self-bound.

Physical Review A 94, 062704 (2016)

Two-body physics in the Su-Schrieffer-Heeger model

Marco Di Liberto, Alessio Recati, Iacopo Carusotto, and Chiara Menotti

In a perfectly periodic system, states outside the allowed bands can appear for both attractive and repulsive interactions when composite objects are formed. The existence of so-called exotic repulsive bound pairs, also known as doublons, was directly observed ten years ago by implementing a single-band Hubbard model with ultracold Bose gases in an optical lattice. On the other hand, any real crystal is made of a bulk and a surface. The study of how surfaces modify the spectrum of a particle in a finite crystal started with the seminal papers by Tamm and Shockley, who pointed out the existence of localized states at the surface with energy outside the allowed energy bands. Such surface states can play an important role in the transport properties. Particular attention has been devoted in the recent years to their characterization in the so-called topological insulator materials. While most of the surface states are well explained by single-particle band theory, the physics becomes much more intriguing in the presence of strong interparticle interactions.

In this work, we made an important step forward by trying to combine a topologically nontrivial single-particle band structure with interactions. In this first ground-breaking work, we focused our attention on the minimal model of two interacting particles in a Su-Schrieffer-Heeger (SSH) lattice. The full two-body spectrum can be calculated and very rich physics emerges in spite of the simplicity of the model. In particular we found: (i) the hybridization of different channels leading to Fano-Feshbach resonances; (ii) the existence of out-of-cell (long-range) bound pairs; and (iii) edge states for the bound pairs. The article includes the proposal of an experimentally realistic optical fiber setup to quantum simulate the two-body SSH model in the laboratory and experimentally highlight our predictions. Subsequent works have extended these results to more complex configurations involving nearest-neighbor interactions (Di Liberto et al., Eur. Phys. J. Special Topics 226, 2751 (2017)), while in G. Salerno et al., arXiv:1711.01272, we have calculated the two-particle bound states in a two dimensional Haldane model where topologically protected two-body edge states exist.

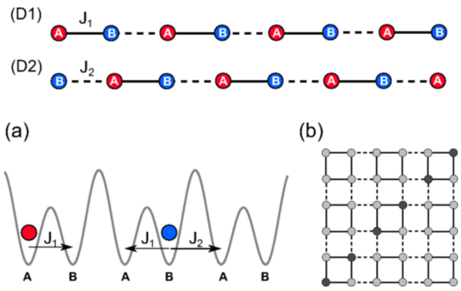


Figure 19: Sketch of the SSH model. Dimerization D1 starting and ending with a strong link J_1, and dimerization D2 starting and ending with a weak link J_2. (a) Example of two particles in a dimerized potential described by a SSH model. (b) Sketch of the mapping onto a 2D single-particle system: strong links J_1 (full lines), weak links J_2 (dashed lines), and local potential U (dark sites).

Physical Review Letters 118, 045301 (2017)

Casimir forces and quantum friction from Ginzburg radiation in atomic BECs

Jamir Marino, Alessio Recati, and Iacopo Carusotto

One of the most exciting features of quantum field theory consists of the nontrivial structure of the vacuum state and of the associated zero-point fluctuations. Among their most celebrated observable consequences in the electromagnetic context, we can mention the static Casimir force between neutral objects and the dynamical Casimir emission of correlated pairs of photons by suitably accelerated neutral objects. The physics underlying such pair emission processes is perhaps cleanest in the case of Ginzburg radiation from neutral but polarizable objects uniformly moving at superluminal speeds. The so-called anomalous Doppler effect allows in fact an atom moving in a medium at $v > c/n$ (n being the medium refractive index) to jump from its ground state to an excited state by emitting (and not absorbing) a photon.

In this article, we developed and exploited a general framework to study a wide variety of quantum vacuum effects using state-of-the-art cold atom technology. Following the same spirit of the quest for analog Hawking radiation in analog models of gravity and building on recent works on analog Casimir forces and analog Unruh temperature in quantum fluids, we propose to employ a dilute Bose-Einstein condensate as the medium and Bogoliubov sound waves in place of EM waves as the quantum field. The requirement for an ultra-relativistic motion is in this way replaced by a much more accessible condition involving the speed of sound in the condensate, typically in the cm/s range. In contrast to previous works on analog Casimir forces in quantum fluids where the coupling is a charge-like one, here the impurity behaves as a neutral two-level atom coupled to the EM field, i.e., with a vanishing charge but a non-vanishing polarizability.

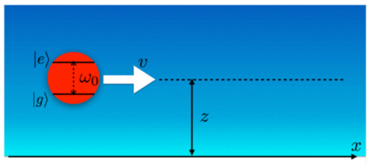


Figure 20: Schematic representation of the moving impurity with internal frequency ω_0 and the plate on the $z = 0$ plane, confining the condensate (in blue).

As a first application of our general theory, we showed how simple atomic spectroscopy tools may provide crucial information on the Ginzburg emission from a uniformly moving impurity. As soon as its speed exceeds the speed of sound, the atomic ground state acquires a detectably finite linewidth due to spontaneous excitation processes to the excited state and experiences a mechanical friction force in response to the Ginzburg emission. When the supersonic moving impurity is located in the vicinity of the edge of the condensate, it experiences an analog of the zero-temperature Casimir force with a novel power-law scaling and an analog of the Casimir friction of quantum electrodynamics. This novel phenomenology sets apart our results from previous studies of Casimir forces in condensed-matter settings. Experimentally realistic protocols to highlight these effects as frequency shifts and broadenings of the atomic transition lines are put forward, as well as estimates for the observability of our predictions.

Physical Review B 94, 144518 (2016)

Theoretical study of stimulated and spontaneous Hawking effects from an acoustic black hole in a hydrodynamically flowing fluid of light

Pjotrs Grisins, Hai Son Nguyen, Jacqueline Bloch, Alberto Amo, and Iacopo Carusotto

In this work, we proposed and numerically characterized an experimental setup to study the Hawking effect in a flowing fluid of exciton polaritons in a laterally patterned semiconductor microcavity device under a coherent monochromatic pump. A stimulated analog Hawking effect can be studied in a pump-and-probe-type measurement, while the spontaneous analog Hawking effect is observable in the correlations function of the intensity noise in the secondary emission. The main conclusion of this work was that both effects can be observed in a state-of-the-art device with standard quantum optical tools.

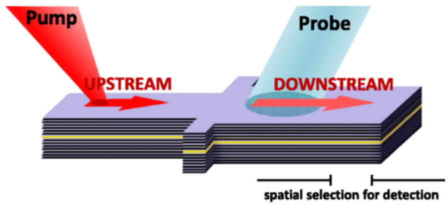


Figure 21: Proposed device to observe the stimulated Hawking radiation. A semiconductor microcavity device has the form of a long one-dimensional photonic wire oriented along the x direction, with a micrometer-sized x-dependent lateral profile. The flowing condensate is created by a focused coherent pump laser beam incident at a finite angle. The attractive defect potential created by the wider region around x=0 creates an analog black-hole horizon in its vicinity, which separates an upstream region of subsonic flow from a downstream region of supersonic flow. A weak probe laser is shone in the downstream region so to generate the Bogoliubov waves which then stimulate the Hawking radiation. The cavity emission is collected in the far downstream region.

In order to detect the stimulated Hawking emission, we proposed to shine an additional weak and monochromatic probe beam onto the cavity, so to generate a coherent Bogoliubov excitation propagating against the horizon. The stimulated Hawking emission is detected by isolating the scattered waves at the probe and four-wave-mixed frequencies and measuring their wave-vector distribution. With respect to previous studies, the pump-probe experiment proposed here appears to be technologically much easier to implement as it only requires a pair of continuous-wave laser beams and an angularly and spectrally selective detection system, with no need for time-resolved technology to generate and detect the time-dependent signals of a pulsed laser. The numerically observed exponential decay of the scattered amplitude at the four-wave-mixed frequency as the function of the pump-probe detuning provides a prediction for the Hawking temperature around 1.4 K in good agreement with the value expected from the surface gravity of the horizon. As a novel unexpected phenomenon, we identified the spontaneous appearance of an emergent resonant Fabry-Perot-type cavity for sound waves, formed by the strong pump beam, which completely reflects the quasiparticles, and the semitransparent horizon. As a consequence, the stimulated Hawking response shows a strong modulation on top of the exponential decay, with well-defined peaks at the cavity resonances.

Physical Review Letters 118, 013601 (2017)

Synthetic Dimensions with Magnetic Fields and Local Interactions in Photonic Lattices

Tomoki Ozawa and Iacopo Carusotto

From the perspective of condensed matter physics, systems of dimensions 4 or higher were long considered relatively featureless because their properties are typically well captured by mean-field theories. This expectation was overturned by recent developments in the study of topological phases of matter, which hinted at rich novel physics in higher dimensional systems. In particular, analogues of the quantum Hall effect are predicted for any even dimensions, with new topological invariants appearing from four dimensions. While such predictions are clearly unaccessible in traditional condensed matter systems, a novel approach of simulating higher-dimensional topological models using "synthetic dimensions" has very recently moved its first steps. Such developments in synthetic dimensions open a prospect of exploring physics in four dimensions using physically three-dimensional lattices. Going beyond to explore fractional quantum Hall states is however facing great difficulties because of the very long range nature of interactions along the synthetic dimension in both atomic and photonic systems. It is therefore of great interest to find schemes to realize synthetic dimensions where interactions are short ranged.

In this work, we proposed a general framework to realize a photonic lattice that combines synthetic dimensions and synthetic magnetic fields with local interactions. We considered an array of ring-shaped photonic cavities, with hoppings between adjacent cavities of (real) amplitude J and a θ-dependent hopping phase equal to $c\theta$ as one hops from sites (x, θ) to $(x + 1, \theta)$. Differently from previous proposals where the focus was on the mode index w, the synthetic dimension is here spanned by the geometrical angular coordinate θ around the disk that is conjugate to w. We presented our idea on the intuitively most transparent case of a 1D chain of cavities along the x direction. In this way, an effectively two-dimensional model in the x-θ plane is obtained, and a synthetic magnetic field naturally appears if the resonators are designed in a way that hopping along the x direction is accompanied by a change in w. The spatially local photon-photon interactions within a cavity lead to the desired local interaction along both x and θ. We confirmed the validity of our framework by numerical simulations of the cyclotron motion and the expansion dynamics of a suitably initialized wave packet.

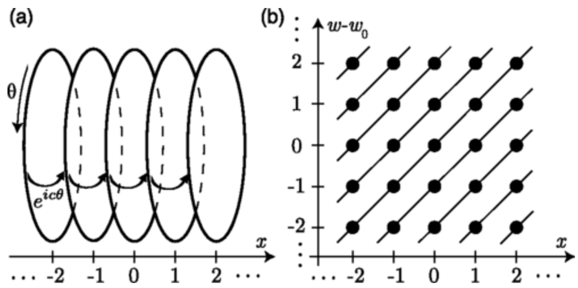


Figure 22: Schematic illustration of hoppings (a) in the x-θ plane and (b) in the x-w plane when $c = 1$.

Nature Physics 13, 545 (2017)

Experimental Measurement of the Berry Curvature from Anomalous Transport

Martin Wimmer, Hannah M. Price, Iacopo Carusotto, Ulf Peschel

The geometric properties of energy bands underlie fascinating phenomena in many systems, including solid-state, ultracold gases and photonics. The local geometric characteristics such as the Berry curvature can be related to global topological invariants such as those classifying the quantum Hall states or topological insulators. Regardless of the band topology, however, any non-zero Berry curvature can have important consequences, such as in the semi-classical evolution of a coherent wavepacket. In this article, we experimentally demonstrated that the wavepacket dynamics can be used to directly map out the Berry curvature. To this end, we used optical pulses in two coupled fibre loops to study the discrete time evolution of a wavepacket in a one-dimensional geometric 'charge' pump, where the Berry curvature leads to an anomalous displacement of the wavepacket. This is both the first direct observation of Berry curvature effects in an optical system, and a proof-of-principle demonstration that wavepacket dynamics can serve as a high-resolution tool for mapping out geometric properties.

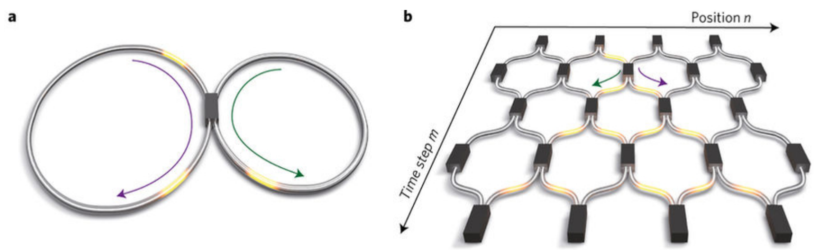


Figure 23: a) Optical pulses propagating along two coupled fibre loops of slightly different lengths are used to simulate light evolution on a 1+1 D lattice spanned by a discrete time m and position n. b) The light evolution in the fibre loops is mapped onto a lattice, where a round trip in the short loop stands for the motion from northeast to southwest, while the propagation from northwest to southeast is equivalent to a round trip through the long loop.

The work was the result of the joint efforts of the experimental group of M.Wimmer at the Erlangen Graduate School in Advanced Optical Technologies and Institute of Solid State Theory and Optics, Abbe Center of Photonics in Jena, and the theory group of the BEC Center. The two teams demonstrated that anomalous wavepacket dynamics can provide an important experimental tool for mapping out the local geometrical properties of energy bands. This versatility of this scheme should allow applications in a variety of configurations, including systems with gain and loss and/or non-trivial topological invariants. In the presence of nonlinearities, this technique could provide a new approach for the creation and manipulation of different wavepacket structures, such as solitons. Given its simplicity, the experimental set-up also holds the promise of transferring geometrical and topological concepts into the applied world of optoelectronics.

Reviews of Modern Physics 91, 015006 (2019)

Topological Photonics

Tomoki Ozawa, Hannah M. Price, Alberto Amo, Nathan Goldman, Mohammad Hafezi, Ling Lu, Mikael Rechtsman, David Schuster, Jonathan Simon, Oded Zilberberg, Iacopo Carusotto

Over the last decade, topological photonics appeared as a rapidly growing field of study. This new field is rooted in ideas that were first developed to understand topological phases of matter in solid-state physics, the simplest example being the integer quantum Hall effect discovered in 1980. In this effect, a two-dimensional electron gas in the presence of a strong perpendicular magnetic field was found to exhibit robust plateaus in the Hall conductance as a function of the magnetic field at values equal to integer multiples of the fundamental constant e^2/h. The far-reaching conceptual consequences of this effect were soon highlighted in a series of works relating the integer appearing in the Hall conductance to a topological invariant, the so-called Chern number, describing the global structure of the wave function in momentum space over the Brillouin zone, and, within the so-called bulk-boundary correspondence, to the number of chiral modes living on the edge of a spatially finite sample of topological material.

Figure 24: A pause during a meeting of the co-authors in the library in Banff, Canada. From bottom: Hafezi, Carusotto, Price, Ozawa, Lu, Zilberberg, Rechtsman. The four missing ones were connected on skype.

Parallel to the growth in the study of topological phases of matter in condensed-matter systems, Haldane and Raghu made in 2008 the crucial observation that topological band structures are, in fact, a ubiquitous property of waves inside a periodic medium, regardless of the classical or quantum nature of the waves. In their seminal works, they considered electromagnetic waves in two-dimensional spatially periodic devices embedding time-reversal-breaking magneto-optical elements and showed that robust chiral states propagating along the edge of the system appear as a direct consequence of the non-trivial photonic band topology.

This review is focused on the recent developments in the study of topological phases of matter in the photonics context. In the last decade, topological ideas have successfully permeated the field of photonics, having been applied to a wide range of different material platforms, arranged in lattices of various dimensionalities, and operating in different regions of the electromagnetic spectrum, from radio waves and microwaves up to visible light. In addition to opening up perspectives for exploring the fundamental physics of topological phases of matter beyond solid-state systems, topological photonics also offers rich potential applications to a novel generation of optoelectronic devices, such as optical isolators and topological lasers.

This review was written by a team of 11 world-leading researchers in this field. The writing process was coordinated by the BEC Center, who have also personally written the lion's share of the text. This work is classified as *Hot* and *Highly-Cited* paper in the Web of Science.

Physical Review Research 1, 033148 (2019)

Theory of chiral edge state lasing in a 2D topological system

Matteo Seclì, Massimo Capone, Iacopo Carusotto

One of the most promising applications of topological photonics concerns laser operation in topological systems displaying optical gain, the so-called topological lasing. Specifically in their two-dimensional version, such topological lasers appear promising to solve a long-standing technological problem in optoelectronics, namely, the realization of large-area devices offering high-power coherent emission. The purpose of this paper is to build a generic theory of topological laser operation.

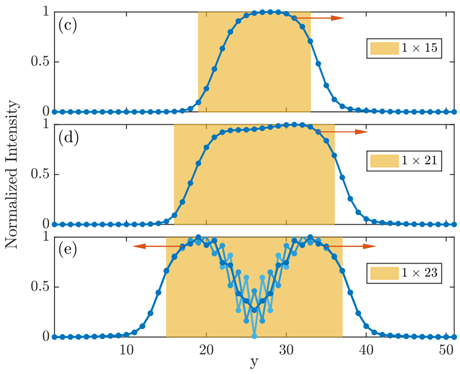


Figure 25: Spatial profiles of the lasing mode for growing size of the pumped region. The signature of chirality is visible in the lasing mode being shifted in the downstream direction.

Going beyond the pioneering works, we identify a number of peculiar effects that differentiate topological lasers from standard lasers. Striking consequences of the chirality of the lasing mode have been highlighted: when gain is distributed around the whole edge, lasing can occur in a number of closely spaced modes and relaxation towards the steady-state occurs on a very slow timescale. The consequences of this feature on the spatio-temporal coherence functions of the laser emission have been highlighted in a successive study by Amelio and Carusotto. On the other hand, when gain is restricted to a finite strip (see figure), relaxation is fast but the distinction between convective and absolute instabilities causes an increase of the threshold and introduces new amplification regimes.

To complete the picture, we have quantitatively assessed the impact of disorder on topological lasing. Our analysis will provide a powerful conceptual framework in view of future studies of the complex nonlinear physics of specific realizations of topological laser devices and, on the longer run, will be a useful starting point to understand the fundamental quantum limits of topological laser operation.

This work has been extracted from Matteo Seclì's Master thesis work carried out at Trento University under the co-supervision of the two senior co-authors.

Nature Communications 10, 3869 (2019)

Dispersion relation of the collective excitations in a resonantly driven polariton fluid

P. Stepanov, I. Amelio, J.-G. Rousset, J. Bloch, A. Lemaître, A. Amo, A. Minguzzi, I. Carusotto, M. Richard

The root cause of superfluidity can be traced back to the dispersion relation of elementary excitations in the quantum fluid. In a low-temperature and weak-interactions regime, Bogoliubov derived in 1947 an analytical description of this regime, and could thus reveal the link between the dispersion relation of the excitations and the superfluid state.

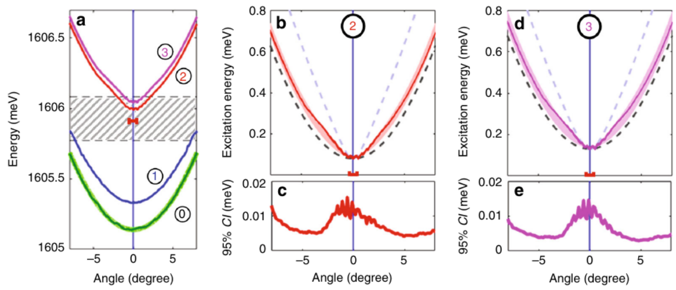


Figure 26: Experimentally observed dispersion relation of the collective excitations for different pump powers and comparison with different theoretical models.

Recently, quantum fluids of light have emerged as a new class of quantum fluids, characterized by their nonequilibrium char- acter. A paradigmatic member of this class is the fluid of exciton–polaritons. While a superfluid–like frictionless flow has been experimentally demonstrated in 2009 in a steady-state polariton fluid following theoretical predictions co-authored by the BEC Center, a complete quantitative measurement measurement of the dispersion relation was still missing.

In this work, we resonantly drive a nonequilibrium condensate of exciton–polaritons with a CW laser. We focus our attention on the high-density regime, in which the interaction energy is comparable or exceed the linewidth, such that the excitations are of collective nature. We perform a direct measurement of their dispersion relation using an angle–resolved spectroscopy technique inspired from Brillouin scattering experiments. We find that the results differ strongly from the pure polariton condensate situation described by the generalized Gross–Pitaevskii equation, like for example a speed of sound which is apparently twice too low. Inspired by previous work suggesting that a reservoir of long-lived excitons coexists with polaritons even in this resonant excitation regime, we developed a theoretical framework in which polaritons can be converted into reservoir excitons, and in which the reservoir provides an additional two-body interaction channel. The resulting excitations are of hybrid reservoir density and Bogoliubov-excitations nature, and agree quantitatively with our measurements.

The experimental work was carried out in Grenoble, while the theoretical modelling of the observations was performed in Trento. This work stimulated a series of follow-up theoretical works that are investigating further consequences of the reservoir.

Articles, preprints and highlights

Here below we list all publications of the BEC Center since July 2016: first the articles already published in peer-reviewed journals, then the preprints that have been submitted to journals and posted on the arXiv, and finally a few highlights. The following figure shows the remarkable interdisciplinarity of the research activities of the Center, quantified by the number of articles falling into the subject classification scheme of ISI - Web of Science.

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Spin-dipole mode in a trapped Fermi gas near unitarity, Hiroyuki Tajima, Alessio Recati, Yoji Ohashi, Phys. Rev. A **101**, 013610 (2020)

Quantum fluctuations of the friction force induced by the dynamical Casimir emission, Salvatore Butera, Iacopo Carusotto, EPL **128**, 24002 (2020)

A Sideband-Enhanced Cold Atomic Source For Optical Clocks, Matteo Barbiero, Marco G. Tarallo, Davide Calonico, Filippo Levi, G. Lamporesi, G. Ferrari, Phys. Rev. Applied **13**, 014013 (2020)

Design and characterisation of a compact magnetic shield for ultracold atomic gas experiments, Arturo Farolfi, Dimitrios Trypogeorgos, Giacomo Colzi, Eleonora Fava, Giacomo Lamporesi, Gabriele Ferrari, Rev. Scient. Instr. **90**, 115114 (2019)

Decay of the relative phase domain wall into confined vortex pairs: the case of a coherently coupled bosonic mixture, Albert Gallemí, Lev P. Pitaevskii, Sandro Stringari, Alessio Recati, Phys. Rev. A **100**, 023607 (2019)

Supersolid symmetry breaking from compressional oscillations in a dipolar quantum gas, L. Tanzi, S. M. Roccuzzo, E. Lucioni, F. Fam, A. Fioretti, C. Gabbanini, G. Modugno, A. Recati, S. Stringari, Nature **574**, 382 (2019)

Two-dimensional repulsive Fermi polarons with short and long-range interactions, Raúl Bombín, Tommaso Comparin, Gianluca Bertaina, Ferran Mazzanti, Stefano Giorgini, Jordi Boronat, Phys. Rev. A **100**, 023608 (2019)

Quench Dynamics of an Ultracold 2D Bose Gas, Paolo Comaron, Fabrizio Larcher, Franco Dalfovo, Nikolaos P. Proukakis, Phys. Rev. A **100**, 033618 (2019)

A generalized Gross-Pitaevskii model for intersubband polariton lasing, Jacopo Nespolo and Iacopo Carusotto, Phys. Rev. **B 100**, 035305 (2019)

Fusion Channels of Non-Abelian Anyons from Angular-Momentum and Density-Profile Measurements, Elia Macaluso, Tommaso Comparin, Leonardo Mazza, Iacopo Carusotto, Phys. Rev. Lett. **123**, 266801 (2019)

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Theory of chiral edge state lasing in a two-dimensional topological system, Matteo Seclí, Massimo Capone, Iacopo Carusotto, Phys. Rev. Research **1**, 033148 (2019)

Quantum well infrared photo-detectors operating in the strong light-matter coupling regime, P.-B. Vigneron, S.Pirotta, I.Carusotto, N.-L. Tran, G. Biasiol, J.-M. Manceau, A. Bousseksou, R. Colombelli, Appl. Phys. Lett. **114**, 131104 (2019)

Hermitian and Non-Hermitian Mode Coupling in a Microdisk Resonator Due to Stochastic Surface Roughness Scattering, S. Biasi, F. Ramiro-Manzano, F. Turri, P.-É. Larré, M. Ghulinyan, I. Carusotto, L. Pavesi, IEEE Photonics Journal **11**, 1 (2019)

Supersolid behavior of a dipolar Bose-Einstein condensate confined in a tube, Santo Maria Roccuzzo and Francesco Ancilotto, Phys. Rev. A **99**, 041601 (2019)

Collisions of self-bound quantum droplets, G.Ferioli, G. Semeghini, L. Masi, G. Giusti, G. Modugno, M. Inguscio, A. Gallemí, A. Recati, M. Fattori, Phys. Rev. Lett. **122**, 090401 (2019)

Two-dimensional Mixture of Dipolar Fermions: Equation of State and Magnetic Phases, T. Comparin, R. Bombn, M. Holzmann, F. Mazzanti, J. Boronat, S. Giorgini, Phys. Rev. A **99**, 043609 (2019)

Magnetic phase transition in a mixture of two interacting Bose gases at finite temperature, Miki Ota, Stefano Giorgini, Sandro Stringari, Phys. Rev. Lett. **123**, 075301 (2019)

Analyzing the Bose Polaron Across Resonant Interactions, L.A. Peña Ardila, N.B. Jorgensen, T. Pohl, S. Giorgini, G.M. Bruun, J.J. Arlt, Phys. Rev. A **99**, 063607 (2019)

Dispersion relation of the collective excitations in a resonantly driven polariton fluid, P. Stepanov, I. Amelio, J. Rousset, J. Bloch, A. Amo, A. Minguzzi, I. Carusotto, M. Richard, Nat. Communications **10**, 3869 (2019)

Mechanical back-reaction effect of the dynamical Casimir emission, Salvatore Butera, Iacopo Carusotto, Phys. Rev. A **99**, 053815 (2019)

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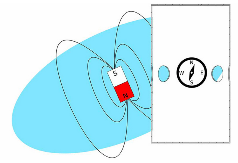
Highlights

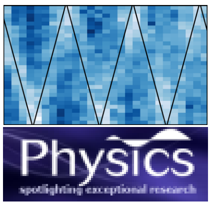


The article *Design and characterization of a compact magnetic shield for ultracold atomic gas experiments*, by Farolfi et al., published in Review of Scientific Instruments 90, 115114 (2019), has been selected by AIP **Sci**light.

The article *Supersolid symmetry breaking from compressional oscillations in a dipolar quantum gas*, by L.Tanzi et al., has been published in Nature 574, 382 (2019). It was also selected for a Research Highlight in Nature Physics and for a News and Views article in Nature.

The article *Static-response theory and the roton-maxon spectrum of a flattened dipolar Bose-Einstein condensate* by R. N. Bisset, P. B. Blakie, S. Stringari, Phys. Rev. A 100, 013620 (2019), has been selected as PRA Editors' Suggestion.

The Journal of Experimental and Theoretical Physics (JETP) has dedicated a Special Issue in Honor of L.P. Pitaevskii's 85th Birthday (Volume 127, Issue 5, November 2018).

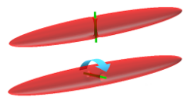


The article *Collisionless Sound in a Uniform Two-Dimensional Bose Gas* by Miki Ota et al., published in Phys. Rev. Lett. 121, 145302 (2018), has been highlighted with a Synopsis by the on-line journal Physics together with the article by Ville et al. Phys. Rev. Lett. 121, 145301 (2018).

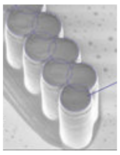
The article *Dynamical Equilibration Across a Quenched Phase Transition in a Trapped Quantum Gas*, by I.-K. Liu et al., Communications Physics 1, 24 (2018), has been picked up for a Research Highlight in Nature Physics.

The article *Second sound in a two-dimensional Bose gas: From the weakly to the strongly interacting regime* by M.Ota and S.Stringari, Phys. Rev. A 97, 033604 (2018), has been selected as PRA Editors' Suggestion.

The article *Exploring 4D quantum Hall physics with a 2D topological charge pump*, by Lohse et al., has been published in Nature **553**, 55 (2018).



The article *Observation of a spinning top in a Bose-Einstein condensate* by Bisset et al., published in Physical Review A 96, 053605 (2017), has been highlighted with a Synopsis by the on-line journal Physics and has been selected as PRA Editors' Suggestion.



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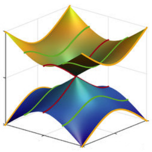

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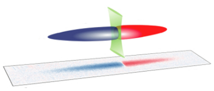

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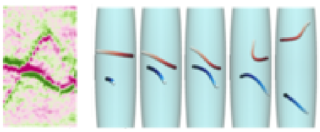
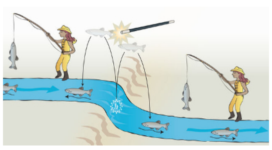


The article *Vortex Reconnections and Rebounds in Trapped Atomic Bose-Einstein Condensates* by S.Serafini et al., has been published in Phys. Rev. X 7, 021031 (2017).

The article *Repulsive Fermi polarons in a resonant mixture of ultracold 6Li atoms* by F.Scazza et al., Phys. Rev. Lett. 118, 083602 (2017), has been selected as PRL Editors' Suggestion.

The article *Diffused Vorticity and Moment of Inertia of a Spin-Orbit Coupled Bose-Einstein Condensate* by Sandro Stringari, Phys. Rev. Lett. 118, 145302 (2017), has been selected as PRL Editors' Suggestion.

The article *Self-bound dipolar droplet: A localized matter wave in free space* by D.Baillie et al., Phys. Rev. A 94, 021602 (2016), has been selected as PRA Editors' Suggestion.



Iacopo Carusotto and Roberto Balbinot have been invited by the journal Nature Physics to write a "News and Views" article [Nat. Phys., 15 August (2016)] on *Quantum hydrodynamics: Acoustic Hawking radiation.*

Meetings, seminars, conferences, honors, outreach

Group meetings and seminars at the BEC Center

- Thursday, December 19th 2019, at 10:30, Physics seminar room, 2nd floor
  BEC Seminar, Andreas Haller (Johannes Gutenberg Universitt Mainz)
  About the tuning of transport by repulsive interactions and the detection of topology through bulk dynamics in interacting fermionic ladder systems

- Wednesday, December 18th 2019, at 14:00, A207, Povo 1
  BEC Colloquium, Michele Parrinello (ETH Zurich and Universit della Svizzera Italiana, Switzerland)
  Atoms and Computers

- Tuesday, December 17th 2019, at 14:00, Physics seminar room, 2nd floor
  BEC Seminar, Barak Hirshberga and Valerio Rizzi (ETH Zurich and Universit della Svizzera Italiana, Switzerland)
  Path Integral Molecular Dynamics for Bosons

- Thursday, December 12th 2019, at 10:30, Physics seminar room, 2nd floor
  BEC Seminar, Alonso Viladomat (Universitt Heidelberg)
  Implementing Topological Entanglement as a Resource Theory

- Tuesday, December 10th 2019, at 10:30, A108, Povo 1
  BEC Internal Report, Jacopo Nespolo (BEC Center)
  Generalized Gross-Pitaevskii models for intersubband polariton lasers

- Thursday, December 5th 2019, at 10:00, Physics seminar room, 2nd floor
  BEC Seminar, Murray Holland (University of Colorado Boulder)
  Extreme sensing, clocks, and squeezing atoms and molecules with light

- Wednesday, December 4th 2019, at 10:00, Physics seminar room, 2nd floor
  BEC Seminar, Johannes Lang (Max Planck Institute for the Physics of Complex Systems, Dresden)
  Loschmidt echo in infinite range spin chains

- Monday, December 2nd 2019, at 10:30, B103, Povo 2
  BEC Colloquium, Matteo Rizzi (Kln University)
  Exploring synthetic quantum matter with tensor networks

- Friday, November 29th 2019, at 10:30, Physics seminar room, 2nd floor
  BEC Seminar, Manel Bosch Aguilera (Laboratoire Kastler Brossel)
  Dissipation in optical lattices: Zeno suppression of losses and anomalous decay of coherence

- Tuesday, November 26th 2019, at 10:30, A108, Povo 1
  BEC Internal Report, Luca Parisi (BEC Center)
  Quantum droplets in 1D Bose mixtures

- Friday, November 22nd 2019, at 14:30, A208, Povo 1
  Q at TN Seminar, Florent Michel (Durham University)
  Vacuum decay: from cosmology to cold atoms

- Thursday, November 21st 2019, at 10:30, Physics seminar room, 2nd floor
  BEC Seminar, Vijay Singh (Universitt Hamburg)
  Berezinskii-Kosterlitz-Thouless scaling in a Josephson junction of an ultracold two-dimensional Bose gas

- Monday, November 18th 2019, at 10:30, B103, Povo 2
  BEC Colloquium, Philipp Hauke (BEC Center)
  Strongly entangled quantum matter

- Friday, November 15th 2019, at 14:00, A203, Povo 1
  Q at TN Seminar, Antoine Browaeys (Lab. Charles Fabry, Inst. d Optique, CNRS, Palaiseau, France)
  Many-body physics with arrays of individual Rydberg atoms

- Tuesday, November 12th 2019, at 10:30, A108, Povo 1
  BEC Internal Report, Arturo Farolfi (BEC Center)
  Observation of Magnetic Solitons

- Tuesday, November 5th 2019, at 10:30, A108, Povo 1
  BEC Internal Report, Albert Gallem (BEC Center)
  Rotating supersolids

- Wednesday, October 16th 2019, at 15:15, Physics seminar room, 2nd floor
  BEC Seminar, Robert Ott (Heidelberg University)
  Gauge theory phenomena and their quantum simulation

- Monday, September 23rd 2019, at 14:00, Physics seminar room, 2nd floor
  BEC Seminar, Davide Squizzato (University Grenoble-Alpes)
  Evidences of Kardar-Parisi-Zhang Universality Class in One-Dimensional Exciton-Polaritons

- Wednesday, September 11th 2019, at 11:00, Mathematics seminar room, 1st floor
  BEC Seminar Alessio Chiocchetta (University of Cologne)
  Ultracold quantum wires with localized dissipation: fluctuation-induced quantum Zeno effect

- Monday, September 2nd 2019, at 9:30, Physics seminar room, 2nd floor
  BEC Seminar, Onur Umucal lar (Mimar Sinan Fine Arts University)
  Signatures of anyonic statistics in charge-neutral quantum gases

- Monday, July 1st 2019, at 14:30, Physics seminar room, 2nd floor
  Santo Maria Roccuzzo (BEC Center)
  Supersolid symmetry breaking from compressional oscillations in a dipolar quantum gas

- Friday, June 21th 2019, at 9:30, Aula A107, Povo 1
  PhD Thesis defense, Carmelo Mordini
  Measurement of the density profile of quantized vortices and of the equation of state in a 3D interacting Bose gas

- Tuesday, June 18th 2019, at 14:00, Aula A203, Povo 1
  Paolo Ochner (Osserv. Astronomico e Universit di Padova)
  Interferometry in astronomy: from the Hanbury Brown and Twiss optical interferometer to the global very long baseline array

- Monday, June 17th 2019, at 14:30, Physics seminar room, 2nd floor
  Fabio Caleffi (SISSA Trieste)
  Quantum fluctuations beyond the Gutzwiller approximation in the Bose-Hubbard model

- Monday, June 3rd 2019, Physics seminar room, 2nd floor
  Arko Roy (BEC center)
  Cluster Gutzwiller algorithm for 2D interacting lattice bosons

- Friday, May 31st 2019, at 14:00, Aula Seminari di Fisica Teorica, 2nd floor
  Matteo Soriente (ETH Zurich, Switzerland)
  Dynamical phase transitions in dissipative light-matter systems

- Monday, May 20th, 2019, Physics seminar room, 2nd floor
  Wataru Kohno (Hokkaido University)
  Macroscopic coherence due to the dynamical relaxation processes in Bose-Einstein condensates

- Friday, May 10th 2019, at 15:00, Aula A108 Povo1
  PhD Thesis defense, Luca Parisi
  Mixtures of ultracold Bose gases in one dimension: a Quantum Monte-Carlo study

- Monday, April 15th, 2019, Physics seminar room, 2nd floor
  Alessio Recati (BEC Center):
  Particle-Hole Character of the Higgs and Goldstone Modes in Strongly Interacting Lattice Bosons

- Monday, April 1st, 2019, Physics seminar room, 2nd floor
  Albert Gallemí(BEC Center):
  Wall-Vortex Composite Defects in a Spinor Bose-Einstein Condensate

- Monday, March 25th, 2019, Physics seminar room, 2nd floor
  Elia Macaluso (BEC Center)
  Looking for the amplitude (Higgs) mode in a spinor BEC

- Thursday, March 21th, at 11:30, Sala Stringa, FBK
  Q at TN Seminar, Serge Haroche (Collège de France, Paris)
  Rydberg atoms in Cavity QED and in quantum metrology

- Wednesday, March 20th, at 14:30 Room A101
  Collège de France Visiting Chair, Serge Haroche (Collège de France, Paris)
  Laser breakthroughs in basic science

- Thursday, March 7th, at 14:30, Room A108 Povo1
  Q at TN seminar, Philipp Hauke (Univ. of Heidelberg)
  Cold-atom quantum simulation of high-energy physics

- Monday, February 25th, 2019, Physics seminar room, 2nd floor
  Luca Giacomelli (BEC center)
  Black hole superradiance, Klein paradox and the stability of vortices in BECs

- Wednesday, February 20th, 2019, at 14:30, aula A108 Povo1
  Physics Colloquium, Ines de Vega (LMU Munich)
  Open quantum systems: models, limits and simulation

- Tuesday, February 19th, 2019, at 14:30, Physics seminar room, 2nd floor
  Léonie Canet (Université Grenoble Alpes)
  Kardar-Parisi-Zhang universality in 1D exciton-polariton systems

- Monday, February 18th, 2019, at 11:00, Math seminar room, 1st floor
  Journal Club, Arturo Farolfi (BEC Center)
  Spontaneous formation and relaxation of spin domains in antiferromagnetic spin-1 quasi-condensates

- Friday, February 8th, 2019, at 14:30, Room A108
  Q at TN seminar, Quentin Glorieux (LKB Sorbonne Université, Paris, France)
  Quantum simulation with light: from superfluidity to rotating black holes

- Monday, January 28th, 2019, at 14:30, Physics seminar room, 2nd floor
  Donato Romito (BEC center and University of Southampton)
  Localisation Transition in the Driven Aubry-Andr Model

- Thursday, January 24, 2019, at Rustico ECT*
  BEC DAY: *An overview of present and future projects of the BEC Center*

- Monday, December 10th, 2018, at 14:30, Physics seminar room, 2nd floor
  Giulio Salvatore Butera (BEC Center)
  Mechanical back-reaction effect of the dynamical Casimir emission

- Monday, December 3th, 2018, at 14:30, Physics seminar room, 2nd floor
  Alberto Biella (MPQ, Paris Diderot)
  Phases and criticalities in nonequilibirum open quantum systems

- Friday, November 30th, 2018, at 14:30, Physics seminar room, 2nd floor
  Dimitrios Trypogeorgos (BEC Center)
  Subwavelength lattices using Raman-coupled synthetic clocked states

- Monday, November 26th, 2018, at 14:30, Physics seminar room, 2nd floor Miki Ota (BEC Center)
  Magnetic phase transition in a mixture of two interacting Bose gases at finite temperature

- Friday, November 9th, 2018, at 14:30, Room A210 - Povo 1
  Q at TN seminar, Alejandro M. Yacomotti (Centre de Nanosciences et de Nanotechnologies C2N, CNRS)
  Towards few photon bifurcations in coupled nanolasers

- Thursday, November 8th, 2018, at 14:30, Aula Seminari di Fisica Teorica, 2nd floor
  Ivan Amelio (BEC Center)
  Ultrastrong coupling regime: towards a dynamical probe of the ground state

- Monday, October 15th, 2018, at 14:30, Aula Seminari di Fisica Teorica, 2nd floor
  Luca Galantucci (Joint Quantum Centre Durham-Newcastle and Newcastle University)
  Vortex Dynamics in Quantum Fluids

- Monday, October 1st, 2018, at 14:30, Physics seminar room, 2nd floor
  Giacomo Mazza (Ecole Polytechnique)
  Strong light-matter coupling and collective phenomena in quantum materials

- Thursday, September 27th, 2018, at 14:30, Physics seminar room, 2nd floor
  Dimitri Gangardt (University of Birmingham)
  Full counting statistics and large deviation in thermal 1D Bose gas

- Monday, September 17th, 2018 at 14:30, Aula Seminari di Fisica, ground floor
  Alexander Leymann (BEC Center)
  Can successive photon subtraction create a lasing state

- Monday, September 3rd, 2018, at 14:30, Aula Seminari di Matematica
  Gregory Astrakharchik (Polytechnic University of Catalonia, Barcelona, Spain)
  Two-ball billiard predicts digits of the number PI in non-integer numerical bases

- Wednesday, July 11, 2018 at 11:00, Aula Seminari di Fisica Teorica
  Guido Pupillo (University of Strasbourg)
  Cavity-enhanced transport of excitons and charge

- Tuesday, July 10, 2018 at 14:30, Aula Seminari di Fisica Teorica
  Gary Liu (National Changhua University of Education)
  Phase transitions of two-Component p-orbital bosons in two-dimensional square lattices

- Monday, July 9th, 2018 at 14:30, Aula Seminari di Fisica Teorica
  Alberto Muñoz (UAM Madrid)
  Early-time dynamics of Bose gases quenched into the strongly interacting regime

- Friday, June 15th 2018 at 11:00, Aula Seminari di Fisica Teorica
  Doerte Blume (University of Oklahoma)
  Few-body aspects of spin-orbit coupled cold atom systems

- Wednesday, June 13th 2018 at 14:30, Aula Seminari di Fisica Teorica
  Federico Tonielli (University of Cologne, Germany)
  Universal slowdown of decoherence for local dephasing channels in gapless quantum many-body systems

- Monday, June 11th 2018 at 14:30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Franco Dalfovo (BEC center)
  Optical visibility and core structure of vortex filaments in a bosonic superfluid

- Monday, June 11th 2018 at 15:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Sandro Stringari (BEC center):
  Quantum fluctuations and Gross-Pitaevskii theory

- Monday, May 28th 2018 at 14:30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Luca Parisi (Internal Seminar)
  One dimensional mixtures: Andreev-Bashkin effect and liquid phase

- Thursday, May 24th 2018 at 14:30, Aula Seminari di Fisica Teorica
  Elio Koenig (Rutgers University)
  Quantum field theory of nematic transitions in spin orbit coupled spin-1 polar bosons

- Wednesday, May 23 2018 at 14:30, Aula A208
  Physics Colloquia, Franco Dalfovo
  Publish or perish, an editor perspective

- Monday, May 21st 2018 at 14:30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Luca Giacomelli (Internal Seminar)
  A Rapidly Expanding Bose-Einstein Condensate: An Expanding Universe in the Lab

- Tuesday, May 15th, 2018, at 11:40, Aula Seminari di Matematica
  Manfred Mark (University of Innsbruck and IQOQI, Austria)
  Dipolar Quantum Mixtures of Er and Dy

- Tuesday, May 15th, 2018, at 11:15, Aula Seminari di Matematica
  Tommaso Comparin (BEC Center, Trento, Italy)
  Ferromagnetism and polarons in 2D dipolar Fermi gases

- Tuesday, May 15th, 2018, at 10:50, Aula Seminari di Matematica
  Alexander Patscheider (University of Innsbruck, Austria)
  Spin Physics with Dipolar Fermions in a 3D Optical Lattice

- Tuesday, May 15th, 2018, at 10:25, Aula Seminari di Matematica
  Russell Bisset (BEC Center, Trento, Italy)
  Response function of a dipolar BEC

- Tuesday, May 15th, 2018, at 10:00, Aula Seminari di Matematica
  Daniel Petter (University of Innsbruck, Austria)
  Observation of Roton Mode Population in a Dipolar Quantum Gas

- Monday, May 7th 2018 at 14:30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, H. A. M. Leymann (Internal Seminar)
  Quantum effects in micro cavity lasers

- Wednesday, May 2nd, 2018, at 14:45, Aula Seminari di Fisica
  Gregory Astrakharchik (Polytechnic University of Catalonia, Barcelona, Spain)
  Ultradilute one-dimensional droplets

- Tuesday, April 24th 2018 at 14:30, Aula Seminari di Fisica Teorica
  Leticia F. Cugliandolo (LPTHE, Paris)
  Dynamics of isolated classical disordered many-body systems

- Monday, April 23, 2018, at 10:00, room A204
  PhD Thesis defense, Fabrizio Larcher
  Dynamical excitations in low-dimensional condensates: sound, vortices and quenched dynamics

- Friday, April 20, 2018, at 14:30, room A205
  PhD Thesis defense, Giacomo Colzi
  A new apparatus to simulate fundamental interactions with ultracold atoms

- Thurday, April 12th, 14h00-17h00 and Friday, April 13th 2018, 10h00-17h00, Aula Seminari di Fisica Teorica
  Informal Mini-Workshop on Black Hole Lasing
  External participants: R. Parentani (LPT Orsay, France), M. Tettamanti and A. Parola (Univ. Insubria, Como)

- Monday, April 9th 2018 at 14:30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Russell Bisset (Internal Seminar)
  Dynamics and interactions of quantum vortices in Bose-Einstein condensates

- Monday, March 26th 2018 at 14:30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Arturo Farolfi (Internal Seminar)
  Deterministic entaglement generation from driving through quantum phase transitions

- Monday, March 19th 2018 at 14:30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Ivan Amelio (Internal Seminar)
  Topologically protected bound states in photonic parity-time-symmetric crystals

- Monday, March 12th 2018 at 14:30, Aula Seminari di Fisica Teorica
  Munir Al-Hashimi (University of Bern, Switzerland)
  Energy and angular momentum dependent potentials and Minimal Position-Velocity Uncertainty Wave Packets in Relativistic and Non-relativistic Quantum Mechanics Friday, March 9th at 14:00, the Villa Tambosi seminar room - ECT*
  Leonardo Mazza (École Normale Supérieure, Paris)
  Quantum simulation of Majorana fermions in cold atoms

- Monday, March 5th 2018 at 14:30, Aula Seminari di Fisica Teorica
  Hiroyuki Tajima (Quantum Hadron Physics Laboratory, RIKEN Nishina Center, Japan)
  Many Fermi polarons in a strongly interacting polarized mixture

- Monday, February 26th 2018 at 15:30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Carmelo Mordini (Internal Seminar)
  Probing many-body dynamics on a 51-atom quantum simulator

- Thursday, February 22 2018 at 14:30, Aula A107
  PhD Thesis defense, Eleonora Fava
  Static and dynamic properties of a miscible two-component Bose-Einstein condensate

- Monday, February 12th 2018 at 14:30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Salvatore Giulio Butera (Internal Seminar)
  Effective charged phonons in analogue spacetime

- Tuesday and Friday, February 8th and 9th 2018, Aula Seminari Matematica (first floor)
  Trento-Salerno Joint Meeting,

Talks by Mario Salerno, Federico Corberi, Roberta Citro, Francesco Romeo, Maria Luisa Chiofalo, Eleonora Fava, Lev Pitaevskii, Chiara Menotti, Iacopo Carusotto, Tommaso Comparin.

- Tuesday, January 30th 2018 at 14:30, Aula Seminari di Fisica (ground floor)
  Andrey Turlapov (RAS, Nizhniy Novgorod, Russia)
  Order in near-field interference of a chain of BECs with random phases

- Monday, January 29th 2018 at 14:30, Aula Seminari di Fisica
  BEC Group Journal Club, Elia Macaluso (Internal Seminar)
  Observing anyonic statistics via time-of-flight measurements

- Friday, January 26th 2018 at 11.00, Aula Seminari di Fisica
  Daniel Benedicto-Orenes (Univ. Birmingham)
  Thermodynamics of a ferromagnetic spin-1 BEC

- Monday, January 22nd 2018 at 14:30, Aula Seminari di Fisica
  BEC Group Journal Club, Jacopo Nespolo (Internal Seminar)
  The Andreev-Bashkin effect: overview and new results

- Tuesday, January 16th 2018 at 14:30, Aula Seminari di Fisica
  Marco Fattori (LENS and Univ. Firenze)
  Self-bound quantum droplets in atomic mixtures

- Monday, January 15th 2018 at 14:30, Aula Seminari di Fisica
  BEC Group Journal Club, Miki Ota (Internal Seminar)
  Dimensional crossover in a strongly interacting ultracold atomic Fermi gas

- Thursday and Friday, 11-12 January 2018, Aula Seminari Teorici
  Two-day informal meeting on *Quantum Coherence in Heterostructure and Cold Gases*
  External participants: Giulio Cerullo (Politecnico di Milano), Massimo Capone, Angelo Valli (SISSA Trieste), Giacomo Roati, Francesco Scazza (INO-CNR and LENS Firenze), Claudio Giannetti, Fausto Borgonovi, Chahan Kropf, Paolo Franceschini (Universit Cattolica, Brescia)

- Friday, January 12th 2018 at 14:30, Aula Seminari di Fisica (ground floor)
  Alessio Ciamei (Institute of Physics, Univ. Amsterdam)
  Production of ultracold molecules for precision measurements and quantum simulation experiments

- Thursday, December 21th 2017 at 14:30, Aula Seminari Dipartimento di Fisica
  Daniele De Bernardis (Vienna Institute for Quantum Science and Technology, Austria)
  Cavity QED in the non-perturbative regime

- Wednesday, December 20th 2017 at 14:30, Aula Seminari Dipartimento di Fisica
  Cristiano Simonelli (Univ. Pisa, Italy)
  Simulating dissipative manybody Physics with cold Rydberg atoms

- Monday, December 18th 2017 at 14:30, Aula Seminari Dipartimento di Fisica
  BEC Group Journal Club, Giacomo Colzi (Internal Seminar)
  Dark state optical lattice with sub-wavelength spatial structure

- Friday, December 15th 2017 at 11:00, Aula Seminari Dipartimento di Fisica
  Nicola Poli (LENS and Università di Firenze, Italy)
  Atom interferometry on narrow intercombination transitions of alkali-earth atoms

- Thursday, December 14th 2017 at 14:30, Aula Seminari Dipartimento di Fisica
  Mathias Van Regemortel (Universiteit Antwerpen, Belgium)
  Spontaneous Beliaev-Landau scattering out of equilibrium

- Tuesday, December 12th 2017 at 14:30, Room A208, Povo1
  Physics Department Colloquium, Jean Dalibard (ENS and Collège de France, Paris)
  Topology in atomic Flatland

- Monday, December 11th 2017 at 14:30, Aula seminari, Dept. Mathematics
  Jean Dalibard (ENS and Collège de France, Paris)
  Uniform quantum gases: A new toolbox for many-body physics

- Thursday, December 7th 2017 at 14.30, Aula B103 (Povo 2)
  PhD Thesis defense, José Lebreuilly
  Strongly correlated quantum fluids and effective thermalization in non-Markovian driven-dissipative photonic systems

- Monday, December 4th 2017 at 14:30, Seminar Room Fisica Teorica - 2nd floor
  Raul Bombin (Universitat Politecnica de Catalunya)
  Quantum Dipolar Systems

- Monday, 27th November 2017 at 14:30, Aula Seminari Dipartimento di Fisica
  BEC Group Journal Club, Albert Gallemí (Internal Seminar)
  Josephson vortices in atomic long Josephson junctions

- Wednesday, 22th November 2017 at 14:30, Aula A207
  Physics Department Colloquium, Matt Visser (Victoria Univ. Wellington, NZ)
  Analogue spacetimes

- Monday, 20th November 2017 at 14:30, Aula Seminari Dipartimento di Fisica
  BEC Group Journal Club, Tommaso Comparin (Internal Seminar)
  Itinerant ferromagnetism

- Monday, 6th November 2017 at 15:00, Aula Seminari Dipartimento di Fisica
  BEC Group Journal Club, Tomoki Ozawa (Internal Seminar)
  Quantum depletion of a homogeneous Bose-Einstein condensate

- Friday, 27th October 2017 at 10.00, Aula Seminari Dipartimento di Fisica
  David Bruschi (Univ. York, UK)
  Bose Einstein Condensates for relativistic quantum technologies

- Thursday, 26th October 2017 at 16.00, Room A208 Povo1
  Physics Department Colloquium, Claudio Giannetti (Univ. Cattolica Brescia)
  Ultrafast dynamics in correlated materials and superconductors

- Monday, 23rd October 2017 at 14:30, Aula Seminari Dipartimento di Fisica
  Danny Baillie (University of Otago, New Zealand)
  Dipolar Droplets

- Wednesday, 18th October 2017 at 9.30, Aula Seminari Dipartimento di Fisica
  Alexander Fetter (Stanford Univ., USA)
  Quantized superfluid vortex dynamics on cylindrical surfaces and planar annuli

- Monday, 16th October 2017 at 14.30, Aula Seminari Dipartimento di Fisica
  R. Onur Umucalilar (Mimar Sinan Fine Arts University, Istanbul, Turkey)
  Generation and spectroscopic signatures of a fractional quantum Hall liquid of photons

- Monday 25th September 2017 at 14;30, Aula Seminari di Fisica Teorica
  BEC group meeting, Sandro Stringari summarizes the most interesting results presented at the Sant Feliu conference BEC 2017.

- Wednesday, 19th July 2017 at 15.00, Aula Seminari di Fisica Teorica
  Themis Mavrogordatos (UCL London, UK)
  Quantum phase transitions in the driven dissipative Jaynes-Cummings oscillator

- Friday, 14th July 2017 at 11.00, Aula Seminari di Fisica Teorica
  Maarten Hoogerland (University of Auckland, New Zealand)
  Cavity enhanced atom-light interactions using a fibre ring resonator

- Monday, 10th July 2017 at 11.00, Aula Seminari di Fisica Teorica
  Andrew Sykes (LPTMS Orsay)
  Two- and three-body problem with Floquet-driven zero-range interactions

- Thursday, 29th June 2017 at 11.15, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, José Lebreuilly (Internal Seminar)
  Stabilizing strongly correlated photon fluids with a non-Markovian reservoir

- Tuesday, 20nd June 2017 at 14.30, Aula Seminari di Fisica
  Manuele Tettamanti (Univ. Insubria)
  Analogue Hawking effect in BECs

- Thursday, 18th May 2017 at 14.30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Russell Bisset (Internal Seminar)
  Quantum and Thermal Spin Fluctuations in a Trapped Binary Condensate

- Wednesday, 17th May 2017 at 11.45, Aula Seminari di Fisica Teorica
  Ajit Srivastava (Emory University, USA)
  2D Materials – A New Platform for Strong Light-Matter Interactions

- Tuesday, 2 May 2017 at 14.30, Aula Seminari di Fisica Teorica
  Maxim Gorlach (ITMO University, Saint Petersburg, Russia)
  Edge states of bound photon pairs: interactions and topology

- Thursday, 27 April 2017 at 15.00, Povo1, Room A203
  PhD Thesis defense, Giulia De Rosi
  Collective oscillations of a trapped atomic gas in low dimensions and thermodynamics of one-dimensional Bose gas

- Thursday, 27 April 2017 at 11.00, Povo1, Room A212
  Nick Proukakis (Newcastle Univ.)
  Non-Equilibrium Atomic Gases at Finite Temperatures

- Wednesday, 26 April 2017 at 15.30, Aula Seminari di Fisica Teorica
  Nick Proukakis (Newcastle Univ.)
  (Im)Miscibility, Growth and Expansion of Two-Component Condensates

- Wednesday, 19 April 2017 at 11.30, Povo1, Room A108
  Davide Dreon (Collège de France, Paris)
  Cooling and trapping Dysprosium atoms

- Thursday, March 23rd 2017 at 14.30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Matteo Barbiero
  Phase Locking a Clock Oscillator to a Coherent Atomic Ensemble

- Thursday, March 16th 2017 at 14.00, Aula Seminari di Fisica Teorica
  Luca Salasnich (Univ. Padova and INO-CNR, Italy)
  Beyond-mean-field analysis of the 2D BCS-BEC crossover

- Wednesday, March 15th 2017 at 10.30, Aula A108
  PhD Thesis Defense, Simone Serafini
  Dynamics of Vortices and their Interactions in Bose-Einstein Condensates

- Thursday, March 9th 2017 at 14.30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Luca Parisi
  One-dimensional bosonic mixtures
- Wednesday, March 1st 2017 at 11.00, Aula Seminari di Fisica Teorica
  Tommaso Comparin (ENS Paris, France)
  Thermodynamics of the unitary Bose gas from first principles
- Monday, February 20th 2017 at 14.30, Aula Seminari di Fisica Teorica
  Sergej Moroz (TU Munich, Germany)
  Multiply quantised vortices in fermionic superfluids: angular momentum, unpaired fermions, and spectral asymmetry
- Thursday, February 16th at 14.30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Tom Bienaimé
  Quantum regime of optical nonlinearities and strongly-correlated photonic matter
- Monday, January 30th at 14.30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Carmelo Mordini (Journal Club)
  Emergence and scaling of spin turbulence in quenched antiferromagnetic spinor Bose-Einstein condensates
- Wednesday, January 25th 2017 at 10.30, Aula Seminari di Fisica Teorica
  Thomas Bland (Newcastle Univ., UK)
  Dark Solitons in Dipolar Bose-Einstein Condensates
- Monday, January 16th at 14.30, Aula Seminari di Fisica Teorica
  Maxime Richard (Institut Néel, Grenoble)
  Nonequilibrium character of polariton quantum fluids
- Wednesday, January 11th 2017 at 11.00, Aula Seminari di Fisica Teorica
  Jonathan Keeling (Univ. St Andrews)
  Supermode-Density-Wave-Polariton Condensation and Meissner-like Effect with Multi-mode Cavity-QED
- Thursday, December 22nd 2016 at 14.30, Aula Seminari di Fisica Teorica
  Roberto Onofrio (Univ. Padova and Dartmouth College, USA)
  Towards deeper quantum degeneracy of dilute Fermi gases
- Monday, December 12th 2016 at 14.30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Eleonora Fava (Journal Club)
  Observation of the supersolid stripe phase in spin-orbit coupled Bose-Einstein condensates
- Thursday, December 1st 2016 at 16.00, Aula Seminari di Fisica Teorica
  Jogundas Armaitis (Vilnius University)
  Superfluidity and spin superfluidity in spinor Bose gases

- Monday, November 21st 2016 at 14.30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Fabrizio Larcher (Internal Seminar)
  Finite Temperature Dynamics in Quasi-2D Bose-Einstein Condensates
- Wednesday, November 16th 2016 at 18.00, Dip. Lettere e Filosofia - Aula 001
  Serie di conferenze pubbliche: Comprendere i Nobel
  Iacopo Carusotto (BEC Center) introduce il *Nobel per la Fisica 2016*
- Thursday, November 3rd 2016 at 14.30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club, Giulia De Rosi (Internal Seminar)
  Collective oscillations of trapped atomic gases in low dimensions: a tool for the investigation of collisional processes
- Tuesday, October 25th 2016 at 14.30, Aula Seminari di Fisica Teorica
  Markus Heyl (Dresden, Germany)
  Dynamical Quantum Phase Transitions
- Monday, October 17rd 2016 at 11.30, Aula Seminari di Fisica Teorica
  Antonio Negretti (Univ. Hamburg, Germany)
  Many-body simulations of an ion-impurity immersed in an atomic condensate
- Friday, October 7rd 2016 at 14.30, Aula Seminari di Fisica Teorica
  Sebastian Will (Columbia Univ. and MIT, USA)
  Coherent Quantum Control of Ultracold Dipolar Molecules
- Monday, October 3rd 2016 at 15.00, Aula Seminari di Fisica Teorica
  Leonardo Mazza (ENS Paris, France)
  Interacting quantum gases with synthetic gauge fields in synthetic dimension
- Thursday, September 29th 2016 at 11.00, Aula Seminari di Fisica Teorica
  Jamir Marino (ITP, Univ. Cologne, Germany)
  Field theory for dissipative phenomena in driven systems: from Casimir friction in cold gases to non-equilibrium quantum criticality
- Wednesday, September 28th 2016 at 14.30, Aula A205
  Physics Department Colloquium, Francesca Ferlaino (IQOQI and Univ. Innsbruck)
  The Discreet Charm of Dipolar Quantum Matter near Absolute Zero Temperature
- Wednesday, September 21st 2016 at 11.30, Aula Seminari Dipartimento di Fisica
  Peter Schuck (Institut de Physique Nucleaire, Orsay, France)
  Theory of quartet condensation in four component Fermi (nuclear) systems and life on Earth
- Monday, September 19th 2016 at 17.00, Aula Seminari Dipartimento di Fisica
  LI Yun (Swinburne Univ. of Technology, Australia)
  Dipolar Bose gas: instability and new quantum phases

- Tuesday, July 19th 2016 at 14.30, Aula Seminari Dipartimento di Fisica
  Jan Carl Budich (Univ. Innsbruck, Austria)
  Topological Insulators far from Equilibrium

- Thursday, July 14th 2016 at 14.30, Aula Seminari di Fisica Teorica
  Christophe Salomon (LKB-ENS, Paris, France)
  From ultrafast to ultra slow: simulating Weyl particles with cold atoms

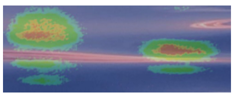
- Tuesday, July 5th 2016 at 11.00, Aula Seminari di Fisica Teorica
  Gediminas Juzeliunas (Univ. Vilnius, Lituania)
  Artificial magnetic field and spin-orbit coupling for ultracold atomic gases

Meetings organized or co-organized by the BEC Center

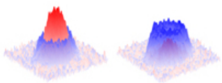
International workshop on *Quantum Mixtures* and celebration of the 70th anniversary of Sandro Stringari, Trento, July 15-17, 2019. The workshop aimed at providing an overview of the most recent results on multicomponent quantum gases, impurities and polarons, quantum droplets, and related areas. About 130 researchers attended the meeting. Web: http://bec.science.unitn.it/qmix2019/

ECT*

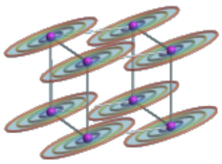
International workshop on *Simulating gravitation and cosmology in condensed matter and optical systems*, ECT* Trento, 22-25 July 2019. This interdisciplinary workshop gathered specialists from theoretical and experimental condensed matter physics and quantum optics and from theoretical cosmology, gravitation and astrophysics. Web: http://www.ectstar.eu/node/4445



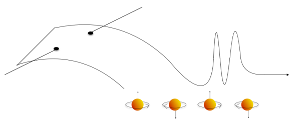
Florence-Trento joint meeting on *Quantum Gases*. The meeting involved about 60 researchers of the BEC Center, the LENS groups in Florence and also groups in Pisa, working with ultracold gases. These meetings are organized on a regular basis and are aimed at strengthening the interteam national collaborations. This edition was held at the Scuola Normale Superiore in Pisa on October 22-23, 2018.



International conference on *Quantum Gases and Quantum Coherence*, WE-Heraeus-Seminar, Bad Honnef, April 15-18, 2018, https://qgqc2018.sciencesconf.org
This conference brings together a broad community of senior and junior scientists to address the most recent developments in the emerging cross-disciplinary research field involing ultracold atoms, quantum many-body physics, quantum simulation and quantum information. It is the ninth edition of a series co-organized by the BEC Center. This meeting involved about 80 researchers.



International workshop on *Synthetic Dimensions in Quantum Engineered Systems*, ETH Zürich, November 20-23, 2017, https://quest.phys.ethz.ch/synth_17/index.html
The aim of this workshop was to bring together experimental and theoretical leading figures in order to discuss the far-reaching prospects of the emerging field of topological phenomena in engineered bosonic systems.



International workshop on *Quantum Physics and Geometry*, Levico, 4-6 July 2017, http://www.science.unitn.it/ carusott/QUANTUMGEO17/
This workshop explored possible interdisciplinary links between quantum information and geometry and contributed to the creation of a community of researchers trying to export advanced mathematical concepts to this new applicative field. The objective was to convey to a single event leading experts from the two fields, so to explore interdisciplinary connections and contribute establishing an active and long-lasting community.

Istituto Nazionale di Ottica, *Annual Symposium*, Trento, 9-10 February 2017, Polo scientifico e tecnologico di Povo, Room B107, Povo2, http://www.inosymposium.cnr.it/
The Symposium brought together 110 researchers from the Istituto Nazionale di Ottica, CNR and academic communities, presenting and discussing their most recent scientific results in a lively two-day meeting. The meeting was organized by the BEC Center.

Trento-Florence joint meeting on *Cold Matter*, Trento, 8 February 2017, room B107, Povo2.
The meeting involved about 40 researchers of the BEC Center and the LENS groups working with ultracold gases. Similar meetings between the two groups have been organized periodically in the last years, aimed at strengthening the inter-team collaborations.

90 years of Fermions, An International Conference to Celebrate the *90th Anniversary of Enrico Fermi's Paper on Quantum Statistics*, Accademia Nazionale dei Lincei, Roma, 20-21 October 2016.
Sandro Stringari, accademico dei Lincei, was involved in the organization.

International conference *BEC2016 - Quantum gases and quantum coherence*, Salerno, August 31 - September 3, 2016, http://bec2016.physics.unisa.it/
This was the eighth edition of a successful series of workshops dedicated to the theoretical and experimental challenges in the field of quantum gases. One of the main goals of this workshop was to bring together young researchers coming from Europe and overseas.

Honors

The Prize Committee of the BEC Awards 2019, sponsored by TOPTICA Photonics AG, has awarded the **senior BEC Award** to Lev Pitaevskii and Sandro Stringari for the key role they have played, with both their individual works and their collaborative ones, on our understanding of Bose-Einstein condensates and Fermi gases. Their theoretical contributions have been essential for guiding a wide range of experimental investigations in this domain.

The **Fermi Prize 2018** of the Italian Physical Society has been awarded to Federico Capasso, Lev P. Pitaevskii and Erio Tosatti for their important contributions to the understanding of quantum properties of condensed matter.

The Kurchatov Institute awarded the **Pomeranchuk Prize 2018** to L.P. Pitaevskii in recognition of his fundamental contributions to modern theoretical physics including the low-temperature physics, plasma physics, and condensed matter physics.

Tomoki Ozawa has been recognized by the Outstanding Referee program 2016 of the American Physical Society. He is the third Outstanding Referee of the BEC Center after Sandro Stringari and Iacopo Carusotto.

Outreach

In occasion of the 58th National Congress of the “Associazione per l’Insegnamento della Fisica”, Franco Dalfovo has been invited to give the opening talk entitled *Entanglement e coerenza: il lato bizzarro della meccanica quantistica*, in Brescia on October 16, 2019.

Within the initiative "SummerLabs in UniTrento", organized by the University of Trento and addressed to kids of age between 8 and 14, Gabriele Ferrari contributed to the activity *Giochiamo con le onde: onde meccaniche, sonore, luminose e, ovviamente, sull'acqua!*, in collaboration with Maria Teresa Lopez Arias, Mariano Dimauro and Daniela Ascenzi, at the Dipartimento di Fisica, on June 19, 2019.
In the frame of the initiative "Orienta Estate", organized by the University of Trento and addressed to high school students, Franco Dalfovo has given a lecture entitled *Certezze e incertezze nella descrizione fisica del mondo*, at the Dipartimento di Lettere e Filosofia, on August 20, 2019.

In the frame of the series of meetings "Beer & Physics" organized by the National Association of Physics Students, the researchers of the BEC Center have been invited to talk about *Gravità analoga: buchi neri in un bicchiere* at "Bookique" in Trento, on July 23, 2019.

In the frame of the series of meetings "Beer & Physics" organized by the National Association of Physics Students, the researchers of the BEC Center have been invited to talk about *Atomi ultrafreddi e superfluidità*, at the Bar Il Circolino in Trento, on May 8, 2019.

In the frame of the "Festival Co.Scienza" organized by UNITiN in collaboration with Open Wet Lab, Franco Dalfovo has been invited to speak in a public debate on the topic *Parlando di coscienza*, together with Giorgio Vallortigara (neuroscience) and Paola Giacomoni (philosophy), at the Sala della Fondazione Caritro in on April 7, 2019

Within the initiative "La matematica nel mondo contemporaneo" organized by the Scuola Normale Superiore di Pisa and addressed to high school teachers, Iacopo Carusotto has been invited to give two public lectures on *I mille volti della luce: ondulatoria, corpuscolare e … superfluidà*, at SNS in Pisa on April 4 and 5, 2019.

Within the Interdisciplinary Program of "Collegio Bernardo Clesio", Iacopo Carusotto has been invited to give a public talk on *I mille volti della luce: ondulatoria, corpuscolare e ... superfluidà*, in Aula Seminari of the Collegio Bernardo Clesio in Trento, on May 17, 2018.

In the frame of the "Festival Co.Scienza" organized by UNITiN e OWL - Open Wet Lab, Franco Dalfovo has been invited to give a talk entitled *Etica, metodi e linguaggio della comunicazione scientifica, tra pubblicazioni e predatory journals*, at Palazzo di Economia, Trento, on March 6, 2018.

In the frame of the series of meetings "Beer & Physics" organized by the National Association of Physics Students, the researchers of the BEC Center have been invited to talk about *Superfluids of atoms and light* at Circolo Culturale Don Quijote in Trento, on 5 December 2017.

The researchers of the BEC experimental laboratory have been involved in the European Researchers' Night 2017, for the activities organized in Trento at the Museum of Science (MUSE, http://www.nottedeiricercatori.tn.it/). In particular, the BEC Center invited Wolfgang Ketterle to give a public talk entitled *Towards Absolute Zero*, with an introduction by Sandro Stringari and an interview by the journalist Marco Motta. Wolfgang Ketterle entertained the audience with interesting experiments and told about his work on cold atoms with temperatures close to absolute zero. The talk was attended by more than 2000 people. The program of the Researchers' Night also included a short talk by Franco Dalfovo on the role of scientific journals and peer review in the progress of science.

In the frame of the series of public seminars “Da dove nasce una scoperta ” organized by the “Associazione studentesca Amici del Faggio”, Franco Dalfovo has been invited to talk about *1900-1925: Stories of atoms and scientists*, in Trento, at the Auditorium del Dipartimento di Lettere e Filosofia, on 27 February 2017. The video https://www.youtube.com/watch v=Bv3tGenyngo&t=27s had more than 500 views.

In the frame of the series of public seminars “Comprendere i Nobel” organized by the University of Trento, Iacopo Carusotto has been invited to talk about the Nobel Prize in Physics 2016, in Trento, Aula 1 of the Dipartimento di Lettere e Filosofia, on 16 November 2016.

In August 2016, Alessio Recati has been interviewed by Repubblica-TV about the meaning and the relevance of the recent experiment by J.Steinhauer on the analogue of Hawking radiation in black holes.

Within the thematic seminars for high school students organized by the University of Trento, Franco Dalfovo held the seminar *1900-1925: Stories of atoms and scientists* at Liceo Lioy in Vicenza on February 23, 2017; at Liceo G.Veronese in San Bonifacio (VR) on February 1st, 2018; at Istituto Guetti in Tione (TN) on February 9, 2018; at Liceo da Vinci in Trento on February 19, 2018. He also held the seminar *Il mondo di carta: il ruolo dell’editoria scientifica ai tempi di internet* at Liceo Zanella di Schio on March 14, 2019.