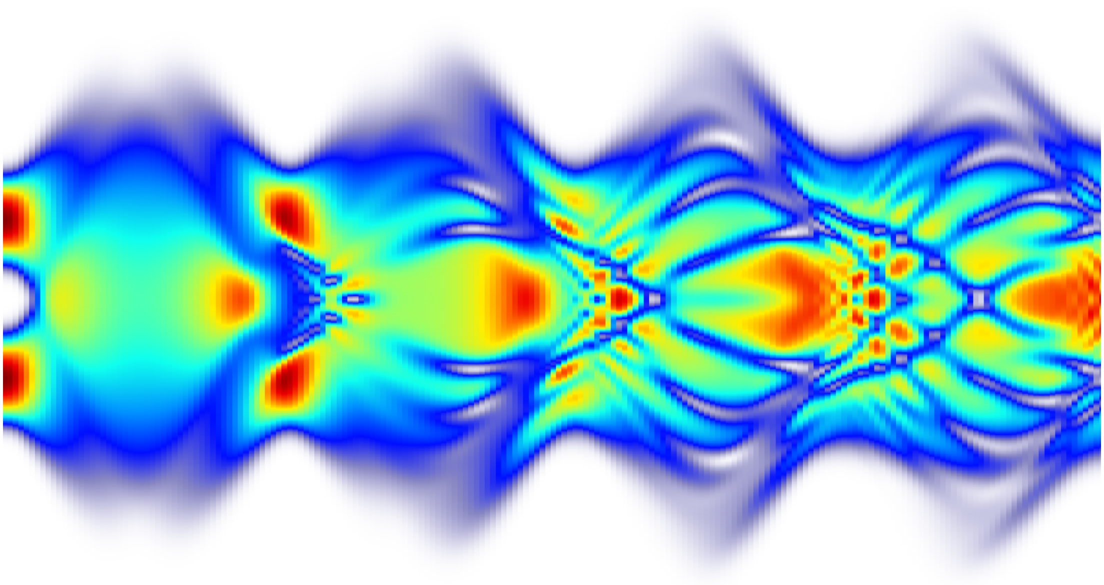
Istituto Nazionale di Ottica
Consiglio Nazionale delle Ricerche
Center on **Bose-Einstein Condensation**, Trento, Italy

Scientific Report
January 2013 - June 2016



The BEC Center is a joint initiative of

Istituto Nazionale di Ottica, CNR

Dipartimento di Fisica, Università di Trento

Contents

Overview

This is the final report on the research activities of the Center on Bose-Einstein Condensation within the program funded by the Provincia Autonoma di Trento (PAT) for the years 2013-2015, extended till June 2016. The agreement with PAT is aimed at supporting scientific research in the field of ultracold gases, as well as in the related areas of quantum information and quantum optics, with special attention to the activities of the new experimental laboratory of the BEC Center. In these three years the laboratory was expected to reach the conditions of full operation, in terms of capability to perform original experiments with ultracold atoms in magnetic and optical traps. Another purpose of the program was to reinforce the theoretical activities and orient part of them towards the themes of research of the new experimental laboratory.

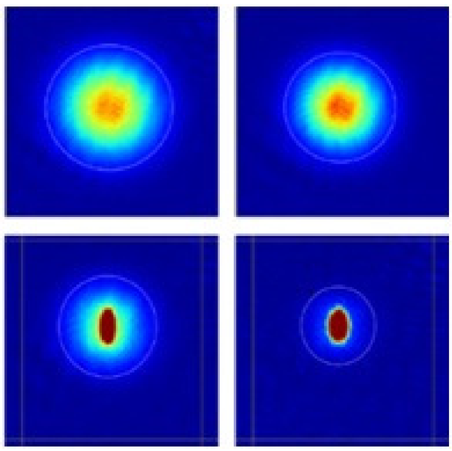


Figure 1: First images of a condensate of Sodium atoms obtained in the new laboratory of the BEC Center, in December 2012.

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 (UNITN) which provides facilities and services as well as a multidisciplinary scientific environment. Personnel and researchers of INO and UNITN 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 Center can be seen as a good example of close collaboration between CNR and the University.

Since the very beginning the BEC Center was supported by PAT. The Provincia co-funded the first five years (2002-2006) of the Center with an amount which corresponded roughly to one third of the total budget. A second agreement was signed with PAT in 2007 for funding a three-year project (2007-2009) aimed to reinforce the activities of the Center, particularly in the fields of quantum information and interferometry with cold atoms. A third agreement was signed in 2010 for the next three-years (2010-2012); its main purpose was the start-up of a new line of research in experimental physics with ultracold atoms. More than half of the total funds coming from PAT were dedicated to cover the expenses for buying and installing the experimental equipment and facilities. The last agreement with PAT started in January 2013.

In these years, the BEC Center has gained a solid international reputation as one of the leading groups in the theory of quantum gases, superfluids, quantum optics and related areas. The recent creation of an experimental laboratory has opened new perspectives. On the one hand, it has had the effect of widening the links with other scientists and groups worldwide, increasing visits from other labs and widening the network of collaborations. On the other hand, it has boosted new theoretical activities, providing a good balance of theories and experiments developed side by side.

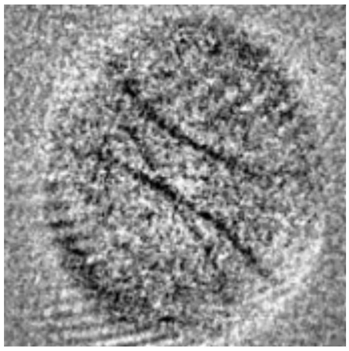


Figure 2: Images of three quantized vortices in a condensate of Sodium atoms. Each line is a little "tornado" in the superfluid, around which each atom rotates with angular momentum $\hbar$.

After completing the core of the experimental set-up, described in the first article of the team published in Review of Scientific Instruments in 2013, the new laboratory has started to produce original results. The first set of observations on the spontaneous creation of solitonic defects in a sodium condensate via the Kibble-Zurek mechanism has been the subject of an article published in Nature Physics (October 2013); the images of the expanding condensates with defects have been chosen for the cover of the journal and a "news & views" article has been written by M. Zwierlein to highlight the Trento experiment. The second set of measurements, in which these defects are clearly identified as solitonic vortices, has been published in Physical Review Letters in 2014 and selected for its relevance as an Editors' Suggestion. Another article has been published in Physical Review Letters in 2015 on the characterization of the dynamics of vortices and presently the group is collecting data for a paper focused on the real time visualization of vortex-vortex collisions. In the meanwhile the team has also been working hard to produce mixtures of sodium and potassium and a master thesis has been devoted to this problem.

The first experimental set-up is now running in a continuous way, alternating measurements on the production and imaging of vortices in a BEC of Sodium, on the characterization of the collective properties of a two-component spinor condensate, and on the equation of state of a weakly interacting Bose gas at low temperatures, both above and below the BEC transition. Moreover, a second experimental apparatus is under construction in a contiguous room.

At the same time, several projects have been carried out by the theory group of the BEC Center. The main lines of research have been: the dynamics of superfluid bosons and fermions; artificial gauge fields and synthetic magnetic fields; dipolar gases; ab initio simulations; photons, polaritons and analog black holes. A significant fraction of the theory work has been done in collaboration with researchers of other universities and institutions in Italy and abroad.

Since 2013 the researchers of the BEC Center have published more than 100 articles in peer reviewed journals, including 1 Reviews of Modern Physics, 1 Nature, 1 Nature Physics, 19 Physical Review Letters, 45 Physical Review, 7 EPL and 4 New Journal of Physics. Five papers have been selected as Editors' Suggestion in Physical Review and Physical Review Letter; four papers has been highlighted in the on-line APS journal Physics with three Synopses and a Viewpoint article. Members of the Trento team have been also invited to write a Perspective article in Science magazine and a News and Views article in Nature Physics.

In the last three and a half years, the activities of the BEC Center have involved 34 graduate students and postdocs, half of them coming from abroad, namely from China, Japan, France, Poland, Spain, Great Britain, Latvia, Russia, and New Zealand. In addition, 13 undergraduate and graduate students, , coming from other universities in Italy and abroad, have spent a few months in Trento for internships and stages. About 150 scientists have visited the Center to give a seminar, or to discuss with local researchers about projects of common interest. The Center has organized and co-organized several international meetings, including Summer and Winter Schools, as well as interdisciplinary workshops.

A detailed description of these achievements in 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, June 30th, 2016

Staff, researchers, scientific board

Principal Investigator of the PAT 2013-15 Project

Gabriele Ferrari

Head of the Trento Unit of Istituto Nazionale di Ottica

Franco Dalfovo

Secretariat

Beatrice Ricci (INO-CNR)
Rachele Zanchetta (ERC project)

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Lev P. Pitaevskii
Sandro Stringari

Personnel of INO-CNR

Iacopo Carusotto
Gabriele Ferrari
Giacomo Lamporesi
Chiara Menotti
Alessio Recati

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David Papoular
Stefano Finazzi
Riccardo Rota
Marta Abad Garcia
Tomoki Ozawa
Zeng-Qiang Yu
Marek Tylutki
Pjotrs Grisins
Pierre-Élie Larré

Hannah Price

Natalia Matveeva

Tom Bienaimé

Russell N. Bisset

Marco Di Liberto

Chunlei Qu

PhD Students

Marco Larcher (Thesis defense in February 2013)

Hou Yan-Hua (Thesis defense in December 2013)

Zou Peng (Thesis defense in May 2014)

Nicola Bartolo (Thesis defense in Dec 2014, co-tutelle Univ. Montpellier 2)

Giovanni Martone (Thesis defense in December 2014)

Luis Aldemar Peña Ardila (Thesis defense in April 2015)

Alberto Sartori (Thesis defense in March 2016)

Simone Donadello (Thesis defense in April 2016)

Grazia Salerno (Thesis defense in April 2016)

Simone Serafini

Giulia De Rosi

José Lebreuilly

Fabrizio Larcher (joint PhD Program with Univ. Newcastle)

Eleonora Fava

Giacomo Colzi

Carmelo Mordini

Luca Parisi

Matteo Barbiero (in collaboration with INRIM and Politecnico di Torino)

Student internships and stages

Alexis Amouretti (École Normale Supérieure de Cachan, France), April - July 2016

Salvatore Giulio Butera (Heriot-Watt, Edinburgh), April - July 2016

Francesco Rosati (Univ. Pisa), April - September 2016

Julia A. Binefa (Univ. Politecnica Catalunya), February - June 2016

Mathieu Isoard (École Normale Supérieure de Cachan), September 2015 - July 2016

Mathias Van Regemortel (Univ. Antwerp), November 2015 - April 2016

Andrei C. Berceanu (Univ. Auton. Madrid), Feb.-April, 2014, and Dec. 2014 - May 2015

Carmelo Mordini (SNS Pisa), January - August, 2014

Lucas Verney (ENS Paris), February - July, 2014

Fabrizio Miganti (ENS Paris) February - July, 2014
Thibault Congy (Univ. Paris Sud, Orsay) April - July, 2013
José Lebreuilly (ENS Paris), February - July, 2012, and October 2013 - July 2014
Juan Ramon Munoz De Nova (UCM Madrid), June - November, 2013

Technical Staff

Giuseppe Froner

Scientific board

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

Visiting scientists and scientific collaborations

Visiting scientists

Lukas Sieberer (Weizmann, Israel), June 29 - July 1, 2016
Alessio Chiocchetta (SISSA Trieste), June 27-29, 2016
William D. Phillips (JQI and NIST, USA), June 22-24, 2016
Jogundas Armaitis (Vilnius, Lithuania), June 20 - July 10, 2016
Gediminas Juzeliunas (Vilnius, Lithuania), June 20 - July 10, 2016
Michael Gullans (JQI and Univ. Maryland, USA), June 20-21, 2016
Nicolas Pavloff (LPTMS Université Paris Sud and CNRS), June 9, 2016
Nadine Meyer (Birmingham University), June 6, 2016
Gabriele Veneziano (Collège de France, Paris), May 18-20, 2016
Renaud Parentani (Univ. Paris-Sud), May 11-13, 2016
Florent Michel (Univ. Paris-Sud), May 11-13, 2016
Tommaso Calarco (Univ. Ulm), May 6, 2016
Roberto Balbinot (Univ. Bologna), April 26, 2016
Alessandro Fabbri (Centro Fermi, Roma), April 26, 2016
Matteo Lostaglio (Imperial College London), April 22, 2016
Rifat Onur Umucalılar (Koc University, Istanbul, Turkey), April 18-29, 2016
Mikael Rechtsman (Penn State, USA), April 18-20, 2016

Fabrice Mortessagne (Univ. Nice-Sophia Antipolis, France), April 18-20, 2016
Giovanni Modugno (LENS and Univ. Firenze), April 8, 2016
Hanns-Christoph Nägerl (Univ. Innsbruck), April 8, 2018
Nathan Goldman (ULB, Bruxelles), April 5-8, 2016
Thomas Scaffidi (Univ. Oxford), April 5, 2016
Otfried Gühne (Univ. Siegen), March 22-24, 2016
Michiel Wouters (Univ. Antwerp), March 21-25, 2016
Markus Oberthaler (Univ. Heidelberg), March 7-8, 2016
Wilhelm Zwerger (Technische Univ. Muenchen), March 7-8, 2016
David Clément (Institut d'Optique, Palaiseau), February 29, 2016
Luca Galantucci (JQC of Newcastle and Durham, UK), December 14-18, 2015
Paolo Comaron (JQC of Newcastle and Durham, UK) December 14-18, 2015
Alex Zamora (UCL London), December 16-18, 2015
Martin Wimmer (Univ. Jena, Germany), December 15-16, 2015
Sandro Wimberger (Univ. di Parma), December 9, 2015
Gareth Conduit (University of Cambridge), December 2, 2015
Daisuke Satow (ECT*, Trento), November 11, 2015
Francesco Piazza (Univ. Innsbruck), November 25-26, 2015
Alessio Chiocchetta (SISSA, Trieste), November 19-27, 2015
Grigori E. Astrakharchik (UPC, Barcelona), September 1-4, 2015
Paolo Comaron (JQC of Newcastle and Durham, UK), July 29-31, 2015
Muneto Nitta (Keio Univ., Japan), June 26 - July 1, 2015
Tom Bienaimé (LKB-ENS and Collge de France), July 20-21, 2015
Yulia E. Shchadilova (Russian Quantum Center), July 2-3, 2015
Hadrien Kurkjian (LBK-ENS Paris), June 3-4, 2015
Yanko Todorov (Univ. Paris Diderot), May 18-20, 2015
Francesco Scazza (LMU-MPI Munich), May 20-21, 2015
Jacques Tempere (Univ. Antwerp), April 27, 2015
Pierbiagio Pieri (Univ. Camerino), April 27, 2015
Dmitry Kobyakov (TU Darmstadt), April 17, 2015
Paolo Comaron (Univ. Newcastle, UK), April 13-17, 2015
Nicolas Pavloff (LPTMS Université Paris Sud and CNRS), April 13-15, 2015
Giovanni Martone (Univ. Bari), April 13-17
Marco Di Liberto (ITP, Utrecht University), March 23-25, 2015
Matteo Zaccanti (LENS Florence), March 5-6, 2015
Giacomo Roati (LENS Florence), March 5-6, 2015
Zoltán Vörös (University of Innsbruck), February 23-24, 2015

Sauro Succi (IAC-CNR, Roma), February 12-13, 2015
Nathan Goldman (Univ. libre de Bruxelles), February 4-6, 2015
Vincent Corre (LKB-ENS and Collège de France, Paris), February 4-7, 2015
Pjotrs Grisins (Univ. Vienna), January 15-16, 2015
Grigori E. Astrakharchik (UPC, Barcelona), December 14-30, 2014
Lauriane Chomaz (LBK-ENS and Collège de France, Paris), December 8-10, 2014
Yong P. Chen (Purdue University, USA), November 17, 2014
Patrizia Vignolo (Univ. Nice, France) June 25, 2014
Giuseppe Mussardo (SISSA, Trieste) June 11, 2014
Luis Santos (Leibniz Univ. Hannover, Germany), June 6-20, 2014
Grigori E. Astrakharchik (UPC, Barcelona), June 6-23, 2014
Tarik Yefsah (MIT, USA), May 15, 2014
Hui Hu (Swinburne University), May 11-17, 2014
Luca Barbiero (Univ. Padova, March 27, 2014
Elisa Ercolessi (Univ. di Bologna), March 25-26, 2014
Davide Vodola (Univ. di Bologna), March 25-26, 2014
Piero Naldesi (Univ. di Bologna), March 25-26, 2014
Rosario Fazio (SNS, Pisa), March 3-4, 2014
Davide Rossini (SNS, Pisa), March 3-4, 2014
Leonardo Mazza (SNS, Pisa), March 3-4, 2014
Alberto Biella (SNS, Pisa), March 3-4, 2014
Jin Jiasen (SNS, Pisa), March 3-4, 2014
Michiel Wouters (Univ. Antwerpen, Belgium), March 2-8, 2014
Marco Grilli (Univ. La Sapienza, Roma), February 20-21, 2014
Valentina Brosco (Univ. La Sapienza, Roma), February 20-21, 2014
Jose Lorenzana (Univ. La Sapienza, Roma), February 20-21, 2014
Daniel Bucheli (Univ. La Sapienza, Roma), February 20-21, 2014
Claudio Castellani (Univ. La Sapienza, Roma), February 20-21, 2014
Carlo Di Castro (Univ. La Sapienza, Roma), February 20-21, 2014
Mattia Jona-Lasinio (Univ. La Sapienza, Roma), February 20-21, 2014
Luca Lepori (Univ. Strasbourg, France), February 18-20, 2014
Taofiq K. Paraiso (Caltech, USA), January 27, 2014
Tilman Enss (Univ. Heidelberg), January 21-23, 2014
Amor Toumiat (Univ. Costantina, Algeria), January 20 - February 7, 2014
Grigori E. Astrakharchik (UPC, Barcelona), December 16, 2013
Francesco Piazza (TUM, Muenchen), December 13, 2013
Luca Salasnich (Univ. Padova), November 15, 2013

Josè Lebreuilly (ENS Paris), October 15, 2013 - July 31, 2014
Aurel Bulgac (University of Washington, Seattle), October 25, 2013
Joel Corney (Univ. Queensland, Australia), October 21, 2013
Michael McNeil Forbes (University of Washington, Seattle), October 18, 2013
Richard Packard (University of California, Berkeley), October 18, 2013
Juan Ramon Munoz De Nova (UCM Madrid), June 6 - November 15, 2013
Frank Deuretzbacher (Univ. Hannover), September 16-17, 2013
Pierrick Cheiney (Cambridge, UK), September 4-6, 2013
Alberto Amo (CNRS, Marcoussis, France), July 1-8, 2013
Gordon Baym (UIUC, Urbana-Champaign, USA), July 1-12, 2013
Immanuel Bloch (LMU, Munich), July 10-11, 2013
Georg Bruun (University of Aarhus), July 3-7, 2013
Roberta Citro (INFN and Univ. Salerno), July 2-7, 2013
Nigel Cooper (University of Cambridge), July 1-12, 2013
Xiaoling Cui (Tsinghua University, Beijing),
Jean Dalibard (LKB-ENS, Paris), July 1-7, 2013
Eugene Demler (Harvard University, Cambridge, USA), July 1-8, 2013
Tilman Esslinger (ETH, Zurich), July 7-10, 2013
Leonardo Fallani (LENS, Firenze), July 5-12, 2013
Nathan Goldman (ULB, Bruxelles), July 3-12, 2013
Zoran Hadzibabic (University of Cambridge), July 1-7, 2013
Mohammad Hafezi (University of Maryland, College Park), July 1-12, 2013
Duncan Haldane (Princeton University), July 5-12, 2013
Jason Ho (Ohio State University, Columbus), July 1-12, 2013
Hui Hu (Renmin University, Beijing), July 1-12, 2013
Gediminas Juzeliunas (Vilnius University), July 1-12, 2013
Franck Laloe (LKB-ENS, Paris), July 4-7, 2013
Maciek Lewenstein (ICFO, Barcelona), July 5-12, 2013
Allan MacDonald (University of Texas, Austin), July 1-6, 2013
Pietro Massignan (ICFO, Barcelona), July 1-6, 2013
Sylvain Nascimbene (LKB-ENS, Paris), July 1-4, 2013
Patrik Ohberg (Heriot Watt University, Edinburgh), July 1-12, 2013
Yonatan Plotnik (TECHNION, Haifa), July 2-11, 2013
Mikael C. Rechtsman (TECHNION, Haifa), July 2-9, 2013
Benni Reznik (Tel Aviv University), July 1-6, 2013
Carlos Sa de Melo (Georgia Institute of Technology, Atlanta), July 10-12, 2013
Luis Santos (Leibniz Universitat of Hannover), July 1-11, 2013

Vijay B. Shenoy (Indian Institute of Science, Bangalore), July 1-12, 2013
Chen Shuai (University of Science and Technology of China, Hefei) July 1-7, 2013
Fernando Sols (Universidad Complutense de Madrid), July 5-12, 2013
Shunji Tsuchiya (Tokyo Univ. of Science), July 1-7, 2013
Onur Umucalilar (University of Antwerp), July 1-12, 2013
Qi Zhou (The Chineese University of Hong Kong, Hong Kong), July 3-10, 2013
Erez Zohar (Tel Aviv University), July 1-6, 2013
Peter Zoller (University of Innsbruck), July 1-8, 2013
Martin Zwierlein (MIT, Cambridge, USA), July 4-8, 2013
Jamir Marino (SISSA Trieste), June 6, 2013
Sebastian Diehl (Univ. Innsbruck), May 22-23, 2013
Lukas Sieberer (Univ. Innsbruck), May 22-23, 2013
Andrea Gambassi (SISSA Trieste) May 22-23, 2013
Enrique Rico Ortega (Univ. Ulm, Germany), May 20-23, 2013
Anton Zeilinger (Univ. Wien and Austrian Academy of Sciences), April 11-12, 2013
Francesco Piazza (TUM Munich, Germany), March 19-24, 2013
Jan Chwedenczuk (Univ. Warsaw, Poland), March 19-24, 2013
Scott Robertson (Univ. St.Andrews, Scotland), March 2-9, 2013
Dario Gerace (Univ. Pavia), March 3-8, 2013
Renaud Parentani (Univ. Paris-Sud, Orsay, France) March 1-10, 2013
Pierbiagio Pieri (Univ. Camerino), February 18, 2013
Guido Pupillo (Univ. Strasbourg, France), February 18, 2013
Giovanni Modugno (LENS and Univ. Firenze), February 18, 2013
Gianni Carugno (Univ. Padova), February 18, 2013
Nicolas Pavloff (LPTMS Orsay, France), February 18-19, 2013
Pierre-Elie Larré (LPTMS Orsay, France), February 11-14, 2013
Grigori Astrakharchik (UPC, Barcelona), February 1-8, 2013
Francesco Bariani (Univ. of Arizona), February 5-8, 2013
Peter Zoller (IQOQI and Univ. Innsbruck, Austria), January 16-17, 2013

Scientific collaborations

The BEC Center operates within a wide network of scientific collaborations. More than half of the papers published by the BEC team since 2002 have been the result of joint projects with theoretical and experimental groups in the main laboratories around the world. Among them long and fruitful collaborations have been established with the groups at LENS-Florence, the

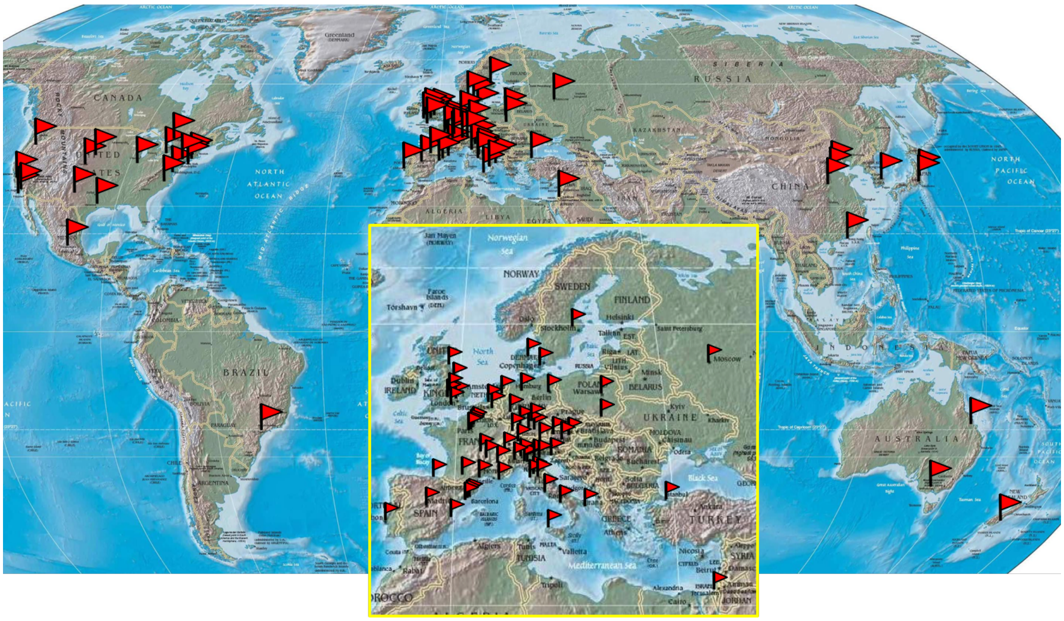


Figure 3: A worldwide network of collaborations

experimental and theory groups at Innsbruck, and with several groups in Paris, in Munich, and Barcelona. In more details, the projects carried out since January 2013 have involved the following collaborations:

- Rudolf Grimm (University of Innsbruck and IQOQI) and his group, within a joint theory-experiment of second sound propagation in superfluid Fermi gases;
- Marcello Dalmonte (IQOQI Innsbruck) and Mario Di Dio (SISSA Trieste) on the properties of one-dimensional dipolar gases;
- Luca Barbiero (Università di Padova) on several topics related to atoms in optical lattices;
- Mauro Antezza (Université Montpellier II, France) in the framework of the PhD cotutelle program of Nicola Bartolo for a thesis centered on the study of various aspects of the physics of ultra-cold atoms in optical lattices;
- Patrizia Vignolo (Institut Non Lineaire de Nice, France) on the theory of dipolar interactions and disordered systems;
- Rosario Fazio and Davide Rossini (Scuola Normale Superiore, Pisa) on the theory of strongly correlated photon systems;
- Pierbiagio Pieri (Università di Camerino) and Gianluca Bertaina (EPFL Lausanne and Univ. Milano) on Quantum Monte Carlo simulations of resonant Bose-Fermi mixtures;

- Davide Galli (Università di Milano) on Quantum Monte Carlo study of the dynamic structure factor in a system of bosons at zero temperature and the hard-sphere model;
- Joachim Brand (Massey University, Auckland, New Zealand) and his group, on the theory of solitons in superfluid fermions in the BCS-BEC crossover;
- Grigori Astrakharchik and Jordi Boronat (Univ. Politec. de Catalunya, Barcelona) on several topics in the physics of low dimensional quantum gases and Monte Carlo calculations;
- Michiel Wouters (University of Antwerp) on theoretical investigations of non-equilibrium condensation and superfluidity in fluids of light;
- Alessio Chiocchetta and Andrea Gambassi (SISSA Trieste) on theoretical investigations of non-equilibrium condensation;
- Roberto Balbinot (Università di Bologna), Renaud Parentani (Orsay), Stefano Finazzi (Paris 7), Dario Gerace (Università di Pavia) on the theory of analog Hawking radiation from acoustic black holes in quantum fluids of atoms and of light;
- Alberto Amo, Jacqueline Bloch (LPN, Marcoussis, France) on experiments with polariton fluids: from superfluidity and condensation to topological effects and artificial black holes;
- Quentin Glorieux, Alberto Bramati and Elisabeth Giacobino (LKB-Paris 6) on quantum fluids of light in microcavity and propagating geometries;
- Cristiano Ciuti (Univ. Paris 7) on the theory of quantum fluids of light;
- Frédéric Chevy (Ecole Normale Superieure, Paris) on the Chandrasekhar-Clogston limit and critical polarization in a Fermi-Bose superfluid mixture;
- Maurizio Artoni (Univ. Brescia) and Giuseppe La Rocca (Ecole Normale Superieure, Paris) on the study of driven Bloch oscillations of atoms in optical lattices;
- Daniele Faccio (Heriot-Watt, Edinburgh) on experiments with quantum fluids of light in propagating geometries;
- Matthieu Bellec and Fabrice Mortessagne (LPMC, Nice, France) on experiments with photonic analogues of graphene;
- Raffaele Colombelli (Orsay) on Bose-Einstein condensation of intersubband polaritons and applications to mid-IR photonic devices;
- Francesca M. Marchetti (Univ. Autonoma de Madrid) and Marzena H. Szymanska (Univ. College London) on the study of nonequilibrium Berezinskii-Kosterlitz-Thouless transition in a driven open quantum system and of multicomponent polariton superfluidity in the optical parametric oscillator regime;

- Luis Santos (Univ. Hannover) on the study of out-of-equilibrium states and quasi-many-body localization in polar lattice gases;
- William D. Phillips and Gretchen K. Campbell (NIST Gaithersburg and Univ. Maryland) on the observation of quantized superfluid flow by means of a minimally destructive Doppler measurement.
- Gentaro Watanabe (APCTP Pohang, Korea) on the investigation of superfluid Fermi gases in optical lattices by means of Bogoliubov - de Gennes equations;
- Jamir Marino (TU Dresden) on the study of Casimir forces and quantum friction from Ginzburg radiation in atomic Bose-Einstein condensates, and of spin-dipole oscillation and relaxation of coherently coupled BECs;
- Giacomo Roati, Matteo Zaccanti and Massimo Inguscio (LENS and Univ. Florence) on the study of ferromagnetic instability in a repulsive Fermi gas of ultracold atoms;
- Shizhong Zhang (Univ. Hong Kong) on the study of the superfluid density of a spin-orbit coupled Bose gas;
- Nathan Goldman (Univ. Libre Bruxelles) and Oded Zilberberg (ETH Zurich) on the investigation of synthetic dimensions in systems of cold atoms and in integrated photonics;
- Rifat Onur Umucalilar (Koc University, Istanbul) on the fractional quantum Hall effect with light;
- Nigel Cooper (Cambridge, UK) on the study of artificial magnetic fields in spin-orbit coupled systems;
- Nick Proukakis and Carlo Barenghi (JQC and Newcastle University, UK) on the study of the formation and dynamics of vortices in elongated Bose-Einstein condensates;
- Fabio Cinti (NITheP, Stellenbosch, South Africa) on Monte Carlo simulations of dipolar gases;
- Martin Wimmer and Ulf Peschel (IFTO Jena, Germany) on experimental studies of topological effects in photonics.

Experiments with ultracold atoms

Overview

The first BEC was produced in Trento in late December 2012. Since then, the laboratory has been fully operative. This is a list of the main activities carried out in the last three years:

i) development of instruments and methods towards the production and study of quantum gases of dipolar NaK molecules;

ii) study of quenched cooling across the phase transition to Bose-Einstein condensation;

iii) study of the vortex dynamics in superfluids and vortex-vortex interactions;

iv) development of novel imaging methods suited to the measurement of the equation of state of weakly interacting Bose gases;

v) demonstration of novel laser cooling mechanism towards the study of spinor BECs in highly-stable magnetic fields;

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

The first point includes various actions ranging from the technical development of specifically designed instruments, to the achievement of intermediate experimental scientific results related to the production and study of the atomic mixture of Sodium with Potassium.

The second point addresses the problem of adiabaticity *vs.* non-adiabaticity in crossing second order phase transitions. While initially not foreseen in the program, this research line came to the attention of the laboratory after unexpected observations occurred while optimizing the evaporative cooling towards the production of the Bose-Einstein condensate. A closer study on this offered a new perspective on a physical mechanism, the Kibble-Zurek mechanism, which is ubiquitous in nature but rather elusive.

The third point developed from the results obtained in Trento on the production of topological excitations in condensates and, by means of a novel real-time imaging procedure, it allowed us to study the dynamics of single, as well as multiple vortices, in the condensate. The case of multiple vortices within the same condensate is of particular interest in view of studying the open problem of vortex reconnection, which is a general process also leading to thermalization in fluids.

The fourth point relates again to the development of novel imaging procedures but it tackles the different problem of measuring the density profile of samples of relatively high optical depth. In this case the goal consists in observing the first-order corrections to the equation of state of the ideal Bose gas induced by atom-atom interaction, in particular in the vicinity of the phase-transition.

The fifth point has to do with the setting-up of an experiment with a completely new apparatus (doubling the space of the laboratory), which will focus on the study of spinor condensates in the spirit of *quantum simulation* of particle physics, as well as of supersolid phases. This is a challenge, which is also co-funded by the Italian Institute of Nuclear Physics and by the European Union, in which we will use novel methods and tools to study Bose condensates in unprecedented conditions of stability of the magnetic field. In order to optimize the available resources and to progress at the fastest pace, we first performed tests on the existing apparatus to validate procedures which will be crucial to the realization of the new laboratory. These led to the demonstration of a novel scheme for the cooling of sodium gases to even lower temperatures, to the measurements of the many-body response to spin excitations in fully-miscible spinor Bose-condensates.

Finally, the sixth point deals with optical clocks: we are extending the concept previously developed in Trento for the Sodium cold atomic source to additional atoms, such as Strontium or Ytterbium, which can be used for implementing optical atomic clocks. This further research line, results from a collaboration recently activated between the BEC Center and the Italian Institute for Metrological Research (INRIM) in Turin and which aims at the realization of the next generation of atomic clocks operating on forbidden optical transitions.

The details of these activities are given in the following.

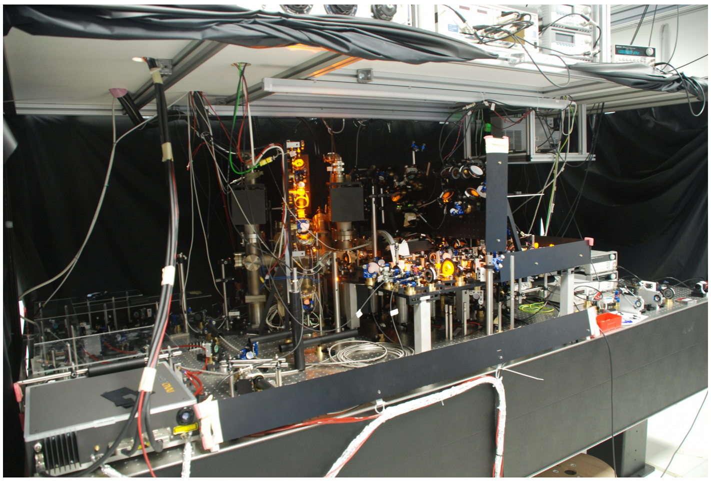


Figure 4: View of the main optical table of the laboratory: the ultra-high vacuum chamber, which is the core of the experiment, is partially illuminated with the orange light of the sodium laser cooling. The infrared laser source for optical dipole trapping of Na-K atomic mixtures and molecules is visible in the bottom left corner of the picture.

Towards the production of NaK dipolar molecules

We plan to produce NaK dipolar molecules following a procedure similar to the one demonstrated in 2008 at JILA for the KRb case. In this regard we achieved the following intermediate results which at present involve the bosonic ^{39}K isotope:

- Potassium atoms were laser cooled first individually and then simultaneously with sodium atoms. In the latter case the impossibility to fulfill the optimal MOT loading conditions simultaneously for the two atoms (in particular concerning the magnetic field gradient) led us to use a sequential loading procedure where we first collect sodium in an ordinary optimized MOT, and then switch to a different setting which allows us to collect Potassium atoms while keeping the Sodium already present in the trap. With this approach we can collect about 10^9 Sodium atoms together with 10^7 Potassium atoms within 10 seconds.

- the laser cooled mixture was transferred into a magnetic trap where we perform selective evaporation of Sodium and sympathetic cooling of Potassium. While the evaporative and sympathetic cooling processes proved to work as expected, hence allowing us to reach temperatures of the order of 10^{-6} K, the atom number remained unsatisfactorily low in the magnetic trap (N_{Na}=10^6 atoms, N_K=10^5 atoms). The issue is attributed to inelastic collisions between Potassium atoms and unpolarized Sodium atoms in the early moments of magnetic trapping. As Potassium atom number is much less than Sodium one, even a small fraction of unpolarized Sodium may cause the complete loss of Potassium. We plan to circumvent this limitation by using a shelving method as already demonstrated by the Zwierlein's group at MIT with the same atomic mixture.

- the atomic mixture was transferred into an optical-dipole trap suited for confining the sample during the Feshbach molecular association. We could achieve BEC in this trap by loading and evaporating pure Sodium samples.

- the development and assembly of both the pump and Stokes STIRAP laser has begun, including the spectral narrowing of the two lasers by the tight locking onto resonant modes of high finesse optical cavities. The laser frequency will be stabilized with respect to a resonance mode of a high-finesse cavity by means of a serrodyne frequency shifter that ensures at the same time, a high modulation bandwidth (larger than 10 MHz) and a wide spectral width (larger 100 MHz). The latter feature allows for an increased capture range of the laser lock with respect to the traditional diode laser modulation approaches based on the modulation of the diode's current.

All results involving the cooling of Potassium atoms, as well as the Sodium-Potassium mixture, were the object of the master thesis work of the student Alessandro Toffali, who got his degree on December 2013.

Besides the progresses in the laboratory, we anticipated the experimental research on the Na-K Feshbach resonances by contacting the group of Dr. Andrea Simoni at the University of Rennes, France, with the request of calculating the scattering properties of the atomic mixtures of the various isotopes in the different hyperfine states. The calculations were performed using codes previously developed by Dr Simoni and the information available to date in the literature.

The outcome of this research will provide us with important details concerning the stability and miscibility of mixtures of Sodium and Potassium Bose condensates, as well as the location and width of heteronuclear Feshbach resonances.

The Kibble-Zurek mechanism and topological excitations in Bose gases

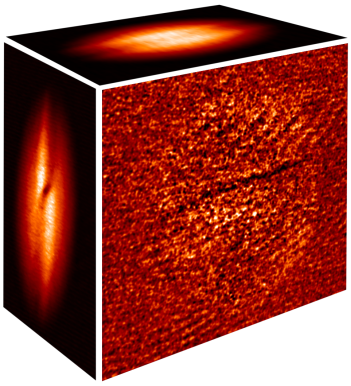


Figure 5: 3D absorption imaging of a freely expanded solitonic vortex.

This research line was started to learn more about unexpected effects observed in the optimization of the evaporative cooling of Sodium samples into the Bose condensed phase. While varying the cooling rate across the BEC phase transition we made the observation that fast cooling often resulted in the creation of solitonic defects in the condensate. The effects has been studied extensively in the laboratory and unambiguously attributed to the Kibble-Zurek mechanism (KZM). The KZM, which generally applies to second order phase transitions, is here observed on the thermal to Bose-condensed thermodynamic phase transition, and by measuring the average number of defects produced under various experimental conditions we were able to provide the very first quantitative characterization of the mechanism in dilute elongated Bose gases.

The article reporting our experimental observations was published in the journal Nature Physics in October 2013, alongside the related "news & views" article written by M. Zwierlein from the Massachusetts Institute of Technologies. The cover of the journal issue showed the images taken in our laboratory. Appreciation of the results from the scientific community was demonstrated by the number of invitations to report at scientific meetings, as well as at the "Quantum Lunch" of the Los Alamos National Laboratory, USA, under the invitation of W. H. Zurek. These results have also had some resonance in the press. In less than three years, this article has got already 53 citation according to ISI - Web of Science, and 101 according to Google Scholar.

We then continued the study of quenched BECs with a deeper analysis of the structure of the defects created by KZM. This led to the additional discovery of solitonic vortices, which are topological excitations of the condensate trapped in elongated geometries, theoretically predicted about twelve years ago, having a hybrid character of solitons and vortices. They present the discretized circulation typical of vortices and, at the same time, they show a planar-like symmetry as typically observed in 3-dimensional solitons. This intriguing form of excitation has been studied in detail in our laboratory, in collaboration with the theory group; we had also fruitful exchanges of information with the group of M.Zwierlein at MIT, where similar objects have been observed in Fermi superfluids. The close comparison between the experimental data and numerical simulations has allowed us to confirm the key features of the solitonic vortices, as expected from previous theoretical predictions, and to characterize their peculiar behavior in the free expansion of the condensate. The results of this research have been reported in an article published in the Physical Review Letters in 2014, which was also selected as an "Editors' Suggestion" by the journal and highlighted in the online journal Physics with a *Viewpoint* article written by Frédéric Chevy (ENS, Paris).

We have also taken additional data on the quenched cooling dynamics whereby optimized cooling ramps have allowed us to characterize the Kibble-Zurek mechanism independently of the decay process of gray solitons into solitonic vortices. This analysis led to a longer article published in Physical Review A in 2016, where we confirmed the observation of the power-law scaling of the average defect number with the quench rate, predicted by the KZM, but in addition we found a breakdown of such a scaling for fast quenches, leading to a saturation of the average defect number. Such a saturation effect has likely to do with the complex post-quench dynamics in the condensate, in between the creation of defects and their observation. In order to better understand the post-quench dynamics we started a collaboration with the group of Nick Proukakis at the University of Newcastle, where a stochastic Gross-Pitaevskii approach is used to simulate the behavior of the condensate with the parameters of our experiment. This work is in progress.

Dynamics and interaction of quantized vortices

This research line takes advantage of the capabilities developed in Trento of generating BECs with one, two, or more vortices *via* the Kibble-Zurek mechanism. While on the one hand the KZM elegantly solves the open problem of generating non-aligned vortices in superfluids, on the other hand each vortex is randomly generated due to the stochastic nature of the process, and this prevents the study of the vortex dynamics by means of the standard destructive imaging techniques. To circumvent this limitation we developed a set of novel imaging procedures that allowed us to repeatedly extract important information about the condensate wave function in real time, leaving it essentially unperturbed. In this way, we obtained multiple images of the condensate at different times, thus observing the in-trap dynamics of vortices.

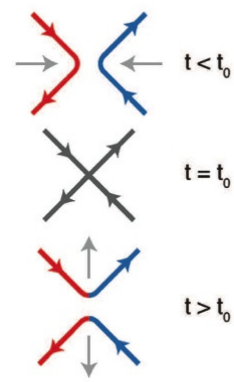


Figure 6: Sketch of a reconnecting vortex pair.

We applied this general idea to different specific problems such as the study of the dynamics of single vortices in elongated condensates, and the investigation of the role of vortex-vortex interaction in the dynamics of vortices orbiting in confined geometries. The first set of measurements, which was published in the Physical Review Letters in 2015, provided clean experimental observations in support of theories proposed a few years earlier. Subsequent measurements, made with a refined approach, led to intriguing results prompting to novel and unexpected mechanisms of interaction among vortices. We soon felt that these observations could be of interest for a wider community of physicists working on the physics of vorticity and turbulence in classical and quantum fluids and hence we decided to activate a collaboration with Prof. Carlo Barenghi at the University of Newcastle, who is a world leading expert in this field. Numerical simulations and new measurements in this direction are in progress and preliminary results hint at the observation of vortex reconnections, as well as of unexpected vortex-vortex rebounds.

Equation of state of weakly interacting Bose gases

When studying the thermodynamics of a physical system, the Equation of State (EoS) relates all the quantities of interest. Regarding the physics of 3D homogeneous and weakly interacting Bose systems, a direct measure of the thermodynamics is limited by the difficulty of obtaining an homogeneous BEC in laboratory conditions and by the very high density which characterizes the condensed phase. With this research line we extend the methods introduced in the previous section to image highly dense atomic clouds, hence setting the conditions to measure the EoS of a Bose gas. More specifically we focus on the effects of interactions in the vicinity of the phase-transition, which are expected to lift the chemical potential to positive values, making non-monotonic the trend of chemical potential with respect to temperature changes.

We tested various strategies to perform the measurement and we identified solutions to circumvent the technical limits which at present are preventing us from achieving conclusive results, namely the noise floor of our industrial-grade imaging camera and the power of a microwave amplifier. In the coming months we will upgrade the experimental setup in order to solve these technical limitations and we expect to do the final measurements for the EoS project in the course of the next year.

Towards resonantly-coupled spinor BECs

The new laboratory focusing on the study of spinor condensates will use novel methods and tools to study Bose condensates in unprecedented experimental conditions. To achieve this goal we have been working along various directions as listed in the following:

- the space allocated for the new laboratory (BEC2) was renovated to provide all technical infrastructures required to perform ultracold atom experiments, such as air conditioning, optical tables, radiofrequency shields, recirculating pressurized chilled water circuitry, etc. The room is adjacent to the first laboratory in order to insure the optimal use of all

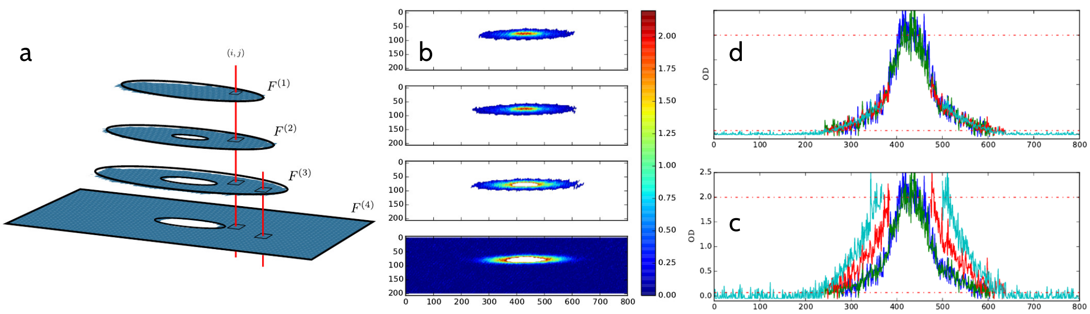


Figure 7: Procedure for extracting the density distribution of an optically thick sample. a) and b): successive images of the same sample are acquired while varying the extracted fraction. c) The different density profiles are overlapped in the significant regions by introducing a population-ration multiplier. d) The resulting density profile will be used to extract determine the equation of state.

shareable technical infrastructures and scientific instruments;

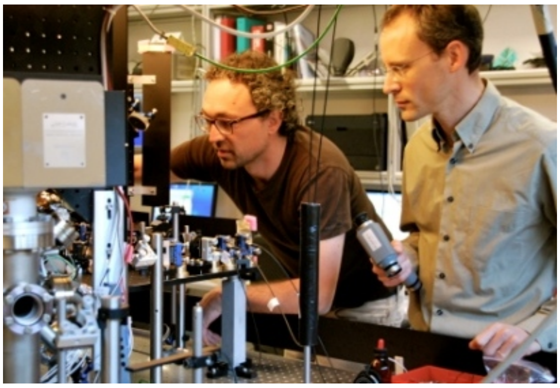
- the existing laboratory (BEC1) has been used to test a novel approach to laser cooling optically-dense sample of Sodium atoms to temperature close to the recoil limit, which will have a crucial impact on the production of the ultracold sample in the very specific conditions of BEC2. We also made a quantitative study of the stability properties of mixtures of superfluid Sodium atoms populating different internal states, performing the first ever measurement of polarizability in superfluid mixtures, and observing the softening of spin-dipole oscillations in the vicinity of the transition to the immiscible phase; this is a key test of feasibility for the future experiments in BEC2;
- along the same line, we implemented the experimental setup to excite and study magnetic solitons, as recently predicted by C. Qu et al., Phys. Rev. Lett. 116, 160402 (2016). This research will offer the opportunity to put in place and verify the performances of new scientific tools in BEC2.

Optical atomic clocks

This research line, which was activated during the last year of the project, aims at developing in Trento a source of cold Strontium atoms at conditions of temperature and confinement suitable to the accurate interrogation of the optical clock transition. Once operational and tested, the atomic source will be transferred to INRIM for operation and characterization in the final optical clock setup. The current activity of this project focusses on the design and assembly of the cold atomic source, as well as the assembly of the computer controlled electronics required for the preparation and interrogation of the atomic sample.

Along the related topic of optical frequency metrology, we are also doing some preliminary tests towards the realization of optical frequency combs characterized by high repetition rate, in the range of 10 GHz or larger.

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



Nature Physics 9, 656 (2013)

Spontaneous creation of Kibble-Zurek solitons in a Bose-Einstein condensate

G.Lamporesi, S.Donadello, S.Serafini, F.Dalfovo, and G.Ferrari

When a system crosses a second-order phase transition on a finite timescale, spontaneous symmetry breaking can cause the development of domains with independent order parameters, which then grow and approach each other creating boundary defects. This is known as Kibble-Zurek mechanism. Originally introduced in cosmology, it applies both to classical and quantum phase transitions, in a wide variety of physical systems.

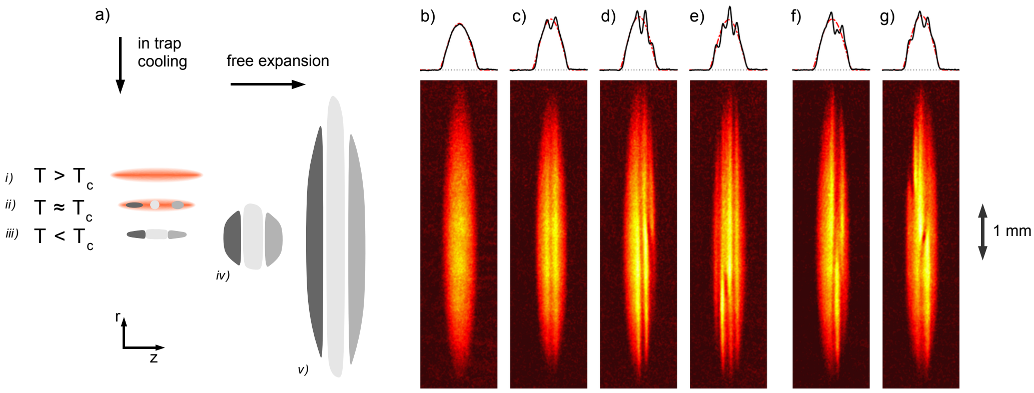


Figure 8: **a** Formation after a quenched cooling on a thermal gas (*i*, red) across the BEC transition, BEC is locally achieved forming several isles (*ii*) each with its own phase (grey). Further cooling makes them grow and get close (*iii*) forming solitons. The sample is released from the trap and let expand (*iv*-*v*) in a levitating field. A TOF of 180 ms is needed to allow the solitons to expand and be clearly detected. **b**-**e**, Sample pictures of the BEC after expansion containing 0,1,2,3 solitons or even fancier structures with bending and crossings (**f**-**g**). For each picture the integrated profiles of the central region (1/3 of the Thomas-Fermi diameter) are shown in black and compared to the parabolic Thomas-Fermi fit in red.

In this article we report on the observation of solitonic defects resulting from phase defects of the order parameter, spontaneously created in an elongated Bose-Einstein condensate (BEC) of Sodium atoms. We show that the number of defects in the final condensate grows according to a power-law as a function of the rate at which the BEC transition is crossed, consistently with the expectations of the KZM, and provide the first check of the KZM scaling with the sonic horizon. We support our observations by comparing the estimated speed of the transition front in the gas to the speed of the sonic causal horizon, showing that defects are produced in a regime of inhomogeneous Kibble-Zurek mechanism (IKZM), and providing the first check of the Kibble-Zurek scaling with the sonic horizon.

The KZM predicts the formation of independent condensates when the system crosses the BEC transition at a sufficiently fast rate (Fig. 8a *i*-*ii*). Further cooling and thermalization

below the critical temperature causes the independent condensates to grow. In axially elongated trapping potentials neighboring condensates with different phases will approach forming solitons (Fig. 8a *iii*). We characterize this process by counting the defects as a function of the quench time and the atom number at the transition by means of direct imaging after a ballistic expansion of the sample (Fig. 8a *iv*-*v* and Fig. 9). Typical density distributions after time-of-flight (TOF) are shown in Fig. 8b-g. The case in panel b) corresponds to a condensate with negligible thermal component and almost in its ground state. Panel c), instead, shows a density depletion which we interpret as a solitonic defects (in a subsequent deeper investigation we identified most of these defects as solitonic vortices; see next article). More solitons are shown in the other panels, including cases where the solitonic planes are bent and/or collide as in f) and g). As opposed to artificially created solitons via phase imprinting techniques or by exciting the superfluid with laser pulses or through collisions, our solitons spontaneously form when the BEC is created by crossing the transition temperature.
Those measurements can open the way to the determination of the critical exponents of the BEC transition in trapped gases, for which so far little information is available.

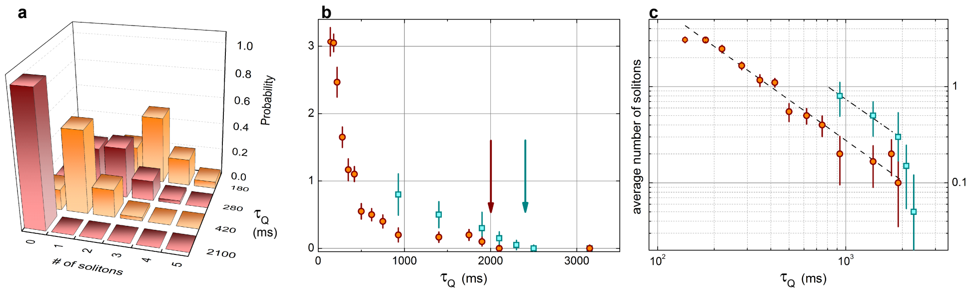


Figure 9: **a**, Counting statistics of the number of solitons observed in each shot for four different quench times and for the data set with 25 million atoms at T_c. Lin-lin (**b**) and log-log (**c**) plots of the average soliton number observed as a function of the quench time τ_Q. Red circles and blue squares correspond to series of data taken with different number of atoms at the BEC transition, respectively 25 and 4 millions. Arrows in panel (**b**) indicate the maximum τ_Q for which solitons were observed. The black dashed line in panel (**c**) shows the power-law dependence with exponent -1.38 ± 0.06 as resulting from the best fit with the data points (red circles), excluding the point at the fastest quench. Dot-dashed line with the same slope, but shifted on the second data set, serves as a guide to the eye showing similar power-law.

Phys. Rev. Lett. 113, 065302 (2014)

Observation of Solitonic Vortices in Bose-Einstein Condensates

Simone Donadello, Simone Serafini, Marek Tylutki, Lev P. Pitaevskii, Franco Dalfovo, Giacomo Lamporesi, and Gabriele Ferrari

In our previous experiment we reported on the observation of defects in a Bose-Einstein condensate (BEC) after rapid quench across the BEC transition. Those defects showed a planar structure, as expected for grey solitons spontaneously created *via* the Kibble-Zurek mechanism (KZM) in an elongated cigar-shaped condensate, but with a surprisingly long lifetime compared to the one predicted for this type of excitations. Motivated by this observation, we decided to set up a new protocol for the observation of defects in our BEC in order to better characterize their density and phase structure. In this way, we unambiguously identify them as solitonic vortices, which are likely the remnants of the decay processes of grey solitons. These topological defects, which were termed as solitonic vortices (SV) were predicted more than a decade ago, while the first experimental reports on them arrived during 2013.

Triggered by various observations, ours as well as others done on Bose-Einstein condensates and unitary Fermi gases, an exciting discussion grew up in the scientific community with theoretical contributions sent by various research groups worldwide. This was also motivated by the number of the implications this topic has in the study of superfluidity and quantum turbulence, with connections in wider context which includes superfluid helium, neutron stars, polariton condensates, and cosmological models.

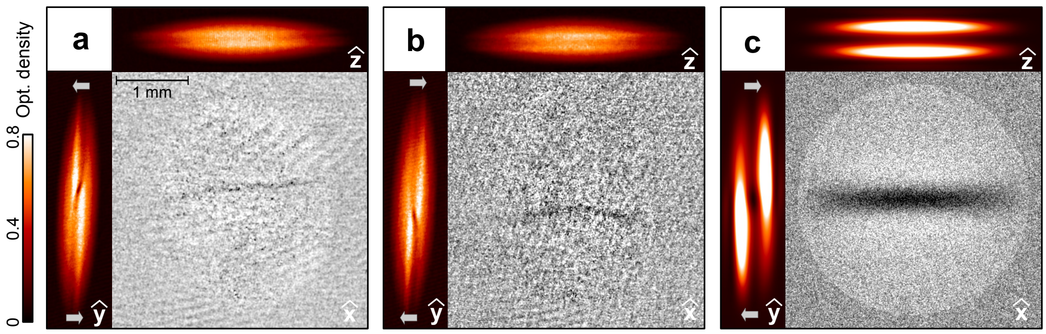


Figure 10: Integrated triaxial density distribution of a BEC after a time of flight of 120 ms in presence of a solitonic vortex aligned along y. For each condensate we report absorption images along the two radial directions, horizontal y (left) and vertical z (top), and the residuals of axial (x) imaging after subtracting the Thomas-Fermi profile fit. a-b) Experimental snapshots of two condensates with opposite circulation. c) Theoretical 3D calculation with clockwise circulation and a $\mu_{\text{theo}} \simeq \mu_{\text{exp}}/3$ (white noise has been added in order to better compare the theoretical calculation to the experimental results). Arrows indicate the atomic flow.

Fig. 10a-b show two typical examples of simultaneous triaxial absorption imaging after a time of flight $t_{\text{TOF}} = 120$ ms. The expanded condensate has an oblate ellipsoidal shape. For each of the two condensates we report standard absorption imaging along two radial directions y and z, and also the residuals of the axial absorption imaging, after the removal of fitting

Thomas-Fermi (TF) density profile. Clear vortex lines are visible from the axial direction. The contrast of the vortex lines is low, thus digital filtering of the images was performed to enhance the visibility of the defects. In Fig. 10 we report two selected images of condensates with a vortical line aligned along y and compare them to a theoretical simulation (Fig. 10c). In general, any time we see a vortex line from the axial direction we also detect a stripe when looking from both radial directions. This is the first signature of the solitonic nature of the defect.

In order to prove the quantized vorticity of the observed defects, we implement a matter wave interferometer (see Fig. 11). The presence of vorticity appears as a dislocation in the fringe pattern in a heterodyne interferometer, while in the case of homodyne detection a single vortex gives rise to a pair of dislocations with opposite orientations. Our interferometer is based on homodyne detection: the original condensate is coherently split in two clouds using coherent Bragg pulses.

This works shows how to distinguish vortices from antivortices by looking at the expanded density distribution and provide quantitative data supporting the idea that solitonic vortices are likely the remnants of the snaking instability of grey solitons in elongated condensates. It may also may serve as a basis for a systematic investigation of topological defects and solitons in quantum gases with variable geometry, from highly elongated quasi-1D to strongly oblate quasi-2D.

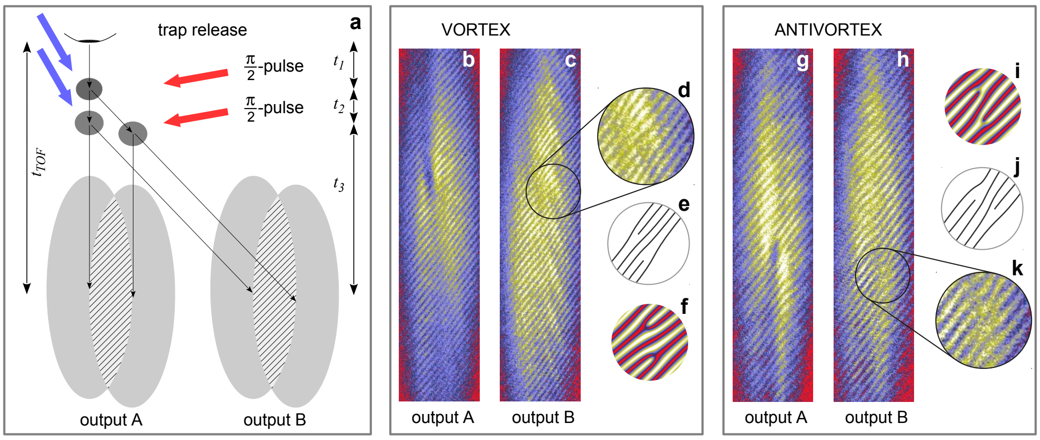


Figure 11: a) Time sequence for the two-pulse Bragg interferometer. After t_1 from the atoms release a first $\frac{\pi}{2}$ Bragg pulse splits the condensate in two parts, one at rest and the other moving at the Bragg velocity. After t_2 a second pulse further splits each condensate and imaging after a long t_3 allows for the separation of the two outputs and for the creation of the interference pattern. b-c) Experimental images of the two interferometer outputs in presence of a vortex with clockwise circulation (as observed from the twisted line of the density dip in b). d) Zoom on the interference pattern showing the dislocation-antidislocation pair and a guide to the eye (e) sketching the interference pattern. f) 2D numerical simulation of the experiment. g-k) The same, but for an antivortex with counterclockwise circulation.

Phys. Rev. Lett. 115, 170402 (2015)

Dynamics and Interaction of Vortex Lines in an Elongated Bose-Einstein Condensate

S. Serafini, M. Barbiero, M. Debortoli, S. Donadello, F. Larcher, F. Dalfovo, G. Lamporesi, and G. Ferrari

Vortex dynamics is an essential feature of quantum fluids and plays a key role in superfluid helium, superconductors, neutron stars, and magnetohydrodynamics. The interaction between vortices is crucial for understanding the formation of vortex lattices in rotating superfluids

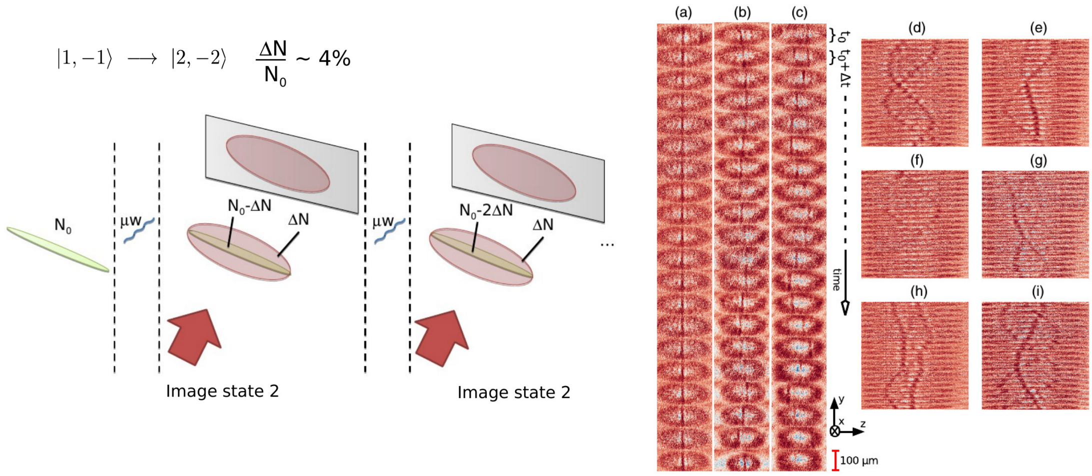


Figure 12: Left panel: sketch of the iterated imaging procedure. Panels on the right: Sets of sequences of 20 images each, of the density distribution of the atoms extracted from given BECs; frames belonging to the same set are taken every 84 ms, each after a 13 ms expansion.

and is the basic mechanism leading to quantum turbulence via vortex reconnection. Vortices have been extensively investigated in atomic gases, where a variety of techniques permits the observation of single ones up to a few hundreds, interacting in a clean environment and on a spatial scale ranging from the healing length (core size) ξ to a few tens of ξ. The fact that atoms are confined by external fields of tunable geometry makes them suitable to explore the physics of reconnection and dissipation in inhomogeneous systems and in the presence of boundaries. Seminal experiments were performed in rotating Bose-Einstein condensates (BECs), where the effect of rotation and long-range interaction favors vortex alignment and the formation of vortex lattices and hence crossing and reconnection mechanisms are inhibited. Interacting vortices have been observed in nonrotating oblate BECs, where vortex lines are short and either parallel or antiparallel, thus behaving as pointlike particles dominated by their long-range interaction in a quasi-2D background.

In our experiment we use a cigar-shaped BEC which is particularly suitable for studying the dynamics of vortex lines in 3D. Because of the boundary conditions imposed by the tight radial confinement each vortex line lies in a plane perpendicular to the long axis z of the trap, such to minimize its length and therefore its energy, as in the solitonic vortex configuration recently observed at the BEC Center. The line is randomly oriented in the plane, and away from it, at distances of the order of the system transverse size, the superfluid flow quickly vanishes and the long-range part of the vortex-vortex interaction is suppressed. Hence, vortices can move almost independently along elliptic orbits except when they approach each other and may collide with a random relative angle. At the scale of the healing length, where reconnection can take place, the system is still equivalent to a uniform superfluid, like liquid He, but with the advantage that vortex filaments collide at measurable relative velocities.

Here the vortices are produced via the Kibble-Zurek mechanism and are observed with a novel imaging procedure that, relying on the partial transfer between internal states which are either trapped in the confining potential and dark to the imaging, or non-trapped and bright to the imaging (see the left panel in figure 12), it allows us to extract important information about the condensate wavefunction leaving it essentially unchanged. This method permits the iterated imaging of the condensate at different times, hence giving access to the real time of the dynamics of vortices in real-time (right panel of figure 12).

With this procedure we could observe the precession of vortices in our harmonically-trapped and elongated Bose condensate, verifying the theoretical predictions relating the period of the orbits to the key parameters of the system, namely the trapping oscillator frequencies, the chemical potential of the sample, and the orbit amplitudes (see figure 13). Few sets images provided preliminary indications of interaction between vortices.

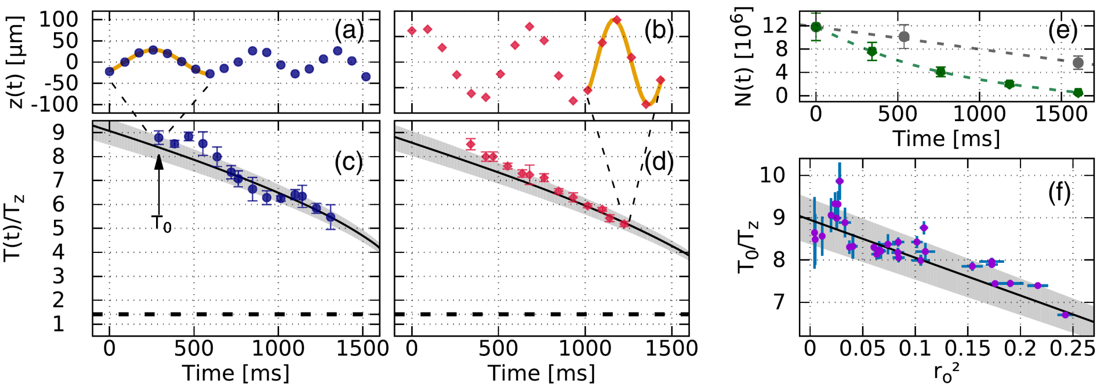


Figure 13: (a),(b) Vortex axial position after expansion for the condensates in Figs. 1(b) and 1(c). (c),(d) Instantaneous period normalized to the trapping period $T_z = 77$ ms (points) obtained by fitting the above oscillations; the solid line is the theoretical prediction for the measured atom number $N(t)$ and its 20% uncertainty (grey region); the dashed line is the prediction for a dark or grey soliton. (e) BEC atom number, with (green) and without (grey) the extraction sequence. (f) Period T extracted from the vortex position in the first frames in units of T_z as a function of r_o^2; the solid line represents the predicted $(1 - r_o^2)$ behavior, with no free parameters.

Phys. Rev. A 94, 023628 (2016)

Creation and counting of defects in a temperature-quenched Bose-Einstein condensate

S. Donadello, S. Serafini, T. Bienaimé, F. Dalfovo, G. Lamporesi, and G. Ferrari

This is a follow-up article to our paper Nature Physics (2013) on the creation of defects in a quenched BEC via the Kibble-Zurek mechanism (KZM). The motivation was to deepen our previous analysis and reach a better understanding of KZM in our elongated condensates.

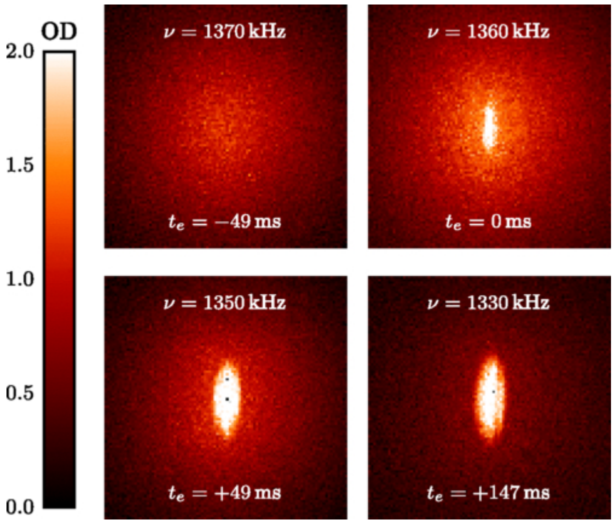


Figure 14: Sequence of experimental absorption pictures of the atomic sample around the transition, occurring at the rf frequency 1360 kHz for a ramp of 203 kHz/s with aspect ratio 10.1. All these pictures have been taken after a time of flight of 50 ms. At $t = 0$ a small condensate fraction of about 1% of the atoms appears in the thermal cloud and grows for $t > 0$. In the last picture the condensate appears much more definite, and a defect becomes visible in the form of a vertical stripe in the integrated density distribution. With such a technique it is almost impossible to detect the presence of defects around $t = 0$, as they start to become observable only about 100 ms after the transition.

The theory predicts a power-law scaling of the density of defects that the order parameter would contain after crossing the transition as a function of the quench rate. The scaling exponent depends on the intrinsic properties of the system and is the same for all systems belonging to a given universality class, independently of the microscopic details. A quantitative comparison with the observed behavior of actual systems, however, is rather challenging. For instance, the exact time at which defects are created cannot be easily estimated and very little is known in the case of nonlinear quenches or quenches where the control parameter is spatially inhomogeneous. Furthermore, interactions between defects are ignored in the KZM, whereas real systems are likely affected by such interactions during the post-quench evolution, or even at the early stages after the transition crossing.

In this work, we extend our previous experiments, where we observed the KZM scaling law, by collecting further data with an improved protocol for quenching and imaging. We explore

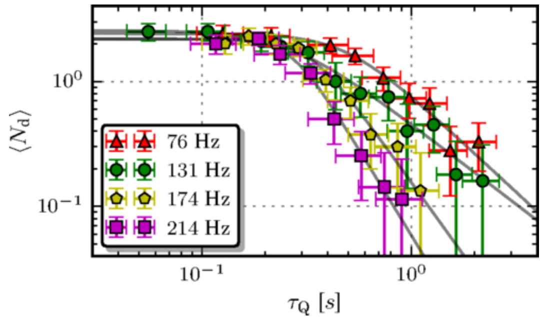


Figure 15: Average number of defects as a function of the quench time for several transverse confinements and with a fixed evolution time 250 ms after the transition. Each point with its error bar is calculated by averaging over tens of experimental realizations. A power-law behavior (linear in the log-log scale) is observed for large quench time, while a saturation effect is present for small quench time. The lines correspond to the function $\langle N_d \rangle = N_{\rm sat}[1 + (\tau_Q/\tau_{0Q})^{2\alpha}]^{-1/2}$. The fitting parameters are the saturation number $N_{\rm sat}$, the KZ power-law exponent α, and the characteristic quench time τ_{0Q} at which the two regimes interpolate.

faster quench regimes and find an unexpected saturation of the measured average defect number. We use a different quench protocol that keeps the observation time after the transition point fixed, instead of keeping the final temperature fixed. We also provide new data for different values of the transverse confinement frequencies, in order to possibly explore effects related to the dimensionality of the system.

From the observed data we clearly distinguish two regimes:

- For slow cooling rates a power-law behavior of the average defect number is observed as predicted by the KZM. In the case of strong confinement, our results are consistent with the exponent predicted for a harmonically trapped elongated gas in which vortices are spontaneously produced. Conversely, in the case of weaker confinement, the exponent turns out to be slightly smaller. However, the comparison with theory must be taken with care. The experimental error bars on the exponent α are still too large to make definitive statements and, in addition, the KZM predictions for α assume a spatially uniform temperature profile in the system during the quench, while the temperature profile is actually nonuniform along the axis of our elongated condensate due to the different thermalization times in the axial and transverse directions.

- For fast cooling rates we see a clear saturation of the measured average defect number to a value around 2.4, almost independent of the transverse confinement. We provide a qualitative interpretation in terms of the post-quench dynamics and interaction between vortices, with a simple model including the finite life-time of solitonic vortices. More quantitative and extensive numerical simulations of the condensate dynamics at finite temperature are in progress within a collaboration with the group of Nick Proukakis at the University of Newcastle.

Phys. Rev. A 93, 023421 (2016)

Sub-Doppler cooling of Sodium atoms in gray molasses

G. Colzi, G. Durastante, E. Fava, S. Serafini, G. Lamporesi, and G. Ferrari

Sub-Doppler laser cooling has been a well-established and widespread technique since the late 1980s. It consists in using light polarization gradients and optical pumping to cool down atoms below the Doppler temperature limit $T_{\mathrm{D}} = \hbar\Gamma/2k_{\mathrm{B}}$, where Γ is the natural linewidth. This technique, following a Doppler precooling stage in a standard magneto-optical trap (MOT), greatly improves the efficiency of the cooling process within its velocity capture range, but fundamentally does not remove the heating effects associated with the stochastic nature of photon absorption and spontaneous emission cycles. In addition, the atomic sample density remains

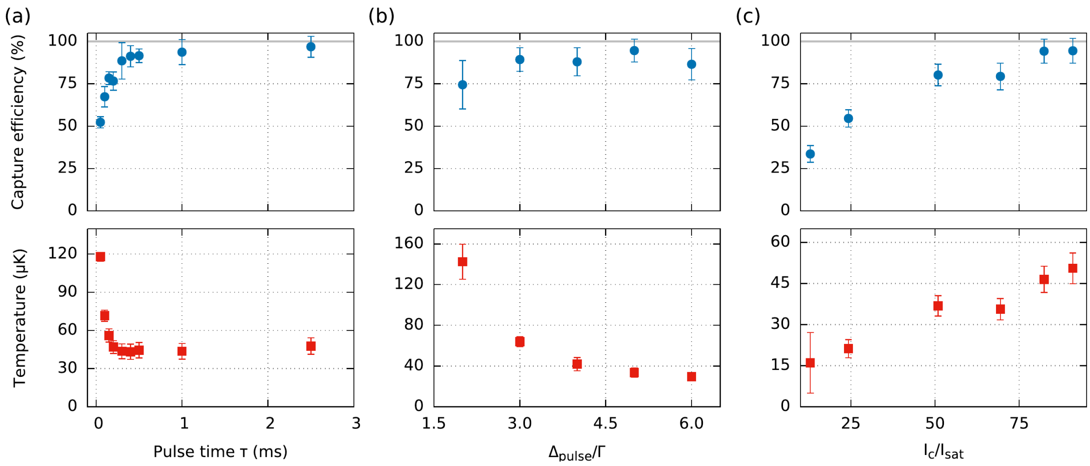


Figure 16: (a) Capture efficiency (blue circles) and temperature (red squares) after a single gray molasses pulse at constant intensity $I_C = 80\ I_{\mathrm{sat}}$ and fixed detuning $\Delta_{\mathrm{pulse}} = 4\Gamma$, as a function of the pulse duration τ, (b) as a function of the detuning Δ_{pulse} with $\tau = 0.5$ ms and $I_C = 80\ I_{\mathrm{sat}}$, and (c) as a function of the total cooler intensity I_C with $\tau = 0.5$ ms and $\Delta_{\mathrm{pulse}} = 5\Gamma$.

limited both by light-assisted collisions and by effective atom-atom repulsive forces caused by reabsorption of scattered photons. Improvements are obtained in schemes where slowed atoms are preserved from the above mentioned effects through selective trapping into dark states—states that are not coupled with the light field. Examples include the dark-spot (DS) -MOT scheme and schemes where the fraction of atoms optically pumped in a dark hyperfine state is dynamically controlled. The use of dark states in the achievement of lower and lower temperatures clearly leads to a gain in evaporation efficiency, hence in the final atom number. For this reason, studying techniques that take advantage of atomic dark states is still a promising field of study. This holds especially true given the fact that highly degenerate quantum gases shifted rapidly from being the object of study to being an experimental tool in addressing fundamental problems in physics and in devising cold-atom based quantum simulators, as the ones that will be addressed in the new ultracold atom laboratory under construction in Trento (BEC2 laboratory). There, spinor condensates will be studied in conditions of unprecedented coherence of the spin states on timescales of the order of one second, hence requiring the stability of the magnetic field at the μ-Gauss level. In this regime the standard techniques of evaporative cooling in magnetic traps do not apply because of the incompatibility between the operation of the magnetic trap and the use of μ-metal shileds required to screen the atomic sample from the noise induced by environmental stray magnetic fields. Alternative approaches to the final cooling into the quantum degenerate regime are based on optical trapping in far-detuned, focussed laser beams, which are efficient in terms evaporative cooling rate versus atom loss but, because of the mismatch of overlap between the the atomic sample and the trap volume, and the temperature of the sample versus the trap depth, they are rather inefficient with respect to the loading from an ordinary laser cooled sample.

With the present work we demonstrated a novel approach to laser cool Sodium atoms which:

- allows us to reach temperatures as low as 4 recoil temperature,
- shows no density-dependent heating for densities up to 10^{11} cm^{-3},
- efficiently allows us to reach phase-space densities in the range of 10^{-4}, hence reaching the current state-of-the-art in laser cooling of alkali atoms,
- will considerably improve the loading efficiency into optical trap, as required in the BEC2 laboratory under construction at our Center.

The cooling performances were assessed both in a single stage configuration, by changing the duration of the cooling while keeping constant the parameters of the cooling laser (see figure 16), and in a multi-stage approach where the parameters of the cooling laser were also optimized as a function of the time sequence (see figure 17).

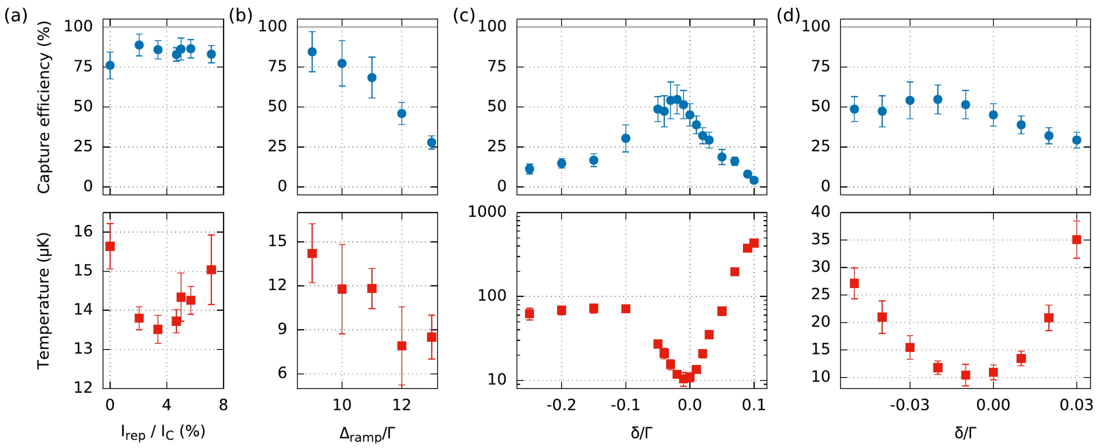


Figure 17: Cooler detuning Δ/Γ (blue line) and intensity I_C/I_{sat} (red line) as a function of time for the single GM pulse, and (b) for the GM sequence with ramp.

Theory of quantum gases

Theoretical activities were planned along the following main directions: dynamics of superfluid bosons and fermions; artificial gauge fields and synthetic magnetic fields; dipolar gases; ab initio simulations; photons, polaritons, analog black holes. Here below we briefly summarize the main achievements.

Dynamics of superfluid bosons and fermions

3D solitons, vortices and persistent currents. We investigated the behavior of dark solitons in a Fermi superfluid in the BCS-BEC crossover, by calculating the rate of snaking instability (Cetoli et al., PRA 88, 043639, 2013). This work, done in collaboration with the group of J.Brand, was quite timely in view of the on-going discussions about a recent experiment by M.Zwierlein. The behavior of solitonic excitations is interesting in Bose superfluids as well. Part of the theoretical activities of the BEC team has been devoted to the simulation and the physical interpretation of the observations made by the local experimental team with the condensate of sodium, as described in the previous section of this report. A closely related problem is the motion of quantized vortex rings in trapped superfluid gases, for which a hydrodynamic model has been developed (Pitaevskii, arXiv:1311.4693). We also studied the behavior of persistent currents in two-component condensates in a toroidal trap (Abad et al., PRA 89, 053602, 2014). The detection of supercurrent in a toroidal condensate has been the subject of a collaboration with the experimental team at NIST Gaithersburg, which led to the joint publication Kumar et al., NJP 18, 025001 (2016).

Fermions in double wells and optical lattices. We studied Josephson oscillations and self-trapping of superfluid fermions in a double-well potential (Peng and Dalfovo, JLTP 177, 240, 2014) and the occurrence of multiple period states of the superfluid Fermi gas in an optical lattice (Yoon et al., NJP 18, 023011, 2016).

Low dimensions and restricted geometries. We have investigated Lieb's soliton-like excitations in harmonic trap (Astrakharchik and Pitaevskii, EPL 102, 30004, 2013), the collective oscillations of a trapped in 1D and 2D (De Rosi and Stringari, PRA 92, 053617, 2015), the thermalization and Helmholtz oscillations of an ultracold Bose gas (Papoular et al., PRL 113, 170601, 2014), the shortcut to adiabaticity for an anisotropic 2D Bose gas (Papoular and Stringari, PRL 115, 025302, 2015), while in Ozawa et al., PRL 112, 025302 (2014) a new method to observe the Berezinskii-Kosterlitz-Thouless transition in a 2D Bose gas has been suggested, based on the occurrence of discontinuities in the first and second sound velocities.

Bose-Bose and Bose-Fermi mixtures. Mixtures of ultracold bosons and fermions have been investigated in Sartori and Recati, EPJD 67, 260 (2013), and in Ozawa et al., PRA 90, 043608 (2014). In Tylutki et al., NJP 18, 053014, (2016), we have studied solitons in Bose-Fermi mixtures, and we have found a peculiar bright-dark soliton in the partially miscible phase.

Hydrodynamic models and sound propagation. A series of papers has been devoted to the problem of two-fluid hydrodynamics of Fermi gases at unitarity: Sidorenkov et al., Nature 498, 78 (2013); Hou et al., PRA 87, 033620 (2013), Hou et al. PRA 88, 043630 (2013); and Khoon Tey et al., PRL 110, 055303 (2013). These works are the results of a fruitful collaboration with the experimental team of R.Grimm at Innsbruck. In particular the paper Sidorenkov et al., Nature 498, 78 (2013) contains a joint theoretical and experimental study of the propagation of second sound in strongly interacting Fermi gases from which it was possible to extract the temperature dependence of the superfluid density. Finally, the hybridization of first and second sound in a weakly-interacting Bose gas was the subject of the article Verney et al., EPL 111, 40005 (2015).

Artificial gauge fields and synthetic magnetic fields

Coherent coupling and spin-orbit coupling. The concept of synthetic gauge fields has been simultaneously explored in both atomic and luminous gases. On the atomic side, we considered spin-orbit coupling in different cases: the ground-state phase diagram and the critical temperature of two-component Bose gases with Rashba spin-orbit coupling (Zeng-Qiang Yu, PRA 87, 051606, 2013); the behavior of supercurrents and the occurrence of dynamical instabilities in the presence of spin-orbit coupling in Bose gases (Ozawa et al., PRA 87, 063610, 2013); an interpretation in terms of momentum space magnetic fields (Price et al., PRA 91, 033606, 2015); the possible observation of super-stripes in a spin-orbit-coupled Bose-Einstein condensate (Yun Li et al., PRL 110, 235302, 2013 and Martone et al., PRA 90, 041604, 2014). The properties of coherently coupled two-component Bose-Einstein condensates has been studied in Abad et al., EPJD 67, 148 (2013), while a novel type of magnetic solitons has been predicted to occur in a binary BEC with coherent coupling (Chunlei Qu et al., PRL 116, 160402, 2016). Similar magnetic phenomena have been also studied for Bose gases in optical lattices; in particular we pointed out the emergence of a spin-orbit correlation for repulsive bound states in the low density limit (Menotti et al. PRA 93, 033602 (2016)), and characterize the ferro- to para-magnetic transition (Barbiero et al., PRA 93, 033645 (2016)) for unity filling.
Nontrivial topological states. Building on top of the semiclassical theory of (Cominotti et al., EPL 103, 10001, 2013) a framework to describe the dynamics of particles in topologically nontrivial bands in terms of a momentum space magnetic field has been developed (Price et al., PRL 113, 190403, 2014). In addition to its natural applications to both atomic and photonic systems, this work has paved the way to an unexpected but very promising research direction on momentum-space quantum Hall effects, where the intrinsically toroidal geometry of the ambient space is promising in view of quantum applications (Ozawa et al., PRA 92, 023609, 2015; PRB 93, 195201, 2016). Finally, in collaboration with leading experts of topological physics we have successfully attacked the problem of realizing high-dimensional $d > 3$ topological systems using the concept of synthetic dimension for either atoms (H. M. Price et al., PRL 115, 195303, 2015) or photons (T. Ozawa et al., PRA 93, 043827, 2016). More details on our advances in topological photonics are summarized in the next "Photon and polaritons" paragraph.

Dipolar gases

The field of ultracold gases with dipolar interaction has also been central in our research activities. The peculiarity of such systems lies in the fact that, contrary to usual systems where particles interact through a contact potential, in this case interactions show a long-range and anisotropic character, with important consequences for the physics both at the two and at the many-body level. To start with, the existence of a dipolar induced resonance for two bosons in a quasi one-dimensional geometry modifies crucially the many-body behaviour in 1D lattices and their phase diagram (Bartolo et al., PRA 88, 023603, 2013). Other important effects of the dipolar interactions in 1D lattices arise due to the competition between short and long-range interactions, which leads, through frustration effects, to spontaneous Peierls polarization, namely the formation of dimerized phases, characterized by bond-ordering (Di Dio et al., PRA 90, 063608, 2014).

Furthermore, long-range interactions between a test particle and a system of dipoles trapped at random positions in an optical lattice have been exploited to create a disordered potential, whose correlations are given by both long and short-range correlations (Larcher et al., PRA 88, 013632, 2013). The interplay between those two types of correlations can modify in a crucial way the localization properties of the system. Special attention has been devoted to the dependence of the impurity effective mass on the distance between the two layers and to the possibility of a transition to a localization regime. The same kind of system has also been studied in the case of relatively weak interactions through the Brueckner-Hartree-Fock approach (Klawunn and Recati, PRA 88, 013633, 2013). Recently, interesting dynamics for polar gases have been investigated in Barbiero, Menotti, Recati, and Santos, PRB, 92, 180406(R) (2015). The absence of energy dissipation produces an intriguing out-of-equilibrium dynamics for ultracold polar gases in optical lattices, characterized by the formation of dynamically bound on-site and inter-site clusters of two or more particles, and by an effective blockade repulsion. These effects lead to quasi-equilibrated effectively repulsive 1D gases for attractive dipolar interactions, dynamically bound crystals and quasi-many-body localization in the absence of quenched disorder.

Ab initio simulations

Quantum Monte Carlo methods have been used for investigating the dynamic structure factor in the gas and crystal phase of hard-sphere bosons (Rota et al., PRB 88, 214505, 2013). Ab initio calculations have been performed also on dipolar gases, for studying two-dimensional bilayer geometries. The behaviour of a single impurity with a fermionic system either in the gaseous or Wigner crystal phase in the second layer has been investigated giving particular emphasis on the dependence of the effective mass of the impurity on the interlayer distance (Matveeva and Giorgini, PRL 111, 220405, 2013). The main result consists in the emergence of a crossover from a free-moving to a tightly bound regime for the impurity coupled to a Wigner crystal phase.

Other studies concerned dipolar fermions and bosons in a bilayer configuration with equal

populations in the two layers, where as a function of the interlayer distance an exotic BCS-BEC crossover occurs in the case of fermions (Matveeva and Giorgini, PRA 90, 053620, 2014) and a quantum phase transition between an atomic and a pair superfluid in the case of bosons (Macia et al., PRA 90, 043623, 2014). Resonant Bose-Fermi mixtures with a small concentration of bosons have also been simulated in Bertaina et al., PRL 110, 115303 (2013). A first-order quantum phase transition is found from a state with condensed bosons immersed in a Fermi sea to a Fermi-Fermi mixture of composite fermions and unpaired fermions.
Finally, the problem of an impurity immersed in a Bose-Einstein condensate with resonant coupling to the bath has been investigated in Peña Ardila and Giorgini, PRA 92, 033612 (2015). The binding energy and the effective mass of the impurity have been calculated both for the ground-state attractive branch and the metastable repulsive branch. These latter results have important implications for the experiments carried out in the groups of D. Jin and J. Artl on the so called Bose polaron problem.

Photons and polaritons

After summarizing our study of the superfluidity properties of the fluid of light in the long review article (Carusotto and Ciuti, RMP 2013), in the period under examination this research line focused on the study of more complex geometries and/or on the effect of an artificial gauge field for light. On one hand, the presence of the synthetic gauge field for photons can lead to novel topological effects; our main advances in this direction are summarized in the “Artificial gauge fields and synthetic magnetic fields” section of this report. On the other hand, the intrinsically driven-dissipative nature of the luminous gas provides schemes to spectroscopically investigate the topological features and Hall-like effects (Ozawa and Carusotto, 112, 133902, 2014; Salerno et al., 2D Mater. 2, 034015, 2015; Berceanu et al., PRA 93, 013827, 2016). Our study of interacting gases in the presence of rotation/synthetic gauge field continued in Umucalilar et al., PRA 89, 023803 (2014).
In addition to this purely theoretical research, we have been involved in intense collaborations with experimental groups which have implemented our theory. Together with colleagues at LPN, we have studied a photonic graphene device in Jacqmin et al. PRL 112, 116402 (2014), its edge states in Milicevic et al, 2D Mater 2, 034012 (2015), and a photon analog of spin-orbit coupling (Sala et al., PRX 5, 011304, 2015). Another collaboration on a similar subject is in progress with researchers in Nice at LPMC.
Finally, a quite unexpected development has been the extension of topological concepts to a purely classical context of newtonian mechanics in Salerno and Carusotto, EPL 106, 24002 (2014) and in PRB 93, 085105 (2016), which opens interesting new experimental perspectives to topological physics. Given the simplicity of the experimental set-up, a concrete implementation in Trento is under way in collaboration with N. Pugno’s group in the civil engineering department.

Analog black holes

An important result in the field of artificial black holes has been the first ab initio study of Hawking radiation in nonlinear optical systems, as recently experimentally investigated by some groups. The work Finazzi and Carusotto, PRA 89, 053807 (2014), highlighted as an "Editor's Suggestion" and selected for a Synopsis on the Physics on-line magazine, reports a critical analysis of the experiment and of its conclusions, and proposes new strategies to obtain a solid experimental evidence of the analog Hawking radiation.
Simultaneously, we started investigating a new nonlinear optical configuration where superfluid light and artificial black holes may be studied with a better experimental control on the generation of the horizon (Carusotto, Proc. R. Soc. A. 470, 20140320, 2014). A general quantum theory for this configuration was developed in (Larré and Carusotto, PRA 92, 043802, 2015) and an application of this configuration to the measurement of the drag force in a superfluid was proposed in (Larré and Carusotto, PRA 91, 053809, 2015). An experimental collaboration on this physics is in progress with D. Faccio's group at Heriot-Watt (Edinburgh), with a special attention to nonlocal fluids of light (Vocke et al., Optica 2, 484, 2015; PRA 94, 013849 (2016)).
Very recently, our historical collaboration with E. Giacobino and A. Bramati has been extended to these novel propagating fluids of light using atomic gases as nonlinear media.
Another platform that turned out very promising for studying analog Hawking radiation are analog black holes in flowing quantum fluids of polaritons. In addition to pushing forward our theoretical activity (Grisins et al., arXiv:1606.02277), we gave important contributions to the first experiment showing such novel analogs of black holes (Nguyen et al., PRL 114, 036402, 2015; this work was selected as Editor's suggestion and featured in Physics).
Finally, an interesting development has come from the application of the entanglement concept to characterize Hawking radiation in both atomic (Finazzi et al., PRA 90, 033607, 2014, and Boiron et al., PRL 115, 025301, 2015) and photon fluids (Busch et al., PRA 89, 043819, 2014). It is worth mentioning that right after the end of the reporting period, a first experimental paper by J. Steinhauer claiming observation of analog Hawking radiation and its entanglement has appeared. Remarkably, the techniques used for the experiment are strongly inspired by theoretical works at the BEC Center by Recati, Finazzi and Carusotto.

A selection of articles is presented in the following, with a brief summary for each of them.

Phys. Rev. A 88, 043639 (2013)

Snake instability of dark solitons in fermionic superfluids

A. Cetoli, J. Brand, R.G. Scott, F. Dalfovo, L.P. Pitaevskii

Solitons are a ubiquitous feature of fluid dynamics. In cold gases they are created in processes of nonequilibrium dynamics such as a shock waves, phase and density imprinting, collisions between condensates, and moving obstacles, or a rapid quench through a superfluid phase transition, and may be observed long after the event if they are sufficiently stable. In strongly correlated Fermi superfluids, solitons provide a link between hydrodynamics and the poorly understood dynamics at interatomic length scales.

While solitons may live long enough to be observed, they are subject to a dynamical instability that leads to bending (snaking) of the depletion plane and eventually to the formation of vortex filaments or vortex rings. This process limits the lifetime of the soliton as the structure of the initial topological excitation is lost. The timescale of the decay is given by the excitation spectrum of this snake instability.

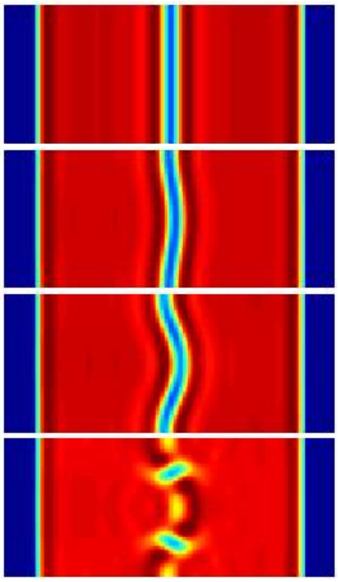


Figure 18: A dark soliton (top panel) bends and decays into a pair of vortices (lower panel).

This article presents numerical calculations of the snake instability of a dark soliton in a Fermi superfluid within the Bogoliubov-de Gennes theory of the BEC to BCS crossover using the random phase approximation complemented by time-dependent simulations. The snaking behaviour is investigated across the crossover and the timescale and lengthscale of the instability are calculated. In the long wavelength limit mean-field hydrodynamic arguments predict that the timescale of the decay is set by the soliton energy and mass. Our BdG calculations well agree with this prediction. However, for smaller wavelengths in the BCS regime there is a departure from this behavior; the departure might be due to pair-breaking or boundary conditions.

It is shown that, while the dynamic exhibits extensive snaking before eventually producing vortices and sound on the BEC side of the crossover, the snaking dynamics is preempted by decay into sound due to pair breaking in the deep BCS regime. At the unitarity limit, hydrodynamic arguments allow us to link the rate of snaking to the experimentally observable ratio of inertial to physical mass of the soliton. In this limit we witness a significant discrepancy between our numerical estimates for the critical wavenumber of suppression of the snake instability and recent experimental observations with an ultra-cold Fermi gas in the group of M.Zwierlein (eventually, the same group lately identified the observed excited states as solitonic vortices instead of dark solitons; since solitonic vortices are known to have a much longer life time, this solves the discrepancy).

New J. Phys. 18, 053014 (2016)

Dark-Bright Solitons in a Superfluid Bose-Fermi Mixture

Marek Tylutki, Alessio Recati, Franco Dalfovo, Sandro Stringari

In one dimension, a soliton corresponds a well defined deformation of the modulus and phase of the order parameter of the system, which can propagate without dispersion. Now, since it became experimentally possible to realise mixtures of Bose and Fermi superfluids with ultracold gases, we decided to study the properties of such systems theoretically, focusing precisely on the solitonic solutions. To this purpose, we use Bogoliubov-de Gennes equations in order to describe the Fermi superfluid and the Gross-Pitaevskii equation for the condensate of Bosons.

The phase diagram of the mixture of superfluid bosons and an ideal Fermi gas was already calculated in the recent past and features three phases: a uniform mixture, where both gases coexist and occupy the same space, a complete phase separation, where bosons separate in space from fermions, and the least obvious phase, where some fraction of fermions separates in space from the rest, while the remaining region is filled by a mixture of Bosons and Fermions. Using our equations, we indeed reproduce all three phases by varying the strength of the interaction. Between the coexistence phase and the fully separated phase, a narrow range of interaction parameter exists, where only a fraction of fermions separates from the mixture.

As the next step, we study a dark soliton in the Fermi superfluid and how it is modified by bosons in all those three regimes. In the coexistence regime the bosons merely feel the Fermi soliton as an external potential, which attracts them, but the effect is weak and does not change the overall properties of the soliton. In the phase separated regime the solitonic depletion is completely filled by bosons and the two components of the gas are spatially separated. The partial separated regime brings the most interesting result: bosons localize around the depletion in the Fermi gas, which in turn becomes very wide and deep, maintaining the phase coherence between the two sides. This is a novel structure in the form of a dark-bright soliton.

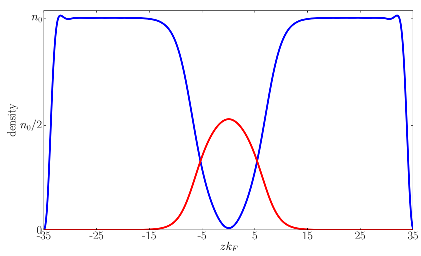


Figure 19: Fermionic (blue) and bosonic (red) density distributions in a bright-dark soliton in the mixture.

Our results may have some interesting implications in the search for the elusive FFLO phase. In such a phase, due to the imbalance between spin up and spin down fermions, the Fermi radius of the two spin components is different. As a consequence, Cooper pairs have a finite center-of-mass momentum and the order parameter exhibits a spatial modulation with the period set by this momentum. Our results suggest that the presence of a small bosonic component can be used as a way to stabilize the density modulation of the fermionic order parameter and also to make them more directly observable.

Nature 498, 78 (2013)

Second sound and the superfluid fraction in a Fermi gas with resonant interactions

L.A. Sidorenkov, M.K.Tey, R.Grimm, Y.-H. Hou, L.Pitaevskii, S.Stringari

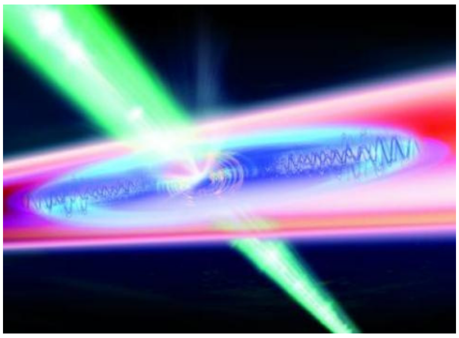


Figure 20: The cigar-shaped atom cloud is locally heated with a power-modulated laser beam (green). (Credit: IQOQI/Ritsch)

Superfluidity is a macroscopic quantum phenomenon, which shows up below a critical temperature and leads to a peculiar behavior of matter, with frictionless flow, the formation of quantized vortices, and the quenching of the moment of inertia being intriguing examples. A remarkable explanation for many phenomena exhibited by a superfluid at finite temperature can be given in terms of a two-fluid mixture comprised of a normal component that behaves like a usual fluid and a superfluid component with zero viscosity and zero entropy. Important examples of superfluid systems are liquid helium and neutron stars. More recently, ultracold atomic gases have emerged as new superfluid systems with unprecedented possibilities to control interactions and external confinement. This article reports the first observation of 'second sound' in an ultracold Fermi gas with resonant interactions. Second sound is a striking manifestation of the two-component nature of a superfluid and corresponds to an entropy wave, where the superfluid and the non-superfluid components oscillate in opposite phase, different from ordinary sound ('first sound'), where they oscillate in phase. The speed of second sound depends explicitly on the value of the superfluid fraction, a quantity sensitive to the spectrum of elementary excitations. In the laboratory of the Institute of Experimental Physics at the University of Innsbruck, the team lead by R.Grimm prepared a quantum gas consisting of about 300,000 lithium atoms. They heated the cigar-shaped particle cloud locally with a power-modulated laser beam and then observed the propagating temperature wave. While in superfluid helium only one entropy wave is generated, the Fermi gas also exhibited some thermal expansion and, thus, a measurable density wave. The measurements allowed them to extract the temperature dependence of the superfluid fraction, which in strongly interacting quantum gases has been an inaccessible quantity so far.

The research work, published Nature, is the result of a long-term close collaboration between the physicists in Innsbruck and the BEC Center in Trento. The Trento group adapted Lev Landau's theory of the description of second sound for the almost one-dimensional geometry of the Innsbruck experiments in order to give a conceptual basis and a consistent interpretation of the measurements.

Phys. Rev. Lett. 112, 025302 (2014)

Discontinuities in the First and Second Sound Velocities at the Berezinskii-Kosterlitz-Thouless Transition

Tomoki Ozawa and Sandro Stringari

Two dimensional superfluids differ in a profound way from their 3D counterparts. In fact the Hohenberg-Mermin-Wagner theorem rules out the occurrence of long range order at finite temperature in 2D systems with continuous symmetry. Furthermore the superfluid density approaches a finite value at the critical point of a 2D superfluid, known as Berezinskii-Kosterlitz-Thouless (BKT) transition, rather than vanishing, as happens in 3D. A peculiar property of these 2D systems is also the absence of discontinuities in the thermodynamic functions at the critical temperature characterizing the transition to the superfluid phase. In order to identify the transition point one has consequently to measure suitable transport properties.

The experimental measurement of second sound has recently proven successful in determining the temperature dependence of the superfluid density in a 3D strongly interacting Fermi gas (see also the summary of Sidorenkov *et al.* Nature 498, 78 (2013) in this report), and we expect that a similar measurement of sound velocities in 2D Bose gases can be exploited in determining the details of the BKT transition.

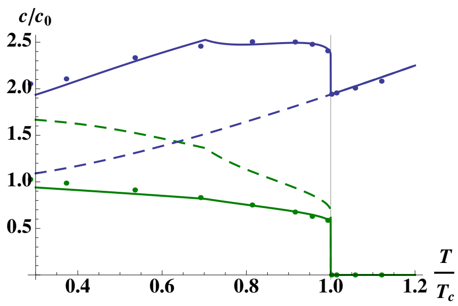


Figure 21: First and second sound velocities. Thermodynamic quantities are taken from approximate analytical expressions (solid lines) or numerical values (dots) given by Prokof'ev and Svistunov, Phys. Rev. A 66, 043608 (2002). The dashed lines are the sound velocities for less compressible fluids.

In this paper, we calculated the temperature dependence of the first and second sound velocities in the superfluid phase of a 2D Bose gas by solving Landau's two fluid hydrodynamic equations. We predicted the occurrence of a significant discontinuity in both velocities at the critical temperature, as a consequence of the jump of the superfluid density characterizing the BKT transition. We found that, unlike in superfluid liquid Helium, first and second sound in 2D Bose gas cannot be identified as density and entropy oscillations. This is due to the sizable coupling effects between these two oscillations as a consequence of the system being highly compressible, which is characterized by the large thermal expansion coefficient. We also found that second sound in the dilute Bose gas can be easily excited through a density perturbation, thereby, making the perspective of the measurement of the superfluid density particularly favorable.

Phys. Rev. A 89, 053602 (2014)

Persistent currents in two-component condensates in a toroidal trap

M. Abad, A. Sartori, S. Finazzi, and A. Recati

Persistent currents are dissipationless flows representing one of the strongest signatures of superfluidity. They are topological long-lived metastable states of quantum fluids which are described by a macroscopic wave function (order parameter in Bose-Einstein condensates). Persistent currents become unstable above a certain velocity threshold. In the absence of a weak-link, their decay is a complex, stochastic process mediated by phase slips, and is related to the existence of energy barriers for the excitations to cross the bulk superfluid.

The versatility of gaseous Bose-Einstein condensates (BECs) and the ability to experimentally control their properties offer new scenarios to probe superfluidity. One of the most intriguing systems that can be realized nowadays is the spinor condensate, which is described by a vectorial order parameter. The simplest example is the two-component condensate, where spin exchange can be implemented by a coherent coupling between internal levels of the atoms.

In this work we study the microscopic mechanism that triggers the decay of persistent currents and we build the stability diagram in a quasi-two-dimensional ring geometry, as a function of the mixture polarization P_z and the flow velocity. In the miscible regime our theoretical analysis is based on the solution of Bogoliubov excitations and it is addressed numerically both with imaginary-time and real-time simulations for a toroidal geometry. We show that there exists a regime of partial instability where the minority component could lose angular momentum without affecting the majority component, as shown in Fig. 22 . The existence of this regime is the main result of this work and could be at the origin of the experimental observations done in Cambridge by Zoran Hadzibabic group (S. Beattie, S. Moulder, R. J. Fletcher, and Z. Hadzibabic, Phys. Rev. Lett. 110, 025301 (2013)), although to test it fully new experiments should be carried out with different parameters. We also discuss the stability conditions in the phase separated regime and in the presence of a coherent coupling between the two components. In the latter case a gap opens in the spin channels, making the super-current more stable, since naively in the large coherent coupling limit one recovers the single component result.

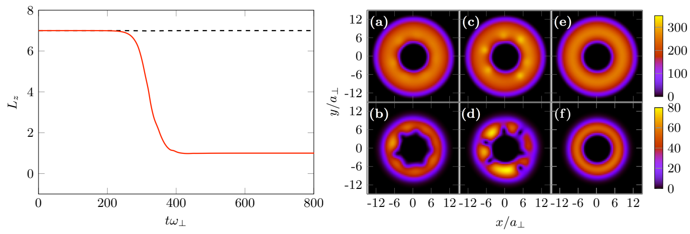


Figure 22: Left panel: time-dependence of angular momentum of components a (dashed line) and b (solid line) in real-time dynamics in the partially stable region. Right panels: density snapshots of components a (upper row) and b (lower row) at times: $t = 260\omega_\perp^{-1}$ in panels (a) and (b), $t = 305\omega_\perp^{-1}$ in panels (c) and (d), and $t = 560\omega_\perp^{-1}$ in panels (e) and (f). The density (in units of $a_\perp^{?2}$) is represented in the color scale. For this case $P_z = 0.8$ and $\kappa = 7$ is the quantum circulation in the toroidal geometry. In the numerics $\omega_\perp = 2\pi \times 50$Hz

Eur. Phys. J. D 69, 126 (2015)

Counter-flow instability of a quantum mixture of two superfluids

M. Abad, A. Recati, S. Stringari, F. Chevy

An important direction of research in the physics of ultra-cold atoms concerns the study of quantum mixtures of two superfluids and the onset of their instability when they move against each other (counterflow instability). In the case of weakly interacting Bose-Einstein condensates the dynamical counterflow instability has been already the object of theoretical work studied and has been experimentally seen to lead to the formation of soliton trains. Recent results carried out at the LKB presented in mixtures of Bosons and Fermions have demonstrated the possibility of reaching double superfluidity with atomic gases belonging to different statistics, opening a new scenario for the study of superfluid mixtures. These experiments on the collective excitations of the mixture raised, in particular, the question of the critical velocity of their relative superfluid motion.

In the present article, written in collaboration with Frédéric Chevy of LKB, we study the stability of a superfluid counter-flow in the hydrodynamic approximation, discussing in an explicit way the role of the interspecies interaction, going beyond the small interspecies coupling limit.

Our results hold also for fluids belonging to different quantum statistics and generalize previous results derived for mixtures of Bose-Einstein condensates. For relative velocities larger than some critical value the solutions of the hydrodynamic equations exhibit an imaginary component in the sound velocity which is responsible for decay processes. The role of the interspecies interaction has been explicitly investigated and shown to decrease the value of the critical velocity with respect to the of small interspecies coupling constant. Special emphasis has been given to the behavior of Bose-Fermi superfluid mixtures where experimental measurements of the collective motion have recently become available.

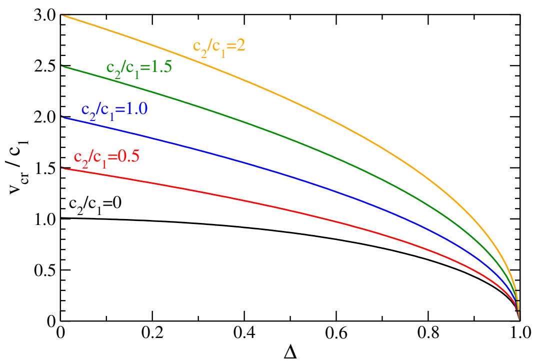


Figure 23: Critical relative velocity, v/c_1, as a function of the interfluid coupling Δ, for various values of c_2/c_1.

The figure shows the typical behavior of the critical velocity for the onset of dynamic instability as a function of the relevant parameter $\Delta = c_{12}^2/(c_1c_2)$ for different values of the ratio c_2/c_1 between the sound velocities in the two fluids and where c_{12} is a sort of cross compressibility due to the interaction between the two superfluids.

New J. Phys. 18, 025001 (2016)

Minimally destructive, Doppler measurement of a quantized, superfluid flow

A. Kumar, N. Anderson, W.D. Phillips, S. Eckel, G.K. Campbell and S. Stringari

Ring-shaped Bose-Einstein condensates use topology to exploit one of the key features of a BEC: superfluidity. In particular, the topology supports superfluid persistent currents [Ryu et al., PRL 99, 260401 (2007)]. The addition of one or more rotating perturbations or weak links into the ring can form devices that are similar to the rf-superconducting quantum interference device (SQUID). Operation of these devices typically requires measuring the persistent current. Here, we present a technique for measuring the persistent current of a ring that uses the Doppler effect and, unlike other methods, is done in-situ and can be minimally destructive.

To this purpose we take advantage of the fact that, in addition to supporting bulk persistent flows, the BEC also serves as a medium in which sound can travel. Because of the trap's boundary conditions, only certain wavelengths of sound are permitted. These phonon, or Bogoliubov, modes are the lowest energy collective excitations of the condensate. In this work, we excite a standing wave mode as shown in the figure (panels (a) and (b)). Such a standing wave corresponds to an equal superposition of clockwise and counterclockwise traveling waves with the same wavelength. In the presence of a background flow, the Doppler effect shifts the relative frequencies of the two traveling waves. This shift causes the standing wave to precess, as shown in panels (c) of the figure. Here, we use this precession to detect the background flow velocity of the superfluid and to identify the quanta of circulation associated with the superfluid flow. This method is analogous to earlier techniques [Haljan et al., PRL 87, 210403 (2001)], where the precession of a quadrupole oscillation was used to measure the sign and charge of a quantized vortex in a simply connected, harmonic trap.

This work is the result of a collaboration with the team of G.K Campbell and W.D. Phillips at the Joint Quantum Institute, National Institute of Standards and Technology and University of Maryland, where the experiment was done.

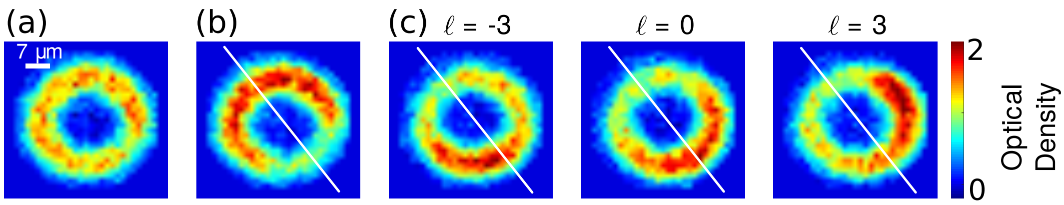


Figure 24: (a) Image of the ring condensate in situ without an applied perturbation. (b) A sinusoidal perturbation excites a standingwave superposition of counterpropagating phonon modes. (c) The density modulation rotates relative to the initial perturbation in the presence of superfluid flow. The winding numbers are shown above the images.

Phys. Rev. Lett. 115, 025302 (2015)

Shortcut to adiabaticity for an anisotropic gas containing quantum defects

David Papoular and Sandro Stringari

Shortcut To Adiabaticity (STA) protocols offer a reversible way to evolve a many–body system from one state to another, achieving the same target state as an adiabatic transformation within a much shorter time over which decoherence and losses are minimal. Up to now, STAs have been demonstrated either in the ideal–gas or the Thomas–Fermi regimes. Their application to a gas containing defects requires going beyond these approximations, as the existence and dynamics of the defects result from the interplay between quantum pressure and interactions.

We introduce a novel STA protocol applicable to anisotropic 2D Bose gases and 3D unitary Fermi gases hosting defects, as well as to classical Boltzmann gases. It links two stationary states in initial and final traps with the same anisotropy. It allows for a reversible and arbitrarily fast compression or expansion of the cloud which conserves the aspect ratios and acts as a homothety, i.e. a perfect microscope, on the defects (Fig. 25 A & B). This sharply contrasts with the free expansion of the anisotropic cloud, which inverts the cloud anisotropy and dramatically affects the density and phase profiles of vortices (Fig. 25C). Our STA can be used to quench the cloud from one anisotropic stationary state to another. It relies on a new and exact scaling solution for the dynamics of the cloud in a time–dependent anisotropic harmonic trap $V(\vec{r},t) = m\sum_{j=1}^{D}\omega_j^2(t)x_j^2/2$, with D being the spatial dimensionality. It is applicable if the spatial aspect ratios remain constant in time, and it involves a single scaling parameter $b(t)$, proportional to the cloud radii, which determines the squared trapping frequencies $\omega_j^2(t)$ through the relation:

$$\omega_j^2(t) = \frac{\omega_j^2(0)}{b^4} - \frac{\ddot{b}}{b} \quad \text{for } 1 \leq j \leq D \, .$$

Exact solutions for quantum dynamics are rare, and we believe ours to be the first analytical solution for the dynamics of a quantum gas in a time–dependent anisotropic trap.

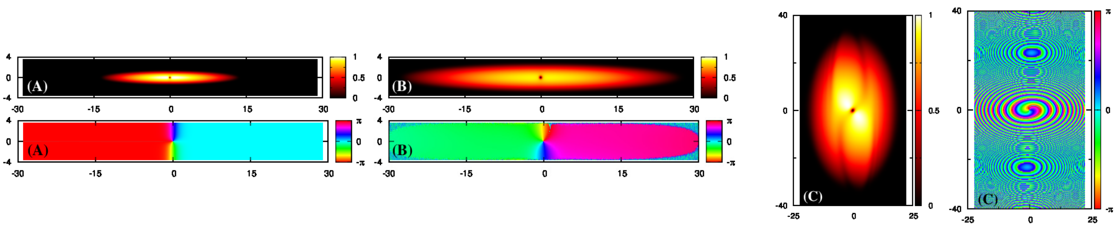


Figure 25: (A) Density (top) and phase (bottom) profiles for an inital anisotropic 2D Bose cloud at temperature $T = 0$ containing a vortex. (B) Density and phase profiles after a STA evolution. (C) Density and phase profiles after the free expansion of the same inital cloud during the same time. All six plots result from a numerical solution of the 2D Gross–Pitaevskii equation.

Eur. Phys. J. D 67, 148 (2013)

A study of coherently coupled two-component Bose-Einstein Condensates

Marta Abad and Alessio Recati

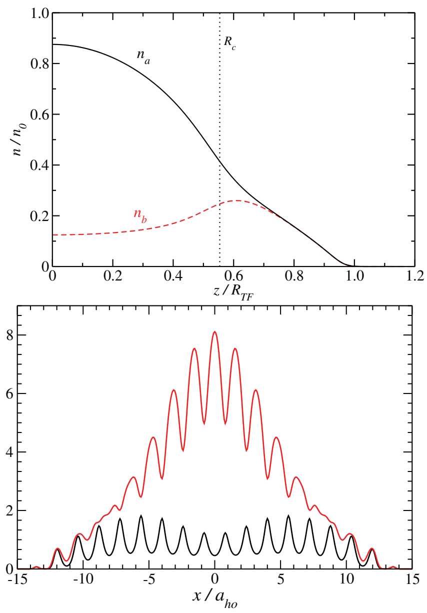


Figure 26: (Upper panel) Harmonically trapped spinor gas with a polarized state in the center. (Lower panel) Spinor gas in an optical lattice plus harmonic continent. The optical lattice is felt only by one component (the black one) and the system is in the ferromagnetic phase in the centre of the trap.

The physics of multi-component condensates is very rich due to the possibility of vector order parameters and therefore the presence of different zero-temperature phases. In this work we present a self-consistent study of coherently coupled two-component Bose-Einstein condensates at the mean field level and within Bogoliubov approach.

A Bose-Bose mixture without coherent coupling has a $U(1)\times U(1)$ symmetry responsible for the two gapless mode spectrum: density and spin Goldstone modes. The zero temperature phases are either a homogeneous phase or a phase separated regime. Finite spin-flipping coupling reduces the symmetry to a $U(1) \times \mathbf{Z}_2$ and it opens a gap in the spin sector and it changes the first order de-mixing phase transition to a second order phase transition between an unpolarized and a polarized state. The latter transition is similar to the ferromagnetic transition in a classical Ising model in transverse field. We analyze the excitation spectrum and the density and spin dynamic structure factor along the transition for a homogeneous system and discuss the main differences at the transition between a coherent coupled gas and a two-component mixture. In particular magnetic fluctuations due to the coherent coupling make the value of the spin static structure factor different from zero for $q \to 0$. Such a value diverge at the phase transition point. In the case of trapped gas we find in particular that: (i) harmonic confinement allow for a single shot measurement of the phase digram as shown in Fig. 26; (ii) spin-dependent optical lattices give rise to interesting new configurations like out-of-phase oscillation with respect to the background lattice as reported in Fig. 26.

New J. Phys. 17, 093036 (2015)

Spin-dipole oscillation and relaxation of coherently coupled Bose-Einstein condensates

Alberto Sartori, Jamir Marino, Sandro Stringari, Alessio Recati

We consider a zero temperature trapped two-component BEC with an interconversion external field between the two atomic levels forming the condensate, also known as Rabi coupling. The system is a generalisation to non-linear atom optics of the well-known linear Rabi problem and in general is an extension of quantum optics concepts to condensates. The interplay between the intra-(g) and the inter-(g_{ab}) two-body interaction strengths and the Rabi coupling strength (Ω) makes the physics of the system very reach. The Rabi coupling tries to create an equal superposition of the two possible internal levels. On the other hand large interspecies interaction tries to favour a situation where the population of the two internal levels is unbalanced. It turns out that the system exhibits a ferromagnetic-like phase transition.

In this article, we study the spin dipole polarizability and the dynamics of the spin dipole mode in the presence of harmonic trapping. The spin polarizability in uniform matter has the simple expression

$$\chi_s = \frac{2}{g - g_{ab} + \Omega/n_0}$$

which reveals the crucial role of the Rabi coupling in determining the emergence of the phase transition where χ_s exhibits a divergent behavior. Starting from the above equation, we have calculated within local density approximation the spin dipole polarizability as well as, using a sum rule approach, the frequency of the spin dipole oscillation. The latter is shown in the figure. The theoretical results (lines) are in good agreement with the full solution of Gross-Pitaevskii equation (points). The simple spin dipole oscillation and the previous analysis is valid until the whole cloud remains paramagnetic. When instead the cloud has a ferromagnetic core we observe phenomena of ground state selection and relaxation. The gas is initially trapped in a magnetic domain wall, whose trapped time before starting evaporating is found to be proportional to the square root of the surface tension of the wall, or equivalently of the distance from the ferro- to paramagnetic transition point.

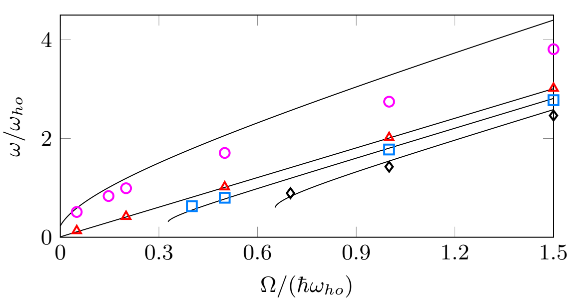


Figure 27: Spin dipole mode frequency as a function of the Rabi coupling Ω and for different values of interspecies interaction: $g_{ab}/g = 0.9$ (purple circles), $g_{ab}/g = 1$ (red triangles), $g_{ab}/g = 1.01$ (blue squares), $g_{ab}/g = 1.02$ (black diamonds). Lines are analytical results and points are numerical data. In order to have a fully paramagnetic phase for $g_{ab} > g$ one needs $\Omega \geq \Omega_{cr}$.

Phys. Rev. Lett. 116, 160402 (2016)

Magnetic Solitons in a Binary Bose-Einstein Condensate

Chunlei Qu, Lev P. Pitaevskii and Sandro Stringari

Solitons, the fascinating topological excitations of nonlinear systems, have drawn a considerable research interest in many physical systems. Among them, ultracold atomic gases provide a prominent platform for the investigation of solitons which can be engineered by phase imprinting, density imprinting, etc.. Soon after the realization of Bose-Einstein condensation, dark and bight solitons have been actually observed in repulsive [Burger et al., PRL 83, 5198 (1999) and Denschlag et al., Science 287, 97 (2000)] and attractive [Khaykovich et al., Science 296, 1290 (2002)] interacting Bose gases. Recently, vector solitons such as dark-bright solitons have been explored in spinor Bose gases where the underlying physics is even richer [Busch and Anglin, PRL 87, 010401 (2001)].

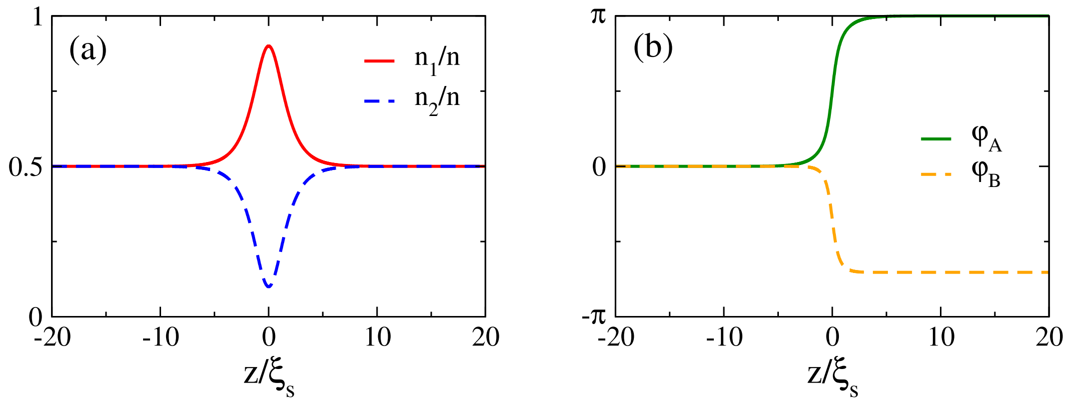


Figure 28: Plot of the densities, the total phase (φ_B) and relative phase (φ_A) of a magnetic soliton with velocity $V = 0.6c_s$.

In this article, we investigate magnetic solitons in a two-component Bose gas which exist only when the repulsive intra- and interspin interactions of the two species are unequal. Different from dark-bright solitons, the magnetic soliton manifests itself as a localized spin polarization $n_1 - n_2$ where $n_{1,2}$ are the densities of the two components, and resides in a spin-balanced density background. In this work we were able to derive an analytic solution of the coupled Gross-Pitaevskii equations holding in the case of equal intraspin coupling $g_{11} = g_{22} \equiv g$ and for $0 < \delta g \equiv g - g_{12} \ll g$. The hyperfine states $|3^2S_{1/2}, F = 1, m_F = \pm 1\rangle$ of sodium atoms satisfy the above condition with high accuracy, thereby providing a realistic perspective for the observation of magnetic solitons. In the above figure, we show a typical profile of a magnetic soliton propagating with velocity $V = 0.6c_s$ where c_s is the spin sound velocity. An important peculiarity of these magnetic solitons is that their spatial width, fixed by the spin healing length $\xi_s = \hbar/\sqrt{2mn\delta g}$, is much larger than the width of usual solitons, thereby indicating that magnetic solitions are more stable against snake instability in the presence of radial trapping.

Phys. Rev. A 87, 063610 (2013)

Supercurrent and dynamical instability of spin-orbit-coupled ultracold Bose gases

Tomoki Ozawa, Lev P. Pitaevskii, and Sandro Stringari

A characteristic feature of superfluids is their ability to support a current flow (supercurrent) without dissipation. In a Galilean invariant, uniform configuration the supercurrent does not decay if the velocity of the fluid is lower than the critical velocity fixed by the Landau criterion. Landau's instability has an energetic nature, being associated with a negative value of the excitation energy. Nonuniform superfluid systems, like ultracold Bose-Einstein condensates in optical lattices, are known also to exhibit dynamical instabilities. Both energetic and dynamical instabilities have been the subject of intense theoretical and experimental investigations in ultracold atomic gases.

The recent realization of spin-orbit-coupled gases is opening new perspectives in the study of superfluid phenomena. These systems lack Galilean invariance and show the consequences also in uniform density configurations. In particular, in these systems the usual Landau criterion cannot be used to determine the stability of configurations carrying a supercurrent, the corresponding critical velocities being dramatically different.

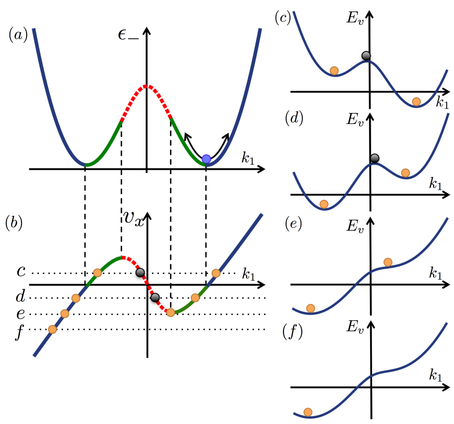


Figure 29: (a) Single-particle eigenenergy and (b) corresponding speed as a function of the momentum k_1. The dotted (red) lines indicate the dynamically unstable region. (c-f) The energy per particle for four different supercurrent speeds.

In this paper, we investigate the stability of supercurrents in a Bose-Einstein condensate with one-dimensional spin-orbit and Raman couplings. We show that the supercurrent state can become dynamically unstable as a consequence of the lack of Galilean invariance even for configurations with a uniform density. The instability is associated with the occurrence of a complex sound velocity, in a region where the effective mass is negative. We also discuss the emergence of energetic instability in these supercurrent states. We argue that both the dynamical and the energetic instabilities in these systems can be generated experimentally through excitation of the collective dipole oscillation. Our analysis explains an experiment [Zhang *et al.* Phys. Rev. Lett. 109, 115301 (2012)], in which an instability of the dipole oscillation is observed when the oscillation amplitude is too large and the condensate reaches the dynamically unstable region.

Phys. Rev. Lett. 110, 235302 (2013)

Superstripes and the Excitation Spectrum of a Spin-Orbit-Coupled Bose-Einstein Condensate

Yun Li, Giovanni I. Martone, Lev P. Pitaevskii, Sandro Stringari

The recent realization of spinor BECs with spin-orbit (SO) coupling is opening new perspectives in the field of supersolidity. In systems with equal Rashba and Dresselhaus SO couplings and for small values of the Raman coupling, theory predicts the occurrence of a stripe phase, which is characterized by the coexistence of two spontaneously broken symmetries. The breaking of gauge symmetry gives rise to off-diagonal long-range order yielding superfluidity, while the breaking of translational invariance yields diagonal long-range order characterizing the crystalline structure.

By using Bogoliubov theory, in this work we calculate the excitation spectrum of the gas in the stripe phase. The emergence of a double gapless band structure is pointed out as a key signature of Bose-Einstein condensation and of the spontaneous breaking of translational invariance. The lowest four excitation bands along the x direction are reported in Fig. 30, with the widths of the bands representing the contributions to the density (left) and spin density (right) static structure factor. In the long wavelength limit, the lower and upper gapless branches exhibit, respectively, a clear spin and density nature. For wave vectors q_x close to the border of the Brillouin zone $2k_1$, the lower branch acquires an important density character, which responsible for the divergent behavior of the structure factor and of the static response function, reflecting the occurrence of crystalline order. The sound velocities are calculated as functions of the Raman coupling for excitations propagating orthogonal and parallel to the stripes. Since the excitation spectrum is measurable in Bragg spectroscopy experiments, our predictions provide new perspectives for the identification of supersolid phenomena in ultracold atomic gases.

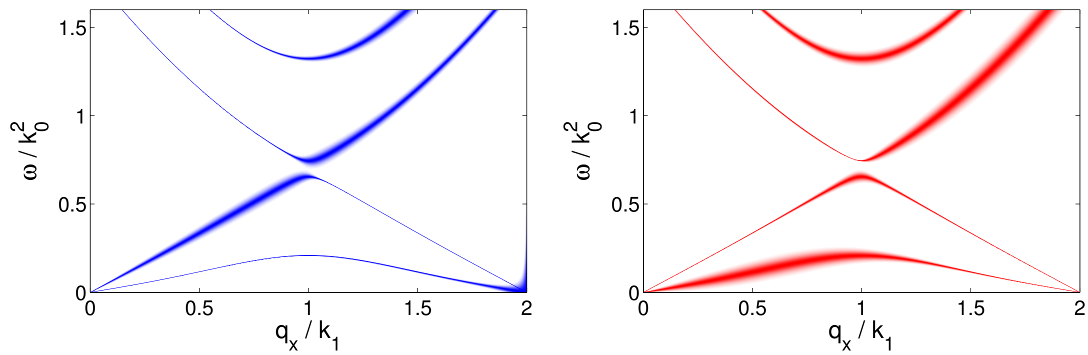


Figure 30: Lowest four excitation bands along x direction. The parameters are $\Omega/k_0^2 = 1.0$, $G_1/k_0^2 = 0.3$, and $G_2/k_0^2 = 0.08$, where k_0 is the SO coupling strength. The width of each band represents its contribution to the density (left) and spin density (right) static structure factor.

New J. Phys. 18, 023011 (2016)

Multiple Period States of the Superfluid Fermi Gas in an Optical Lattice

Sukjin Yoon, Franco Dalfovo, Takashi Nakatsukasa, Gentaro Watanabe

Density structures and patterns caused by the interplay of competing effects are ubiquitous in nature. Examples are the competition between dispersion and nonlinearity, which yields solitons, the competition between crystalline order and Peierls instability of conduction electrons, which results in charge and spin density waves, or the FFLO state, with a spatially dependent pairing field originating from the competition between the mismatch of the Fermi surfaces in the imbalanced systems and the energy gain by the condensation. In the case of superfluids in a periodic lattice, nonlinearity due to the presence of the order parameter, which favors a quadratic energy dispersion, can lead to the persistence of the quadratic-like dispersion beyond the Brillouin zone edge and give rise to non-trivial loop structure called 'swallowtail' in the energy band. Due to their high controllability, ultracold gases offer an excellent test bed for exploring these intriguing phenomena.

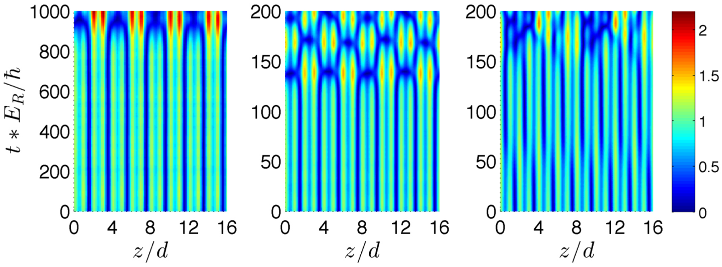


Figure 31: Time evolution of the magnitude of the pairing field Δ of the period-doubled state for three different values of the quasi-momentum of the superfluid in the lattice. The lattice spacing is d.

For atomic BECs flowing in periodic potentials with finite quasi-momentum, it was found that nonlinearity of the interaction can cause the appearance of stationary states whose period is not equal to the lattice constant as in the usual Bloch states, but is a multiple of it. Here we investigate multiple period states in atomic Fermi superfluids, which are particularly interesting for their analogs in condensed matter physics and nuclear physics, such as superconducting electrons in solids and superfluid neutrons in neutron stars. Unlike the case of BECs, little has been studied about multiple period states in Fermi gases and their existence itself along the BCS-BEC crossover is an open question. In our paper, we show that they indeed exist and they can be energetically favorable compared to the normal Bloch states in the BCS regime. The multiple period nature distinctly appears in the pairing field, which could be observed by the fast magnetic field sweep technique. The emergence of the period-doubled states in the BCS side is also connected to the disappearance of the swallowtails, which exist in the BEC side. Finally, we find that, despite being dynamically unstable, their lifetime becomes drastically long by going toward the deep BCS limit, possibly allowing for their experimental observation.

Phys. Rev. A 89, 053602 (2014)

Polar molecules in bilayers with high population imbalance

Michael Klawunn and Alessio Recati

During the last years ultracold dipolar gases have attracted great interest because the dipole-dipole interaction (DDI) drastically changes the nature of quantum degenerate regimes compared to ordinary short-range interacting gases. The main obstacle is the decay of the system due to ultra-cold chemical reactions. However, if the molecules are confined in a 2D geometry and oriented perpendicularly to the plane of their motion by a strong external electric field, these reactions are expected to be suppressed by the intermolecular repulsion. Bilayer arrangements with this dipolar orientation are particularly interesting, since they allow for both, stability against chemical reactions and effects induced by the anisotropy of the DDI. In this work we investigate a dilute Fermi gas of polar molecules confined into a bilayer setup with dipole moments polarized perpendicular to the layers. In particular, we consider the extreme case of population imbalance, where we have only one particle in one layer and many particles in the other one.

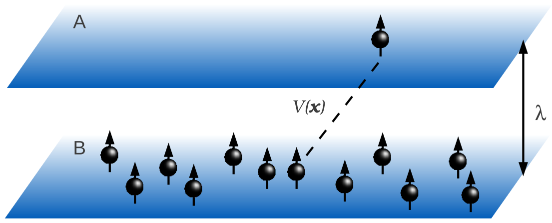


Figure 32: Scheme of the studied system. The lower layer plays the role of a bath and the upper layer particle is the impurity whose properties we calculated.

The single molecule is attracted by the dilute Fermi-gas through the interlayer dipole- dipole force presenting an interesting impurity problem with long range anisotropic interaction. We calculate the chemical potential of the impurity, in second order perturbation theory and in ladder approximation with a Brueckner-Hartree-Fock approach. Moreover, we determine the momentum relaxation rate of the impurity, which is related to the dipolar drag effect. For a confined system we relate the results for the chemical potential with the measurement of the collective modes of the impurity. The momentum relaxation rate provide instead an estimate on how quickly the oscillations are damped.

Recent quantum Monte-Carlo calculation carried out at the BEC Center for the dressed impurity energy have confirmed that our analytical results indeed reproduces accurately the physics in the weak interacting regime.

Phys. Rev. A 88, 023603 (2014)

Dipolar-induced resonance for ultracold bosons in a quasi-1D optical lattice

N. Bartolo, D.J. Papoular, L. Barbiero, C. Menotti, and A. Recati

The standard theoretical description for dipolar bosons in optical lattices relies on the extended Bose-Hubbard model (EBHM) accounting for the interaction between nearest and more distant neighbors. The one-dimensional (1D) EBHM has revealed the occurrence, beyond the standard Mott-insulator (MI) and superfluid (SF) phases, of a mass density wave (MDW) phase and a Haldane insulator phase. The proper description of specific atomic systems by lattice models such as the EBHM requires a careful mapping between the model parameters and the physical systems. This has already been pointed out for the Hubbard model, but the nontrivial effects associated with long-range and anisotropic interactions are even more important. As a first step in this direction, we analyzed the important role played by the dipolar-induced resonance (DIR), which is a low-energy resonance occurring when the dipole strength is varied. We have shown that the DIR affects both the two-body and the many-body physics of the system.

We have focused our attention on quasi-one-dimensional systems of ultracold bosons. We have first described the effect of the DIR on two particles in a quasi 1D harmonic trap. Then, we have considered a deep 1D optical lattice loaded with ultracold dipolar bosons. In order to describe the lattice system, we introduced a novel atom-dimer extended Bose-Hubbard model, which is the minimal model correctly accounting for the DIR. We analyzed the impact of the DIR on the phase diagram at $T = 0$ by exact diagonalization of a small-sized system and comparing with quasi-analytical results. We have shown that the DIR strongly affects the phase diagram. In particular, we have predicted the mass density wave to occur in a narrow domain corresponding to weak nearest-neighbor interactions, and the occurrence of a collapse phase for stronger dipolar interactions.

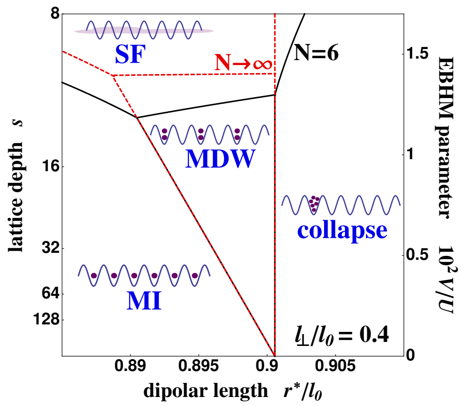


Figure 33: Quasi-analytical phase boundaries calculated for N = 6 (solid black) and $N \to \infty$ (dashed red).

Those quantum phases may be experimentally identified using in situ imaging techniques as well as the recent advances allowing for the detection of nonlocal order. It would be interesting to extend our work to 2D geometries, where the anisotropy of the dipolar interaction is expected to play a role. Our analysis would also be relevant for the understanding of the fermionic 1D EBHM with repulsive interactions, where the relevant phases are the spin density wave, the charge density wave, and the bond order wave.

Phys. Rev. A 88, 013632 (2014)

Metal-insulator transition induced by random dipoles

M. Larcher, C. Menotti, B. Tanatar, and P. Vignolo

Interference effects induced by random potentials deeply modify wave diffusion up to even stopping wave transport on a length L_{loc}, the localization length. This phenomenon is called strong localization or Anderson localization. Anderson theory relies essentially on the fact that the potential has to be δ-correlated and the waves non-interacting. If on the one hand noninteracting waves exist in nature, on the other hand real uncorrelated potentials do not exist.

In this paper we have proposed a physical model for a random potential where long-range and short-range correlations arise naturally from the system itself, exploiting the properties of the dipolar interaction in ultracold atomic or molecular gases. We considered a test dipole feeling the disordered potential induced by dipolar impurities trapped at random positions in an optical lattice. This random potential is marked by correlations which are a convolution of short-range and long-range ones. In particular, short-range correlations are introduced by repulsive dipolar interactions due to the fact that occupations of neighboring sites are forbidden.

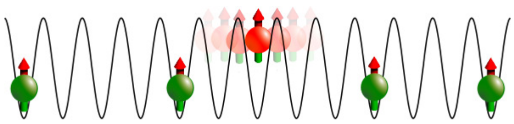


Figure 34: Schematic representation of the physical model. Dipolar impurities (green spheres) are trapped at the minima of the optical lattice, occupying random positions. The test dipole (red upper sphere), excited to a different internal level, feels a shallower optical potential and a disordered potential due to the dipolar interaction with the impurities.

The localization properties of the model were calculated by means of a renormalization-decimation technique which allowed us to calculate properties of very large systems and study the extended or localized nature of the states. We have shown that when short-range correlations are dominant, extended states can appear in the spectrum. Introducing long-range correlations, the extended states, if any, are wiped out and localization is restored over the whole spectrum. Moreover, long-range correlations can either increase or decrease the localization length at the center of the band, which indicates a richer behavior than previously predicted. Long-range correlations been studied not only for the dipolar case but also for a more general two-point correlation function decaying as $C(\ell)1/\ell^{\beta}$, where the case $\beta = 3$ corresponds to the dipolar case.

Our work has shed light on the interplay between short-range and long-range correlations and can be a guide for experiments devoted to the study of Anderson localization with ultracold dipolar gases. Natural extensions of the present work include the study of two-dimensional (2D) geometries and the role of interactions between many test dipoles.

Phys. Rev. A 93, 033602 (2016)

Momentum-dependent pseudospin dimers of coherently coupled bosons in optical lattices

Chiara Menotti, Fabrizio Minganti, and Alessio Recati

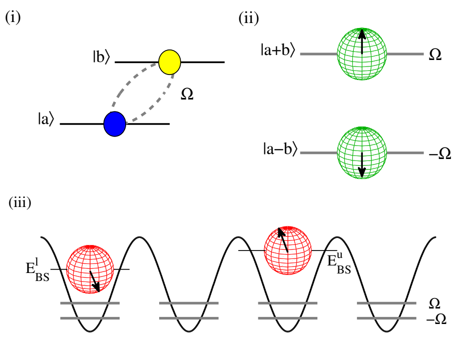


Figure 35: Schematic representation of two coherently coupled interacting bosons in an optical lattice for $U_a = U_b = U$: (i) two internal levels $|a\rangle$ and $|b\rangle$ coherently coupled by a resonant coupling Ω; (ii) single-particle eigenstates of Ω at energies $\pm\Omega$ provided by the internal state superpositions $|a \pm b\rangle$; (iii) repulsive lower and upper two-body bound states respectively at energies $E^{l,u}_{BS}$.

In this paper, we have studied the two-body bound and scattering states of two particles in a one dimensional optical lattice in the presence of a coherent coupling Ω between two internal atomic levels $|a\rangle$ and $|b\rangle$ [Fig. 1 (a)]. The coherent coupling tends to force the atoms in the $|a \pm b\rangle$ superposition [Fig. 1 (b)], which for different intra- and inter-species interactions are not eigenstates of the interactions. The periodic potential leads to a non separability of the centre of mass and relative coordinates. Hence, due to the interplay of optical lattice, interactions and coherent coupling, the internal structure of the bound states depends on their center of mass momentum. As schematically indicated in [Fig. 1 (c)] the internal state can be viewed as a pseudo-spin oriented by an effective magnetic field. Hence, this phenomenon corresponds to an effective momentum-dependent magnetic field for the dimer pseudo-spin, which could be observed in a chirping of the precession frequency during Bloch oscillations.

We have derived an effective Hamiltonian, which has allowed us to give a direct interpretation of the coherently coupled system in terms of effectively coherently coupled bound states, and tested its validity against exact solutions based on the Lippmann-Schwinger equation and exact diagonalization. The general character of our results has been stressed by introducing a similar model for two indistinguishable particles where only one needs to be dressed by a Rabi coupling. As a general feature the two-body eigenstates can present simultaneously attractive and repulsive bound-state nature or even bound and scattering properties.

On the experimental side, many of the ingredients necessary to study the physics of spin-momentum coupling are already available. Many experiments have been already realized for coherently coupled Bose gases. The most difficult issue is the possibility of realizing large enough differences between intra- and inter-species interactions. We have proposed some possible solutions, like using two different atomic species, using spin-selective microwave pulses or working in spin-dependent lattices.

Phys. Rev. B 92, 180406(R) (2015)

Out-of-equilibrium states and quasi-many-body localization in polar lattice gases

L. Barbiero, C. Menotti, A. Recati, and L. Santos

The absence of dissipation in polar lattice gases leads to rich out-of-equilibrium dynamics characterized by the formation of inter-site bound clusters and blockade repulsion even for attractive DDI. The combination of these effects with the control possibilities of ultracold gases may allow the realization of effective repulsive 1D gases with attractive DDI, the creation of dynamically bound crystals, and most interestingly, quasi-MBL in the absence of disorder. The latter opens interesting perspectives for observing a dynamical phase transition in polar lattice gases from a delocalized to a quasi-MBL regime without disorder. This idea is related to the localization of ^{3}He in ^{4}He crystals first discussed in the '80, and could be now tested in a better controlled environment with polar lattice gases.

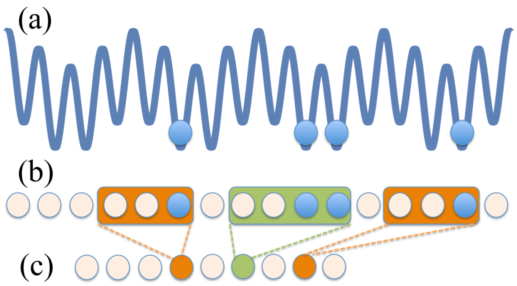


Figure 36: (a) A dimerized lattice can be used to create a gas of singlons and dynamically bound NN dimers; (b) due to the BR a NN dimer (singlon) forms a block $D = 0011$ ($S = 001$); (c) effective lattice formed by the blocks D, S, and additional empty sites. This effective lattice is employed to show the realization of quasi-MBL.

Resembling recent experiments, in this work we have proposed to use dimerized lattices [Fig. 1(a)] to initialize an effective lattice whose sites are occupied either by effective doblons D, effective singlons S, or empty [Fig. 1(b,c)]. Effective D and S account for the blockade repulsion between particles initially at a distance $r_{in} > r_c$, where r_c is defined by the maximum inter-particle distance of deeply bound pairs [$r_c = 2$ in Fig.1 (b)]. Blockade repulsion suppresses doblon-singlon swapping processes and provides the crucial difference with respect to the standard Bose-Hubbard model, where singlons may resonantly move through on-site pairs via single-particle hopping. For large enough dipolar interaction, a swap rate small compared to single particle hopping may lead to localization. Exact diagonalization calculations with periodic boundary conditions of the evolution of the many-body state show the appearance of quasi-localization in the many-body space.

Furthermore we have demonstrated that thanks to the blockade repulsion, one can create an effectively repulsive 1D gas with attractive dipolar interaction. Through t-DMRG simulations, we have characterized the dynamics of the gas and shown that it reaches quasi-equilibrium.

Phys. Rev. Lett. 111, 220405 (2013)

The impurity problem in a bilayer system of dipoles

N. Matveeva and S. Giorgini

The polaron problem, in the broad sense of an impurity coupled to a bath of elementary excitations, is of general and fundamental interest in condensed matter physics. The original formulation of the polaron model addressed the motion of electrons coupled to the lattice vibrations of a crystal. In this context phonon excitations are found to dress the impurity, thereby increasing its effective mass. For strong interactions, self-trapping of polarons was predicted as a result of the dragged phonon cloud which creates a confining potential where the impurity is finally trapped. Since the variational calculation by Landau and Pekar, the polaron problem in the strong-coupling regime has been investigated using many different theoretical tools, including exact quantum Monte Carlo (QMC) methods.

We propose a realization of the polaron model by using an impurity coupled via dipolar interactions to a two-dimensional (2D) system of fermions in a bilayer geometry. By tuning the in-plane dipolar interaction strength the state of the fermions can be turned from the Fermi liquid (FL) to the Wigner crystal (WC) phase, thereby changing the nature of the elementary excitations of the bath from fermionic to bosonic. QMC simulations are performed to calculate the binding energy and the effective mass of the impurity as a function of the distance between layers assuming that the interlayer potential barrier is high enough to suppress tunneling. In the WC phase the impurity exhibits a crossover from a free-moving to a tightly-bound regime similar to the self-trapping transition. However, in contrast to the paradigmatic case of electrons in a crystal, the coupling to phonons is found to decrease the effective mass of the impurity with respect to the band mass determined by the static periodic potential and to favor hopping processes of the impurity between lattice sites.

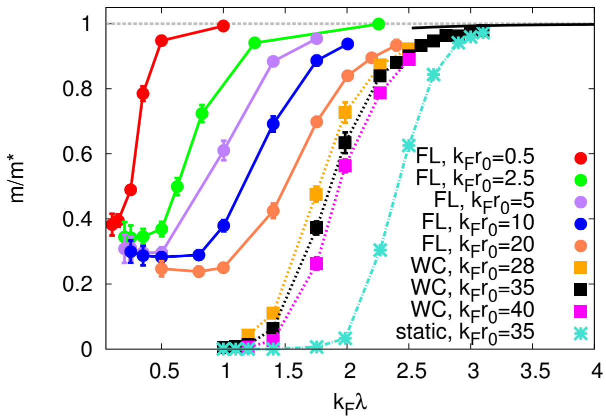


Figure 37: Inverse effective mass of the impurity as a function of the distance between layers for different values of the in-plane interaction strength $k_F r_0$. Circles refer to the FL and squares to the WC phase. The stars correspond to m/m^* when only the static periodic potential $U(\mathbf{r}_a)$ is considered and phonons are frozen.

Phys. Rev. B 88, 214505 (2013)

Quantum Monte Carlo study of the dynamic structure factor in the gas and crystal phase of hard-sphere bosons

R. Rota, F. Tramonto, D. E. Galli and S. Giorgini

The dynamic structure factor of a many-body system contains a wealth of information about the nature and energy spectrum of the excitations coupled to density fluctuations. In the context of quantum degenerate Bose systems, the dynamic structure factor has provided an invaluable tool for the experimental and theoretical investigation of superfluid ^{4}He as well as of ultracold atomic gases. A landmark achievement of these studies has been the precise measurement of the phonon-maxon-roton spectrum in superfluid ^{4}He and, in more recent years, important experimental contributions came from the observation of the Bogoliubov dispersion in a dilute condensate of ^{87}Rb atoms.

In the most interesting regime of strong interactions, quantitative theoretical investigations of the dynamic structure factor can only rely on numerical simulations. In this work we investigate the dynamic structure factor of a system of Bose particles at zero temperature using quantum Monte Carlo methods. Interactions are modeled using a hard-sphere potential of size a and simulations are performed for values of the gas parameter na^3 ranging from the dilute regime up to densities n where the thermodynamically stable phase is a solid. With increasing density we observe a crossover of the dispersion of elementary excitations from a Bogoliubov-like spectrum to a phonon–maxon–roton curve and the emergence of a broad multiphonon contribution accompanying the single-quasiparticle peak.

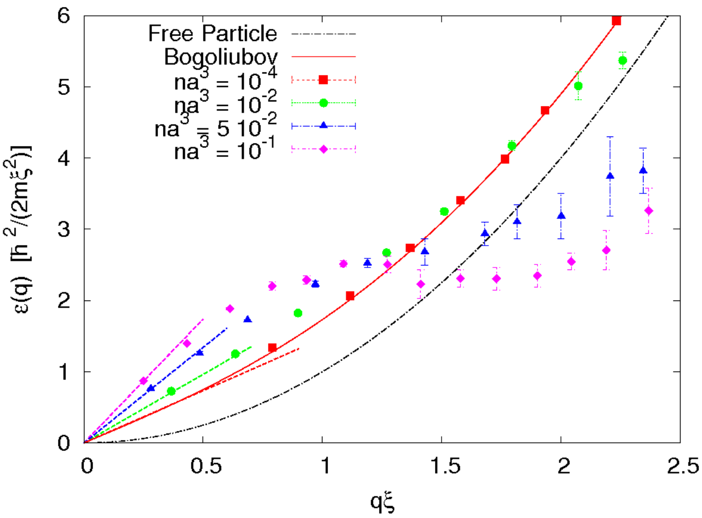


Figure 38: Dispersion of the central position of the highest peak in $S(\mathbf{q},\omega)$ for different values of the gas parameter. The error–bars represent the 1/2–height widths of the peaks. The solid line is the Bogoliubov prediction and the dot–dashed line corresponds to the free-particle dispersion $(q\xi)^2$. The dashed lines show the phonon dispersion $c\hbar q$, where the speed of sound c is calculated from the equation of state.

Phys. Rev. Lett. 110, 115303 (2013)

Quantum Monte Carlo study of a resonant Bose-Fermi mixture

G. Bertaina, E. Fratini, S. Giorgini and P. Pieri

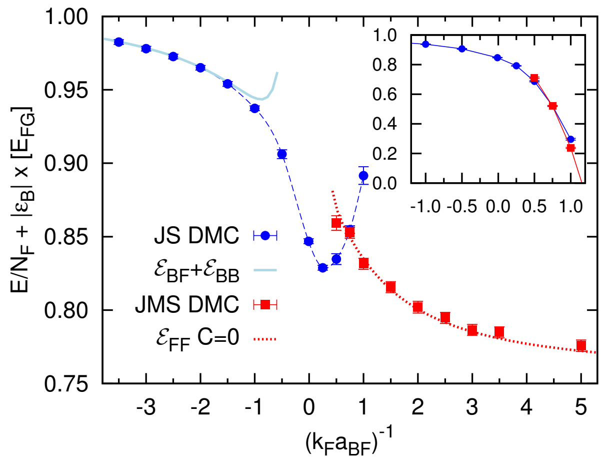


Figure 39: Energy of a Bose-Fermi mixture with the concentration $x = 0.175$ of bosons and bosonic coupling $\zeta = 1$, with the contribution of the bare binding energy of the molecules subtracted for $a_{BF} > 0$. Inset: Energy without subtracting the bare binding energy.

Let us consider a system of bosons and spinless fermions with a tunable short-range boson-fermion (BF) attraction. For weak attraction, at sufficiently low temperature the bosons condense, while the fermions fill a Fermi sphere, and the BF interaction can be treated with perturbative methods. For sufficiently strong attraction, bosons and fermions pair into molecules. In particular, for a fermion density n_F larger than the boson density n_B one expects all the bosons to pair with fermions. The boson condensate is then absent in such a regime and the system should be described as a weakly interacting Fermi-Fermi mixture, one component consisting of molecules, with density $n_M = n_B$, and the other component of unpaired fermions, with density $n_U = n_F - n_B$. However, it is not clear how the system evolves at zero temperature between the two above physical regimes?

In this work we investigate a resonant Bose-Fermi mixture at zero temperature using the fixed-node Diffusion Monte Carlo method. We explore the system from weak to strong boson-fermion interaction, for different concentrations of the bosons relative to the fermion component. We focus on the case where the boson density n_B is smaller than the fermion density n_F, for which a first-order quantum phase transition is found from a state with condensed bosons immersed in a Fermi sea, to a Fermi-Fermi mixture of composite fermions and unpaired fermions. We obtain the equation of state and the phase diagram and we find that the region of phase separation shrinks to zero for vanishing n_B.

Phys. Rev. A 92, 033612 (2015)

Impurity in a Bose-Einstein condensate: study of the attractive and repulsive branch using quantum Monte-Carlo methods

L. A. Peña Ardila and S. Giorgini

The polaron problem is a paradigmatic topic in condensed matter physics: it concerns the effect of the quantum fluctuations of the surrounding medium on the properties of an impurity immersed in a bath. In this paper we investigated the properties of an impurity immersed in a dilute Bose gas at zero temperature using quantum Monte-Carlo methods. The interactions between bosons are modeled by a hard sphere potential with scattering length a, whereas the interactions between the impurity and the bosons are modeled by a short-range, square-well potential where both the sign and the strength of the scattering length b can be varied by adjusting the well depth. We characterized the attractive and the repulsive polaron branch by calculating the binding energy and the effective mass of the impurity. Furthermore, we investigated structural properties of the bath, such as the impurity-boson contact parameter and the change of the density profile around the impurity. At the unitary limit of the impurity-boson interaction, we found that the effective mass of the impurity remains smaller than twice its bare mass, while the binding energy scales with $\hbar^2 n^{2/3}/m$, where n is the density of the bath and m is the common mass of the impurity and the bosons in the bath. We also discussed the implications for the phase diagram of binary Bose-Bose mixtures at small concentrations.

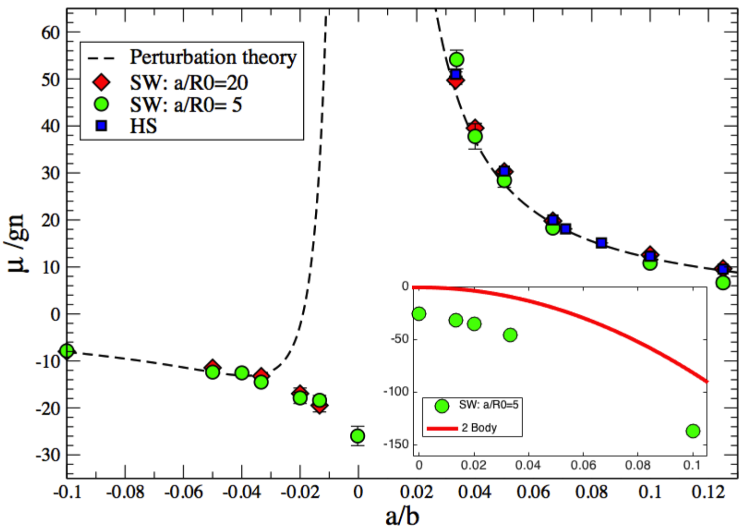


Figure 40: Polaron energy μ as a function of the ratio a/b of scattering lengths for both the repulsive and the attractive branch. The gas parameter of the bosonic bath is $na^3 = 10^{-5}$. The symbols are the DMC results obtained with the following impurity-boson interaction potential: hard sphere (blue squares); square well with $a/R_0 = 5$ (green circles); square well with $a/R_0 = 20$ (red diamonds). The dashed line is the result of perturbation theory for the two branches. Inset: Polaron energy along the attractive branch on the positive side of the resonance value for the impurity-boson scattering length. The solid line corresponds to the binding energy ϵ_b in the square well potential with $a/R_0 = 5$.

Rev. Mod. Phys. 85, 299 (2013)

Quantum Fluids of Light

Iacopo Carusotto and Cristiano Ciuti

In recent decades, the study of the physics of quantum fluids has attracted tremendous interest in a variety of different many-particle systems, from liquid helium, to electrons in solid-state materials, to trapped gases of ultracold atoms, to quark-gluon plasma in colliders, to nuclear matter. Historically, most of the theoretical and experimental activities in the field of many-body physics addressed systems of material particles such as atoms, electrons, nucleons, or quarks. However, a growing community of researchers has started wondering whether in suitable circumstances light can be considered as a fluid composed of a large number of corpuscular photons with sizable photon-photon interactions, the so-called *quantum fluid of light*. Even if this point of view is perfectly legitimate within the wave-particle duality in quantum mechanics, it is somehow at odds with our intuitive picture of light: The historical development of our understandings of matter and light have in fact followed very different paths.

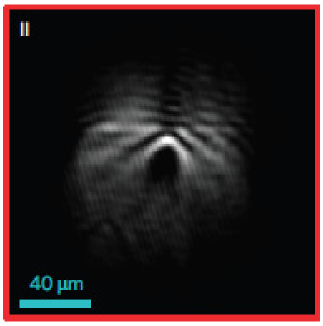


Figure 41: Experimental images of a mach-Cherenkov cone in a fast moving fluid of light hitting a point defect.

This review article was written together with our historical collaborator Cristiano Ciuti and has quickly become one of the most authoritative references in its field. It summarizes recent theoretical and experimental advances in the fundamental understanding and active control of quantum fluids of light in nonlinear optical systems. In the presence of effective photon-photon interactions induced by the optical nonlinearity of the medium, a many-photon system can behave collectively as a quantum fluid with a number of novel features stemming from its intrinsically nonequilibrium nature. A rich variety of recently observed photon hydrodynamical effects is presented, from the superfluid flow around a defect at low speeds, to the appearance of a Mach-Cherenkov cone in a supersonic flow (see figure), to the hydrodynamic formation of topological excitations such as quantized vortices and dark solitons.

While the review is mostly focused on a specific class of semiconductor systems that have been extensively studied in recent years (planar semiconductor microcavities in the strong light-matter coupling regime having cavity polaritons as elementary excitations), the very concept of quantum fluids of light applies to a broad spectrum of systems, ranging from bulk nonlinear crystals, to atomic clouds embedded in optical fibers and cavities, to photonic crystal cavities, to superconducting quantum circuits based on Josephson junctions. The conclusive part of the article is devoted to a review of the future perspectives in the direction of strongly correlated photon gases and of artificial gauge fields for photons. In particular, several mechanisms to obtain efficient photon blockade are presented, together with their application to the generation of novel quantum phases.

Phys. Rev. Lett. 112, 116402 (2014)

Direct observation of Dirac cones and a flatband in a honeycomb lattice for polaritons

T. Jacqmin, I. Carusotto, I. Sagnes, M. Abbarchi, D. D. Solnyshkov, G. Malpuech, E. Galopin, A. Lemaître, J. Bloch, and A. Amo

Engineering Hamiltonians in controlled systems has proven to be a useful tool to simulate and unveil complex condensed matter phenomena otherwise experimentally inaccessible. Indeed, condensed-matter systems usually lack control and observables, whereas model systems such as ultracold atoms, arrays of photonic waveguides, or polariton gases enable the control of the density, the temperature, and, in the case of lattice systems, the topology of the band structure.

In this paper, we report on a joint experimental-theoretical study of polaritons in a honeycomb geometry made of hundreds of coupled micropillars etched in a planar semiconductor microcavity. By monitoring the photoluminescence at low excitation density, we directly image the energy dispersion of the structure. In particular, we evidence six Dirac cones at the corners of the first Brillouin zone (Bz), around which the energy dispersion is linear. When increasing the excitation intensity, we observe polariton condensation occurring at the top of the Π^* band. Additionally, we observe a non-dispersive higher-energy band arising from the coupling between higher-energy modes of the pillars, in which polaritons have an infinite effective mass.

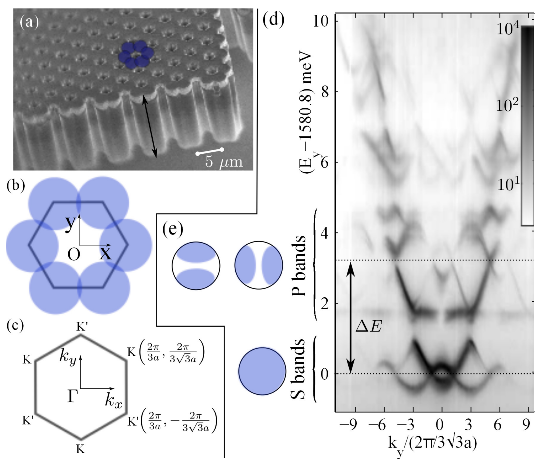


Figure 42: (a) Scanning electron microscope image of the microstructure. (d) Measured momentum- and energy-resolved photoluminescence spectrum under nonresonant low-power excitation, showing the Dirac points in the S bands and a flat P band.

Capitalizing over the theoretical and experimental know-how of the two groups, the collaboration between the Trento-BEC and the LPN groups is presently attacking a number of effects in the honeycomb lattice, like Klein tunneling at a potential step, the geometrical Berry curvature of the bands and the topological physics in the presence of synthetic gauge fields. Furthermore, the observation of a bright flatband suggests the possibility of investigating the interplay between frustration, dispersion, interactions in such flatbands. The theoretical investigations are carried in Trento by Tomoki Ozawa and Hannah Price under the supervision of Iacopo Carusotto. This work on honeycomb geometries naturally connects to the study of coupled pendulums lattices that are the subject of Grazia Salerno's PhD thesis.

Phys. Rev. Lett. 112, 133902 (2014)

Anomalous and Quantum Hall effects in lossy photonic lattices

T. Ozawa and I. Carusotto

The amazing developments in the experimental study of quantum fluids of light in the past decade are opening the way to use photonic systems to improve our understanding of phenomena originally known in the context of condensed matter physics. After pioneering studies of Bose-Einstein condensation and superfluidity effects to which the Trento-BEC group has given crucial contributions in the last decade, a great interest is presently devoted to topological effects, such as synthetic gauge fields for photons and edge states in photonic topological insulators. Inspired by related developments in solid state physics, these advances are opening exciting perspectives in the direction of quantum Hall effects with light as well as promising applications to photonic devices. Crucial concepts in the theoretical description of quantum mechanical particles in periodic lattices under a strong gauge field are the Berry curvature of a band and its integral over the Brillouin zone, the Chern number. This latter is a topological invariant of a band, and, in two-dimensional solid state systems, it is related to the quantized Hall conductance and to the number of chiral edge states.

In this paper, we propose a scheme to observe optical analogues of the anomalous and the (integer) quantum Hall effects in coupled cavity arrays, possibly with complex hopping amplitudes. This work takes explicit advantage of the driven-dissipative nature of the system to relate the Berry curvature and the Chern number to observable quantities. Our ideas are first illustrated on the simplest case of the square-lattice photonic Hofstadter model, and then we generalize the proposal to photonic honeycomb lattices (see page on Jacqmin et al. PRL 2014), where a nonzero Berry curvature appears in the vicinity of the (gapped) Dirac points when a lattice asymmetry is introduced.

The extension of this work to more complex external potentials than a uniform force is unveiling intriguing features of the duality between magnetism and the Berry curvature in momentum space. This research line is pushed forward by T. Ozawa and H. Price and is potentially applicable to both photonic and atomic gases.

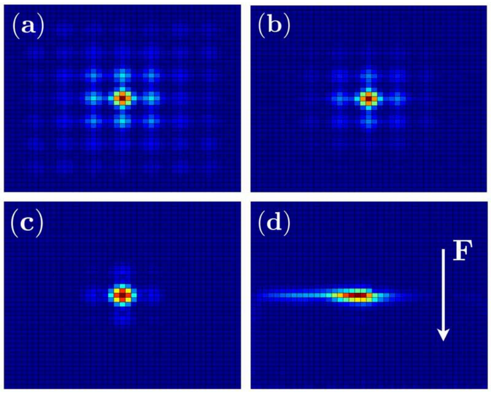


Figure 43: Photon amplitude distribution on a photonic square lattice with a (synthetic) magnetic flux per plaquette $\alpha = 1/5$. The central sites are pumped. The force is zero for (a-c), and in the downward direction for (d). In (a,b,d), the pump frequency is tuned within the lowest energy band; in (c), it is tuned within a bandgap. The Hall effect is visible in (d) as an overall leftward transverse shift of the light intensity distribution.

Phys. Rev. A 89, 053807 (2014)

Spontaneous quantum emission from analog white holes in a nonlinear optical medium

S.Finazzi and I.Carusotto

The most celebrated example of spontaneous particle creation from vacuum fluctuations was predicted by Hawking in the context of quantum field theory in curved spacetime and consists of the emission of a thermal radiation from the horizon of black holes. In the last decades, the extreme difficulty of detecting this emission from astrophysical black holes has stimulated the investigation of analogous phenomena in condensed-matter or optical systems. The first claim of observation of spontaneous analog Hawking radiation in a laboratory was indeed made by a group in Como group in 2010 using a nonlinear optical setup, see the sketch in the figure. As the interpretation of the experimental results as Hawking radiation is still considered as controversial by several authors, the purpose of this specific article was to use quantum optical techniques to build an ab initio theoretical model and compute the spectrum of the spontaneously emitted radiation to be compared with experiments.

The main result is the recognition of the fundamental role played by the material dispersion in determining the spectral properties of spontaneous vacuum emission from analog white holes in nonlinear optical systems. While a thermal-like emission is found in the comoving frame in nonpolar dielectrics like diamond, other materials, like the fused silica used in the experiments, show a strongly distorted emission spectrum, as the white-hole horizon is only active within a finite frequency window. As a result, the thermal character of the comoving frame emission is lost. Doppler transformation to the laboratory frame then leads to a sizable shift of the emission peak from the expected wavelength.

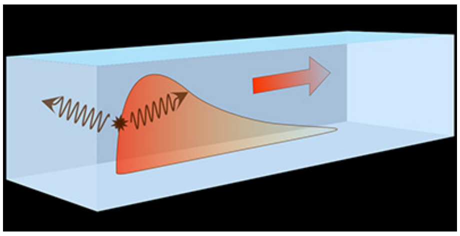


Figure 44: Sketch of the experimental configuration considered in the Como experiment: a strong laser pulse was sent through a nonlinear medium and created a moving modulation of the refractive index. Seen from the comoving reference frame, the leading (trailing) edge of the pulse appears then as the analog of a black (white) hole horizon.

As an illustrative example, we have performed a critical comparison with experimental data. While the theoretical spectrum of the spontaneous emission is in good qualitative agreement with the measured one, the strong sensitivity of the spectral features on experimental parameters such as the pulse speed makes a quantitative comparison very difficult. In particular, it is hard to completely rule out competing effects with similar emission spectra and possibly stronger intensities such as negative resonant radiation. An incontrovertible proof of the spontaneous nature of the emission could be obtained by looking at the nonclassical correlations among the emitted phonons.

Phys. Rev. A 90, 033607 (2014)

Entangled phonons in atomic Bose-Einstein condensates

Stefano Finazzi and Iacopo Carusotto

Pairs of entangled photons are a crucial element of many quantum optical experiments, from Hong-Ou-Mandel two-photon interference, to fundamental tests of Bell inequalities, to linear optical schemes for quantum information processing. Following the dramatic advances in cooling and manipulating atomic samples, many groups have recently demonstrated entanglement effects using atomic matter waves. A most exciting challenge is now to extend quantum optical concepts from single-particle excitations such as photons or atoms to the collective hydrodynamic degrees of freedom of a macroscopic fluid. The experimental investigation of quantum hydrodynamical entangled states is in fact a fundamental step in the study of exquisite quantum effects in macroscopic mechanical systems.

Among the first proposals in this *quantum hydrodynamics direction*, pioneering work by Unruh in 1981 anticipated that quantum hydrodynamical fluctuations in a moving fluid are converted at a black-hole sonic horizon into pairs of propagating phonons via a mechanism analogous to the Hawking effect of gravitational physics. Since then, this analogy between phonons in fluids and quantum fields on curved space-times has experienced impressive developments, in particular using flowing atomic BECs.

In this paper we discuss how entanglement between phonon degrees of freedom can be exploited as a probe to study the physics of atomic Bose-Einstein condensates and we illustrate a viable experimental method to study the quantum coherence of the phonons emitted by analog dynamical Casimir and Hawking radiation processes. Numerical simulations show that the temperatures needed to observe entanglement are within the reach of state-of-the-art experiments and that a deep insight in the emission processes can be extracted from the rich structure of the entanglement patterns in real and momentum spaces (see figure).

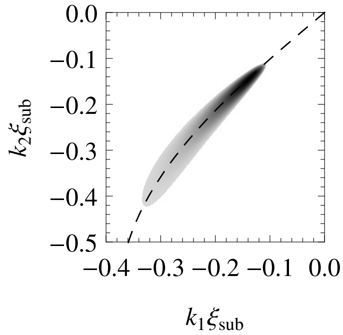


Figure 45: Momentum-space entanglement diagram of Hawking phonons.

In particular, such an experiment would provide an unambiguous proof of the quantum origin of the analog dynamical Casimir and Hawking radiations from zero-point fluctuations. Furthermore, as parametric downconversion and homodyne detection are nowadays routinely used to generate and detect entangled photons in photonics, we anticipate that spontaneous phonon-pair generation processes and our proposed entanglement detection scheme will become standard tools to study entangled phonons in BECs.

First experimental reports in this direction has recently appeared by Jeff Steinhauer at Technion (Israel), including the detection of analog Hawking radiation and some evidence for phonon entanglement.

EPL 106, 24002 (2014)

Dynamical decoupling and dynamical isolation in temporally modulated coupled pendulums

G. Salerno and I. Carusotto

Dynamical localization is a surprising consequence of quantum mechanics applied to particles subject to a strong time-dependent external force. This effect was first observed as renormalization of the magnetic response of an atom illuminated by a strong rf field. In a solid-state context, dynamical localization was originally proposed as a dramatic suppression of the d.c. conductivity of a metal in a strong a.c. field. While the experimental study of these effects in solids is made difficult by the unavoidable material imperfections, the robust coherence and the clean periodic potential experienced by atomic matter waves has allowed for a clear observation of this physics. Very exciting further developments of these ideas aim at using more complex modulation schemes to generate non-trivial hopping phases between the lattice sites and then synthetic gauge fields for neutral atoms. Correspondingly to these advances in atomic physics, the same ideas are being explored in photonics to observe dynamical localization of light in coupled optical waveguides and, very recently, to generate synthetic gauge field for photons.

In this letter, we report a theoretical study of dynamical localization phenomena in a classical mechanics context. Specifically, we consider a system of two coupled pendulums, whose oscillation frequencies are independently and periodically varied in time. In particular, we predict a dynamical decoupling effect, where exchange of energy between the pendulums is suppressed. When the pendulums are driven by an external force, we anticipate a novel dynamic isolation effect, where the temporal modulation effectively decouples the system from the external force.

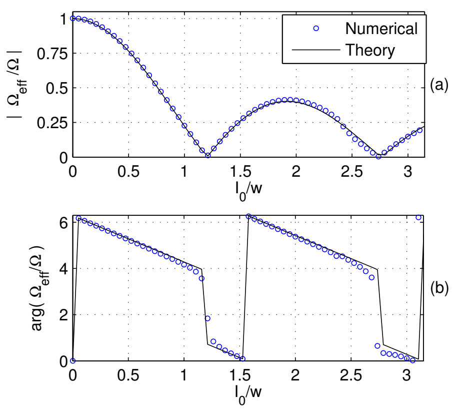


Figure 46: (a) Effective coupling frequency $|\Omega_{\text{eff}}|/\Omega$ and (b) its phase $\text{Arg}(\Omega_{\text{eff}})$. Dots are the results of the numerical calculations, while the solid lines are analytical predictions.

From the point of view of fundamental physics, the non-trivial coupling phase that appears between the pendulums is analogous to the Peierls phase of Bose-Hubbard models of quantum condensed-matter physics. In analogy to orbital magnetism and topological insulation, new intriguing phenomena are expected to appear in multi-dimensional lattices of many temporally modulated pendulums. Further exciting developments in nonlinear physics are expected to arise as a result of the intrinsic anharmonicity of pendulums. As our results are valid for coupled oscillators of any physical nature with a time-dependent frequency (e.g. RLC electric circuits), this work opens an interesting new route to experimentally explore topological physics.

Proc. R. Soc. A 470, 20140320 (2014)

Superfluid light in bulk nonlinear media

I. Carusotto

Experimental studies of the so-called fluids of light are opening new perspectives to the field of many-body physics: as it is summarized in our recent review on Rev. Mod. Phys., they allow unprecedented control and flexibility in the generation, manipulation and control of Bose fluids. So far, a number of striking experimental observation have been performed using a semiconductor planar microcavity architecture, including the demonstration of a superfluid flow and of the hydrodynamic nucleation of solitons and quantized vortices.

An alternative and technologically easier platform for studying many body physics in fluids of light consists of a bulk nonlinear medium showing an intensity-dependent refractive index: under the paraxial approximation, the propagation of monochromatic light can be described in terms of a Gross-Pitaevskii equation for the order parameter, in our case the electric field amplitude of the monochromatic beam. Experimental studies of this system have started in early days of laser physics and have experienced remarkable success in the last years with observations of soliton and vortex physics, dynamical localization, honeycomb lattices, and Floquet-like synthetic gauge fields. On the other hand, only a limited attention has been devoted to hydrodynamic and superfluid features.

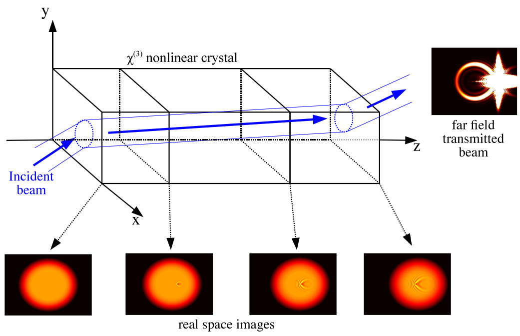


Figure 47: Sketch of the experimental configuration under investigation in the present work.

This article aims at laying the foundations of the study of many-body physics using light propagating in bulk nonlinear crystals: as a first example of this program, we report a detailed investigation of superfluid hydrodynamics concepts in the novel geometry. After reviewing the derivation of the paraxial wave equation in a Kerr nonlinear medium, we point out how, in contrast to the microcavity architecture used in earlier experiments, it directly leads to a fully conservative Gross-Pitaevskii equation. Schemes where a second laser beam is used to generate and observe collective excitations in the fluid of light are proposed. The core of the work deals with the interaction of a flowing fluid of light with a localized defect: signatures of superfluid behavior are highlighted, as well as the main mechanisms for breaking superfluidity such as Bogoliubov-Cerenkov emission of sound waves and generation of topological excitations such as vortices and solitons. As a follow-up, the mechanical drag force exerted by the fluid of light on the defect was investigated in Phys. Rev. A 91, 053809 (2015). Some perspectives in view of using superfluids of light in bulk nonlinear crystals for experimental studies of analog models of gravity are finally highlighted.

Phys. Rev. X 5, 041028 (2015)

Nonequilibrium Phase Transition in a Two-Dimensional Driven Open Quantum System

G. Dagvadorj, J. M. Fellows, S. Matyjaśkiewicz, F. M. Marchetti, I. Carusotto, and M. H. Szymańska

The Hohenberg-Mermin-Wagner theorem prohibits spontaneous symmetry breaking of continuous symmetries and associated off-diagonal long-range order for systems with short-range interactions at thermal equilibrium in two (or fewer) dimensions. The Berezinskii-Kosterlitz-Thouless (BKT) mechanism provides a loophole to this theorem: 2D systems can still exhibit a phase transition between a quasi-long-range ordered phase below a critical temperature, where correlations decay algebraically and topological defects are bound together, and a high-T disordered phase, where defects unbind and proliferate, causing exponential decay of correlations.

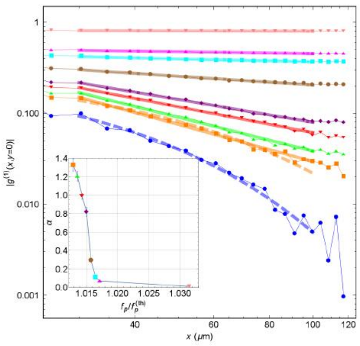


Figure 48: Algebraic and exponential decay of the first-order correlation function across the BKT transition.

The BKT transition is relevant for a wide class of systems. Perhaps the most celebrated examples are those in the context of 2D superfluids, as in He and ultracold atoms: Here, despite the absence of true long-range order clear evidence of superfluid behavior has been observed in the ordered phase. These considerations are applicable to systems in thermal equilibrium. However, in recent years a new class of strongly driven and highly dissipative 2D systems have emerged using polaritons in semiconductor microcavities. In spite of their driven-dissipative nature, a transition from a normal to a superfluid phase has been observed but it is not obvious whether it is of the BKT type, i.e., due to vortex- antivortex pairs unbinding.

In this work, we consider the case of microcavity polaritons coherently driven into the optical parametric oscillator (OPO) regime for which researchers of the BEC Center have developed along the years an efficient Wigner Monte Carlo numerical description able to account for topological defects and large fluctuations. Analyzing the nonequilibrium steady state, we show that for realistic system sizes the transition from the normal to the superfluid phase is of the BKT type, i.e., governed by binding and dissociation of vortex-antivortex pairs as a function of particle density, and bares a lot of similarities to the equilibrium counterpart. However, as recent experiments suggested, we find that larger exponents of the power-law decay of the first- order correlation function are possible before vortices unbind and destroy the quasi-long-range order leading to exponential decay (see figure). Comparison with experiments and with complementary analytical works based on renormalization group techniques are under way.

Phys. Rev. Lett 114, 036402 (2015)

Acoustic Black Hole in a Stationary Hydrodynamic Flow of Microcavity Polaritons,

H.S.Nguyen, D. Gerace, I. Carusotto, D. Sanvitto, E. Galopin, A. Lemaitre, I. Sagnes, J. Bloch, and A. Amo

Back in 1974, Hawking predicted that the zero-point fluctuations of the quantum vacuum may be converted into correlated pairs of real particles at the event horizon of an astrophysical black hole. Unfortunately, a direct observation of this Hawking radiation in an astrophysical context is made very difficult by the extremely low value of its temperature T_H.

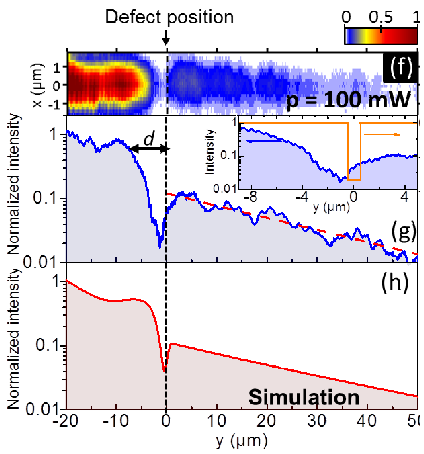


Figure 49: Experimental (upper and middle) and theoretical (lower) profile of the density of a quantum fluid of light displaying an acoustic horizon.

To overcome this severe limitation, a pioneering work by Unruh in 1981 introduced the idea of condensed-matter analogs of gravitational systems, and anticipated the occurrence of an analog Hawking emission of sound waves whenever a fluid shows an acoustic horizon separating regions of sub- and supersonic flow. Since this early prediction, intense theoretical activity was devoted to the study of different condensed-matter and optical platforms where such analog black holes could be created. In the last decade, quantum fluids of light have emerged as a promising system to study quantum hydrodynamics effects, and strategies to study acoustic Hawking emission from analog black holes in photon or polariton fluids have been recently proposed.

This Letter reports a joint experimental and theoretical study of an acoustic black holes in the hydrodynamic flow of microcavity polaritons. Experiments were carried out at LPN, while the theory was mostly done in Trento in collaboration with the Pavia colleague. A stationary one-dimensional (1D) flowing polariton fluid is generated by resonant cw excitation of a microcavity device laterally patterned into a photonic wire showing a localized defect potential. At high excitation power the defect separates regions of high-density subsonic flow from low-density supersonic flow, setting up an acoustic horizon (see figure). Detailed in situ information on the flow is obtained from real- and momentum-space photoluminescence (PL) experiments, which show full quantitative agreement with theoretical predictions based on the generalized Gross-Pitaevskii equation. Finally, theoretical Wigner Monte Carlo calculations show that this configuration is amenable to the detection of a Hawking radiation signal in the spatially resolved correlation function of the intensity noise of photoluminescence, a quantity directly accessible by quantum optical techniques. Our results suggest promising perspectives as a quantum simulator for quantum field theories on a curved space-time.

Phys. Rev. Lett. 113, 190403 (2014)

Quantum Mechanics with a Momentum-Space Artificial Magnetic Field

Hannah M. Price, Tomoki Ozawa, and Iacopo Carusotto

The Hamiltonian of a charged particle in an e.m. field

$$\mathcal{H} = \frac{(\mathbf{p} - eA(\mathbf{r}))^2}{2M} + e\Phi(\mathbf{r})$$

is a familiar and fundamental result in quantum mechanics. The magnetic vector potential, $A(\mathbf{r})$, is a function of position which redefines the relationship between the canonical, $\mathbf{p}$, and physical, $\mathbf{p} - eA(\mathbf{r})$, momenta.

The momentum space counterpart

$$\mathcal{H} = E(\mathbf{p}) + W(\mathbf{r} + \mathcal{A}(\mathbf{p}))$$

of this magnetic Hamiltonian underlies many intriguing phenomena in solid state physics such as the anomalous and spin Hall effects as well as peculiar features of graphene and bulk Rashba semiconductors. In this formalism, $E(\mathbf{p})$ is the energy dispersion of the band under consideration, while $\mathcal{A}(\mathbf{p})$ is the geometrical Berry connection of the band. The Berry connection acts as a momentum space vector potential, redefining the relationship between the canonical, $\mathbf{r}$, and physical, $\mathbf{r} - \mathcal{A}(\mathbf{p})$, position operators appearing in the external potential term $W(\mathbf{r} - \mathcal{A}(\mathbf{p}))$. This replacement has important physical consequences that have been studied primarily, so far, at the semiclassical level. In particular, it was noticed that the curvature $\Omega(\mathbf{p}) = \nabla_{\mathbf{p}} \times \mathcal{A}(\mathbf{p})$ giving the Hall-like transverse shift of Bloch oscillations can be interpreted as a momentum space magnetic field.

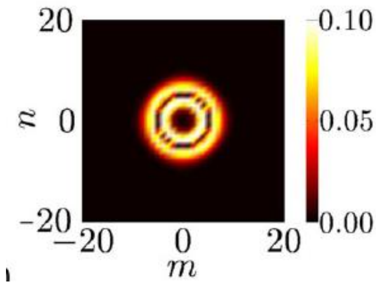


Figure 50: Real-space profile of a momentum-space toroidal Landau level.

In this Letter, we discuss how the momentum space magnetic Hamiltonian can be exploited as a fully quantum theory to understand the quantum mechanics of single particles in energy bands with nontrivial geometrical and topological properties, in the presence of additional external potentials. To illustrate this most clearly, we focus on the example of a two-dimensional system where the energy and the Berry curvature of the lowest band are nearly flat over the first BZ. In the presence of an external harmonic potential, the equispaced eigenstates are then the momentum space counterpart of Landau levels in a constant magnetic field. Remarkably, these eigenstates have novel features directly stemming from the global toroidal topology of the BZ. The recent experimental realizations of the Harper-Hofstadter model in ultracold gases, photonic systems, and solid-state superlattices suggest a prompt experimental implementation of our approach. Schemes to spectroscopically investigate this physics using state-of-the-art photonic devices were explored in the follow-up work by Berceanu et al., Phys. Rev. A. 93, 013827 (2016). From a general perspective, this opens up new avenues to experimentally study quantum mechanics and magnetism on topologically nontrivial manifolds such as a torus.

Phys. Rev. Lett. 115, 195303 (2015)

Four-Dimensional Quantum Hall Effect with Ultracold Atoms,

H.M.Price, O. Zilberberg, T. Ozawa, I. Carusotto, and N. Goldman

Fascinating artificial systems can now be engineered with atoms in optical lattices, where topological order, gauge structures, disorder, and interactions can all be tuned and probed in novel ways. One such important recent achievement has been the realization of artificial magnetic fields and topological Bloch bands using time-modulated 2D optical lattices.

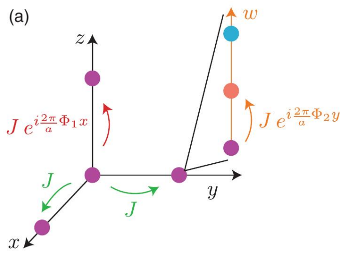


Figure 51: Sketch of the physical system under consideration.

Optical lattices can be tailored to realize lattice geometries of varying spatial dimensions $d_{\text{real}} = 1, 2, 3$. Moreover, increasing control over atomic internal states has extended design flexibility as "motion" along an auxiliary (synthetic) dimension can be mimicked by laser-induced transitions between internal states. This effectively generates dynamics within synthetic geometries with $d = (d_{\text{real}} + 1)$ "spatial" dimensions, in addition to the usual time dimension. While first experiments have demonstrated 2D physics in a 1D optical lattice with a synthetic dimension, these developments naturally open up the possibility of emulating systems with higher dimensions $d > 3$. Importantly, artificial gauge potentials can naturally be introduced in atomic systems with synthetic dimensions in the form of Peierls phase factors (see the sketch in the figure).

In the fast-expanding field of topological phases of matter, the energy bands of a system are associated with topological indices that are robust to continuous deformations. Nontrivial indices are usually associated with interesting boundary phenomena, quantized responses, and exotic quasiparticles. In the 2D quantum Hall (QH) effect, the quantized Hall conductance is related to the sum of the first Chern numbers (1CNs) of the filled energy bands. In 4D, even more intriguing quantum Hall phases may exist, as energy bands possess an additional topological index, the second Chern number (2CN), leading to a nonlinear quantized response.

This Letter is the first outcome of a successful collaboration between our group and leading experts of topological physics, and describes a concrete proposal for realizing the 4D QH effect using ultracold gases in optical lattices. We present a semiclassical analysis predicting the general transport equations in 4D setups: this includes a nonlinear response, related to the 2CN, but also a linear response, associated with an exotic 2D QH effect for the current flowing across 2D planes within the 4D system. We then propose realistic protocols through which these responses could be measured experimentally. Our proposal sets the stage for the future experimental exploration of higher-dimensional topological phases. Realizing such 4D systems experimentally will be especially intriguing as they may harbor exotic collective excitations.

Phys. Rev. A 93, 043827 (2016)

Synthetic dimensions in integrated photonics: From optical isolation to four-dimensional quantum Hall physics

T. Ozawa, H. M. Price, N. Goldman, O. Zilberberg, I. Carusotto

The study of topological systems originated in the setting of electronic condensed matter. In these systems, the energy bands can be characterized by nontrivial topological invariants, which are robust under small perturbations. Importantly, these invariants can have many physical consequences such as quantized bulk responses and topologically protected edge physics. More recently, the introduction of topological concepts into photonics has opened up many exciting avenues of research. Much of this activity has been focused on the experimental observation of topologically protected edge states in a variety of systems. In all these works, spatially periodic structures act as lattices for light which, in combination with an engineered synthetic gauge field, lead to topologically nontrivial 2D photonic energy bands. Going beyond two dimensions, the first experimental works on 3D lattices have recently unveiled peculiar and intriguing topological features in their photonic band dispersion, such as Weyl points.

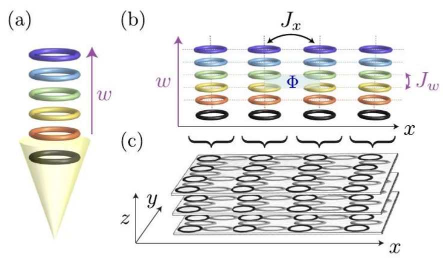


Figure 52: An illustration of the synthetic dimension scheme.

At the same time, exciting new perspectives have arisen in the cold-atom context from the combination of engineered gauge fields with a synthetic dimension, where internal atomic degrees of freedom are exploited as an additional lattice dimension. In the previous paper, we have capitalized over these advances to propose a method for the realization of 4D topological systems using atoms.

In this paper, we describe how this idea of a synthetic dimension can be extended and exploited in an integrated photonics architecture, leading to engineered gauge fields and nontrivial band topologies. Our proposal relies on a ring-resonator array device where the different modes of each resonator act as the synthetic dimension. Coupling between different resonator modes is produced through an external time-dependent modulation of the dielectric properties of each cavity at a frequency equal to (or a multiple of) the free-spectral range. By independently tuning the modulation phase of the resonators, spatially dependent gauge fields can be realized, leading to nontrivial band topologies (see figure).

Our scheme has important implications in different dimensionalities: (i) 1D chains of resonators coupled in this way behave as 2D topological systems with propagating edge states that may be exploited to provide on-chip optical isolation; and (ii) photonic topological lattice models can be constructed in dimensions higher than three dimensions. This may have dramatic applications in integrated photonic circuits with higher connectivity, where the mode index can be naturally associated with the different frequency channels of an optical signal.

Articles, preprints and highlights

Here we list all publications of the BEC Center since January 2013: 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.

Published articles

The role of geometry in the superfluid flow of nonlocal photon fluids,
D. Vocke, K. Wilson, F. Marino, I. Carusotto, E. M. Wright, T. Roger, B. P. Anderson, P. Öhberg, D. Faccio,
Phys. Rev. A **94**, 013849 (2016)

Numerical study of a recent black hole lasing experiment,
M. Tettamanti, S. L. Cacciatori, A. Parola, I. Carusotto,
EPL **114** 60011 (2016)

Momentum-dependent pseudo-spin dimers of coherently coupled bosons in optical lattices,
Chiara Menotti, Fabrizio Minganti, Alessio Recati,
Phys. Rev. A **93**, 033602 (2016)

Quantum Hall effect in momentum space,
Tomoki Ozawa, Hannah M. Price, and Iacopo Carusotto,
Phys. Rev. B **93**, 195201 (2016)

Measurement of Chern numbers through center-of-mass responses,
H. M. Price, O. Zilberberg, T. Ozawa, I. Carusotto, and N. Goldman,
Phys. Rev. B **93**, 245113 (2016)

Magnetic phase transition in coherently coupled Bose gases in optical lattices,
L. Barbiero, M. Abad, A. Recati,
Phys. Rev. A **93**, 033645 (2016)

Confinement and precession of vortex pairs in coherently coupled Bose-Einstein condensates,
Marek Tylutki, Lev P. Pitaevskii, Alessio Recati, Sandro Stringari,
Phys. Rev. A **93**, 043623 (2016)

Magnetic Solitons in a Binary Bose-Einstein Condensate,
Chunlei Qu, Lev P. Pitaevskii, Sandro Stringari,
Phys. Rev. Lett. **116**, 160402 (2016)

Dark-Bright Solitons in a Superfluid Bose-Fermi Mixture,
Marek Tylutki, Alessio Recati, Franco Dalfovo, Sandro Stringari,
New J. Phys. **18**, 053014 (2016)

Momentum-space Landau levels in arrays of coupled ring resonators,
Hannah M. Price, A.Berceanu, T.Ozawa, and I.Carusotto,
Proc. SPIE 9762, Adv. Photonics of Quantum Computing, Memory, and Communication IX, 97620W (2016)

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Prethermalization in a quenched one-dimensional quantum fluid of light: Intrinsic limits to the coherent propagation of a light beam in a nonlinear optical fiber,
P.-É. Larré, I. Carusotto,
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Floquet topological system based on frequency-modulated classical coupled harmonic oscillators,
Grazia Salerno, Tomoki Ozawa, Hannah M. Price, Iacopo Carusotto,
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Synthetic dimensions in integrated photonics: From optical isolation to 4D quantum Hall physics,
Tomoki Ozawa, Hannah M. Price, Nathan Goldman, Oded Zilberberg, Iacopo Carusotto,
Phys. Rev. A **93**, 043827 (2016)

Sub-Doppler cooling of sodium atoms in gray molasses,
G.Colzi, G.Durastante, E.Fava, S.Serafini, G.Lamporesi, G.Ferrari,
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Multiple Period States of the Superfluid Fermi Gas in an Optical Lattice,
Sukjin Yoon, Franco Dalfovo, Takashi Nakatsukasa, Gentaro Watanabe,
New J. Phys. **18**, 023011 (2016)

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A. Kumar, N. Anderson, W.D. Phillips, S. Eckel, G.K. Campbell, S. Stringari,
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Momentum-space Landau levels in driven-dissipative cavity arrays,
Andrei C. Berceanu, Hannah M. Price, Tomoki Ozawa, Iacopo Carusotto,
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Dynamics and interaction of vortex lines in an elongated Bose-Einstein condensate,
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Phys. Rev. A **90**, 033617 (2014)

Intermode reactive coupling induced by waveguide-resonator interaction,
M.Ghulinyan, F.R.Manzano, N.Prtljaga, M.Bernard, L.Pavesi, G.Pucker, and I.Carusotto,
Phys. Rev. A **90**, 053811 (2014)

Matter Waves in Atomic Artificial Graphene,
Nicola Bartolo and Mauro Antezza,
Europhys. Lett. **107**, 30006 (2014)

Approach for making visible and stable stripes in a spin-orbit-coupled Bose-Einstein superfluid,
Giovanni I. Martone, Yun Li, Sandro Stringari,
Phys. Rev. A **90**, 041604(R) (2014)

Quasi-periodic Wannier-Stark ladders from driven atomic Bloch oscillations,
M. Artoni, G.C. La Rocca and G. Ferrari,
Proc. Royal Soc. A **470**, 20140421 (2014)

Condensation of bosons with Rashba-Dresselhaus spin-orbit coupling,
Gordon Baym and Tomoki Ozawa,
J. Phys.: Conf. Ser. **529**, 012006 (2014)

Many-body Bose systems and the hard-sphere model: dynamic properties from the weak to the strong interaction regime,
R. Rota, F. Tramonto, D. E. Galli and S. Giorgini,
J. Phys.: Conf. Ser. **529** 012022 (2014)

On the momentum of solitons and vortex rings in a superfluid,
L.P. Pitaevskii,
J. Exper. Theor. Phys. **119**, 1097 (2014)

Single-particle vs. pair superfluidity in a bilayer system of dipolar bosons,
A. Macia, G. E. Astrakharchik, F. Mazzanti, S. Giorgini, and J.Boronat,
Phys. Rev. A **90**, 043623 (2014)

Fixed-node diffusion Monte Carlo study of the BCS-BEC crossover in a bilayer system of fermionic dipoles,
Natalia Matveeva and Stefano Giorgini,
Phys. Rev. A **90**, 053620 (2014)

Chandrasekhar-Clogston limit and critical polarization in a Fermi-Bose superfluid mixture,
T.Ozawa, A.Recati, M.Delehaye, F.Chevy, S.Stringari,
Phys. Rev. A **90**, 043608 (2014)

Quantum Langevin model for nonequilibrium condensation,
Alessio Chiocchetta, Iacopo Carusotto,
Phys. Rev. A **90**, 023633 (2014)

Fast thermalization and Helmholtz oscillations of an ultracold Bose gas,
D.J. Papoular, L.P. Pitaevskii, and S. Stringari,
Phys. Rev. Lett. **113**, 170601 (2014)

Spontaneous quantum emission from analog white holes in a nonlinear optical medium,
S.Finazzi and I.Carusotto,
Phys. Rev. A **89**, 053807 (2014)

Observation of Solitonic Vortices in Bose-Einstein Condensates,
S.Donadello, S.Serafini, M.Tylutki, L.P.Pitaevskii, F.Dalfovo, G.Lamporesi, G.Ferrari,
Phys. Rev. Lett. **113**, 065302 (2014)

Quantum Mechanics with a Momentum-Space Artificial Magnetic Field,
Hannah M. Price, Tomoki Ozawa and Iacopo Carusotto,
Phys. Rev. Lett. **113**, 190403 (2014)

Josephson oscillations and self-trapping of superfluid fermions in a double-well potential,
Peng Zou and Franco Dalfovo,
J. Low Temp. Phys. **177**, 240 (2014)

Equation of state and phase transition in spin-orbit-coupled Bose gases at finite temperature: A perturbation approach,
Zeng-Qiang Yu,
Phys. Rev. A **90**, 053608 (2014)

Superfluid light in bulk nonlinear media,
Iacopo Carusotto,
Proc. R. Soc. A **470**, 20140320 (2014)

Entangled phonons in atomic Bose-Einstein condensates,
Stefano Finazzi, Iacopo Carusotto,
Phys. Rev. A **90**, 033607 (2014)

Spontaneous Peierls dimerization and emergent bond order in one-dimensional dipolar gases,
M. Di Dio, L. Barbiero, A. Recati, M. Dalmonte,
Phys. Rev. A **90**, 063608 (2014)

Probing few-particle Laughlin states of photons via correlation measurements,
R. O. Umucalilar, M. Wouters, I. Carusotto,
Phys. Rev. A **89**, 023803 (2014)

Spectrum and entanglement of phonons in quantum fluids of light,
Xavier Busch, Iacopo Carusotto, Renaud Parentani,
Phys. Rev. A **89**, 043819 (2014)

Direct observation of Dirac cones and a flatband in a honeycomb lattice for polaritons,
T.Jacqmin, I.Carusotto, I.Sagnes, M.Abbarchi, D.Solnyshkov, G.Malpuech, E.Galopin, A.Lemaitre, J.Bloch, A.Amo,
Phys. Rev. Lett. **112**, 116402 (2014)

Dynamical decoupling and dynamical isolation in temporally modulated coupled pendulums,
Grazia Salerno, Iacopo Carusotto,
EPL **106**, 24002 (2014)

Discontinuities in the First and Second Sound Velocities at the Berezinskii-Kosterlitz-Thouless Transition,
Tomoki Ozawa, Sandro Stringari,
Phys. Rev. Lett. **112**, 025302 (2014)

Persistent currents in two-component condensates in a toroidal trap,
M. Abad, A. Sartori, S. Finazzi, and A. Recati,
Phys. Rev. A **89**, 053602 (2014)

Anomalous and Quantum Hall Effects in Lossy Photonic Lattices,
Tomoki Ozawa and Iacopo Carusotto,
Phys. Rev. Lett. **112**, 133902 (2014)

Many-body braiding phases in a rotating strongly correlated photon gas,
R. O. Umucalilar, I. Carusotto,
Phys. Lett. A **377**, 2074 (2013)

Snake instability of dark solitons in fermionic superfluids,
A. Cetoli, J. Brand, R.G. Scott, F. Dalfovo, L.P. Pitaevskii,
Phys. Rev. A **88**, 043639 (2013)

The impurity problem in a bilayer system of dipoles,
Natalia Matveeva and Stefano Giorgini,
Phys. Rev. Lett. **111**, 220405 (2013)

Spontaneous creation of Kibble-Zurek solitons in a Bose-Einstein condensate,
G.Lamporesi, S.Donadello, S.Serafini, F.Dalfovo, G.Ferrari,
Nature Physics **9**, 656 (2013)

Ground-state phase diagram and critical temperature of two-component Bose gases with Rashba spin-orbit coupling,
Zeng-Qiang Yu,
Phys. Rev. A **87**, 051606 (2013)

Second sound and the superfluid fraction in a Fermi gas with resonant interactions,
L.A. Sidorenkov, M.K.Tey, R.Grimm,Y.-H. Hou, L.Pitaevskii, S.Stringari,
Nature **498**, 78 (2013)

Dynamics of highly unbalanced Bose-Bose mixtures: miscible vs immiscible gases,
Alberto Sartori and Alessio Recati,
Eur. Phys. J. D **67**, 260 (2013)

Supercurrent and dynamical instability of spin-orbit coupled ultracold Bose gases,
Tomoki Ozawa, Lev P. Pitaevskii, and Sandro Stringari,
Phys. Rev. A **87**, 063610 (2013)

Superstripes and the excitation spectrum of a spin-orbit-coupled Bose-Einstein condensate,
Yun Li, G.I.Martone, L.P.Pitaevskii, and S.Stringari,
Phys. Rev. Lett. **110**, 235302 (2013)

A Metal-Insulator transition induced by Random Dipoles,
M. Larcher, C. Menotti, B. Tanatar and P. Vignolo,
Phys. Rev. A **88**, 013632 (2013)

Dipolar-Induced Resonance for Ultracold Bosons in a Quasi-1D Optical Lattices,
N. Bartolo, D.J. Papoular, L. Barbiero, C. Menotti, A. Recati,
Phys. Rev. A **88**, 023603 (2013)

Non-equilibrium quasi-condensates in reduced dimensions,
Alessio Chiocchetta and Iacopo Carusotto,
EPL **102** 67007 (2013)

Berry curvature effects in the Bloch oscillations of a quantum particle under a strong (synthetic) magnetic field,
Marco Cominotti and Iacopo Carusotto,
EPL **103** 10001 (2013)

Scaling solutions of the two fluid hydrodynamic equations in a harmonically trapped gas at unitarity,
Yan-Hua Hou, Lev P. Pitaevskii, Sandro Stringari,
Phys. Rev. A **87**, 033620 (2013)

A study of coherently coupled two-component Bose-Einstein Condensates,
M. Abad and A. Recati,
Eur. Phys. J. D **67**, 148 (2013)

A compact high-flux source of cold sodium atoms,
G. Lamporesi, S. Donadello, S. Serafini, and G. Ferrari,
Rev. Sci. Instrum. **84**, 063102 (2013)

First and second sound in a highly elongated Fermi gas at unitarity,
Yan-Hua Hou, Lev P. Pitaevskii and Sandro Stringari,
Phys. Rev. A **88**, 043630 (2013)

Quantum Monte Carlo study of a resonant Bose-Fermi mixture,
G. Bertaina, E. Fratini, S. Giorgini, and P. Pieri,
Phys. Rev. Lett. **110**, 115303 (2013)

Oscillatory Vertical Coupling between a Whispering-Gallery Resonator and a Bus Waveguide,
M. Ghulinyan, F. Ramiro-Manzano, N. Prtljaga, R. Guider, I. Carusotto, A. Pitanti, G. Pucker, and L. Pavesi,
Phys. Rev. Lett. **110**, 163901 (2013)

Collective Modes in a Unitary Fermi Gas across the Superfluid Phase Transition,
M.Khoon Tey, L.A.Sidorenkov, E.R. Sanchez Guajardo, R.Grimm, M.J.H.Ku, M.W.Zwierlein, Yan-Hua Hou, L.Pitaevskii, S.Stringari,
Phys. Rev. Lett. **110**, 055303 (2013)

Lieb's soliton-like excitations in harmonic trap,
G. E. Astrakharchik and L. P. Pitaevskii,
EPL **102**, 30004 (2013)

Many-body braiding phases in a rotating strongly correlated photon gas,
R. O. Umucalilar, I. Carusotto,
Phys. Lett. A **377**, 2074 (2013)

Quantum vacuum emission in a nonlinear optical medium illuminated by a strong laser pulse,
S.Finazzi, I.Carusotto,
Phys. Rev. A **87**, 023803 (2013)

Polar molecules in bilayers with high population imbalances,
Michael Klawunn and Alessio Recati,
Phys. Rev. A **88**, 013633 (2013)

Quantum fluids of light,
Iacopo Carusotto and Cristiano Ciuti,
Rev. Mod. Phys. **85**, 299 (2013)

Preprints

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, Iacopo Carusotto,
arXiv:1606.02277

Tricriticalities and Quantum Phases in Spin-Orbit-Coupled Spin-1 Bose Gases,
G.I. Martone, F.V. Pepe, P. Facchi, S. Pascazio, S. Stringari,
arXiv:1511.09225. To appear in Phys. Rev. Lett.

Optical-lattice-assisted magnetic phase transition in a spin-orbit-coupled Bose-Einstein condensate,
Giovanni I. Martone, Tomoki Ozawa, Chunlei Qu, Sandro Stringari,
arXiv:1605.02108

Synthetic Dimensions for Cold Atoms from Shaking a Harmonic Trap,
Hannah M. Price, Tomoki Ozawa, and Nathan Goldman,
arXiv:1605.09310

Superfluid Density of a Spin-orbit Coupled Bose Gas,
Yi-Cai Zhang, Zeng-Qiang Yu, Tai Kai Ng, Shizhong Zhang, Lev Pitaevskii, Sandro Stringari,
arXiv:1605.02136

Creation and counting of defects in a temperature quenched Bose-Einstein Condensate,
S.Donadello, S.Serafini, T.Bienaimé, F.Dalfovo, G.Lamporesi, G.Ferrari,
arXiv:1605.02982

Evidence for ferromagnetic instability in a repulsive Fermi gas of ultracold atoms,
G. Valtolina, F. Scazza, A. Amico, A. Burchianti, A. Recati, T. Enss, M. Inguscio, M. Zaccanti, G. Roati,
arXiv:1605.07850

Casimir forces and quantum friction from Ginzburg radiation in atomic BECs,
Jamir Marino, Alessio Recati, Iacopo Carusotto,
arXiv:1605.07642

Thermalization and Bose-Einstein condensation of quantum light in bulk nonlinear media,
Alessio Chiocchetta, Pierre-Élie Larré, and Iacopo Carusotto,
arXiv:1605.01870. To appear in EPL (2016)

Topological Varma superfluid in optical lattices,
M. Di Liberto, A. Hemmerich, C. Morais Smith,
arXiv:1604.06055

Quantized conductance with bosonic atoms,
D.J. Papoular, L.P. Pitaevskii, S. Stringari,
arXiv:1510.02618

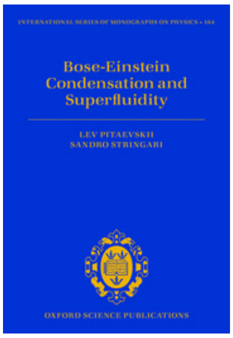
Time-dependent study of a black-hole laser in a flowing atomic condensate,
J. R. M. de Nova, S. Finazzi, I. Carusotto,
arXiv:1509.00795

Laser operation and Bose-Einstein condensation: analogies and differences,
Alessio Chiocchetta, Andrea Gambassi, and Iacopo Carusotto,
arXiv:1503.02816

Strongly interacting photons in arrays of dissipative nonlinear cavities under a frequency-dependent incoherent pumping,
J. Lebreuilly, I. Carusotto, and M. Wouters,
arXiv:1503.02816. To appear on Comptes Rendus de l'Academie des Sciences (2016)

Highlights

Pitaevskii & Stringari, new edition!



In February 2016, Lev Pitaevskii and Sandro Stringari published the new edition of their book, Bose-Einstein Condensation and Superfluidity, in Oxford Science Publications, International Series of Monographs on Physics. The book provides a comprehensive introduction to quantum gases and includes the main theoretical and experimental features characterizing ultracold atomic gases. It emphasizes interdisciplinarity of superfluidity and its key role in many observable properties. It builds on the authors' first book, Bose-Einstein Condensation (Oxford University Press, 2003), offering a more systematic description of Fermi gases, quantum mixtures, low dimensional systems, and dipolar gases. Excerpts from recent reviews: *I expect it to be read widely by graduate students and more senior researchers entering the field* (Dieter Jaksch, University of Oxford). *The earlier version of the textbook by these authors is a remarkable achievement and a 'must have' for any physicist working on cold atoms or teaching Bose-Einstein Condensation. A high quality comprehensive textbook like this one that addresses this expanding interest will clearly be an important milestone in the field* (Jean-Michel Raimond, Universit Pierre et Marie Curie, France). *This is a timely topic and there currently is no competing book at this level of depth. It is difficult to imagine finding a better pairing to write a book about this topic* (Ifan Hughes, Durham University).

Physical Review B "Editors' Suggestions"

The article *Measurement of Chern numbers through center-of-mass responses*, by H,M.Price et al., published in Phys. Rev. B 93, 245113 (2016), was selected as "Editors' Suggestion".

Physical Review Letters "Editors' Suggestion"

The article *Magnetic Solitons in a Binary Bose-Einstein Condensate*, by Chunlei Qu et al., published in Phys. Rev. Lett. 116, 160402 (2016), was selected as "Editors' Suggestion".

PRL paper selected for a "Synopsis" in Physics

The article *Four-Dimensional Quantum Hall Effect with Ultracold Atoms*, by H.M.Price et al., published in Phys. Rev. Lett. 115, 195303 (2015), was selected by Physics for the Synopsis *The Quantum Hall Effect Leaves Flatland*, in http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.115.195303.

Invitation to write a News and Views article in Nature Physics

Tomoki Ozawa was invited to write the News and Views article "Ultracold atoms: Feel the gauge" in Nature Physics, 10 August 2015 (http://www.nature.com/nphys/journal/v11/n10/full/nphys3447.html).

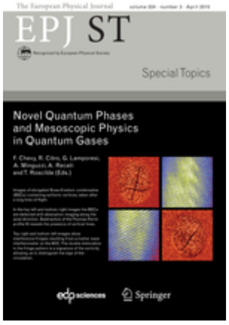
Physical Review Letters "Editors' Suggestion"

The article *Quantum Signature of Analog Hawking Radiation in Momentum Space*, by D. Boiron et al., published in Phys. Rev. Lett. 115, 025301 (2015), was selected as "Editors' Suggestion".

PRX paper selected for a "Synopsis" in Physics

The article *Spin-Orbit Coupling for Photons and Polaritons in Microstructures*, by V.G.Sala et al., published in Phys. Rev. X 5, 011034 (2015), was selected by Physics for the Synopsis *Spin-Orbit-Coupled Photons*, in http://physics.aps.org/synopsis-for/10.1103/PhysRevX.5.011034.

Cover images from the Trento lab



The images of quantized vortices from the experimental laboratory of the BEC Center appeared on cover of The European Physical Journal Special Topics, Vol. 224, No. 3 (2015), entitled *Novel Quantum Phases and Mesoscopic Physics in Quantum Gases*.

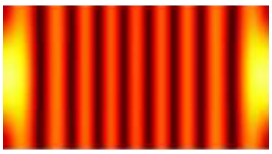
Physical Review Letters "Editors' Suggestions" and "Synopsis" in Physics

The article *Acoustic Black Hole in a Stationary Hydrodynamic Flow of Microcavity Polaritons*, by H.S. Nguyen et al., published in Phys. Rev. Lett. 114, 036402 (2015), was selected as "Editors' Suggestion". It was also selected by Physics for the Synopsis *A Black Hole for Polaritons*, in http://physics.aps.org/synopsis-for/10.1103/PhysRevLett.114.036402.

Invitation to write a Perspective article in Science

Gabriele Ferrari was invited to write the Perspective article "Dynamics of a cold quantum gas" in Science, 9 January 2015 (http://science.sciencemag.org/content/347/6218/127.full).

PRL paper got some coverage



The article *Quantum Mechanics with a Momentum-Space Artificial Magnetic Field*, by H.M.Price et al., published in Physical Review Letters 113, 190403 (2014), was highlighted by Phys.org with an interview with Hannah (http://phys.org/news/2014-11-physicists-magnetism-roles-position-momentum.html).

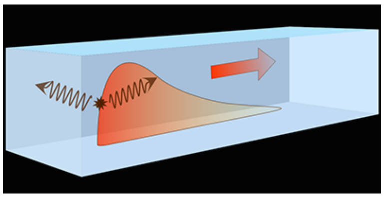
Physical Review Letters "Editors' Suggestion"

The article *Observation of Solitonic Vortices in Bose-Einstein Condensates*, by S.Donadello et al., published in Phys. Rev. Lett. 113, 190403 (2014), was selected as "Editors' Suggestion".

Viewpoint in Physics

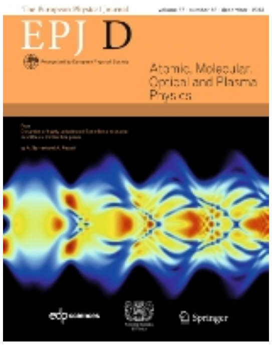
The article *Observation of Solitonic Vortices in Bose-Einstein Condensates*, by S.Donadello et al., published in Phys. Rev. Lett. 113, 190403 (2014), was selected by Physics for the Viewpoint *Soliton with a twist*, written by F. Chevy, in http://physics.aps.org/articles/v7/82.

Physical Review "Editors' Suggestions" and "Synopsis" in Physics



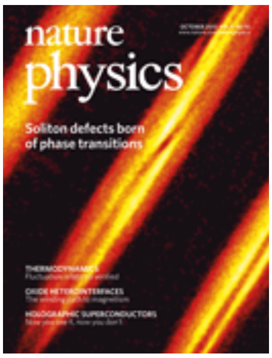
The article *Spontaneous quantum emission from analog white holes in a nonlinear optical medium*, by S.Finazzi and I.Carusotto, published in Phys. Rev. A 89, 053807 (2014), was selected as "Editors' Suggestion". It was also selected by Physics for the Synopsis *Creating Hawking Radiation in the Lab?*, in http://physics.aps.org/synopsis-for/10.1103/PhysRevA.89.053807.

EPJD cover



The article *Dynamics of highly unbalanced Bose-Bose mixtures: miscible vs. immiscible gases*, EPJD 67, 260 (2013), by Alberto Sartori and Alessio Recati, was selected for the cover of European Physical Journal D.

Nature Physics cover and "news & views"

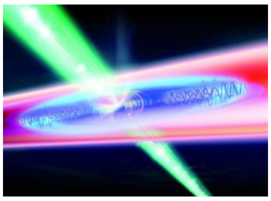


The article *Spontaneous creation of Kibble-Zurek solitons in a Bose-Einstein condensate*, by G.Lamporesi et al., published in Nature Physics, was selected for the cover of October 2013 issue and has been highlighted by a "news & views" article entitled "Shock cooling a universe", written by M.Zwierlein. The results were presented in invited talks at BEC conference 2013 in S.Feliu, APS March Meeting 2014, DAMOP 2014, KITPC conference in Beijing.

Physical Review A "Editors' Suggestions"

The article *Snake instability of dark solitons in fermionic superfluids* , by A.Cetoli et al., published in Phys. Rev. A 88, 043639 (2013), was selected as "Editors' Suggestion".

Nature paper got some coverage



The article *Second sound and the superfluid fraction in a Fermi gas with resonant interactions*, by L.A. Sidorenkov et al., published in Nature, was highlighted by Science Daily (www.sciencedaily.com/releases/2013/05/130515131508.htm), redOrbit (www.redorbit.com/news/science), and ansa.it (www.ansa.it), World News (Wn.com), ScienceNewsline (www.sciencenewsline.com), among others.

Meetings, seminars, conferences, honors, outreach

Group meetings and seminars at the BEC Center

- Thursday, June 30th 2016 at 11.00, Aula Seminari di Fisica Teorica
  Lukas Sieberer (UC Berkeley, USA)
  Electrodynamic duality and vortex unbinding in driven-dissipative condensates

- Thursday, June 23th 2016 at 15.00, Aula A101
  Colloqui in Collina
  William D. Phillips (NIST, Gaithersburg)
  Quantum information: a scientific and technological revolution of the 21st century

- Monday, June 20th 2016 at 11.00, Aula Seminari di Fisica Teorica
  Michael Gullans (JQI, NIST and Univ. Maryland, USA)
  Effective Field Theory for Strongly Interacting Photons

- Thursday, June 16th 2016 at 14.30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Sandro Stringari
  BEC without superfluidity

- Monday, June 6th 2016 at 16.00, Aula Seminari di Fisica Teorica
  Nadine Meyer (Birmingham University)
  Formation of Jones-Roberts solitons in a Bose-Einstein condensate

- Wednesday, May 25th 2016 at 11.00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  José Lebreuilly
  Effective thermalization of driven-dissipative non-markovian systems

- Friday, May 13th 2016 at 9.30, Aula Seminari di Fisica Teorica
  Florent Michel and Renaud Parentani (LPT, Univ. Paris-Sud)
  "No-hair" and uniqueness results for analogue black holes

- Friday, May 6th 2016 at 14.30, Povo1, Room A204
  Tommaso Calarco (ICQ, University of Ulm)
  Optimal control of complex quantum systems

- Friday, April 22th 2016 at 9.30, Aula Seminari di Fisica Teorica
  Matteo Lostaglio (Imperial College London)
  The power of Stochastic Independence

- Tuesday, April 19th 2016 at 14.00, Povo1, Room A108
  PhD Thesis Defence

Grazia Salerno
Artificial Gauge Fields in Photonics and Mechanical Systems

- Friday, April 8th 2016 at 14.00, Povo1, Room A108
  PhD Thesis Defence
  Simone Donadello
  Observation of the Kibble-Zurek mechanism in a bosonic gas

- Friday, April 8th 2016 at 9.30, Aula Seminari di Fisica Teorica
  Hanns-Christoph Nägerl (Univ. Innsbruck)
  Experiments with quantum-gas mixtures and tunable interactions: Dipolar gases, modulated interactions, and impurity transport

- Thursday, April 7th 2016 at 14.30, Aula Seminari di Fisica Teorica
  Thomas Scaffidi (Univ. Oxford)
  Introduction to bosonic symmetry protected topological states

- Tuesday, April 5th 2016 at 11.00, Aula Seminari di Fisica Teorica
  Thomas Scaffidi (Univ. Oxford)
  Exact Solutions of Fractional Chern Insulators: Interacting Particles in the Hofstadter Model at Finite Size

- Monday, April 4th 2016 at 14.30, Aula Seminari di Fisica Teorica
  Thomas Scaffidi (Univ. Oxford)
  Introduction to fractional Chern insulators

- Wednesday, March 23nd 2016 at 15.00, Aula Seminari di Fisica Teorica
  Michiel Wouters (Univ. Antwerp)
  Experimental aspects of polariton BECs

- Wednesday, March 23rd 2016 at 11.00, Aula Seminari di Fisica Teorica
  Otfried Guehne (Univ. Siegen)
  Analyzing multiparticle entanglement

- Tuesday, March 22nd 2016 at 11.00, Aula Seminari di Fisica Teorica
  Michiel Wouters (Univ. Antwerp)
  Time dilation in many-body quantum systems

- Tuesday, March 8th 2016 at 14.30, Aula Seminari di Fisica Teorica
  Wilhelm Zwerger (Technische Uni. Muenchen)
  Dynamical gauge fields and three-body correlations with ultracold atoms

- Tuesday, March 8th 2016 at 11.00, Aula Seminari di Fisica Teorica
  Markus Oberthaler (Uni. Heidelberg)
  Immersed quantum systems: Lamb shift and bound Bose polarons

- Monday, March 7th 2016 at 15.00, Povo1 (Room A208)
  PhD Thesis Defence
  Alberto Sartori
  Dynamical properties of Bose-Bose mixtures

- Wednesday, March 2nd 2016 at 11.00, Aula Seminari di Fisica Teorica
  BEC Journal Club
  Marco Di Liberto
  Topological Varma superfluid in p-bands

- Monday, February 29th 2016 at 14.30, Aula Seminari di Fisica Teorica
  David Clément (Institut d'Optique, Palaiseau)
  Investigating many-body correlations in momentum: An illustration on quantum depletion

- Wednesday, February 24th 2016 at 11.00, Aula Seminari di Fisica Teorica
  Lev Pitaevskii and Sandro Stringari
  Presentation of their new book on "Bose-Einstein Condensation and Superfluidity"

- Wednesday, February 17th 2016 at 10.30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Chunlei Qu
  Magnetic solitons in a binary Bose-Einstein condensate

- Thursday, January 28th 2016 at 15.00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Marek Tylutki
  Superfluid Mixtures of Ultracold Gases

- Wednesday, January 20th 2016 at 10.00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Grazia Salerno (Internal Seminar)
  Microwave analogue of strained honeycomb lattices

- Wednesday, December 16th 2015 at 10.00, Aula Seminari di Fisica Teorica
  Luca Galantucci (JQC of Newcastle and Durham, UK)
  Vortex dynamics in confined geometries

- Tuesday, December 15th 2015 at 9.30, Aula Seminari di Fisica Teorica
  Martin Wimmer (Univ. Jena, Germany)
  Superfluid Propagation of Light in Photonic Mesh Lattices

- Wednesday, December 9nd 2015 at 9.30, Aula Seminari di Fisica Teorica
  Sandro Wimberger (Univ. Parma)
  Non-Equilibrium Transport of Interacting Bosons

- Wednesday, December 2nd 2015 at 10:00, Aula Seminari di Fisica Teorica
  Gareth Conduit (University of Cambridge)
  Using pseudopotentials to study strongly correlated phases

- Tuesday, November 24th 2015 at 16.15, Aula Seminari di Fisica Teorica
  BEC Group Seminar
  Russell Bisset
  Crystallisation of a dilute atomic dipolar condensate

- Wednesday, November 11th 2015 at 10:00, Aula Seminari di Fisica Teorica
  Daisuke Satow (ECT*, Trento)
  Spectral properties of the Goldstino in supersymmetric Bose-Fermi mixtures

- Wednesday, November 4th 2015 at 10:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Simone Donadello
  Beyond Kibble-Zurek mechanism: vortex relaxation after a temperature quench

- Wednesday, October 21th 2015 at 10:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Giacomo Colzi
  Thermometry and cooling of a Bose gas to 0.02 times the condensation temperature

- Wednesday, October 14th 2015 at 10:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Marek Tylutki
  Experiment on Josephson effect in fermionic superfluids

- Monday, September 28st 2015 at 15:00, Aula Seminari di Fisica Teorica
  David Papoular
  Quantized conductance with bosonic atoms

- Wednesday, September 23rd 2015 at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Pjotrs Grisins
  Stimulated and spontaneous Hawking effect in superfluid light

- Monday, September 21st 2015 at 15:00, Aula Seminari di Fisica Teorica
  Chunlei Qu
  Topological Fulde-Ferrell superfluids in spin-orbit coupled Fermi gases

- Wednesday, September 2nd 2015 at 11:00, Aula Seminari di Fisica Teorica
  Grigory E. Astrakharchik (Universitat Politecnica de Catalunya, Barcelona, Spain)
  Continuous-space description of a 1D Bose gas in optical lattice

- Monday, July 20th 2015 at 14:00, Aula Seminari di Fisica Teorica
  Tom Bienaimé (LKB-ENS and Collège de France)
  Quench-induced topological defects in a uniform Bose gas confined in two dimensions

- Friday, July 3rd 2015 at 11:00, Aula Seminari di Fisica Teorica
  Yulia Shchadilova (Harvard University and Russian Quantum Center)
  BEC polarons in systems of ultracold atoms

- Friday, June 19th 2015, at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Simone Serafini and Fabrizio Larcher
  Formation and dynamics of vortices in an elongated Bose-Einstein Condensate

- Wednesday, June 17th 2015, at 14:00, Aula Seminari di Matematica
  Joint Math-Physics seminar
  Tomoki Ozawa (INO-CNR BEC Center and Department of Physics, University of Trento)
  Introduction to topological insulators for mathematicians

- Monday, June 8th 2015 at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Andrei Berceanu
  Driven-dissipative toroidal Landau levels in cavity arrays, with an introduction to the Julia language

- Thursday, June 4th 2015 at 11:00, Aula Seminari di Fisica Teorica
  Hadrien Kurkjian (LKB-ENS, Paris, France)
  Thermal blurring of a coherent Fermi gas

- Wednesday, May 27th 2015 at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Eleonora Fava
  Experimental measurement of the equation of state of a weakly-interacting Bose gas

- Thursday, May 21th 2015 at 11:00, Aula Seminari di Fisica Teorica
  Francesco Scazza (LMU and MPI, Munich)
  Two-orbital physics and SU(N)-symmetric interactions with ultracold gases of ytterbium in optical lattices

- Wednesday, May 13th 2015 at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  José Lebreuilly
  Thermalization of isolated quantum systems

- Wednesday, April 29th 2015 at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club

Pjotrs Grisins
Experimental Observation of a Generalized Gibbs Ensemble

- Friday, April 17th 2015 at 14:30, Aula Seminari Dipartimento di Fisica (ground floor)
  Dmitry Kobyakov (TU Darmstadt, Germany)
  Introduction to quantum turbulence in superfluid mixtures

- Wednesday, April 15th 2015 at 14:00, Aula Seminari di Fisica Teorica
  Paolo Comaron (Univ. Newcastle)
  Stochastic simulations of quantum fluctuations in quantum fluids

- Wednesday, April 15th 2015 at 11:45, Aula Seminari di Fisica Teorica
  Giovanni Martone (Univ. Bari)
  Spin-orbit coupled Bose-Einstein condensates: formation of stripes

- Wednesday, April 15th 2015 at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Tomoki Ozawa
  Observation of Bose-Einstein Condensation in a Strong Synthetic Magnetic Field

- Tuesday, April 14th 2015 at 11:30, Aula Seminari di Fisica Teorica
  Nicolas Pavloff (LPTMS Université Paris Sud and CNRS, France)
  Phase dislocations in the 2D scattering of microcavity polaritons

- Monday, April 13th 2015 at 11:00, Aula Seminari di Fisica Teorica
  Paolo Comaron (Univ. Newcastle)
  Numerical simulations of quantum fluids of exciton-polaritons

- Monday, April 13th 2015 at 14:00, Aula Seminari di Fisica Teorica
  Giovanni Martone (Univ. Bari)
  Spin-orbit coupled Bose-Einstein condensates: rotonic excitation

- Wednesday, March 25th 2015 at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Hannah Price
  Synthetic gauge fields in synthetic dimensions for ultracold atoms

- Tuesday, March 24th 2015 at 15:00, Aula Seminari di Fisica Teorica
  Marco Di Liberto (ITP, Utrecht University)
  Tuning phase coherence in optical lattices

- Wednesday, March 11th 2015 at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Giulia De Rosi
  Collective oscillations of 2D harmonic trapped quantum gases

- Thursday, March 5th 2015 at 17:00, Aula Seminari di Fisica Teorica
  Giacomo Roati (LENS, Firenze)
  Degenerate 6Li atoms in Florence: current and future experiments

- Thursday, March 5th 2015 at 16:30, Aula Seminari di Fisica Teorica
  Matteo Zaccanti (LENS, Firenze)
  Superfluidity and ferromagnetism of unequal mass fermions with two- and three-body resonant interactions

- Wednesday, March 4th 2015 at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Pierre Elie Larrè
  Propagation of a quantum fluid of light in a bulk nonlinear optical medium: General theory and response to a quantum quench

- Monday, February 23th 2015 at 14:30, Aula Seminari di Fisica Teorica
  Zoltán Vörös (University of Innsbruck)
  Correlated photons from microcavity polaritons

- Tuesday, February 17th 2015 at 16:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  David Papoular
  Shortcut to Adiabaticity for an Anisotropic 2D Bose Gas

- Thursday, February 5th 2015 at 14:30, Aula Seminari di Fisica Teorica
  Vincent Corre (LKB-ENS and Collège de France)
  Magnetism with Spinor Bose-Einstein Condensates with Antiferromagnetic Interactions

- Wednesday, February 4th 2015 at 16:00, Aula Seminari di Fisica Teorica
  Nathan Goldman (ULB and Collège de France)
  Creating and Probing Topological Matter in a Cold Atomic Gas

- Thursday, January 15th 2015 at 16:30, Aula Seminari di Fisica Teorica
  Pjotrs Grisins (Univer. Vienna)
  Dissipative cooling of degenerate Bose gases

- Wednesday, December 17th 2014 at 11:00, Aula Seminari di Fisica Teorica
  Grigori E. Astrakharchik (Univ. Politecnica de Catalunya, Barcelona)
  Reentrant behaviour of breathing mode in one-dimensional Bose gas

- Friday, December 12th 2014 at 14:00, Aula A203
  PhD final examination
  Giovanni Martone
  Static and dynamic properties of spin-orbit-coupled Bose-Einstein condensates

- Tuesday, December 9th 2014 at 14:30, Aula Seminari di Fisica Teorica
  Lauriane Chomaz (LKB-ENS and Collège de France, Paris)
  Emergence of coherence in a uniform quasi-two-dimensional Bose gas

- Wednesday, November 26th 2014 at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Marek Tylutki
  Snaking instability of dark solitons in trapped superfluids

- Monday, November 17th 2014 at 14:30, Aula Seminari di Fisica Teorica
  Yong P. Chen (Purdue University)
  Transport and Dynamics in Spin-Orbit Coupled BECs

- Wednesday, November 12th 2014 at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Grazia Salerno (Research Introduction)
  Riccardo Rota (Seminar)
  Variational Monte-Carlo study of the effective mass of soliton excitations in a Bose gas

- Thursday, October 9th, 2014 at 15:30, Aula A212
  TIFPA-BEC-ECT* Colloquium
  Martin Plenio (Univ. Ulm, Germany)
  Quanta, vibrations and biology

- Wednesday, October 8th 2014 at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Hannah Price (Research Introduction)
  Simone Serafini (Journal Club)
  Scalable Spin Squeezing for Quantum-Enhanced Magnetometry with Bose-Einstein Condensates

- Wednesday, September 24th 2014 at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Tomoki Ozawa (Research Introduction)
  Simone Donadello (Journal Club)
  Local emergence of thermal correlations in an isolated quantum many-body system

- Thursday, July 17th 2014, at 09:30, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Fabrizio Minganti (Research Introduction)
  Lucas Verney (Research Introduction)
  José Lebreuilly (Research Introduction)

- Thursday, July 10th 2014, at 11:00, Aula Seminari di Fisica Teorica
  Jamir Marino (Univ. Innsbruck, Austria)
  Thermal and Non-Thermal signatures of the Unruh effect in Casimir-Polder forces

- Wednesday, July 2nd 2014, at 11:00, Aula Seminari di Fisica Teorica
  BEC Group Journal Club
  Giulia De Rosi (Research Introduction)
  Riccardo Rota (Journal Club)
  Defect-induced supersolidity with soft-core bosons

- Wednesday, June 25th 2014, at 11:00, Aula Seminari di Fisica Teorica
  Patrizia Vignolo (INLN, Nice, France)
  Gap labelling in quasicrystals: from microwaves to ultracold atoms

- Wednesday, June 18th 2014, at 11:00, Aula Seminari di Fisica Teorica
  Grigori E. Astrakharchik (Univ. Politecnica de Catalunya, Barcelona)
  Applicability of excitonic description in a two component Coulomb gas

- Tuesday, June 17th 2014, at 11:30, Aula Seminari di Fisica Teorica
  Luis Santos (Institut für Theoretische Physik, Univ. Hannover)
  Ultra-cold lattice gases with density-dependent hopping

- Tuesday, June 17th 2014, at 10:30, Aula Seminari di Fisica Teorica
  Luis Santos (Institut für Theoretische Physik, Univ. Hannover)
  Theory of dipolar gases (lecture II)

- Wednesday, June 11th 2014, at 11:00, Aula Seminari di Fisica Teorica
  Giuseppe Mussardo (SISSA, Trieste)
  Quantum Quench Dynamics

- Tuesday, June 10th 2014, at 10:30, Aula Seminari di Fisica Teorica
  Luis Santos (Institut für Theoretische Physik, Univ. Hannover)
  Theory of dipolar gases (lecture I)

- Friday, June 6th 2014, at 11:00, Aula Seminari di Fisica Teorica
  Anne-Maria Visuri (Aalto University, Finland)
  Moving perturbation in a one-dimensional Fermi gas

- Wednesday, May 21st 2014 at 11:00, Aula Seminari di Fisica Teorica
  Pierre-Élie Larré (Research Talk)
  David Papoular (Journal Club)
  Nonequilibrium Solutions of the Boltzmann Equation under the Action of an External Force

- Monday, May 19th 2014 at 11:00, Aula Seminari di Fisica Teorica
  Tomoki Ozawa (Internal Seminar)
  Chandrasekhar-Clogston limit and critical polarization in a Fermi-Bose superfluid mixture

- Thursday, May 15th 2014, at 14:30, Aula Seminari di Fisica Teorica
  Tarik Yefsah (MIT, USA)
  Dynamical defects in a Strongly Interacting Fermionic Superfluid

- Friday, May 16th, 2014, at 14:30, Aula A203
  Zou Peng (PhD thesis defense)
  Mean-field theory for the dynamics of superfluid fermions in the BCS-BEC crossover

- Wednesday, May 14th 2014, at 11:00, Aula Seminari di Fisica Teorica
  Hui Hu (Swinburne Univ., Melbourne, Australia)
  Gapless topological Fulde-Ferrell superfluidity in spin-orbit coupled atomic Fermi gases

- Wednesday, May 7th 2014 at 11:00, Aula Seminari di Fisica Teorica
  Alberto Sartori (Research Introduction)
  Luis A. Pena Ardila (Internal Seminar)
  Ground state properties of one single impurity immersed into a uniform 3D BEC

- Wednesday, April 9th 2014, at 11:00, Aula Seminari di Fisica Teorica
  Simone Serafini (Research Introduction)
  Zeng-Qiang Yu (Journal Club)
  Spin-orbit coupled Bose gas at finite temperature

- Wednesday, March 26th 2014, at 11:30, Aula Seminari di Fisica Teorica
  Elisa Ercolessi (Univ. Bologna)
  Dynamics of entanglement crossing a quantum phase transition

- Thursday, March 13th 2014, at 14:00, Aula Seminari di Fisica Teorica
  Natalia Matveeva (Research Introduction)
  Hannah Price (Internal Seminar)
  The Berry Curvature as a Magnetic Field in Momentum Space

- Thursday, March 6th 2014, at 14:30, Aula Seminari di Fisica Teorica
  Michiel Wouters (Univ. Antwerp, Belgium)
  Polariton Feshbach resonances

- Tuesday March 4th, room A221
  BEC Trento - Pisa SNS joint meeting
  Talks:
  Leonardo Mazza (Pisa SNS): *String order in 1D quantum systems: from optical lattices to spin chains*

David Papoular (BEC Trento): *Towards the realization of a super-leak for ultracold Bose gases*
Alessio Recati (BEC Trento): *Ferromagnetic phase transition in coherently coupled Bose-Hubbard models*
Davide Rossini (Pisa SNS): *Magnetic properties of strongly interacting spin-orbit coupled bosons on a one-dimensional lattice*

- Wednesday, February 26th 2014, at 11:00, Aula Seminari di Fisica Teorica
Zou Peng (Research Introduction)
Giovanni Martone (Journal Club)
Holonomies in Quantum Systems.

- 20-21 February 2014, room A221
BEC Trento - Roma "La Sapienza" joint meeting
Talks:
Valentina Brosco (Roma): *Exact Density Functional Theory for lattice fermions*
Iacopo Carusotto (Trento): *Synthetic gauge fields and topological physics with photons*
Claudio Castellani (Roma): *Superconductor to Insulator Transition: A short overview on recent ideas*
Carlo Di Castro (Roma): *Hidden order is becoming manifest in High Temperature Cuprate Superconductors*
Stefano Giorgini (Trento): *Ultracold atoms with dipolar interaction: a quantum Monte Carlo perspective*
Marco Grilli (Roma): *Rashba spin-orbit etc.*
Jose Lorenzana (Roma): *Triggering coherent oscillations in a superconducting condensate with a light impulse*
Giovanni Martone (Trento): *Spin-orbit coupled Bose-Einstein condensates*
Tomoki Ozawa (Trento): *Second sound and the BKT transition*

- Wednesday, February 19th 2014, at 17:00, Aula Seminari di Fisica Teorica
Luca Lepori (Univ. Strasbourg, France)
Long-range interacting Kitaev chains

- Wednesday, February 12th 2014, at 11:00, Aula Seminari di Fisica Teorica
Marta Abad (Research Introduction)
Tomoki Ozawa (Journal Club)
Observation of Dirac monopoles in a synthetic magnetic field

- Wednesday, February 5th 2014, at 15:00, Joint Math-Physics seminar
Davide Pastorello (Univ. Trento)
Geometric Hamiltonian formulation of finite-dimensional Quantum Mechanics on complex projective spaces

- Wednesday, February 5th 2014, at 11:00, Aula Seminari di Fisica Teorica
  Amor Toumiat (Univ. Constantine 1, Algeria)
  BEC of excitons

- Wednesday, January 29th 2014 at 11:00, Aula Seminari di Fisica Teorica
  David Papoular (Research Introduction)
  Pierre-Élie Larré (Journal Club) *Acoustic analog to the dynamical Casimir effect in a Bose-Einstein condensate*

- Wednesday, January 22nd 2014, at 11:30, Aula Seminari di Fisica Teorica
  Tilman Enss (Heidelberg)
  Transverse spin diffusion in ultracold Fermi gases

- Wednesday, January 15th 2014 at 11:00, Aula Seminari di Fisica Teorica
  Simone Donadello (Research Introduction)
  Grazia Salerno (Research Seminar):
  Dynamical decoupling and isolation in frequency modulated coupled pendulums: Towards artificial gauge fields in classical mechanics.

- Wednesday, January 8th 2014, at 11:00, Aula Seminari di Fisica Teorica
  Nicola Bartolo (BEC Trento and Univ. Montpellier 2, France)
  Matter Waves in Atomic Artificial Graphene

- Monday, December 16th 2013, at 11:30, Aula Seminari di Fisica Teorica
  Grigori E. Astrakharchik (Univ. Politecnica de Catalunya, Barcelona)
  Trapped one-dimensional ideal Fermi gas with a single impurity

- Friday, December 13th 2013, at 11:30, Aula Seminari di Fisica Teorica
  Francesco Piazza (TUM Munich)
  Umklapp Lasing with a Quantum Degenerate Fermi Gas

- Friday, December 6th 2013, at 15:00, Aula A210 ¡BR¿
  Yan Hua Hou (PhD defense)
  Two fluid hydrodynamics of a quasi-1D Unitary Fermi Gas

- Wednesday, December 4th 2013, at 11:00, Aula Seminari di Fisica Teorica
  Riccardo Rota (Research Introduction),
  Marek Tylutki (Journal Club):
  Kibble-Zurek mechanism and scaling exponent doubling

- Wednesday, November 20th 2013, at 16:00, Aula A103, Dialoghi of the Physics Department
  Gabriele Ferrari (BEC Center)
  The Kibble-Zurek mechanism: origin of defects across a phase transition

- Monday, November 18th 2013, at 17:00, Joint Math-Physics seminar
  Igor Khavkine (Univ. Trento)
  A time delay observable in classical and quantum gravity

- Friday, November 15th 2013, at 11:30, Aula Seminari di Fisica Teorica
  Luca Salasnich (Univ. Padova)
  Mean-field and beyond in the 2D BCS-BEC Crossover

- Thursday, November 14th 2013, at 16:00, Aula A209 (Povo 1)
  Michele Trenti (Univ. Cambridge, UK)
  Stars and Galaxies in the First Billion Years after the Big Bang

- Friday, October 25th 2013, at 14:30, Aula A107 (Povo 1)
  Aurel Bulgac (Univ. Washington, Seattle)
  Time-Dependent Density Functional Theory and real-time dynamics of Fermi superfluids

- Monday, October 21rd 2013, at 14:30, Aula Seminari di Fisica Teorica
  Joel Corney (Univ. Queensland, Australia)
  From photons to fermions: squeezing and correlations in coherent many-body systems

- Friday, October 18rd 2013, at 10:00, Ofek Meeting Room (Povo 1 building)
  Richard Packard (University of California, Berkeley)
  Superfluid Helium Quantum Interference Devices (SHeQUIDS): basic physics and applications

- Thursday, October 3rd 2013, at 14:30, Aula Seminari di Fisica Teorica
  Tomoki Ozawa (BEC Trento)
  Second sound and the BKT transition

- Monday, Sept. 30th 2013, at 15:00, Joint Math-Physics seminar
  Paolo Ghiggini (Univ. Nantes, France)
  Differential Geometry of the falling cat

- Monday, September 16th 2013, at 14:30, aula seminari
  Frank Deuretzbacher (Univ. Hannover, Germany)
  Phase diagram of quasi-1D dipolar Fermi gases: exploiting Bose-Fermi mappings for generalized contact interactions

- Thursday, Sept 5th 2013, at 14:30, aula seminari Pierrick Cheiney (Cambridge, UK)
  Scattering of guided matter waves on a finite size lattice

- Thursday, June 27th 2013, at 11:00, Aula Seminari di Fisica Teorica
  Riccardo Rota (BEC Trento)
  Quantum Monte Carlo study of the dynamic structure factor of Bose hard-sphere systems

- Friday, June 14th 2013, at 14:30, Aula Seminari di Fisica (ground floor)
  Natalia Matveeva (BEC Trento)
  The impurity problem in a bilayer system of dipoles
- Thursday, June 13th 2013, at 14:30, Aula Seminari Teorici
  Marek Tylutki (Krakow, Poland)
  Dynamics of a quantum phase transition in the Bose-Hubbard model
- Thursday, June 6th 2013, at 14:30, Aula Seminari Teorici
  Jamir Marino (SISSA, Trieste)
  Thermalization dynamics of quantum spin chains
- Thursday, May 30th 2013, at 14:30, Aula Seminari Teorici
  Benoit Vermersch (Lille)
  Dynamics of ultracold bosons in disordered lattices: the weakly interacting regime
- Wednesday, May 22th 2013, 14:00-19h00, Aula A207
  Mini-Workshop on Non-equilibrium Bose-Einstein Condensation
  Speakers: I. Carusotto (BEC Trento), A. Gambassi (SISSA), A. Chiocchetta (SISSA), S. Diehl (Innsbruck), L. Sieberer (Innsbruck)
- Monday, May 20nd 2013, at 14:30, Aula Seminari Teorici
  Enrique Rico Ortega (Ulm)
  Atomic Quantum Simulation of U(N) and SU(N) Non-Abelian Lattice Gauge Theories
- Tuesday, May 7th 2013, at 17:00, ECT*, Villa Tambosi, ECT* Colloquium
  Jean-Paul Blaizot (CEA Saclay)
  Thermalization of the quark-gluon plasma and Bose-Einstein condensation in unusual circumstances
- Thursday, May 2nd 2013, at 14:30, Aula Seminari Teorici
  Tomoki Ozawa (BEC, Trento)
  Dynamic Instability of Supercurrents in Spin-Orbit Coupled BECs
- Monday, April 22nd 2013, at 13:30, Aula Seminari Teorici
  Alessio Recati (BEC, Trento)
  Spontaneous Peierls dimerization and emergent bond order in one-dimensional dipolar gases
- Tuesday, April 23rd 2013, at 15:00, Aula Seminari Teorici
  Giacomo Lamporesi (BEC, Trento)
  First results of the new BEC lab
- Thursday, April 11th 2013, at 16:00, Aula A207, Colloquium
  Anton Zeilinger (Univ. Wien, and Austrian Academy of Sciences)
  Quantum information with photons: from the foundations towards a new technology

- Friday, March 22th 2013, at 14:30, Aula Seminari
  Francesco Piazza (TU Munich)
  Finite temperature self-ordering transition of a Bose gas inside an optical cavity

- Wednesday, March 20th 2013, at 14:30, Aula Seminari
  Jan Chwedenczuk (Warsaw)
  Precise Metrology in an Optical Lattice

- Wednesday, March 4th 2013 at 14:00-17:00, ECT* Seminar Room
  Joint ECT*-BEC-LISC Seminars
  Luigi Scorzato (ECT*) *The "Lefschetz thimble" and the sign problem*
  Stefano Finazzi (BEC) *Quantum fluctuations in Bose-Einstein condensates and nonlinear optical media.*
  Pietro Faccioli (LISC) *Quantum field theory approach to quantum transport in macromolecules*

- Wednesday, February 27th 2013 at 15:00, Aula 106 (Padiglione Nord FBK)
  Andrea Bertoldi (Institut d'Optique, Palaiseau, France)
  Localization and spreading of matter waves in disordered potentials

- Monday, February 18th 2013, at 16:30, Aula A212 ¡BR¿
  Natalia Matveeva (PhD defense)
  Study of dynamic and ground-state properties of dipolar Fermi gases using mean-field and quantum Monte Carlo methods

- Monday, February 18th 2013, at 14:30, Aula A212 ¡BR¿
  Marco Larcher (PhD defense)
  Localization and spreading of matter waves in disordered potentials

- Monday, February 11th 2013, at 14:30, Aula Seminari
  Pierre-Élie Larré (LPTMS Orsay, France)
  Wave pattern generated by an obstacle moving in a one-dimensional polariton condensate

- Tuesday, February 5th 2013, at 14:30, Aula Seminari
  Francesco Bariani (Univ. of Arizona)
  Quantum Optics with Rydberg ensembles

- Friday, February 1st 2013, at 14:30, Aula Seminari
  Zeng-Qiang Yu (BEC Trento)
  Two component Bose gases with spin-orbit coupling

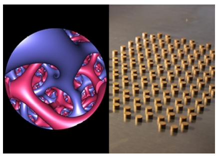
- Wednesday, January 23rd, 2013 at 14:30, Aula Seminari
  Tomoki Ozawa (BEC Trento)
  Landau Critical Velocity in Weakly Interacting Bose Gases

- Tuesday, January 22th 2013, at 14:30, Aula Seminari
  David J. Papoular and Nicola Bartolo (BEC Trento)
  Ultracold Dipolar Bosons in a Quasi-1D Optical Lattice
- Friday, January 18th 2013, at 14:30, Aula Seminari
  Marta Abad (BEC Trento)
  Coupled two-component condensates: ground state and excitations
- Wednesday, January 16th 2013, at 14:30, Aula A105
  Peter Zoller (Univ. Innsbruck, Austria)
  Quantum Simulation with Cold Atoms, Ions and Molecules

Meetings organized or co-organized by the BEC Center

International Workshop on
Equations of state in quantum many-body systems
May 30 - June 1, 2016, ECT*, Trento

The Workshop aimed to bring together researchers actively involved in the investigation of the equation of state in a variety of quantum many-body systems ranging from ultra-cold atoms, nuclear matter and high-pressure hydrogen. The goal of this interdisciplinary initiative was to focus on common threads and methodologies, both at the experimental and theoretical level, and to allow for a fruitful exchange of ideas and perspectives. Organizer: S. Giorgini (BEC Center), M. Holzmann (Grenoble), F. Pederiva (Univ. Trento) and G. Roati (INO-CNR and LENS, Florence). There were 25 speakers and about 60 participants.



TOPODAYS 2016
International informal meeting on
Topological effects in photonics
April 18th-20th, 2016, Trento

This meeting brought together researchers on topological effects in a wide-range of photonics-based systems, including integrated silicon photonics, propagating waveguides, photonic crystals, polariton-cavity arrays and much more. Organizers: Hannah Price and Iacopo Carusotto (BEC Center), and Fernando Ramiro Manzano (Univ. Trento). About 20 speakers gave a talk at the meeting, and the participants were about 40.

International meeting
Frontiers in Ultracold Fermi Gases
90 years after the "birth" of fermions in Florence
March 21-23, 2016, Firenze

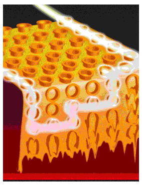
This conference, held in the location on the hill of Arcetri that inspired the work of Fermi, covered the most important developments in the field of ultracold Fermi gases, including: strongly interacting Fermi gases, fermionic superfluidity, fermions in optical lattices, quantum simulation with ultracold fermions. Organizers: M. Inguscio (Univ. Florence), S. Stringari (BEC Center), R. Casalbuoni (Univ. Florence), L. Fallani (Univ. Florence).

International Workshop on
Cold atoms meet high energy physics
June 22-25, 2015, ECT*, Trento

This was intended to be a highly cross-disciplinary meeting, where experts of cold gases and high energy physics could exchange ideas on concepts that are common to both fields. The main topics were: Spontaneously broken symmetries, abelian and non abelian gauge fields, super-symmetries, Fulde-Ferrel-Larchin-Ovchinokov phase, Superfluidity in strongly interacting Fermi systems, High density QCD and bosonic superfluidity, quantum hydrodynamics, Kibble-Zurek mechanism, SU(N) configurations, quantum simulation of quark confinement, magnetic monopoles, Majorana Fermions, role of extra dimensions, lattice QCD, Black holes, Hawking radiation, Higgs excitations in cold atoms, AdS/CFT correspondence, Efimov states, instantons. Organizers: M. Inguscio (Univ. Florence), G. Martinelli (SISSA Trieste), and S. Stringari (BEC Center). The program included 34 invited talks.

Firenze-Trento joint meeting on
Quantum gases: present and future perspectives
April 24, 2015, LENS Firenze

Every few years the two groups of Trento and Florence working with ultracold gases meet together and discuss physical problems of common interest. This time the meeting was held at LENS and about 40 researchers spent the whole day listening to talks and activating lively informal discussions and round tables.



TOPOLIGHT 2015
8th OptoElectronics and Photonics Winter School on
Topological effects in photonics
March 15-21, 2015, Fai della Paganella,

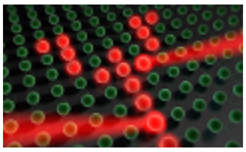
This school was aimed at introducing students and post-docs with an optics background to the concepts of topological physics. These ideas were originally developed in quantum condensed matter physics to explain surprising observations such as the integer and fractional quantum Hall effects. In the last years, a growing interest is being devoted to their translation to electromagnetism and optics, with already a number of remarkable experimental achievements. In addition to theoretical courses on the general theoretical tools, the school offered dedicated lectures on specific optical systems where such physics can be observed and, possibly, exploited in devices. Organizers: I. Carusotto (BEC Center), A. Amo (CNRS, France) and M. Hafezi (Univ. Maryland, USA). There were 12 lecturers and 40 students.

ESF-Polatom International Winter School and Workshop on
Strongly correlated fluids of light and matter
12-23 January, 2015, ECT*, Trento

This meeting was aimed at consolidating the international community working on the young field of Quantum Fluids of Light and at reinforcing its interaction with more traditional fields of many-body physics such as ultracold atomic gases and strongly correlated electrons. The first week had a school character with top-class scientists lecturing from basic concepts up to the most recent developments. The second week had a more workshop character with research seminars covering a broad selection of the hottest topics. Participation were not limited to specialists on quantum fluids of light; an active interest from a broader variety of physicists was encouraged so to reinforce the scientific exchanges between neighboring communities. Organizers: C. Ciuti (MPQ Paris 7, France), R. Fazio (SNS Pisa), A. Imamoglu (ETH Zurich), and I. Carusotto (BEC Center). About 100 people attended the School, including 6 lecturers and 41 speakers.

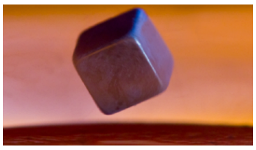
Celebration of the International Year of Light
Fundamental Physics with Light and atoms
27 January 2015, Torino

This Workshop was the first event of the Year of Light following the official opening ceremony in the Senate Chamber of Palazzo Madama. The meeting was held at the Istituto Nazionale di Ricerca Metrologica di Torino. Organizers: M. Inguscio, F. Levi and S. Stringari.



Munich-Trento joint meeting on
Ultracold gases
4-5 December, 2014, MPQ Garching

After a similar meeting held in Trento in 2012, the two groups of the BEC Center and the Max Planck Institute of Quantum Optics in Munich decided to meet again, this time at the IQO in Garching. Eight talks, a poster session and several informal discussions in the first days, and a visit to the laboratories in the second day, were the occasion to strengthen the links between the two groups.

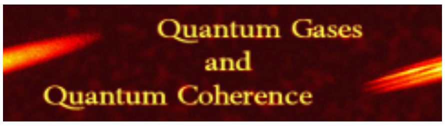


International workshop on
Probing and Understanding
Exotic Superconductors and Superfluids
October 27-31, 2014, ICTP Trieste

This workshop was meant to showcase several new approaches to the experimental and theoretical understanding of superconductors and superfluids, comparing solid-state and ultracold-atoms advances with the aim of a cross-fertilization between the two fields. It featured topics that are rapidly developing, ranging from novel (time-resolved and k-resolved) optical spectroscopies to new trapping and imaging methods for ultracold gases, with the unifying contribution of different theoretical approaches, such as Dynamical Mean-Field theory, Diagrammatic and Quantum Monte Carlo methods. Special attention was devoted to the exotic superfluid and superconducting states which arise from the interplay between pairing, correlations, disorder and reduced dimensionality. Organizers: M. Capone (CNR-IOM and SISSA Trieste), A. Georges (CNRS and Collège de France), S. Giorgini (BEC Center), R. Grimm (Univ. Innsbruck and IQOQI), D. Van del Marel (Univ. Geneva). The program included 32 invited speakers.

Innsbruck-Trento Joint Meeting on
Quantum gases
September 29-30, 2014, Trento

This was one of the traditional meetings of the BEC Center with the colleagues of Innsbruck working in the same field of quantum gases. This time the meeting was held in Trento and the program included, as usual, a few selected talks and many informal discussions.



7th International Workshop on
Quantum gases and quantum coherence
May 28-31, 2014, Levico Terme, Trento

This was the seventh edition of a successful series of workshops dedicated to the theoretical and experimental challenges in the field of quantum gases, with a strong connection to other areas of physics including strongly correlated systems, low-dimensional systems, synthetic fields, disorder effects, dipolar gases, matter waves, etc.. One of the main goals of this workshop was to bring together young researchers coming from Europe and overseas. The program was divided in 5 session opened by leading senior scientists (I.Bloch, T.Pfau, A.Sinatra, N.Cooper, F.Schmidt-Kaler), followed by 4 talks by junior scientists selected by the advisory committee. A poster session opened to all the participants was an important moment of the workshop. The participants were 116. Previous editions of this workshop were held in Salerno (2001), Levico Terme (2003), Cortona (2005), Grenoble (2008), Nice (2010), and Lyon (2012). Organizers of this edition were: A. Recati (INO-CNR BEC), G. Lamporesi (INO-CNR BEC), T. Roscilde (ENS, Lyon), A. Minguzzi (LPMMC, Grenoble), R. Citro (Uni. Salerno), F. Chevy (ENS, Paris).

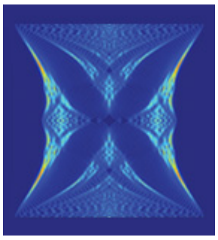
Workshop on
Coherent Phenomena in Disordered Optical Systems
May 26th-30th, 2014. ICTP Trieste

This interdisciplinary workshop was co-organized by D. Basko, I. Carusotto, G. Labeyrie, S. Skipetrov, and V. Kravtsov. The idea of the workshop was to bring together researchers working on various aspects of disordered systems and those working on spontaneous coherence effects in optical systems, in particular Bose-Einstein condensation of polaritons and random lasing. The main topics covered were polariton BECs in disorder, atomic BECs in disorder, disordered photonics and random lasing, Anderson localization, disordered superconductors, glasses.

Workshop in honor of
Lev Pitaevskii's 80th birthday
July 6th, 2013, Trento

This workshop has been an occasion for reviewing the exciting advances of the field of many-body physics to which Lev has given fundamental contributions during more than 50 years.

Talks were given by Gordon Baym (University of Illinois), Eric Cornell (University of Colorado), Rudolf Grimm (University of Innsbruck), Serge Haroche (Collège de France and ENS), Jason Ho (Ohio State University), Massimo Inguscio (LENS and University of Florence), Anthony J. Leggett, (University of Illinois). About 100 people attended the event.



Summer Program on
Synthetic Gauge Fields for Atoms and Photons
July 1-12th, 2013, Trento

Prominent researchers from the cold atom and the photon/polariton communities with a specific interest for quantum gases in synthetic gauge fields were invited to Trento within a two-week program. Experimental investigations of this concept are in rapid progress in both contexts, and several remarkable observations has been already reported. Theoretical work is providing promising results in view of generating and manipulating novel exotic phases of quantum matter with possible applications to quantum information processing. This meeting was one of the very first events in which a community interested in topological effects with light could meet. The meeting involved about 45 participants. Organizers: Iacopo Carusotto (BEC Center), Nigel Cooper (Univ. Cambridge), Jean Dalibard (ENS Paris), Sandro Stringari (BEC Center).

Honors

Iacopo Carusotto has been recognized by the Outstanding Referee program 2014 of the American Physical Society (only three italians have been awarded in 2014). He is the second Outstanding Referee of the BEC Center after Sandro Stringari, who was recognized in 2012.

On June 21, 2013, Lev P. Pitaevskii received the Doctorate Honoris Causa (Ehrendoktorat der Naturwissenschaften) at the Universität Innsbruck.

Marco Larcher has been awarded a "Best PhD Thesis 2013" by the University of Trento for his thesis work on the localization and spreading of matter waves in disordered potentials.

In recognition of his scientific work Alessio Recati has been awarded a Von Humboldt Research Fellowship for Experienced Researcher for 18 months, starting from Summer 2014.

Outreach

The researchers of the BEC experimental laboratory have been involved in the European Researchers' Night 2013, for the activities organized in Trento, at the new museum of Science, MUSE.

The BEC Center promoted public events within the series "Colloqui in collina". The series is aimed at popularizing themes of modern science for a general audience and is co-organized by the several Departments of the University of Trento within the campus of Povo. The BEC Center promoted the colloquium *Quantum information: a scientific and technological revolution for the 21st century*, by William D. Phillips (NIST, Gaithersburg) in June 2016, and the colloquium *A quantum Universe before the Big Bang(s)?*, by G.Veneziano (Collège de France, Paris) in May 2016. Moreover, in February 2016, a public video-conference has been organized with R.Glauber (Harvard University), in occasion of the projection of the documentary *That's the Story. Prof. Roy Glauber Remembers the Making of the Atomic Bomb*.

Members of the BEC Center are involved in the initiative "Incontri con le scuole", offered by the University of Trento, consisting of seminars in various research disciplines held in the high schools of Trento and the surrounding regions. The topics of the seminars offered by the BEC Center include the birth of atomic physics, the evolution of science in the twentieth century, and the basic ideas of quantum mechanics.