Istituto Nazionale di Ottica
Consiglio Nazionale delle Ricerche

Center on

Bose-Einstein Condensation

Trento, Italy

Scientific Report

2010 - 2013

The BEC Center is hosted and supported by Department of Physics, University of Trento
The BEC Center is co-funded by Provincia Autonoma di Trento

Contents

Overview

More than ten years have passed since the opening of the Center on Bose-Einstein Condensation (BEC), which was established in Trento by the Istituto Nazionale per la Fisica della Materia (INFM) in June 2002. The main goal of the Center was to promote theoretical research on the various phenomena related to Bose-Einstein condensation and to the physics of cold atomic gases. This area of research has grown tremendously worldwide after the first observation of BEC in trapped cold gases in 1995. The contribution given by the BEC Center has been significant. Almost four hundred articles have been published in peer reviewed scientific journals with the affiliation of the BEC Center since 2002 and the overall amount of citations obtained by the researchers of the Trento team has increased above 1800 citations a year, according to ISI - Web of Science, with an average of 40 citations per article. The Center has contributed also to the reinforcement and the creation of international collaborations by promoting the mobility of scientists, as well as organizing workshops and conferences. Last but not least, the creation of the BEC Center has been a great opportunity for offering permanent positions to young researchers and a good training to undergraduate and graduate students, who eventually obtained concrete directions for their careers in Italy and abroad.

An important change has occurred in the recent years as regards the institutional framework. In 2006, INFM became part of the Consiglio Nazionale delle Ricerche (CNR), which in turn was reorganized in new institutes. As a result of such a reorganization, since February 2010 the BEC Center has been incorporated into the Istituto Nazionale di Ottica (INO-CNR). The long term strategies and the scientific projects have been almost unaffected by this institutional change, with the positive consequence that the Center now has closer connections with other groups of the INO, especially in Florence, which have a solid expertise in atomic physics and quantum optics.

Figure 1: A photo in occasion of Ketterle's visit in 2010.

The idea of creating a Center devoted to the theoretical investigation of quantum gases came originally from a group in the Physics Department of the University of Trento, led by Sandro Stringari. Thanks to INFM, this idea progressively took the form of a joint initiative of the University of Trento and INFM-CNR, and eventually INO-CNR. The role of the Department of Physics is still very important: it hosts the Center, providing facilities and services, as well as a multidisciplinary scientific environment. Moreover, graduate and undergraduate students of the University actively participate in the scientific projects and CNR researchers are regularly involved in education and training programmes. In this sense, the BEC Center can certainly be regarded as a good example of close collaboration between the University and CNR, working together towards a common goal. Last but not least, the Center benefits from the presence of nearby research institutions, namely, the European Centre for Theoretical Studies in Nuclear Physics and related areas (ECT*) and the Bruno Kessler Foundation (FBK).

Since the very beginning the BEC Center was supported by the Provincia Autonoma di Trento (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, and this starting grant was indeed essential to win the competition opened by INFM for the creation of centers of excellence in Italy. 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). This agreement was aimed to support the activities and the scientific projects of the BEC Center in the field of physics of ultracold atomic gases and related areas, including the start-up of a new line of research in experimental physics with ultracold atoms.

Figure 2: The area in Povo where the BEC Center is located.

The opening of a laboratory for ultracold atoms in Trento represents the true novelty of the last years. The motivations behind this choice are manifold. An impressive number of experimental groups worldwide are actively working in the field of ultracold atomic gases, but only a few of them are operating in Italy, namely at LENS-Florence and in Pisa. This field of research is still growing and there is no sign of saturation; indeed ultracold atoms have proven to be a versatile tool for exploring new physics in an interdisciplinary context, from atomic physics to quantum optics, statistical mechanics and condensed matter physics. Hence there is still plenty of space for novel experimental projects. This offers good opportunities and prospects to the young researchers who are maturing in the top laboratories in Italy and worldwide. It is also an opportunity for increasing the visibility and the attractiveness of the area of Trento, by properly combining the already existing theoretical activities with new experimental programs, thus opening new directions of research and a wider network of collaborations. With these motivations and with the support of INO-CNR, the Department of Physics of the University and the Provincia Autonoma di

Trento, the project has finally started. Rooms were found within the space of the Department of Physics; the works needed to adapt the rooms took a few months; then the installations of equipment and facilities followed. In the meanwhile, the group members have been recruited. In a few months they cooled and trapped Sodium atoms in a magneto-optical trap and then started the evaporative cooling, obtaining the first condensate in December 2012. The laboratory is presently fully operational.

On the theory side, the BEC Center has produced a number of interesting results along the different lines of research, ranging from superfluidity and coherence properties of Bose and Fermi gases, to non-equilibrium BEC in exciton-polariton gases, as well as interferometry and quantum information. The group publishes articles in journals of high impact. Since 2009, the list of publications includes 29 Physical Review Letters, 2 Science, 1 Nature, 1 Nature Physics, 1 Nature Photonics, 1 Reviews of Modern Physics. A summary of the most relevant results will be given in this report, together with other useful information: the structure of the Center, the main achievements, the list of publications, seminars, events, collaborations. What may be missing here, can likely be found on the website of the BEC Center (**http://bec.science.unitn.it**), which is regularly updated.

Trento, June 2013

Figure 3: The BEC group, in Summer 2012.

Staff, researchers, scientific board

Principal Investigator of the PAT-CNR Project

Sandro Stringari

Head of the Trento Unit of Istituto Nazionale di Ottica

Franco Dalfovo

Secretariat

Beatrice Ricci

Flavia Zanon

Personnel of University of Trento

Franco Dalfovo

Stefano Giorgini

Lev P. Pitaevskii

Sandro Stringari

Personnel of INO-CNR

Iacopo Carusotto

Gabriele Ferrari (since 2010)

Giacomo Lamporesi (since 2011)

Chiara Menotti

Alessio Recati

Augusto Smerzi (in Florence, since September 2011)

Postdocs

Davide Sarchi

Francesco Bariani

Jan Chwedenczuk

Philipp Hyllus

Michael Klawunn

Robin G. Scott

Fabrizio Logiurato

Rıfat Onur Umucalılar

Li Yun

David Papoular

Stefano Finazzi

Riccardo Rota

Marta Abad Garcia

Tomoki Ozawa

Zeng-Qiang Yu

PhD Students

Francesco Piazza

Gianluca Bertaina

Manuele Landini

Marco Larcher

Natalia Matveeva

Hou Yan-Hua

Zou Peng

Nicola Bartolo

Giovanni Martone

Luis Aldemar Peña Ardila

Alberto Sartori

Simone Donadello

Grazia Salerno

Technical Staff

Giuseppe Froner

Michele Tomasi

Scientific board

Jean Dalibard

Rudolf Grimm

Christopher J. Pethick

William D. Phillips

Gora Shlyapnikov

Former members of the BEC Center (2002-2010)

Luciano Viverit, Murray Holland, Weidong Li, Luca Giorgetti, Uffe Poulsen, Paolo Pedri, Meret Krämer, Christian Trefzger, Brian Jackson, Marco Cozzini, Cesare Tozzo, Grigory E. Astrakharchik, Michiel Wouters, Nikolai Prokof'ev, Zbigniew Idziaszek, Giuliano Orso, Massimo Boninsegni, Dörte Blume, Shunji Tsuchiya, Tommaso Calarco, Carlos Lobo, Gabriele De Chiara, Mauro Antezza, Luca Pezzè, Georg Morten Bruun, Michele Modugno, Petra Scudo, Gentaro Watanabe, Edward Taylor, Sebastiano Pilati, Ingrid Bausmerth.

Visiting scientists

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 (Univ. Polit. Catalunya, 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

Hannah Price (Univ. Cambridge, UK), January 7-9, 2013

Tommaso Macrì (MPI Dresden, Germany), December 17-20, 2012

Marta Wolak (INLN, Nice and CQT-NUS, Singapore), December 10-13, 2012

Martin Kroner (ETH Zurich, Switzerland), November 12-13, 2012

Grigori Astrakharchik (Univ. Polit. Catalunya, Barcelona), Oct 24 - Nov 6, 2012

Shunji Tsuchiya (Tokyo Univ. of Science, Japan), September 6-7, 2012

Marcello Dalmonte (Univ. Innsbruck, Austria), September 5-7, 2012

Paolo Zanardi (Univ. Southern California), July 20, 2012

Chris Vale (Swinburne University, Australia), July 19-20, 2012

Gianluca Bertaina (EPFL Lausanne), July 2-5, 2012

Dario Poletti (Univ. Geneve, Switzerland), June 11-12, 2012

Jan Chwedenczuk (Univ. Warsaw, Poland), May 23-25, 2012

Federico Becca (SISSA Trieste), May 7-8, 2012

Carlos Lobo (Univ Southampton), April 17-20, 2012

Tomasz Karpiuk (CQT-NUS, Singapore), April 17-27, 2012

Davide Galli (Univ. Milano), April 16-17, 2012

Patrizia Vignolo (Univ. Nice - Sophia Antipolis), April 16-17, 2012

Sebastiano Pilati (ICTP Trieste), April 3-5, 2012

Amit Rai (CQT Singapore), March 21-25, 2012

Christophe Salomon (LKB-ENS, Paris), March 6-7, 2012

Mikhail Baranov (Univ. Innsbruck, Austria), February 27-27, 2012

Hanns-Christoph Ngerl (Univ. Innsbruck), February 20, 2012

Giovanni Modugno (LENS and Univ. Firenze), February 20, 2012

Donatella Ciampini (Univ. Pisa), February 20, 2012

Alessandro Zenesini (Univ. Innsbruck, Austria), February 10, 2012

Francesco Minardi (INO-CNR and LENS, Firenze), February 6, 2012

Grigori Astrakharchik (Univ. Polit. Catalunya, Barcelona), February 6-10, 2012

Hui Zhai (Tsinghua Univ., Beijing, China), 28 January - 10 February, 2012

Zeng-Qiang Yu (Tsinghua Univ., Beijing, China), 28 January - 10 February, 2012

Dario Gerace (Univ. Pavia), January 12-13, 2012

Ulf Leonhardt (University of St Andrews, UK), November 4, 2011

William Simpson (University of St Andrews, UK), September-December, 2011

Grigori Astrakharchik (Univ. Polit. Catalunya, Barcelona), October 17-22, 2011

Roberto Balbinot (Univ. Bologna), October 17, 2011

Dario Gerace (Univ. Pavia), October 3-22, 2011

Jean Dalibard (ENS Paris), October 3-6, 2011

Russel Bisset (Univ. Otago, New Zealand), September 12-16, 2011

Sam Rooney (Univ. Otago, New Zealand), September 12-16, 2011

Martin Zwierlein (MIT Boston), July 18-19, 2011

Drte Blume (Washington State University), July 7-8, 2011

Stefano Giovanazzi (Univ. Heidelberg), June 20-25, 2011

Joachim Brand (Massey Univ., Auckland, New Zealand), June 13-17, 2011

Mohammad Hafezi (JQI, University of Maryland and NIST), June 2-3, 2011

Roland Combescot (ENS Paris), May 27 - 31, 2011

Rudolf Grimm (IQOQI and Univ. Innsbruck), May 27, 2011

Riccardo Rota (Univ. Politecnica de Catalunya, Barcelona), May 18-20, 2011

Grigori Astrakharchik (Univ. Polit. Catalunya, Barcelona), May 16-21, 2011

Lee Collins (Los Alamos Nat. Lab), May 14-28, 2011

Li Weidong (Inst. Theor. Physics, Shanxi University), May 4-14, 2011

Gora Shlyapnikov (LPTMS, Orsay, France), April 7-8, 2011

Roberto Balbinot (Univ. Bologna), April 4, 2011

Stefano Finazzi (SISSA Trieste), April 4-5, 2011

Luca Barbiero (Politecnico Torino), February 28 - March 4, 2011

Mauro Antezza (Univ. Montpellier), March 2, 2011

Luis Santos (Univ. Hannover), February 28 - March 2, 2011

Andrea Trombettoni (SISSA, Trieste), February 28, 2011

Grigori Astrakharchik (Univ. Polit. Catalunya, Barcelona), February 21-26, 2011

Alexander Pikovski (Univ. Hannover, Germany), February 10-18, 2011

Marta Abad Garcia (Universitat de Barcelona), February-May, 2011

Carlos Lobo (Univ. Southampton, UK), February 1-5, 2011

Marco Moratti (LENS and Univ. Firenze), February 1-4, 2011

Luca Barbiero (Politecnico Torino), January 24-28, 2011

Carmen Invernizzi (Univ. Milano), January 24, 2011

Tilman Esslinger (ETH Zuerich), January 18-21, 2011

Angela White (Univ. Newcastle), December 15, 2010

Markus Oberthaler (Univ. Heidelberg), December 13-14, 2010

Vincenzo Savona (EPFL Lausanne), December 13-14, 2010

Jordi Boronat (UPC Barcelona), December 13-14, 2010

Andrea Trombettoni and Giacomo Gori (SISSA Trieste), December 9-12, 2010

Giacomo Roati (INO-CNR, LENS Firenze), December 9, 2010

Montserrat Guilleumas (Universidad de Barcelona), November 24-27, 2010

Marta Abad Garcia (Universidad de Barcelona), November 24-27, 2010

Jan Chwedenczuk (Warsaw University), November 22-27, 2010

Luca Barbiero (Politecnico Torino), September-December, 2010

Matteo Zaccanti (IQOQI, Innsbruck), July 27, 2010

Rudi Grimm (IQOQI, Innsbruck), October 13, 2010

Wolfgang Ketterle (MIT), September 29 - October 2, 2010

Rıfat Onur Umucalılar (Bilkent, Turkey), September 1-3, 2010

Matteo Zaccanti (IQOQI, Innsbruck), July 27, 2010

Christoph Kostall (IQOQI, Innsbruck), July 27, 2010

Yvan Castin (ENS Paris), July 19-23, 2010

Alice Sinatra (ENS Paris), July 19-23, 2010

Li Yun (ENS Paris and ECNU Shanghai), July 12-15, 2010

Carlo Sias (Cambridge, UK) June 21, 2010

Carsten Klempt (Hannover), June 11, 2010

Gentaro Watanabe (APCTP Pohang, Korea) June 7-8, 2010

Gabriele Ferrari (INO-CNR and LENS Florence), June 8, 2010

Daniele Sanvitto (UAM Madrid), May 31 - June 2, 2010

Artur Widera (Univ. Bonn, Germany), May 20, 2010

Matteo Zaccanti (LENS-Florence, and IQOQI-Innsbruck), May 5-6, 2010

Tom Montgomery (Univ. Nottingham), April 15-25, 2010

Corinna Kollath (Ecole Polytechnique, Palaiseau, France), March 3-5, 2010

Michael Köhl (Cambridge, UK), March 3-5, 2010

Wilhelm Zwerger (Technische Univ. Muenchen), Visiting Professor, March-April 2010

Carlo Lobo (Cambridge, UK), February 14-20, 2010

Riccardo Sturani (Univ. Urbino), February 8, 2010

Julian Grond (Univ. Graz, Austria), February 1-14, 2010

Carlos Mayoral (Univ. Valencia, Spain), February 4-26, 2010

Carlo Nicola Colacino (Univ. Pisa and INFN), February 7-9, 2010

Daniel Faccio (Univ. Como), February 1-2, 2010

Nicolas Pavloff (LPTMS, Orsay, France), January 24-27, 2010

Luca Pezzè (Lab. C. Fabry de l'Inst. d'Optique, Orsay), January 11-12, 2010

Philipp Treutlein (LMU Munich), January 11, 2010

Scientific collaborations

The BEC Center operates within a wide network of scientific collaborations. About 60% of the articles published in international journals by the BEC team are the result of joint projects with theoretical and experimental groups in the main laboratories around the world. Among them, those listed below are worth mentioning.

- *Florence, European Laboratory for Nonlinear Spectroscopy.* The Trento team has a long and fruitful experience of collaboration with the experimental group of Massimo Inguscio at LENS. Regular meetings are organized between the two groups on topics of common interest. Recent collaborations regard the properties of ultracold bosons in quasiperiodic lattices and projects in quantum interferometry with cold atoms. The BEC Center also took great advantage of the expertise of the researchers at LENS in planning the creation of the new experimental laboratory in Trento. The CNR researchers involved in this project, Gabriele Ferrari and Giacomo Lamporesi, moved from the labs in Florence to the BEC Center in Trento. In the opposite direction, Augusto Smerzi left Trento to lead a new research group in Florence. Collaborations have been recently opened with researchers of the Istituto Nazionale di Ottica at LENS for projects in photonics and quantum optics.

- *Innsbruck, Austria.* Since the very beginning, the BEC center has been continuously in touch with the colleagues in Innsbruck, namely with the P.Zoller and co-workers at the Institute for Theoretical Physics and with the group of R.Grimm at the Institute for Experimental Physics at the University of Innsbruck and at the Institute for Quantum Optics and Quantum Information (IQOQI) of the Austrian Academy of Sciences. Regular meetings are organized among the groups both in Trento and Innsbruck. Several experiments in Innsbruck have been stimulated by and/or interpreted with theories developed in Trento. The most recent collaboration lead to a publication in Nature on the observation of second sound and the superfluid fraction in a Fermi gas with resonant interactions, with the experiments performed by Grimm's group in Innsbruck and the theory developed in Trento. With the opening of the new laboratory for ultracold atoms in Trento the collaboration between the BEC Center and Innsbruck is further reinforced. Common initiatives are organized also at the level of master and PhD courses.

- *Paris, Ecole Normale Superieure.* The collaboration of I. Carusotto with Yvan Castin is actively going on since 1999. In the last years, the collaboration has concerned the development and characterization of protocols for the local measurement of the normal and superfluid fractions of two-dimensional, trapped Bose gases across the BKT transition temperature. The BEC center also collaborates with Roland Combescot; recent joint activities has focused on the study of elementary excitations in superfluid Fermi gases and on the normal state of highly polarized configurations. A fruitful collaboration has been established also with the experimental group lead by C. Salomon on the topic of the properties of a strongly correlated Landau Fermi liquid in the BCS-BEC crossover.

- *Paris, Laboratoire MPQ of University Paris 7.* The success of the long-standing collaboration of I. Carusotto with Cristiano Ciuti on the physics of the so-called "Quantum Fluids of Light" has been internationally recognized with the invitation to write a few popular science articles on this subject for Europhysics News and Il Nuovo Saggiatore, as well as a long, hopefully authoritative review article for Reviews of Modern Physics. In the meanwhile, close contact has been maintained with the experimental group at LKB, which has actively worked to experimentally investigate our ideas (see next paragraph). In addition to quantum fluids of light, the collaboration with MPQ has also addressed the physics of the electromagnetic quantum vacuum in semi- and super-conductor devices.

- *Paris, LKB of UPMC, ENS, CNRS.* This collaboration of I. Carusotto with Alberto Bramati and Elisabeth Giacobino has started out in 2007 with the aim of experimentally studying the superfluidity properties of polariton condensates. The theoretical work is performed jointly by the BEC Center and University Paris 7 (see previous paragraph). A first joined theoretical-experimental work has demonstrated superfluid flow in the presence of weak defects. In the last few years, we have continued along this line by focussing on more complex quantum hydrodynamic phenomena such as the hydrodynamic generation of topological excitations (i.e. vortices and solitons) in flowing polariton superfluids hitting large defects.

- *Paris, Orsay, LPTMS.* A collaboration with Nicolas Pavloff has been established in the last two years on analog models. The collaboration aims to describe possible, experimentally feasible, sonic hole configuration in one-dimensional Bose gases within Bogoliubov theory. Alessio Recati spent one month at LPTMS to strengthen such collaboration.

- *Copenhagen, Niels Bohr Institute.* A fruitful collaboration with Georg Bruun and Chris Pethick has been carried on in the last years on the problem of damping and decaying of impurities in a Fermi bath.The results obtained have also been recently nicely confirmed by an experiment performed at MIT (Boston) by the Zwierlein's group.

- *Cambridge/Southhampton, UK.* The collaboration with Carlos Lobo on the strongly interacting Fermi gas has been going on for several years. It allowed the BEC Center to have also a good interaction with the experimental group lead by Michael Köhl in Cambridge.

- *EPFL Lausanne and University of Antwerp.* The collaboration of I. Carusotto with Michiel Wouters on the physics of quantum gases of exciton-polaritons in semiconductor microcavities started back in 2004 when Wouters was post-doc at the BEC Center. In the last years this collaboration has focussed on a conceptual study of the meaning of superfluidity for non-equilibrium condensates and the definition of a generalized Landau criterion for superfluid flow. This collaboration is nowadays developing in the direction of studies of Berezinskii-Kosterlitz-Thouless physics in non-equilibrium two-dimensional polariton gases.

- *Zurich, ETH.* Since I. Carusotto's sabbatical semester in the Quantum Photonics Group at ETH during the winter 2008/09, a collaboration is in place in view of creating and studying gases of strongly interacting photons in semiconductor microstructures. This project is being carried out following two main axis: on one hand we are trying to theoretically characterize strongly correlated states of many-photons and identify protocols to prepare them. On the other hand, we are studying specific devices where this physics could be addressed in the lab. Very recently, this collaboration has been included as a workpackage in a project led by prof. Lorenzo Pavesi of Trento University. The BEC team has also collaborated with the group of M. Troyer on various pro jects including the study of itinerant ferromagnetism in a repulsive Fermi gas and the magnetic properties of a strongly interacting normal Fermi liquid.

- *Universität Ulm, Germany.* In the last years, the Trento activity on quantum information has taken great advantage from the collaboration with T. Calarco, a former member of the BEC Center, who got a professorship in Ulm. The activity is mainly based on proposals of realistic quantum gates and entanglement on atom chip.

- *Munich, TUM and LMU, Germany.* In the past years we have had a fruitful collaboration with W. Zwerger at Technical University of Munich (TUM) on the study of cold gases in reduced geometries. Very recently we started a new collaboration with Zwerger's group on the polaron physics in two-dimensional Fermi gases. Alessio Recati spent several months in the group of Zwerger during the academic year 2008-09. Another collaboration has involved Augusto Smerzi in Trento and H.Weinfurther at LMU about Mach-Zehnder interferometers with quantum correlated input states.

- *Amherst, Univ. Massachusetts.* Since the sabbatical leave spent with our group by Prof. Nikolay Prokof'ev in 2006, we have started a fruitful collaboration with him and his group. Recent collaborations regarded the problem of the superfluid transition and the thermodynamic behavior of a Bose gas in the presence of correlated disorder modeled by a speckle optical potential and Beliaev technique for a weakly interacting Bose gas.

- *University of Toronto, Canada.* In the recent years S. Stringari and L. Pitaevskii worked on the problem of second sound in superfluid atomic gases in collaboration with Allan Griffin of the University of Toronto, and Ed Taylor, a former Griffin's student who spent two years in Trento as a postdoc. Another joint project has been involved A. Smerzi in Trento and the experimental group of J. Thywissen in Toronto on the dynamics of a tunable superfluid junction.

- *Barcelona, UPC.* The collaboration between the Trento BEC group and the quantum Monte Carlo group at the Universitat Politecnica de Catalunya (UPC) has been a constant thread over the last years. Members of our group have often visited UPC for short periods and Grigory Astrakharchik, a former research associate in Trento and now at UPC, comes regularly to Trento collaborating with our group on a project concerning quantum Monte Carlo simulations of ultracold fermions with resonant interactions and models for low-dimensional gases.

- *Barcelona, IFCO.* The long lasting collaboration with Maciej Lewenstein (till 2005 in Hannover) has been continued after his move to ICFO - The Institute for Photonic Sciences, Barcelona. Chiara Menotti has spent in his group two years in the framework of an individual Marie Curie Fellowship centered on the study of correlated atoms in optical lattices and in particolar the quantum phases and metastable states of dipolar atoms. Moreover the PhD Thesis of a former Diploma student of the Trento group, Christian Trefzger, has been co-supervised by Maciej Lewenstein and Chiara Menotti.

- *Università di Bologna, Università di Pavia, Universidad de Valencia, LPT Orsay.* The interest of A. Recati and I. Carusotto in the physics of analog Hawking radiation from acoustic black holes in atomic BECs started in early 2006 in collaboration with R. Balbinot in Bologna and his coworker A. Fabbri in Valencia. Their expertise in the physics of black holes and quantum fields in curved space-time was complementary with the one of the BEC Center on many-body physics. After the first numerical observation of Hawking radiation from acoustic black holes in atomic Bose-Einstein condensates in 2008, we have extended our studies to white hole configurations, analog black holes in quantum fluids of light, and analog models based on strong optical pulses propagating through nonlinear optical crystals. In the last years, Dario Gerace from Pavia and Renaud Parentani have actively joined this collaboration, whose members are used to meet at least one per semester to discuss all together.

- *Los Alamos National Laboratory.* Augusto Smerzi has a stable collaboration with the Los Alamos National Laboratory, Los Alamos (New Mexico, USA), namely with the groups of Lee Collins. The investigated problems are mostly related with the superfluidity properties of BEC and entanglement phenomena.

- *Pohang, Asian Pacific Center for Theoretical Physics, Korea.* Gentaro Watanabe, a former postdoc of the BEC Center, has now a position as junior research leader at APCTP. A collaboration with him is active on the problem of superfluid fermions in optical lattices.

- *Bilbao, Universidad del Païs Vasco.* Michele Modugno, who has a position as Ikerbasque Research Professor in Bilbao, has been collaborating with the Trento team since many years. Recent projects include the behavior of condensates in optical lattices and in random potentials.

- *Massey University, Auckland, New Zealand.* A collaboration with Joachim Brand and his group has recently been started for the investigation of superfluid fermions in the BCS-BEC crossover; a joint work has been already published on the stability of solitons, and now the collaboration is focused on the problem of snake instabilities of dark solitons.

- *MPI Dresden, Germany.* A joint project has been realized with the group of Sergej Flach at the Max Planck Institute for the Physics of Complex Systems in Dresden. The project was an essential part of the PhD thesis of Marco Larcher, under the supervision of Franco Dalfovo, for the study of the diffusion of matter waves in quasiperiodic potentials.

- *Beijing, Tsinghua University, China.* We have recently started a new collaboration with the team of Hui Zhai, aimed to investigate the dynamic behavior of quantum gases in the presence of non-abelian gauge fields. In summer 2012, a joint symposium has been organized to strengthen the collaborations between the Trento and the Tsinghua cold atom groups. A postdoc from Tsinghua, Zeng-Qiang Yu, has joined the BEC group at the end of 2012.

- *Nanoscience lab of Trento University and Advanced Photonics and Photovoltaics group of FBK.* This collaboration is active since the mid-2000 on subjects related to integrated optics, in particular silicon-based microresonator devices. The simultaneous presence on the Povo-Trento hill of theoretical and experimental expertise on these themes is leading to exciting developments in the field of classical and, more recently, quantum photonics.

Theory: research outline and selected papers

This report provides an overview of the main scientific activities of the last three years. The scientific work carried out at the BEC Center can be divided into two main parts: an experimental project and the theoretical activities. The experimental project will be the subject of a subsequent section. Here we briefly introduce the main themes of theoretical investigations.

Theory of quantum gases

Ultracold gases are the archetype of a wider class of systems known as quantum fluids. They are dilute and clean; they can be confined in different 3D, 2D and 1D geometries; the interaction between particles can be tuned from very weak to very strong. This is why the theory of these gases is so rich. It is also interdisciplinary, many key concepts being used in different contexts as well, such as solid state physics, superconductors, superfluid helium, neutron stars, but also in systems of photons and more exotic particles.

The theoretical activity in Trento ranges from the description of dilute Bose gases using Gross-Pitaevskii theory to the implementation of more advanced many-body approaches for strongly correlated systems and interacting Fermi gases. Both equilibrium and dynamic properties are investigated at zero and at finite temperatures. Particular attention is devoted to superfluid and quantum coherence effects, quantum mixtures, long range interactions, magnetic properties, low dimensionality and optical lattices.

Superfluidity.

Superfluidity, like superconductivity, is a spectacular manifestation of quantum mechanics in macroscopic systems. It was first observed in liquid Helium in the late 30's and soon became the object of important experimental investigations and theoretical studies, attracting the attention of leading scientists worldwide. Ultracold atoms provide an extremely rich environment for studying superfluid phenomena, which are observed below a critical temperature in both Bose and Fermi gases. The peculiar hydrodynamic nature of the collective oscillations, the propagation of first and second sound, the quantization of vorticity, the reduction of the moment of inertia, the existence of permanent currents, the absence of viscosity, are all key aspects of superfluidity. The Trento team has given important contributions to the understanding of these phenomena, developing theoretical approaches, interpreting experimental observations, and stimulating new experiments to test the theoretical predictions.

Matter waves, coherence and disorder.

Bose-Einstein condensates, and superfluids in general, are characterized by a complex order parameter having a well-defined phase. The appearance of this phase has important consequences. It gives rise to Josephson effects in the presence of weak links or in a double-well geometry. It causes interference patterns in the expansion of BECs, or when a BEC is released from an optical lattice. It produces peculiar effects when the gas is moving in a disordered potential or in the presence of obstacles or impurities. Ultracold atomic gases have been shown to be an extremely versatile tool to investigate all of these effects. Thanks to their extreme controllability, they allow for the characterization of the interplay between phase coherence and decoherence processes, with many implications in the fields of quantum information and quantum computation, among others. Several research lines have been devoted to these topics in Trento.

Strongly interacting Fermi gases.
Interacting Fermi gases exhibit a rich variety of many-body states, ranging from a superfluid phase of Cooper pairs to the formation of bosonic molecules. A continuous transition between those regimes, known as BCS-BEC crossover, can be realized experimentally by using an external magnetic field to tune the value of the scattering length across a Feshbach resonance. Exactly on resonance, one finds the unitary Fermi gas, characterized by an infinitely large scattering length leading to a universal behaviour of the thermodynamic functions. A large number of interesting issues concerning strongly correlated Fermi gases are still open. Among them, the consequences of superfluidity on the dynamics, the properties of solitons and vortices, and the effects of spin polarization are currently the object of deep investigations using different many-body approaches.

Quantum mixtures and spinor gases.
Mixtures of cold gases exhibit many interesting features, related to their ground states and excitations, that are absent in single-component gases. One can realize Bose-Bose, Fermi-Fermi or Fermi-Bose mixtures, controlling the relative population from the case of a single impurity in a bath, to spinor gases or exotic and subtle phases. The impurity problem with fermions is relevant for developing a Landau-Fermi liquid theory for strongly interacting gases. For bosons, the behavior of impurities is directly related to the concepts of superfluidity and quantum dissipation. External fields can be used to convert the different species of a mixture into each other. This gives rise to a wealth of new phenomena, including the internal Josephson effect, SU(2) symmetry-breaking phases, and spin-orbit coupling.

Spin-orbit-coupled gases.
Artificial gauge fields and spin-orbit-coupled configurations have been recently obtained in the laboratory using laser control techniques. This opens new frontiers of research of high interdisciplinary interest, concerning novel quantum phases, unique magnetic properties, anisotropic dynamics, rotonic excitations and supersolid effects. The Trento group has started an intense activity in these new directions.

Low dimensional physics.
Atoms can be optically confined in low-dimensional configurations. Indeed, cold gases are ideal systems for the observation of many-body phenomena where quantum and thermal fluctuations, or frustration, play a prominent role. One-dimensional configurations lead to the realization of exactly solvable models, Luttinger liquids, Tonks-Girardeau gas and spin-charge separation. In 2D it is possible to investigate subtle effects such as the vortex-antivortex proliferation in the Berezinskii-Kosterlitz-Thouless phase transition. Moreover, the presence of the transverse

confinement allows for new effects beyond the textbook models. One of the main goals of using optical lattices is the implementation of Hubbard-like models. This opens a challenging direction of using cold gases as a quantum simulator of known solid-state Hamiltonians and going beyond.

Dipolar gases.
Anisotropy and long range characterize dipolar forces and distinguish them from the usual short-range interatomic potentials. Dipolar forces can have either a magnetic (for atoms with large magnetic moment) or an electric nature (for polar molecules). Dipolar gases are under investigation in Trento, where the emergence of new quantum phases, the effects of dipolar drag and the physics of polarons are currently being studied. Special attention is given to the derivation of the Hubbard models adequate for the description of dipoles in optical lattices.

Monte Carlo simulations.
The aim of quantum Monte Carlo (QMC) methods is to provide an exact solution to the many-body problem using the microscopic Hamiltonian as the only input. Such "ab initio" numerical techniques are particularly well-suited when correlations are strong, in which case mean-field and perturbative approaches are bound to fail. These strong correlations may be induced by interactions, reduced dimensionality, or external fields. In contrast to Bose systems, where exact results are available for both ground-state and thermodynamic properties, simulations of Fermi systems are plagued by a "sign problem" due to the anti-symmetry of the wave function. Approximate schemes have to be used yielding, quantitatively reliable results in most of the cases. QMC methods have been applied by the Trento group to many different systems, including Bose and Fermi gases in low dimensions, bosons with disorder, and strongly coupled Fermi systems.

Quantum Fluids of Light

The long-term objectives of this research line are to explore what new exotic states of matter can be generated in quantum fluids of light and, conversely, how many-body effects in the fluid of light may reflect into new applications to quantum photonic technologies. A summary of our achievements and our perspectives can be found in the review article that we have recently published on Reviews of Modern Physics in collaboration with Cristiano Ciuti from University Paris 7.

These investigations started out in 2004 with the prediction of superfluid phenomena in a fluid of dressed photons (exciton-polaritons) was sent against a structural defect of a micro-cavity. This prediction was soon later experimentally demonstrated at LKB in Paris: While at high speeds a variety of perturbations appear (Cerenkov cones, dark solitons, vortices), at low speeds no excitation is created in the fluid. Theoretical and experimental extension of these studies to more complex hydrodynamical phenomena has followed.

In the last years, several new directions have started been explored, mostly in the direction of observing very quantum behaviours in these gases. When interactions between photons become very large, the photon fluid ceases being a dilute superfluid and enters the regime of a strongly correlated photon fluid, with peculiar new behaviours. While non-equilibrium Tonks-Girardeau gases were studied back in 2008-9, our more recent activities have focussed on cases where the strongly interacting photon gas is subject to a so-called *synthetic magnetic field*: in this case, a much richer phenomenology has been anticipated, with close links with the one of the quantum Hall effect of two-dimensional electron cases under strong magnetic fields. Experimental developments along these lines are very active in many groups in the world.

Another important line is the study of quantum correlation in flowing superfluids of light: in suitably designed geometries, analog black hole configurations can be generated, where sound propagation on the photon fluid is analogous to the one of light around the horizon of an astrophysical black hole. In particular, we have studied how the so-called Hawking radiation process of quantum field theory gives rise to peculiar correlation patterns. This research is being carried out in close collaboration with colleagues expert in gravitational physics.

A selection of articles is presented in the following, with a brief summary for each of them. In ordering the articles, we basically follow the order of the topics in this section, starting from superfluidity of ultracold gases and ending with quantum fluids of light and solid state devices.

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

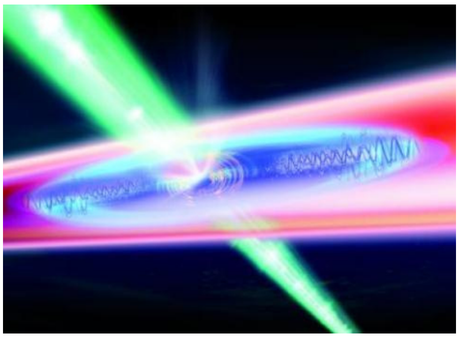

Figure 4: The cigar-shaped atom cloud is locally heated with a power-modulated laser beam (green). (Credit: IQOQI/Ritsch)

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. 105, 150402 (2010)

First and second sound in cylindrically trapped gases

G. Bertaina, L. Pitaevskii, S. Stringari

Superfluids are known to exhibit, in addition to usual sound, an additional mode, called second sound, where the superfluid and normal components move with opposite phase. The propagation of first and second sound in a nonuniform trapped gas exhibits interesting features both in the superfluid and in the normal phase. In this paper we focus on highly elongated configurations where the radial harmonic trapping provides the relevant non-uniformity of the gas. These configurations are well suited for the experimental excitation and detection of sound waves. In addition to requiring the usual hydrodynamic condition $\omega\tau <\ll 1$, where τ is a typical collisional time, we identify two different regimes, depending on the ratio between the viscous penetration depth $\delta = \sqrt{\eta/\rho_n\omega}$, where η is the shear viscosity coefficient, and the radial size $R_\perp$ of the trapped gas. If $\delta \gg R_\perp$, which corresponds to very low frequencies, the viscosity plays a crucial role: it forces the radial gradient of the velocity field of the normal fluid to vanish. Analogously the thermal conductivity imposes that the temperature fluctuations cannot vary as one moves along the radial direction. In the presence of harmonic trapping the condition of large viscosity penetration depth can be also written in the useful form $\omega \ll \omega_\perp 2\tau$. Under this condition, which is easily achieved in highly elongated traps, the Landau two-fluid hydrodynamic equations can be easily integrated radially, yielding a simple 1D hydrodynamic formulation of the macroscopic dynamics of the system. These equations are solved below the critical temperature where one predicts the value of the first and second sound velocities as a function of the temperature. For higher frequencies, corresponding to the opposite condition $\omega \gg \omega_\perp 2\tau$, we predict instead the occurrence of a new surprising class of excitations even above the critical temperature where, in the uniform case, the hydrodynamic equations would predict only the propagation of ordinary (first) sound. In the classical limit of high temperatures the response function is calculated analytically and is characterized, in addition to a pole characterized by the classical sound velocity $c = \sqrt{5k_BT/3m}$, by a continuum of excitations described by the following expression for the imaginary part of the density response function:

$$Im\chi(q,\omega) = \frac{4\rho_1\omega(c_0^2q^2-\omega^2)}{3mc_0^2(c^2q^2-\omega^2)} \tag{1}$$

where $c_0 \equiv \sqrt{24/25}\,c$, $0 < \omega < c_0 q$ and ρ_1 is the radially integrated 1D density. We find that the continuum of excitations described by the above equation, added to the contribution of the first sound pole, is crucial to satisfy both the compressibility and the energy weighted sum rules.

New J. Phys. 12, 043040 (2010)

Second sound and the density response function in uniform superfluid atomic gases

H. Hu, E. Taylor, X.-J. Liu, S. Stringari, A. Griffin

Second sound is one of the most dramatic effects associated with superfluidity in liquid ^{4}He, where it was measured in a rather systematic way. The propagation of second sound requires that the system be in conditions of local hydrodynamic equilibrium, characterized by short collision times between the excitations forming the normal fluid. In dilute gases this condition is difficult to achieve because the density and the s-wave scattering length are typically not large enough. For this reason interacting Fermi gases near unitarity are expected to be promising candidates. They are actually known to fulfil the hydrodynamic conditions even at relatively high temperatures. In this paper we provide a systematic study of the density response function of a uniform superfluid Fermi gas in the hydrodynamic regime, as described by the non-dissipative Landau two-fluid equations below the critical temperature. In particular we compare the poles of the response with the ones characterizing the behavior of superfluid helium, emphasizing differences and analogies. The main difference is that, in the proper units, the unitary Fermi gas is much more compressible than liquid helium. This result in a larger value of the coupling between first and second sound, opening new perspectives for the excitation of second sound employing density probes. The main analogies are related to the relevance of the phonon excitation spectrum which provides the key contribution to the thermodynamic functions at low temperature. In this paper we also compare the density response function of the unitary Fermi gas with the one of a dilute Bose-Einstein condensed gas. The differences are dramatic in this case, due to extremely large compressibility of the BEC gas which deeply changes the nature of second sound with respect to its usual identification as a temperature or entropy wave. In the paper we finally focus on the experimental possibilities to excite experimentally second sound using density probes, like two-photon Bragg scattering or density pulse propagation experiments.

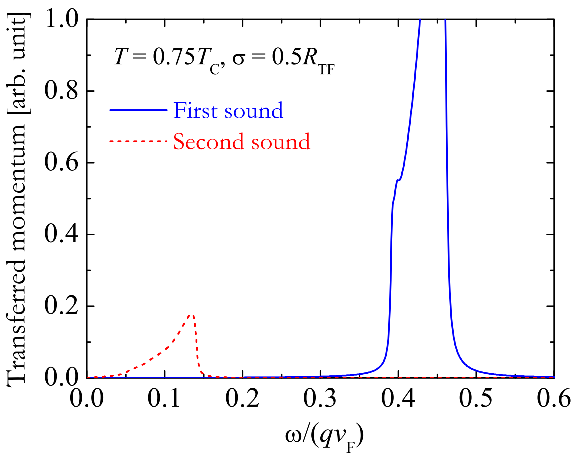

Figure 5: Momentum transferred to a trapped Fermi gas at unitarity by two-photon Bragg scattering due to first and second sound at $T \simeq 0.75T_c$. Blue and red lines show the momentum transferred due to first and second sound, respectively, as a function of the beam detuning ω divided by the relative wave vector q.

Phys. Rev. Lett. 109, 084501 (2012)

Increasing quantum degeneracy by heating a superfluid

D.J. Papoular, G. Ferrari, L.P. Pitaevskii, S. Stringari

The thermomechanical effect is an important manifestation of superfluidity. It has historically been observed via the fountain effect, i.e., the increase in the pressure in a narrow tube, one of whose ends dips in a bath of superfluid helium 4, when the tube is heated. It has recently also attracted interest in the context of dilute ultracold atomic gases as a potential signature of superfluidity in these systems. We have identified a novel thermomechanical effect which yields flows whose direction is inverted with respect to the fountain effect. This effect occurs both in superfluid helium 4 and in ultracold bosonic gases.

We consider a uniform superfluid confined in a box whose total volume is fixed. This box is split in two compartments by a superleak, which is permeable to the superfluid while blocking the thermal part. If one of the two compartments is heated, part of the superfluid flows through the superleak. We have shown that, under certain thermodynamic conditions, the atoms flow from the hotter compartment to the colder one, contrary to what happens in the fountain effect. This flow causes quantum degeneracy to increase in the colder compartment.

In superfluid helium, this novel thermomechanical effect takes place in the phonon regime of very low temperatures. In dilute bosonic gases, it occurs at all temperatures below T_c. It is also expected to take place in a Fermi gas in the superfluid regime. Its occurrence can be linked to the chemical potential increasing with temperature for a fixed value of the density. The effect is strongest in superfluid Bose gases because of their larger compressibility.

Instead of heating one of the compartments, one can also displace the superleak adiabatically. This causes quantum degeneracy to increase in the compartment whose volume increases. This reversible version of the effect is a new adiabatic cooling scheme for ultracold atoms.

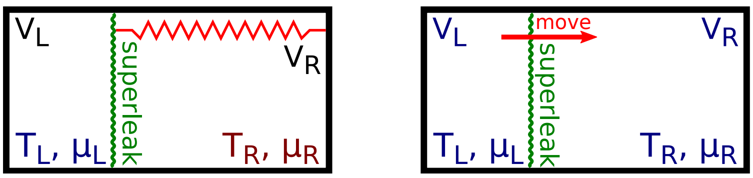

Figure 6: Schematics of the proposed experiment. The left and right compartments, initially at equilibrium, are filled with a homogeneous quantum fluid. Heating the right compartment (left), or displacing the superleak (right), causes the system to evolve towards a new thermodynamic state satisfying chemical, but not thermal, equilibrium.

Phys. Rev. A 81, 033613 (2010)

Current-Phase Relation of a Bose-Einstein Condensate Flowing Through a Weak Link

F. Piazza, L. A. Collins, A. Smerzi

The superfluid dissipation dynamics depends on the dimensionality and geometry of the system. However, they share the same underlying mechanism: the phase-slip. In a phase-slip event, the phase difference across the system drops by 2π, and thereby the velocity is decreased by a quantized amount. In the one-dimensional case, a dark soliton is created inside the weak link. In two- or three-dimensional cases, phase-slippage takes place through the nucleation of quantized vortices. The mechanism of phase-slippage based on vortex nucleation was proposed by Anderson in the context of superfluid helium. However, ultracold dilute atomic gases present some advantages for the study of superfluid dynamics in general, and in particular can shed new light on the physics of phase-slips.

Using the mean-field GP equation, we consider the dynamics of superfluid dilute BECs in the regime that the flow velocity reaches a critical value above which stationary currents are impossible. We study two- and three-dimensional BECs in two different geometries: a toroidal and a waveguide configuration, and also discuss the behavior of the critical current, or critical velocity, in different geometries and dimensionality, establishing a general criterion for the breakdown of stationary superfluid flows.

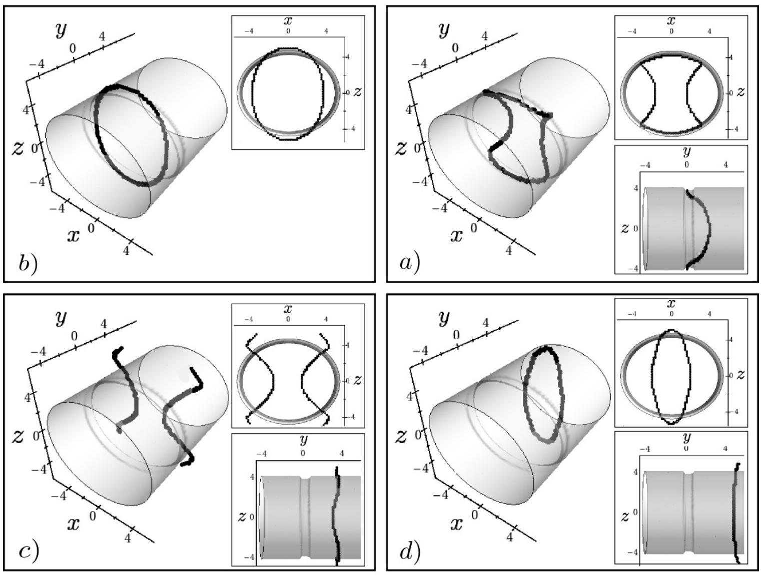

Figure 7: Four subsequent stages of the vortex ring dynamics in the axially asymmetric waveguide. The gray surface indicates the position of the Thomas-Fermi surface of the condensate. Black dots show the position of the vortex cores. Insets show the front and side view. a) A partially-ghost ring vortex has formed. b) The ring vortex is strongly deformed. c) The ring vortex has broken up leaving two vortex lines. d) The vortex lines have joined back to form a new ring vortex.

Phys. Rev. A 84, 023619 (2011)

Mach-Zehnder interferometry with interacting trapped Bose-Einstein condensates

J.Grond, U.Hohenester, J.Schmiedmayer, A.Smerzi

According to the common belief, atom interferometers using trapped Bose-Einstein condensates suffer from atom-atom interactions. Those have the effect of inducing phase diffusion, thereby decreasing the phase coherence. In Mach-Zehnder interferometers, even very small interactions during the interferometer performance destroy coherent spin squeezing and drastically reduce the phase sensitivity. In our studies of a Mach-Zehnder interferometer with trapped interacting condensates we find that the sensitivity is not substantially limited by interactions. This is because the nonlinearity induces small substructures, which serve as the measurement stick. The signal can then be uncovered using a Bayesian or Maximum-Likelihood phase estimation strategy. The phase sensitivity for a Twin-Fock input state always shows up Heisenberg scaling even for large interactions and durations of the nonlinear beam splitters. For input states with finite number squeezing we find a transition: Small number squeezing is in many cases even inferior to a binomial input state. Surprisingly, increasing the number squeezing further improves the phase sensitivity down to the Heisenberg limit. Finally we show that the results of this work are applicable under realistic conditions. We therefore simulate a Mach-Zehnder interferometer sequence in real space using the Multi-configurational time-dependent Hartree for Bosons method. During the beam splitters, rapid condensate oscillations are induced. In order to guarantee stationary condensates during phase accumulation and at the final time, we employ optimal control theory. A phase sensitivity close to the Heisenberg limit can be achieved also within the realistic model. We further demonstrate that the interferometer is robust against a realistic atom detection error, which only induces a gradual loss of sensitivity.

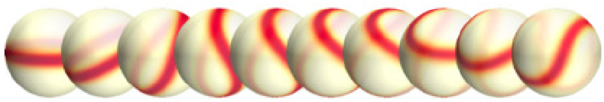

Figure 8: Mach-Zehnder interferometer sequence for a finite phase in presence of interactions, visualized on the Bloch sphere. A number squeezed initial state (small width along z-axis, number squeezing factor 0.2) is transformed into a phase squeezed one (small width along equator) by a BS (rotation around x-axis). Next a phase is accumulated due to an external potential (rotation around z-axis). A second BS transforms the state such that the phase is mapped onto a number difference. In the figure is shown that even for very small interactions the number squeezing in the final state is lost.

Phys. Rev. Lett. 106, 025302 (2011)

Dynamics of a tunable superfluid junction

L. J. LeBlanc, A. B. Bardon, J. McKeever, M. H. T. Extavour, D. Jervis, J. H. Thywissen, F. Piazza, A. Smerzi

Macroscopic quantum coherence phenomena, such as Josephson effects, emerge when superfluids are weakly linked across a barrier region. In the field of ultracold gases, Josephson effect(s) have been experimentally demonstrated in both double-well and multiple-well optical trapping potentials. All the so far performed experiments with dilute BECs are well described by a two-mode model, which is characterized by a sinusoidal current-phase relation. This fact indicates that the regime of transport so far explored was dominated by tunnelling, therefore close to the ideal Josephson regime.

We study the transport of a BEC between two wells separated by a tunable barrier, and experimentally demonstrate the crossover from hydrodynamic to ideal Josephson transport by analysing the measured frequency of the small amplitude plasma oscillations. As the barrier height V_b is adjusted from below to above the BEC chemical potential, μ, the density in the link region decreases until it classically vanishes when $V_b = \mu$. The healing length in the link region, ξ, increases with V_b and dictates the nature of transport through this region. In the low barrier regime, the oscillation frequency is well predicted by using hydrodynamic equations, while when V_b is higher than μ we find good agreement with a two-modes model. The experiments have been performed by the group of J. H. Thywissen in Toronto and the Trento team has contributed to the theoretical analysis.

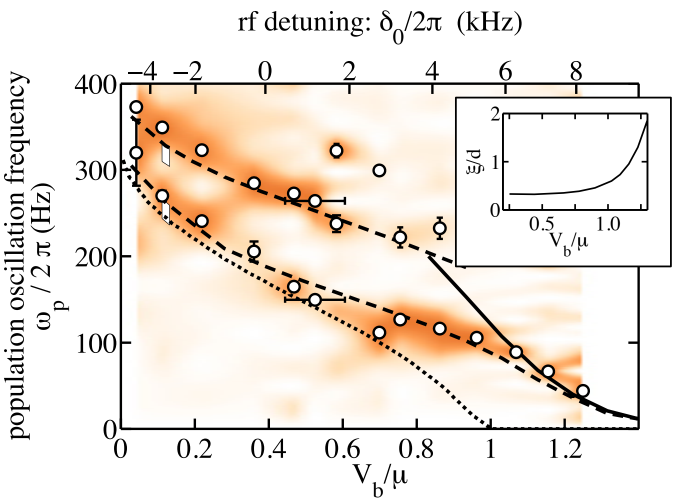

Figure 9: Frequency components of population imbalance vs. RF detuning (measured) and barrier height to chemical potential ratio (calculated). Experimental points (white circles) represent the two dominant Fourier components at each detuning. Dashed line represent 3D GP frequencies, the solid line the plasma oscillation frequency predicted by the TMM, and the dotted line the hydrodynamic result. Inset: ratio of healing length, ξ, to inter-well distance, d, as a function of V_b/μ. ξ is calculated at the center of the barrier.

New J. Phys. 13, 025007 (2011)

Acoustic white holes in flowing atomic Bose-Einstein condensates

C.Mayoral, A.Recati, A.Fabbri, R.Parentani, R.Balbinot, I.Carusotto

In the wake of the formal analogy between the propagation of quantum fields on a curved spacetime background and the propagation of sound on inhomogeneously moving fluids, a great deal of effort is at present being devoted to the quantum features of the condensate hydrodynamics. A very intriguing prediction concerns the emission of correlated pairs of phonons by the horizon of an acoustic black hole configuration via a mechanism that is a condensed-matter analogue of the well-celebrated Hawking radiation from gravitational black holes.

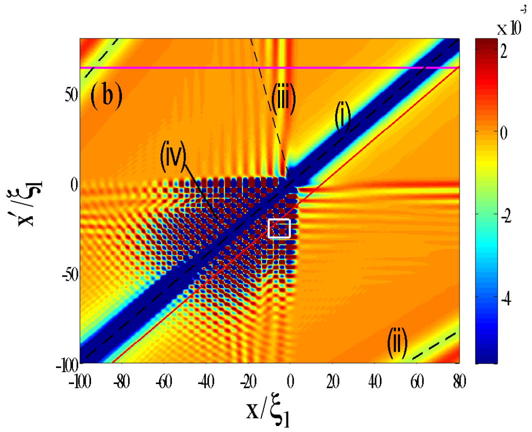

Figure 10: Example of color plot of the density-density correlation function around a white-hole horizon.

An acoustic white hole configuration is obtained by simply reversing the direction of flow of a black hole one: atoms go from an upstream region where the flow is super-sonic to a downstream region where the flow is subsonic: within a naive hydrodynamic picture, dragging by the moving condensate forbids low-energy phonons from crossing the horizon and penetrating the inner region of the white hole.

In this paper, we have reported a comprehensive investigation of the physics of acoustic white hole configurations. Using the Gross-Pitaevskii equation for the condensate dynamics, we have established the dynamical stability of the white hole at the mean-field level: no exponentially growing perturbation of the horizon appears when this is hit by an incident wavepacket of Bogoliubov phonons. A nonlinear back-action effect due to the perturbation of the horizon by the incident wavepacket is visible as a stationary pattern of Bogoliubov-Cerenkov waves by the perturbed horizon.

Quantum fluctuations are included within a truncated Wigner numerical approach. Signatures of the white hole emission by the horizon are identified in the correlation function of density fluctuations. In contrast to the Hawking emission from black holes, the white hole emission does not consist of low-energy excitations only, but involves high wavevector modes. As a result, the density correlation pattern shows fast oscillating features on the scale of the healing length. Furthermore, some of these features are not stationary in time, but indefinitely grow with time with a logarithmic (linear) law for a zero (finite) initial temperature. All of the features found in the numerical observations are fully recovered and physically interpreted by an analytical calculation within a step-like approximation for the horizon. Interestingly, this theory predicts a flat spectral distribution of the radiation emitted outside the acoustic white hole: this is in stark contrast to the thermal character of Hawking radiation from black holes.

Phys. Rev. A 81, 013404 (2010)

Light scattering by ultracold atoms in an optical lattice

Stefan Rist, Chiara Menotti, Giovanna Morigi

In this work, carried out in collaboration with Stefan Rist and Giovanna Morigi (at the time UAB, Barcelona, presently at University of Saarbruecken), we have investigated theoretically light scattering of photons by ultracold atoms in an optical lattice in the linear regime. A full quantum theory for the atom-photon interactions has been developed as a function of the atomic state in the lattice along the Mott-insulator – superfluid phase transition, and the photonic scattering cross section is evaluated as a function of the energy and of the direction of emission. We have shown that, when performing Bragg spectroscopy with light scattering, the photon recoil gives rise to an additional atomic site to site hopping, which can interfere with ordinary tunneling of matter waves and can significantly affect the photonic scattering cross section. Its effect is visible in the behavior of the height of the peaks in the spectrum as a function of the emission angle, and it has been singled out by comparing the spectrum evaluated when this effect is discarded.

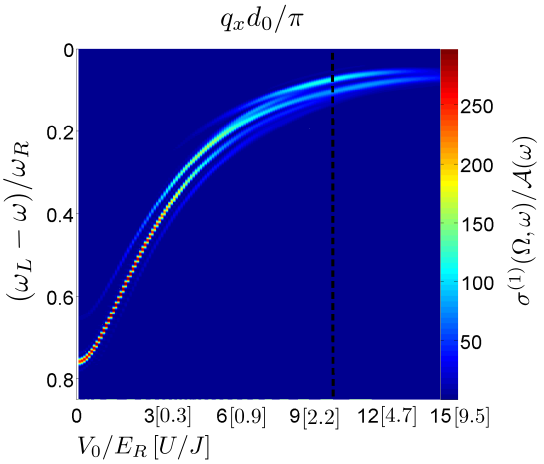

Figure 11: Contour plot of $\sigma^{(1)}$ as a function of frequency and lattice depth V_0 for $q_x d_0 = 6\pi/7$. The black dashed line marks the critical value $[U/J]_c$ at which the phase transition occurs in the thermodynamic limit.

Using Bragg spectroscopy of ultracold bosonic atoms in an optical lattice, is it possible to look for the the signatures of the Mott-insulator and superfluid quantum state in the scattered photons. In the figure, we show the Stokes component of the differential scattering cross section $\sigma^{(1)}$ as a function of the frequency and the depth of the potential, hence sweeping from the Mott-insulator to the superfluid regime at a given Bragg angle, corresponding to large momentum transfer ($q_x d_0 = 6\pi/7$). One observes that the spectrum varies from multiple peaks, deep in the Mott-insulator regime, to a single peak in the weakly-interacting superfluid regime. The single peak appears around a value of U/J much smaller than the critical value $[U/J]_c$ for the Mott to superfluid transition. These features are reminiscent of the excitations of a strongly-interacting superfluid, which contain, beyond the gapless phononic modes, also gapped modes predicted to be dominant at large quasi-momentum (see e.g. C. Menotti and N. Trivedi, PRB 77, 235120 (2008)). Hence the identification of the Mott-insulator to superfluid phase transition should rather rely on the existence of a gapless spectrum.

Phys. Rev. Lett. 107, 270404 (2011)

Swallowtail Band Structure of the Superfluid Fermi Gas in an Optical Lattice

G. Watanabe, S. Yoon, and F. Dalfovo

The role played by interaction in ultracold atomic gases in optical lattices is an important issue. In the case of Bose- Einstein condensates (BECs), the interaction is described by a nonlinear form with respect to the order parameter which competes with the periodic potential of the lattice. The interaction energy tends to reshape the sinusoidal band structure into a quadratic-like energy dispersion of the superfluid flow. This reshaping is accompanied by the appearance of a loop structure at the edge of the Brillouin zone, called swallowtail.

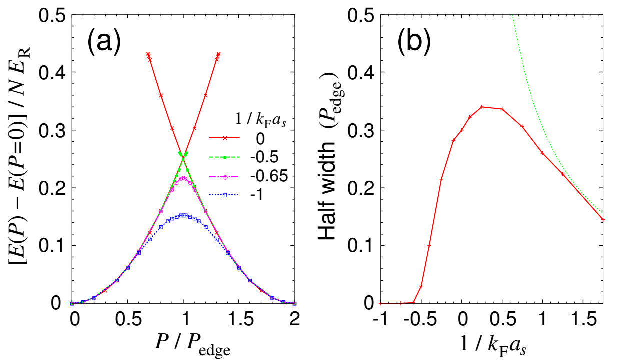

Figure 12: (a) Energy per particle as a function of the quasimomentum P for various values of $1/k_Fa_s$ in the case of $s = 0.1$ and $E_F/E_R = 2.5$. (b) Half-width of the swallowtails along the BCS-BEC crossover in the case of $s = 0.1$ and $E_F/E_R = 2.5$.

The problem of the swallowtail band structure is even more interesting in Fermi superfluids, due to the possible implications in superconducting electrons in solids and superfluid neutrons in neutron stars. In this article we have studied the energy band structure of the superfluid flow of ultracold dilute Fermi gases in an one-dimensional optical lattice along the BCS to BEC crossover. Using numerical simulations based on the Bogoliubov-de Gennes equations, we have shown that, in each side of the crossover region, the swallowtail appears in the Bloch energy band of the superfluid above a critical value of the interaction strength in the quasimomentum space) of the swallowtail is largest near unitarity. The size (width in the quasimomentum space) of the swallowtail is largest near unitarity. More interestingly, we have found that, along with the appearance of the swallowtail in the BCS side, there exists a narrow band in the quasiparticle energy spectrum close to the chemical potential and the incompressibility of the Fermi gas experiences a profound dip, unlike in the BEC side. The emergence of the swallowtail and the dip of the incompressibility can be explained as a consequence of the fact that the chemical potential touches the top of the narrow band in the quasiparticle spectrum when the swallowtail is on the edge of appearing. These results are obtained within a range of parameters compatible with current experiments.

New J. Phys. 14, 103036 (2012)

Subdiffusion of nonlinear waves in quasiperiodic potentials

M.Larcher, T.V.Laptyeva, J.D.Bodyfelt, F.Dalfovo, M.Modugno, S.Flach

In one dimension, a wave packet of noninteracting particles subject to a random potential does not diffuse because of Anderson localization, due to the exponential localization of the eigenstates of the underlying Hamiltonian. Instead, the presence of interactions is expected to act against localization, although the actual mechanism may be highly nontrivial and may depend on the type of disorder and interaction. This is a problem of fundamental importance for many systems in different contexts. The purpose of this work was to clarify the details of the spreading mechanism leading to the destruction of localization in quasiperiodic systems, and to address differences and similarities between quasiperiodic and purely random potentials. We extended and refined previous numerical investigations by pushing the simulations to much longer times, thus allowing for the identification of the strong and weak chaos regimes in quasiperiodic systems and compare the situation with known properties of purely random systems. For this purpose, we used two different models: namely, a discrete nonlinear Schrödinger equation (DNLS) and a quasiperiodic version of the quartic Klein-Gordon (KG) lattice model.

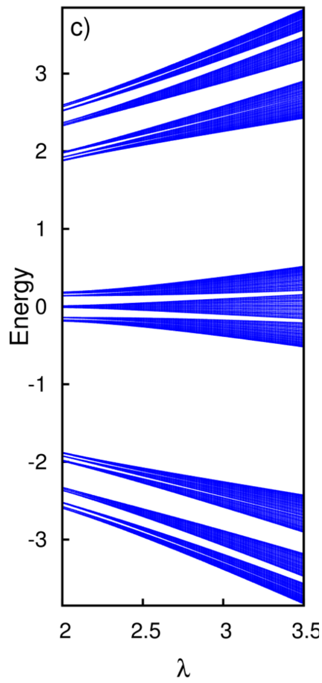

Figure 13: Eigenenergies of atoms in a quasi-periodic potential as a function of the disorder strength λ. The spectrum exhibits gaps and "mini-gaps", which affect the spreading regimes.

A key result of this work is that a regime of weak chaos is indeed observed in the long-time spreading of nonlinear wave packets propagating in quasiperiodic systems; in particular, we find that the asymptotic value of the spreading coefficient is 1/3 as in purely random systems, thus showing that this behaviour is rather general and model independent. Another similarity with purely random systems is the occurrence of self-trapping. However, as opposed to the random system, in the quasiperiodic case partial self-trapping is also possible for weaker nonlinearities. This is due to the complexity of the linear wave spectrum that exhibits a fractal gap structure of sub-bands. Self-trapping gives rise to transient spreading regimes characterized by an intermediate large spreading coefficient (overshooting). We have also observed signatures of strong chaos, but detection of this regime is difficult in quasiperiodic systems, since it is often masked by overshooting and partial self-trapping, which occur on the same temporal scales.

Phys. Rev. Lett. 106, 230403 (2011)

Observation of subdiffusion of a disordered interacting system

E. Lucioni, B. Deissler, L. Tanzi, G. Roati, M. Zaccanti, M. Modugno, M. Larcher, F. Dalfovo, M. Inguscio, and G. Modugno

While a full understanding of the interplay of disorder and interaction has long been sought, systematic experimental investigations are difficult and various aspects of this interplay have not been fully clarified. One of the open questions concerns the dynamics of a wavepacket expanding in a disordered potential in presence of a nonlinear effects induced by the particle-particle interaction.

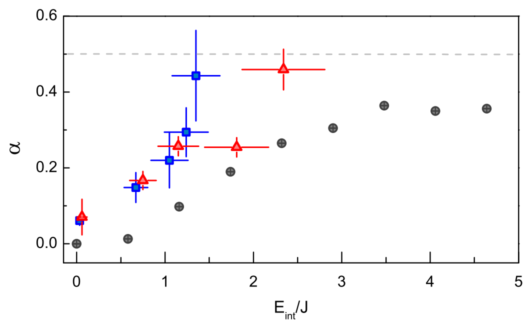

Figure 14: Dependence of the diffusion exponent α on the initial interaction energy $E_{\rm int}$ extracted from the experiment (triangles and squares) and numerical DNLSE simulations (circles). The experimental data are for different values of disorder strength, Δ, and tunneling energy, J.

In this article, we study the dynamics of Bose-Einstein condensates with controllable nonlinearity expanding along a one-dimensional quasiperiodic lattice. We use a BEC of ^{39}K atoms in their lowest internal state, whose s-wave scattering length a can be tuned by means of a Feshbach resonance. If a noninteracting gas is let free to expand along the quasiperiodic lattice, no transport is observed because all single-particle eigenstates are localized. By adding a controlled interatomic repulsion, we observe a slow increase of the width of the sample that asymptotically follows a subdiffusive law $\sigma(t) \propto t^{\alpha}$. We find that the exponent α increases with the interaction energy, in qualitative agreement with both numerical simulations based on a 1D discrete nonlinear Schrödinger equation (DNLSE), as well as with the predictions of a heuristic model. In particular, the observed subdiffusion confirms the microscopic mechanism of the expansion expected for an interacting disordered system where all the single-particle states are localized. The interaction breaks the orthogonality of the states and allows the transfer of population between neighbouring states. Since the transfer rate depends on $E_{\rm int}$, the velocity of expansion decreases as the sample expands and becomes less dense. Moreover, the observed exponents are larger than the one calculated for uncorrelated disordered potentials, suggesting a role of the spatial correlation of the disorder.

The experiments have been carried out at LENS, in the group of Massimo Inguscio and Giovanni Modugno, while the numerical DNLSE simulations have been performed in Trento.

New J. Phys. 12, 073003 (2010)

Dilute Bose gas with correlated disorder: A Path Integral Monte Carlo study

S. Pilati, S. Giorgini, M. Modugno, N. Prokof'ev

The dirty boson problem has become a central and fascinating subject in condensed matter physics starting from the first theoretical investigations more than 20 years ago. In this work we investigate the thermodynamic properties of a dilute Bose gas in a correlated random potential using exact path integral Monte Carlo methods. The study is carried out in continuous space and disorder is produced in the simulations by a 3D speckle pattern with tunable intensity and correlation length. We calculate the shift of the superfluid transition temperature due to disorder and we highlight the role of quantum localization by comparing the critical chemical potential with the classical percolation threshold. The equation of state of the gas is determined in the regime of strong disorder, where superfluidity is suppressed and the normal phase exists down to very low temperatures. We find a T^2 dependence of the energy in agreement with the expected behavior in the Bose glass phase. We also discuss the major role played by the disorder correlation length and we make contact with a Hartree-Fock mean-field approach that holds valid if the correlation length is very large. The density profiles are analyzed as a function of temperature and interaction strength. Effects of localization and the depletion of the order parameter are emphasized in the comparison between local condensate and total density. At very low temperature we find that the energy and the particle distribution of the gas are very well described by the $T = 0$ Gross-Pitaevskii theory even in the regime of very strong disorder.

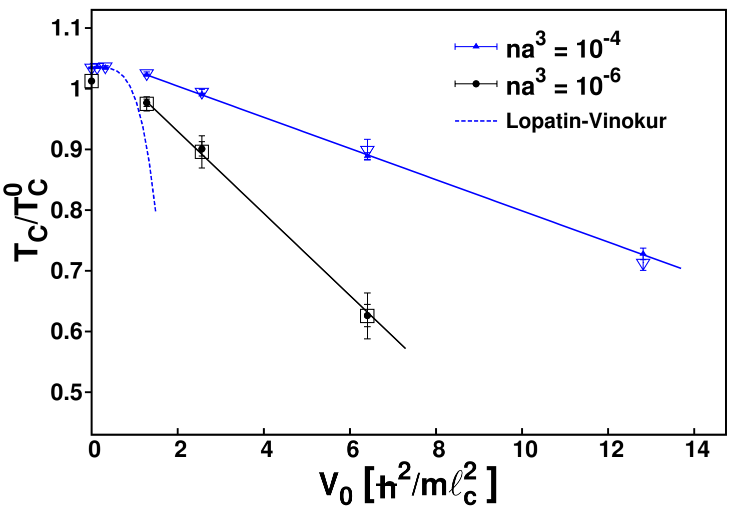

Figure 15: Superfluid transition temperature as a function of the disorder strength for two values of the gas parameter na^3. Open and solid symbols refer respectively to T_c determined from the superfluid and from the condensate fraction. The dashed line is the prediction of a perturbative study by Lopatin and Vinokur at $na^3 = 10^{-4}$ shifted by $(T_c - T_c^0)$ in the absence of disorder.

Phys. Rev. Lett. 106, 185301 (2011)

Dynamics of dark solitons in a trapped superfluid Fermi gas

R. G. Scott, F. Dalfovo, L. P. Pitaevskii and S. Stringari

Solitons have been the focus of much recent research in the field of cold atoms, due to their ubiquitous production in the dynamics of BECs. Their different forms create a broad family, from the common "grey" and "black" solitons in repulsive BECs, to the "bright" solitons in attractive BECs and "gap" solitons in optical lattices, and their more exotic cousins such as the "bright-dark" solitons, which were recently observed in two-component BECs. We expect solitons to play an equally important role in the dynamics of degenerate Fermi gases. Even more fundamentally, topological excitations offer insights into the nature of coherence and superfluidity across the BEC-BCS crossover, as illustrated by the recent observation of vortex lattices. Despite this interest, the nature of soliton dynamics in Fermi gases remains elusive, and only stationary "black" solitons have been simulated across the BEC-BCS crossover.

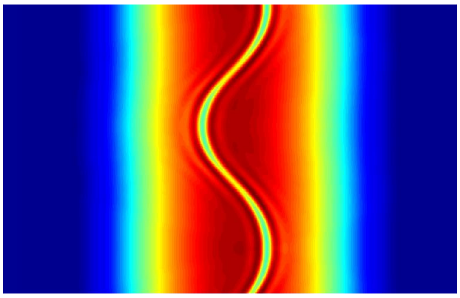

Figure 16: This figure shows the density of the trapped superfluid gas with a grey soliton which oscillates back and forth in time. The vertical axis is time and the horizontal axis is the spatial coordinate. The period of oscillation is found to strongly depend on the interaction parameter $1/k_F a$. In this figure, the time dependent BdG simulation has been done for $1/k_F a = -0.5$, i.e., on the BCS side of the Feshbach resonance of a two-component Fermi gas.

In this article, we investigate the oscillation of solitons in a trapped superfluid Fermi gas across the Bose-Einstein condensate to Bardeen-Cooper-Schrieffer (BEC-BCS) crossover. From fundamental statements about the nature of the soliton and the media it moves in, we derive universal relations, valid for both Bosonic and Fermionic superfluids, relating the soliton energy and oscillation period T_s to observable quantities such as phase jump, speed and density. The special case of unitarity is particularly interesting because the soliton width is of the order of interatomic distances and its observation will give access to the short-range physics. We then perform numerical simulations of the time-dependent Bogoliubov-de Gennes (TDBdG) equations. By extracting the appropriate observable quantities from our simulations we find good agreement between the numerical and analytic models, which show that T_s increases dramatically as the soliton becomes shallower when moving from a BEC to a BCS regime. Finally, we propose and simulate an experimental protocol to demonstrate the variation in T_s across the BEC-BCS crossover.

Phys. Rev. A 81, 043626 (2010)

All-optical pump-and-probe detection of dynamical correlations in a two-dimensional Fermi gas

T.-L. Dao, C.Kollath, I.Carusotto, M. Köhl

The preparation of strongly correlated Fermi gases in an optical lattice will allow for an analog simulation of complex quantum many-body Hamiltonians. While the properties of a Mott-insulating phase can be probed by looking at density-related quantities, the identification and characterization of more complex quantum phases requires the time-resolved measurement of single-particle correlation functions, the so-called Green functions, $\langle \Psi^{\dagger}_{\sigma,r}(t)\,\Psi_{\sigma',r'}(t')\rangle$, where $\Psi_{\sigma,r}(t)$ is the atomic Fermi field operator in the spin state σ at position r and time t. Quantities of this form reveal profound information about the macroscopic coherence and decoherence of the systems and keep track of the subtle properties of quantum phases which are not density-ordered, e.g., the existence of quasiparticles in a strongly correlated Fermi liquid.

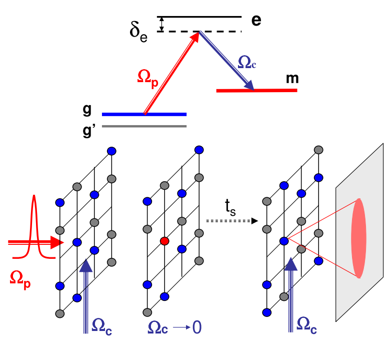

Figure 17: Scheme of the atomic level under investigation (upper panel) and of the proposed pump-probe sequence of optical pulses (lower panel).

Here, we propose an all-optical pump-and-probe scheme to extract quantitative information on the microscopic physics of a Fermi gas and in particular on its two-time correlation functions. A pump sequence firstly brings the system into a quantum superposition of its initial state and an excited state. The response of the system to a second probe pulse sequence is then measured after a variable time delay. In this way, information on the time evolution of the atomic two-time correlations is converted into easily detectable observables, such as the intensity and the phase of the outgoing light.

From an alternative point of view, our scheme can be seen as an application of light storage techniques to the diagnostic of many-body systems: a coherent pulse of light is stored in a quantum gas and retrieved at a later time after a variable interval. Information on the system is extracted from the properties of the retrieved light. Differently from standard light storage experiments where it is a purely detrimental effect, decoherence of the stored pulse as a function of storage time is in our scheme the crucial tool to obtain information on the many-body dynamics of the underlying quantum gas.

The efficiency of the proposed measurement scheme is tested on the specific, analytically tractable example of a two-dimensional BCS superfluid. Protocols to extract the superfluid gap and the quasiparticle dispersion are presented, which take into account some most significant difficulties that arise from the internal structure of the atoms.

Phys. Rev. Lett. 106, 110403 (2011)

BCS-BEC crossover in a two-dimensional Fermi gas

G. Bertaina, S. Giorgini

The study of ultracold atomic Fermi gases has become an active and rich field of research. Important areas of investigation include the BCS-BEC crossover in a superfluid gas with resonantly enhanced interactions, the Chandrasekhar-Clogston instability of the superfluid state when spin polarization is increased, the possible onset of itinerant ferromagnetism in a gas with repulsive interactions and the realization of the Hubbard model for fermions loaded in optical lattices. Low dimensional configurations of degenerate Fermi gases have also been the object of experimental and theoretical studies. In particular, a two-dimensional (2D) ultracold Fermi gas has been recently realized using a highly anisotropic pancake-shaped potential, and the density profile of the cloud has been measured using *in situ* imaging.

We investigate the crossover from Bardeen-Cooper-Schrieffer (BCS) superfluidity to Bose-Einstein condensation (BEC) in a two-dimensional Fermi gas at $T = 0$ using the fixed-node diffusion Monte Carlo method. We calculate the equation of state and the gap parameter as a function of the interaction strength, observing large deviations compared to mean-field predictions. In the BEC regime our results show the important role of dimer-dimer and atom-dimer interaction effects that are completely neglected in the mean-field picture. Results on Tan's contact parameter associated with short-range physics are also reported along the BCS-BEC crossover.

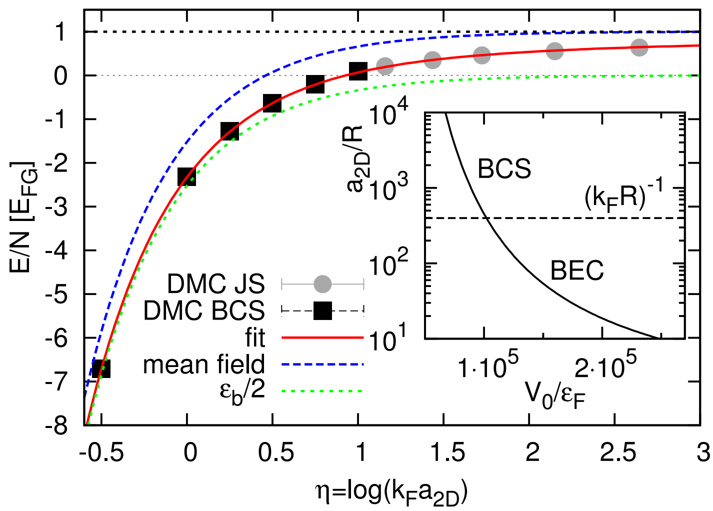

Figure 18: Equation of state in the BCS-BEC crossover. Squares refer to the BCS and circles to the Jastrow-Slater wave function. The solid (red) line is a fit to the data, the dotted (green) line is half of the molecular binding energy and the dashed (blue) line is the prediction of mean-field theory. The horizontal dotted (black) line denotes the energy per particle E_{FG} of the non-interacting gas. Inset: 2D scattering length a_{2D} as a function of the depth V_0 for a square-well potential of radius R. The BCS and BEC regimes correspond, respectively, to $k_F a_{\mathrm{2D}} \gg 1$ and $k_F a_{\mathrm{2D}} \ll 1$.

Phys. Rev. Lett. 106, 215303 (2011)

Fermi-liquid behavior of the normal phase of a strongly interacting gas of cold atoms

S. Nascimbène, N. Navon, S. Pilati, F. Chevy, S. Giorgini, A. Georges, C. Salomon

From the identification of a spin gap associated with superfluidity to the thermodynamic signature of a ferromagnetic instability, the response of strongly-correlated materials to magnetic fields is a valuable tool for the investigation of their physical properties. Another important example is the supposed connection between the strong reduction of the magnetic susceptibility of underdoped cuprates with temperature, and the existence of a pseudogap in the normal phase. In the context of ultracold Fermi gases, most efforts have focused on the study of spin-unpolarized gases, where the gas is superfluid at low temperature whatever the interaction strength.

In this work we investigate both experimentally (ENS group) and theoretically (Trento group) the response of a low-temperature Fermi gas to a chemical potential imbalance, in the BEC-BCS crossover. At low imbalance the gas is superfluid and remains fully paired. Above a critical chemical potential imbalance, the gas becomes normal and we extract the equation of state and magnetic susceptibility of the spin-symmetric normal state as a function of interaction strength. Interpreting our data using Landau's Fermi liquid theory, we extract several Landau parameters of the unitary gas, which agree with a previous study at finite temperature. The Trento group calculates the canonical equation of state of the normal state using quantum Monte Carlo simulations and an excellent agreement is found between theory and experiment.

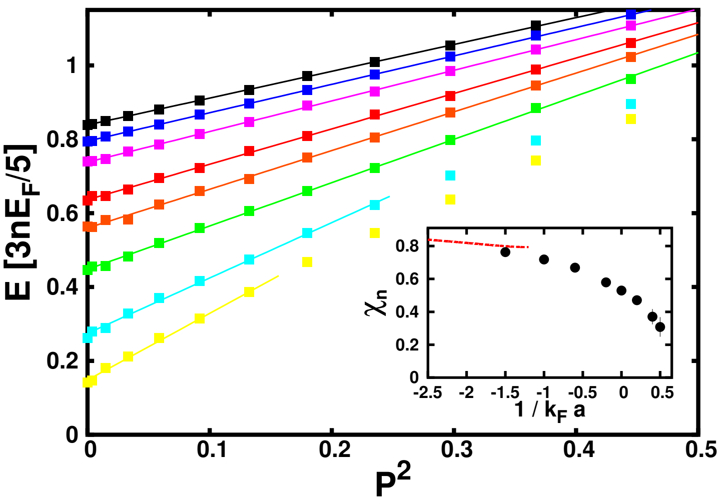

Figure 19: Canonical equation of state of a two-component Fermi gas calculated using quantum Monte Carlo simulations, for $1/k_Fa = -1.5$, -1, -0.6, -0.2, 0, 0.2, 0.4, 0.5 (from top to bottom). The solid lines are fits of the low polarization data using the equation $E(P) = 3NE_F/5(\xi_N + \frac{5}{9}\chi_n^{-1}P2)$. Inset: Extracted values of the susceptibility χ_n as a function of $1/k_Fa$. The dashed red line is the result of a perturbation expansion valid up to order $(k_Fa)2$.

New J. Phys. 13, 055011 (2011)

Metastability in spin-polarized Fermi gases and quasiparticle decays

K. Sadeghzadeh, G. M. Bruun, C. Lobo, P. Massignan and A. Recati

The experimental realization of spin-polarized ultracold Fermi gases has initiated a variety of new physics. Of particular interest is the understanding of strongly interacting unbalance two-component Fermi gases at zero temperature. Recent experiments have observed a rich phase diagram and located a first-order transition from the normal to the superfluid phase changing the polarization of the gas. The normal phase can be thought as build of fermionic quasi-free quasi-particles. If the interaction is large enough the quasi-particle become molecules and the system prefers to phase separate in a molecular-BEC phase and an ideal Fermi gas. Previous studies showed that the critical interaction strength at which the ground state of a single impurity at zero momentum switches from the fermionic to the bosonic branch occurs is higher than the interaction strength at which a superfluid phase was found to emerge in the limit of full polarization.This would imply that no measurements made in the ground state could in principle allow us to study the transition from the polaron to the molecule in the homogeneous phase.

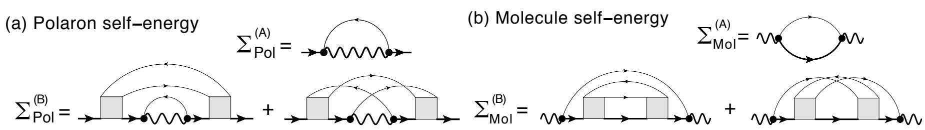

Figure 20: Diagrams showing the decay processes for (a) polarons into molecules and (b) molecules into polarons. The thin lines represent majority atoms, wavy lines a molecule and thick lines a polaron. The polaron-molecule matrix element is represented by a thick dot and the square represents off-resonant scattering between a polaron and the majority atoms.

In the present work we investigate the metastability region associated with the first-order transition from the normal to the superfluid phase in an highly unbalanced spin-1/2 Fermi gas. First we detail the dominant decay processes of single quasiparticles, determining the momentum thresholds of each process and calculating their rates. This task is accomplished by calculating the imaginary part of the on-shell polaron/molecule self-energy including the diagrams shown in Fig. 20. With such an understanding we can face the problem of a Fermi sea of polarons, and we can predict a region of metastability for the normal partially polarized phase. We propose different experiments to observe the threshold of the metastable region, the interaction strength at which the quasiparticle ground state changes character, and the decay rate of polarons.

Phys. Rev. Lett. 106, 080402 (2011)

Spin fluctuations, susceptibility and the dipole oscillation of a nearly ferromagnetic Fermi gas

Alessio Recati and Sandro Stringari

Recently the magnetic properties of interacting Fermi gases have attracted a lot of interest in the cold-gases community, especially due to experimental evidence of itinerant ferromagnetism and advances in reaching magnetic phases in optical lattices. The evidence of magnetic phases has been up to now indirect and there are discrepancies with respect to theory predictions, which suggests that the physical behavior of the system is far from being understood.

In this work, we focus directly on the magnetic properties of interacting Fermi gases. We study spin fluctuations and the role played by the magnetic susceptibility χ when the gas approaches the ferromagnetic instability. At finite temperature T and $N = N_\uparrow + N_\downarrow \gg 1$ the spin susceptibility is proportional to spin fluctuations through the thermodynamical relation: $\Delta(N_\uparrow - N_\downarrow)2 = Nk_BT\frac{\chi(T)}{n}$where $n = N/v$ is the density.

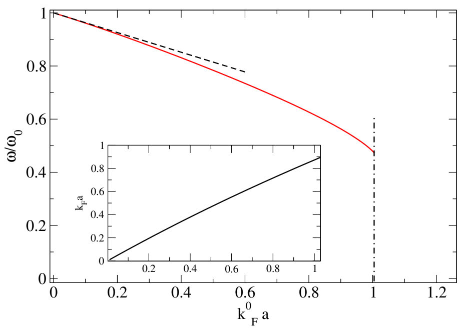

Figure 21: Main panel: Spin dipole frequency as a function of the interaction parameter k_F0a, where a is the s-wave scattering length. The dashed line is the first order expansion. The dashed-dot horizontal line is the position at which the susceptibility should diverge at the centre of the cloud. Inset: the value of the interaction parameter k_Fa in the trap as a function of k_F0a. k_F is the Fermi momentum of the interacting cloud calculated at the centre of the trap.

At low T and small N quantum fluctuations emerge and, to the leading order in N, they read

$$\frac{\Delta(N_\uparrow - N_\downarrow)^2}{N} = 2N\alpha\left(\frac{3}{\pi 4N}\right)^{1/3}\ln(CN^{1/3}), \tag{2}$$

where the parameter α is fixed by the low q behaviour of the static spin structure factor and C is a cut-off constant.

In this work we have first of all shown how both thermodynamical, i.e. χ, and quantum fluctuations diverge as a function of the relevant Landau parameter F_0^a, but with a very different law. We also give the relevant Landau parameters' expressions up to second order in the interaction strength. Moreover using a sum rule approach and recent ab initio Monte Carlo results for the magnetic susceptibility of uniform matter, we provide explicit predictions for the frequency of the spin dipole oscillation of a gas trapped by a harmonic potential – which are inversely proportional to an average susceptibility –and discuss the deviations from the ideal gas behavior when the system approaches the ferromagnetic transition. The result is reported in Fig. 21.

Phys. Rev. A 82, 013635 (2010)

Spin oscillations of the normal polarized Fermi gas at unitarity

Alessio Recati and Sandro Stringari

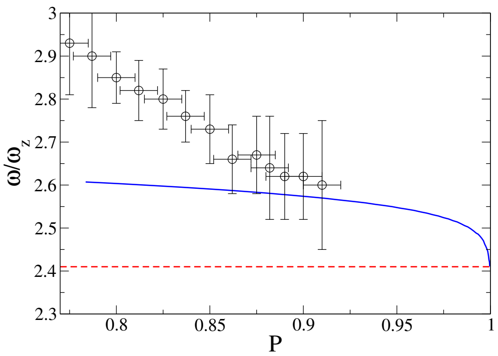

Figure 22: Frequency of the axial compressional mode as a function of the polarization P. Dashed line: the single polaron mode frequency. Solid line: the collisionless value of the mode frequency obtained via the variational principle described in the present work. Points: experimental data of the ENS group of C.Salomon.

It is currently well accepted that a spin-polarized sample of ultracold Fermi gases at unitarity, where the scattering length becomes infinite, is not superfluid, but rather a normal Fermi liquid provided the polarization is large enough. In a harmonically trapped geometry, the critical value is $P = (N_\uparrow N_\downarrow)/(N_\uparrow + N_\downarrow) \simeq 0.77$ of the (global) polarization of the gas, where $N_\uparrow$ ($N_\downarrow$) are the particle numbers of the majority (minority) component. The occurrence of this behavior has been well confirmed experimentally, and the comparison with the theory of the normal phase, first introduced in Trento, is remarkably accurate. The theory is based on the assumption that the normal phase can be thought of as a Fermi gas of polarons, i.e., (in this context) a single impurity immersed in an ideal Fermi sea. The parameters of the quasiparticle are its effective mass and its negative chemical potential.

In this work, using density-functional theory in a time-dependent approach, we determine the frequencies of the compressional modes of the normal phase of a Fermi gas at unitarity as a function of its polarization. Our energy functional accounts for the typical elastic deformations exhibited by Landau theory of Fermi liquids. The frequency as a function of the polarization and the comparison with the latest available experiments is shown in Fig. 22.

The comparison with the available experiments is biased by important collisional effects affecting both the in-phase and the out-of-phase oscillations even at the lowest temperatures. New experiments in the collisionless regime would provide a crucial test of the applicability of Landau theory to the dynamics of these strongly interacting normal Fermi gases.

Phys. Rev. A 84, 033607 (2011)

The Fermi-polaron in two dimensions: Importance of the two-body bound state

Michael Klawunn and Alessio Recati

In this work we try to add new bricks to the theory for Fermi polarons by addressing the two-dimensional (2D) case and comparing it with the one-dimensional (1D) and three-dimensional (3D) cases. Such a problem is relevant in various fields of physics, like 2D electron gas. Thanks to the recent experimental advances in realizing 1D and 2D strongly interacting Fermi gases, it has become of great interest also in the context of ultracold gases.

Important quantities characterizing the polaron are (i) its chemical potential (or interaction energy, or binding energy) and (ii) its effective mass. In 3D these parameters have been calculated in many different ways and recently experimental measurements are also available.

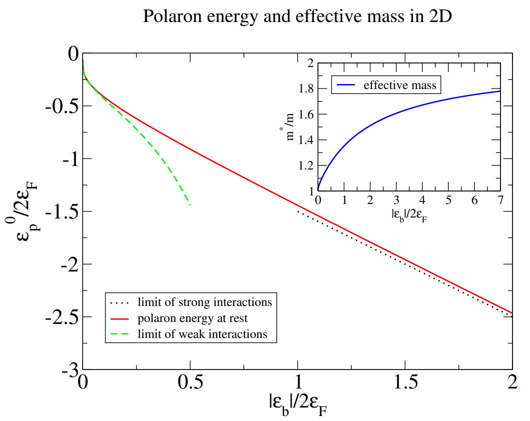

Figure 23: Main: polaron energy as a function of the two-body binding energy ϵ_b as given by Eq. (3). The weakly interacting (dashed-green line) and the strongly interacting (dotted-black line) results are also reported for comparison. Inset: ratio m^*/m between the effective and the bare mass as given by Eq. (4).

In 2D, as well as in 1D, an attractive interaction always allows for a two-body bound state. In the present work, we introduce a new method to solve the impurity problem including such a bound state explicitly. In this way we obtain analytical expressions for the polaron parameters which agree quite well with the known results in 1D and 3D. In 2D the expression for the polaron energy reads

$$\epsilon_p^0 \approx ng(\epsilon_b) = \frac{-2\epsilon_F}{\ln\left[1+\frac{2\epsilon_F}{|\epsilon_b|}\right]}, \qquad (3)$$

where ϵ_F is the Fermi energy of the bath and ϵ_b the two-body binding energy. As we show in Fig. 23 such expression interpolates between the correct and expected limiting values in the weakly and the strongly interacting regime. In the inset we report also the effective mass m^* of the polaron

$$\frac{m}{m^*} = 1 - \frac{1}{2}\left(\frac{\epsilon_p^0}{2\epsilon_F}\right)^2\left(1+\frac{|\epsilon_b|}{2\epsilon_F}\right)^{-2}. \qquad (4)$$

It goes from the bare mass m to the dimer mass $2m$ and we expect to be more accurate then in 3D, due to the always present two-body bound state.

Phys. Rev. Lett. 108, 225301 (2012)

Quantum Tricriticality and Phase Transitions in Spin-Orbit Coupled Bose-Einstein Condensates

Yun Li, Lev P. Pitaevskii, and Sandro Stringari

Spin-orbit (SO) coupling, i.e. the interaction between the spin of a particle spin and its momentum, is a phenomenon that manifests itself in lifting the degeneracy of the one-electron energy levels in atoms, molecules, and solids. In condensed matter physics it gives rise to a variety of intriguing quantum phenomena, such as spin Hall effect and topological insulators. Ultracold atomic gases do not possess intrinsic SO coupling due to the neutrality of the constituent atoms. Recently, however, by controlling the atom-light interaction, a scheme for generating artificial external gauge potentials coupled to neutral atoms has been developed and consequently SO-coupled Bose condensed gases, as well as degenerate Fermi gases, have been realized. Following the experiments, much effort has been devoted to the theoretical study of artificial gauge fields in ultracold atomic gases.

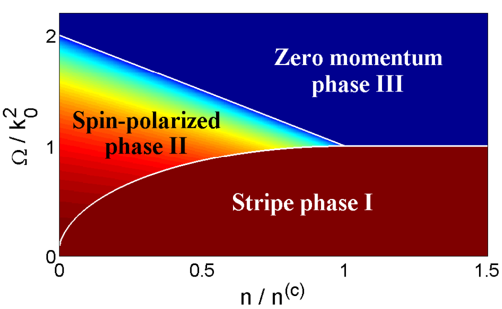

Figure 24: Phase diagram of the ground state as a function of the Rabi frequency Ω and the density of the system n. Here the three scattering lengths are fixed, and $n^{(c)}$ is the critical density depending on k_0 and the interaction strengths.

In this article we consider a SO coupled configuration of spin-1/2 interacting bosons with equal Rashba and Dresselhaus couplings. The phase diagram of the system at $T = 0$ is discussed, with special emphasis on the role of the interactions, treated within the mean-field approximation. We predict the occurrence of three different quantum phases, depending on the value of the relevant parameters: the SO coupling strength k_0, the Rabi frequency Ω, and the atomic interaction strengths. These three phases are (I) the spin-unpolarized stripe phase where the condensation takes place in a combination of plane waves with opposite momenta, (II) the spin-polarized plane-wave phase where the condensate has a unique nonzero momentum, and (III) the zero momentum phase where all the atoms condense in the state with zero momentum. The corresponding phase diagram is shown in Fig. 24, as a function of the density and the Rabi frequency. For a certain value of the density $n^{(c)}$ and of the Rabi frequency, we also predict the occurrence of a characteristic tricritical point separating the three phases. The effect of harmonic trapping as well as the role of the breaking of spin symmetry in the interaction Hamiltonian are also discussed.

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. 25, 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.

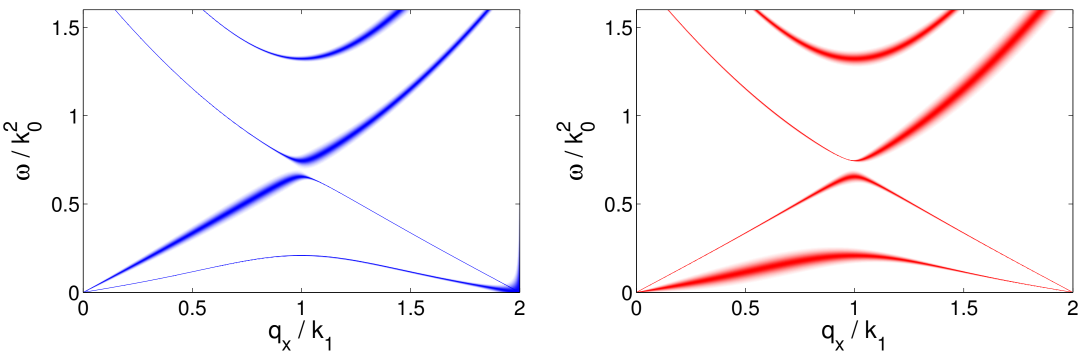

Figure 25: Lowest four excitation bands along x direction. The parameters are $\Omega/k_0^2 = 1.0$, $G_1/k_0^2 = 0.3$, and $G_2/k_0^2 = 0.08$, where k_0 is the SO coupling strength. The width of each band represents its contribution to the density (left) and spin density (right) static structure factor.

New J. Phys. 12, 093008 (2010)

Quantum magnetism and counterflow supersolidity of up-down bosonic dipoles

C. Trefzger, M. Alloing, C. Menotti, F. Dubin, M. Lewenstein

Recently, the physics of ultracold dipolar gases has received growing attention. Experimental and theoretical studies are motivated by the long-range and anisotropic dipole-dipole interaction. Experiments with ultracold atoms have now highlighted the role of dipole-dipole interactions. Notably, with 52Cr, control via Feshbach resonances allows one to efficiently reduce contact interactions and enter a regime where magnetic dipole-dipole interactions become dominant. Polar molecules also appear very promising towards implementation of degenerate dipolar gases, in particular since the demonstration of ultra-cold rubidium-potassium, and lithium-cesium molecules prepared in their ground rotovibrational state.

Dipolar interaction introduces a rich variety of quantum phases. For instance, supersolid and checkerboard phases are predicted in the phase diagram of polarized dipolar bosons confined in a two-dimensional (2D) optical lattice. In bilayer samples where dipole interactions can also be attractive more exotic quantum phases are accessible, for example a pair-supersolid (see C. Trefzger, C. Menotti, and M. Lewenstein, PRL 103, 035304 (2009)).

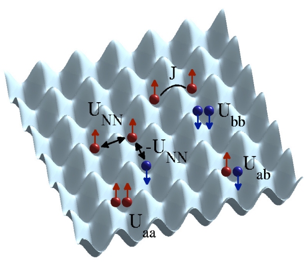

Figure 26: Schematic representation of a 2D optical lattice populated with dipolar Bosons polarized in both directions perpendicular to the lattice plane.

After studying the case of a bilayer system of parallel dipoles, in the present paper, we have studied a gas of dipolar bosons confined in a single layer optical lattice, where the dipoles are considered to point freely in both up and down directions perpendicular to the lattice plane. We find regions of parameters where the ground state of the system exhibits insulating phases with ferromagnetic or anti-ferromagnetic ordering, as well as with rational values of the average magnetization. The possibility of mapping quantum magnetic models onto systems of dipolar ultra-cold atoms in optical lattices is of primary interest.

This work in a sense is the first step in the studies of dipolar gases with non-polarized dipoles, and is relevant, e.g., for experimental studies of the ultracold OH molecules. Moreover, we expect that the methods and ideas developed here will turn out to be useful also for the study of more complex systems, such as exciton gases. Excitons, which are bound electron-hole pairs, obviously carry an electric dipole moment that can a priori attain quite arbitrary directions. Nevertheless, in indirect quantum wells, electrons and holes are confined in spatially separated regions such that electric dipoles can be aligned or anti-aligned in type-II heterostructures.

Phys. Rev. Lett. 109, 200401 (2012)

Liquid and crystal phase of dipolar fermions in two dimensions

N. Matveeva and S. Giorgini

The recent rapid developments in the field of ultracold dipolar atoms and molecules has opened up new fascinating prospects for investigating many-body effects in quantum degenerate gases with long-range interactions. In this work we study the liquid and crystal phase of a single-component dipolar Fermi gas in two spatial dimensions and at zero temperature using quantum Monte Carlo methods. The dipoles are oriented by an external field perpendicular to the plane of motion, resulting in a purely repulsive $1/r^3$ interaction. In the liquid phase we calculate the equation of state as a function of the interaction strength and other relevant properties characterizing the Fermi-liquid behavior: effective mass, discontinuity at the Fermi surface and pair correlation function. In the high density regime we calculate the equation of state of the Wigner crystal phase and the critical density of the liquid to solid quantum phase transition. This transition is found to occur at the value $k_F r_0 = 25 \pm 3$ of the interaction strength parameter defined by the product of the Fermi wave vector k_F and the characteristic length scale of the dipolar interaction $r_0 = md^2/\hbar^2$. Close to the freezing density we also search for the existence of a stripe phase, but such a phase is never found to be energetically favourable.

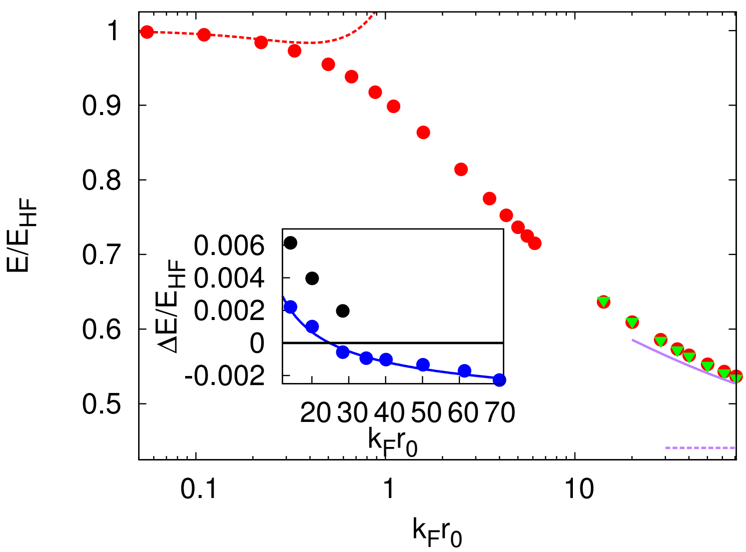

Figure 27: Equation of state of the liquid and solid phase. Circles refer to the liquid and triangles to the solid. The red dashed line corresponds to the second-order expansion in the weakly-interacting liquid phase. The purple dashed horizontal and solid line correspond respectively to the classical energy of the Wigner crystal and to the energy including the correction arising from the zero-point motion of phonons. Inset: Energy difference between the solid and the liquid (blue circles) and between the stripe phase and the liquid (black circles).

Phys. Rev. Lett. 105, 030405 (2010)

Itinerant ferromagnetism of a repulsive Fermi gas: a quantum Monte Carlo study

S. Pilati, G. Bertaina, S. Giorgini, M. Troyer

Over the past decade there has been substantial progress in the experimental realization of quantum degenerate atomic Fermi gases. A major part of the activity carried out so far was devoted to the investigation of the role of *attractive* interactions, but more recently attention was drawn to *repulsive* interactions and the onset of magnetic behavior.

In this work we investigate the phase diagram of a two-component repulsive Fermi gas at $T = 0$ by means of quantum Monte Carlo simulations. Both purely repulsive and resonant attractive model potentials are considered in order to analyse the limits of the universal regime where the details of interatomic forces can be neglected. The equation of state of both balanced and unbalanced systems is calculated as a function of the interaction strength and the critical density for the onset of ferromagnetism is determined. The energy of the strongly polarized gas is calculated and parametrized in terms of the physical properties of repulsive polarons, which are relevant for the stability of the fully ferromagnetic state. We also analyse the phase diagram in the interaction-polarization plane under the assumption that only phases with homogeneous magnetization can be produced.

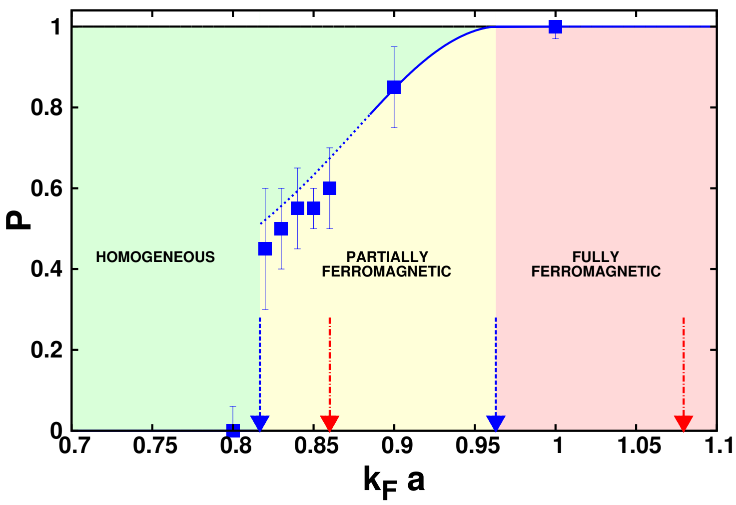

Figure 28: Phase diagram of the hard-sphere gas in the interaction/polarization plane. The green region corresponds to the homogeneous phase. The other regions correspond to phase separated states with partially polarized domains (yellow) and fully ferromagnetic domains (pink). The (blue) symbols correspond to the minimum of the curve $E(P)$ and the solid/dashed line is the phase boundary determined from the equilibrium condition for pressure and chemical potentials. The blue and red arrows indicate the critical densities where the magnetic susceptibility χ diverges and full ferromagnetism sets in, respectively for the hard-sphere and square-well potential.

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

Quantum fluids of light

I. Carusotto, C. Ciuti

An implicit assumption of Newton's corpuscular theory is that the basic constituents of light do not mutually interact. Had Newton foreseen the possibility of efficient collisions between these corpuscles, would he have imagined the possibility of a luminous liquid of such particles? This research line aims at investigating the novel properties of light in systems with large optical nonlinearities where the many photons forming the light field display a rich collective dynamics. As compared to standard many-body systems like helium and ultracold atoms, new perspectives are opened by the intrinsic non-equilibrium nature of the photon gas. A number of material systems can be used for these studies, from nonlinear optical crystals in the strong light-matter coupling regime to semiconductor microcavities and even circuit QED devices in the microwave domain.

This article reviews 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, to the hydrodynamic formation of topological excitations such as quantized vortices and dark solitons at the surface of large impenetrable obstacles. 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.

This is the third review article published by the Trento group in Reviews of Modern Physics, after the highly cited reviews on the theory of Bose-Einstein Condensation in trapped gases (RMP 71, 463 (1999)) and the theory of ultracold Fermi gases (RMP, 80, 1215 (2008)).

Phys. Rev. B 83, 144513 (2011)

Hydrodynamic nucleation of vortices and solitons in a resonantly excited polariton superfluid

S.Pigeon, I.Carusotto, C. Ciuti

Soon after the first demonstration of Bose-Einstein condensation in gases of exciton-polaritons in semiconductor microcavities, researchers have started investigating the peculiar superfluidity properties of these novel quantum gases: Robust propagation of a coherent polariton bullet hitting structural defects has been demonstrated, as well as a strongly enhanced lifetime of supercurrents in a polariton condensate. In the simplest case of a resonantly pumped polariton gas, the Landau criterion for frictionless flow in the presence of weak defects has been experimentally demonstrated in a quantitative way by the LKB group in Paris. In the same work, a Cherenkov-like conical wake of the polariton gas was observed in the density profile when this hits the defect at higher speed. These observations are in full agreement with the theoretical anticipations of the Trento-Paris 7 collaboration.

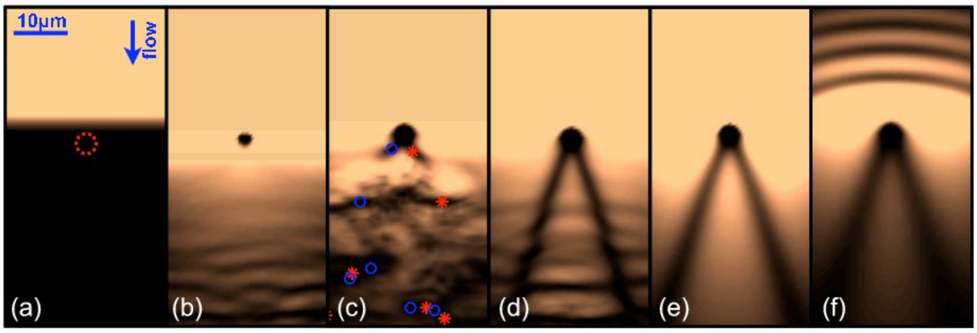

Figure 29: Polariton density profiles in the different regimes: (b) superfluid regime; (c) turbulent generation of vortices; (d,e) pair of solitons appear downstream of the defect; (f) solitons and parabolic precursors in the upstream region. Panel (a) shows the profile of the pump beam.

Pioneering theoretical work using the standard Gross-Pitaevskii equation for a generic superfluid has anticipated the onset of an additional friction mechanism involving nucleation of vortex-antivortex pairs and/or solitons at the surface of a spatially extended and strong defect even at speeds below the Landau critical velocity for phonon emission. In the present paper we present a theoretical investigation of the behavior of a polariton superfluid when hitting a spatially extended and strong defect including the novel features stemming from the non-equilibrium nature of the polariton fluid, i.e., the need of a continuous pumping to compensate for the unavoidable polariton losses. We specifically address different quantum hydrodynamic processes: Depending on the flow speed, the polariton gas can either flow almost unperturbed around the defect, show a weak Cherenkov-like modulation pattern as in the weak defect case, or experience the nucleation of vortices and/or solitons at the surface of the defect. Soon after their appearance, these theoretical predictions have been experimentally verified by the LKB group in Paris, the NNL group in Lecce and the EPFL group in Lausanne.

Science 332, 1167 (2011)

Hydrodynamic solitons in polariton superfluids

A. Amo, S. Pigeon, D. Sanvitto, V. G. Sala, R. Hivet, I. Carusotto, F. Pisanello, G. Lemenager, R. Houdre, E. Giacobino, C. Ciuti, A. Bramati

A quantum fluid passing an obstacle behaves differently from a classical one. When the flow is slow enough, the quantum gas enters a superfluid regime, and neither whirlpools nor waves form around the obstacle. For higher flow velocities, it has been predicted that the perturbation induced by the defect gives rise to the turbulent emission of quantized vortices and to the nucleation of solitons.

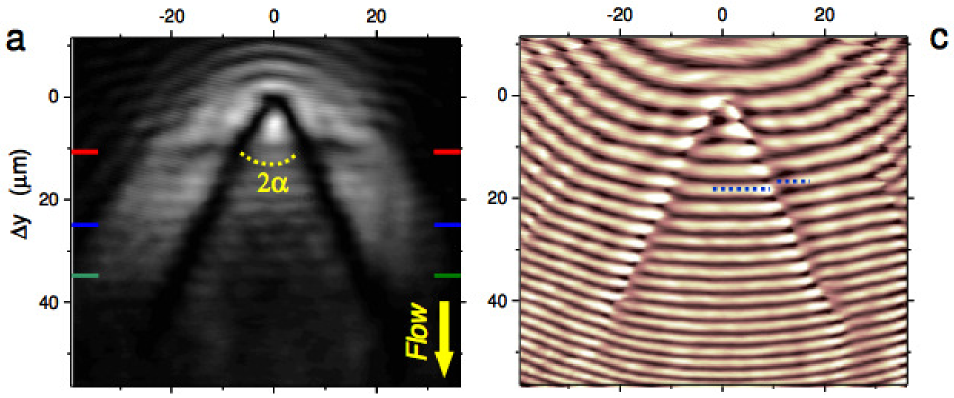

Figure 30: Polariton density (left) and phase (right) profiles when a polariton fluid hits a strong and spatially extended defect. The solitonic nature of the perturbations visible downstream of the defect is confirmed by the jump in the condensate phase across the soliton dark line.

Here we use a polariton condensate to experimentally reveal quantum hydrodynamic features, whereby dark solitons and vortices are generated in the wake of a potential barrier. Following a recent theoretical proposal by the BEC Trento-Paris 7 collaboration, we investigate different regimes at different flow speeds and densities, ranging from superfluidity to the turbulent emission of trains of vortices, to the formation of pairs of oblique dark solitons of high stability. For spatially large enough barriers, soliton quadruplets are also observed.

The properties of the polariton condensates are experimentally accessible from the intensity and phase pattern of the emitted light. An unambiguous characteristic of dark solitons is the phase jump across the dark region. To reveal the phase variations in the polariton quantum fluid, we make the emission from the condensate interfere with a reference beam of homogeneous phase: the result shows a phase jump of up to π as a discontinuity in the interference maxima along the soliton. For lower flow speeds, a turbulent flow occurs because of the random generation of vortices. In the experiment, this is visible as a reduced coherence of the light emission.

Phys. Rev. Lett. 105, 020601 (2010)

Superfluidity and Critical Velocities in Nonequilibrium Bose-Einstein Condensates

M. Wouters, I. Carusotto

Superfluidity is among the most remarkable consequences of macroscopic quantum coherence in condensed matter systems and manifests itself in a number of fascinating effects. The phenomenon of macroscopic coherence is not restricted to systems at (or close to) thermodynamical equilibrium such as liquid Helium, ultracold atomic gases, or superconducting materials, but has been observed also in systems far from thermodynamical equilibrium, whose stationary state is determined by a dynamical balance of driving and losses, e.g. Bose-Einstein condensates of magnons in magnetic solids and of exciton polaritons in semiconductor microcavities.

In particular, the issue of superfluidity in this latter system has attracted a significant interest from both the theoretical and experimental points of view. Recent experiments by the LKB group have demonstrated superfluidity under a resonant pumping, but the situation is less clear in the case of nonresonant or parametric (OPO) pumping schemes: recent experiments by the UAM group in Madrid have observed propagation of polariton bullets without apparent friction, which is in stark contrast with the predictions of a naive Landau criterion.

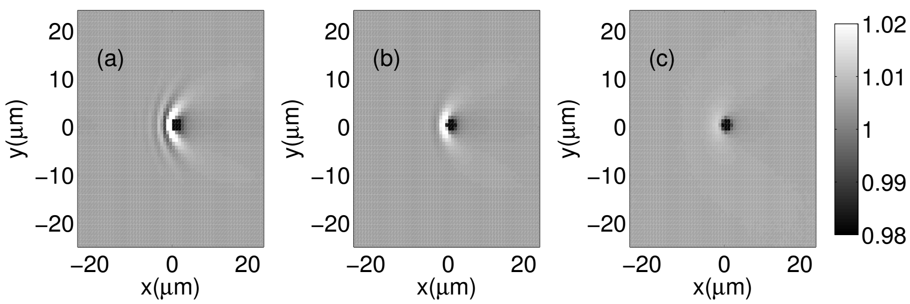

Figure 31: Density profile of a non-equilibrium polariton fluid hitting a defect at different speeds, decreasing from left to right. The central panel corresponds to a speed value in the vicinity of the generalized Landau criterion for superfluidity.

The present Letter reports a comprehensive theoretical investigation of the meaning of superfluidity for non-resonantly pumped polariton condensates. A theoretical model of the condensate dynamics is built in terms of a Complex-Ginzburg-Landau equation including pumping and losses. Contrary to previous expectations, superfluidity is shown to be robust against particle loss. Fringes in the density profile are created by a moving defect only above a critical speed; correspondingly, the drag force shows a pronounced threshold-like behavior. The value of the critical speed is determined in terms of a generalized Landau criterion which includes the intrinsic non-equilibrium nature of the condensate by allowing for complex wavevectors of the elementary excitations. Remarkably, metastability of supercurrents is found to persist even for velocities well above the critical speed.

EPL 90 37001 (2010)

Feshbach blockade: single-photon nonlinear optics using resonantly enhanced cavity-polariton scattering from biexciton states

I. Carusotto, T. Volz, A. Imamoglu

A number of quantum optical applications crucially rely on having a strong value of the effective photon-photon interaction mediated by the optical nonlinearity of the atomic or solid-state medium. As a simplest example, a stream of strongly antibunched photons is emitted by a cavity as soon as the nonlinear shift of the resonance by a single photon is larger than the cavity linewidth. This physics is even more intriguing when more complex devices are considered: photons have been predicted to fermionize into Tonks- Girardeau gases as soon as the impenetrability condition is satisfied in a one-dimensional geometry.

A great deal of the recent advances in the field of strongly correlated atomic gases have been made possible by the discovery of the so-called Feshbach resonance effect in atom-atom collisions: the scattering cross-section is dramatically enhanced when the energy of the pair of colliding atoms is resonant with a long-lived quasi-bound molecular state.

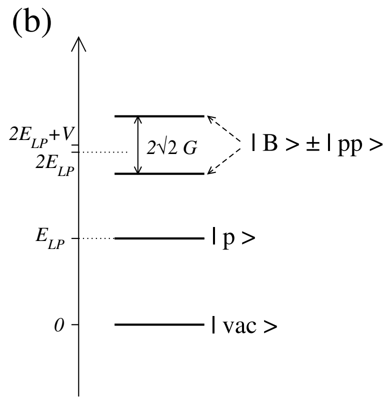

Figure 32: Scheme of the energy levels of an optical microcavity strongly coupled to a exciton state in the vicinity of the Feshbach resonance. The blockade effect is due to the energy splitting of the symmetry and anti-symmetric superpositions of the two-polaritons and single-biexciton states.

In this letter, we show how a similar Feshbach resonance mechanism can be used in a solid-state optical context to dramatically enhance the strength of the interactions between cavity polaritons in a planar microcavity in the strong-coupling regime. Our work follows up on a pioneering proposal by M. Wouters and develops a simple analytical model of the biexciton Feshbach resonance inspired by the atom-molecule approach to strongly interacting degenerate quantum gases. This is used to obtain analytical predictions for the nonlinear and quantum optical properties of specific optoelectronic devices.

The main result of this letter is the characterization of the non-classical antibunching properties of the light emission from a micron-sized polariton dot: the enhancement of the optical nonlinearity on the biexciton Feshbach resonance is anticipated to provide an efficient Feshbach blockade effect where the presence of a single polariton is able to block the entrance of a second one. As polariton dots do not involve quantum confinement of carriers, they are not subject to the fluctuations in the confinement length that are responsible for the typical inhomogeneous broadening of quantum dot samples. For this reason, polariton dots appear as ideal candidates to realize sizeable arrays of identical nonlinear cavities.

Phys. Rev. Lett. 108, 206809 (2012)

Fractional quantum Hall states of photons in an array of dissipative coupled cavities

R. O. Umucalilar and I. Carusotto

In recent years, the hydrodynamic properties of quantum fluids of light have attracted strong interest from both theoretical and experimental points of view, with the demonstration of superfluid flow in degenerate quantum gases of dressed photons in planar semiconductor microcavities (the so-called exciton-polaritons) and the subsequent observation of vortices and solitons in the wake of a strong defect. All these experiments were performed in a dilute gas regime where a mean-field description based on a generalized Gross-Pitaevskii equation is accurate. The present challenge is to go beyond this regime: this requires that the underlying medium show a sufficiently large optical nonlinearity to induce strong effective interactions between the photons, for instance via the so-called *photon blockade* effect.

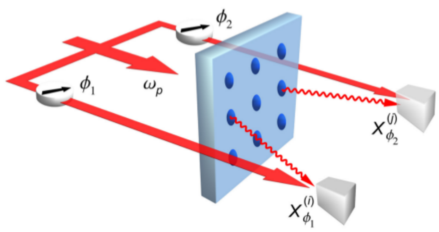

Figure 33: Sketch of the proposed experimental setup to measure the two-photon wavefunction.

In the meanwhile, several proposals have appeared for generating *synthetic magnetic fields* for neutral quantum particles. For instance, the Berry phase accumulated by an optically dressed atom while adiabatically moving in space can be described in terms of a synthetic gauge field: recently,this idea was exploited to demonstrate the nucleation of quantized vortices in a dilute Bose-Einstein condensate under the effect of a synthetic gauge field. Very recently, the extension of this idea to photons has been theoretically investigated in a number of configurations, for instance, arrays of coupled optical cavities confining single atoms, microwaves in circuit-QED devices, and solid-state photonic devices in the infrared or visible spectral range. The BEC Center has provided important contributions to these investigations.

The present Letter reports a theoretical study of the optical response of a coupled cavity system to a coherent laser field in a regime where impenetrable photons experience a strong synthetic magnetic field. In contrast to previous works, we take full advantage of the driven-dissipative nature of the photon gas to propose an all-optical protocol to generate and characterize strongly correlated photon states which are analogs of the fractional quantum Hall (FQH) states of electrons in two-dimensional geometries under a strong magnetic field. The quantum Hall nature of the generated state is assessed in terms of its overlap with the Laughlin wave function. We anticipate that detailed information on the microscopic structure of the many-body wave function can be experimentally extracted from the field quadratures of the secondary emission from the device.

Phys. Rev. A 87, 023803 (2013)

Quantum vacuum emission in a nonlinear optical medium illuminated by a strong laser pulse

S. Finazzi and I. Carusotto

The first claim of observation of analog Hawking radiation in a laboratory was made in Como in 2010 by Daniele Faccio and coworkers: a strong infrared pump pulse was sent through a nonlinear medium (fused silica in the quoted experiment) and created a moving perturbation of the refractive index. As a result, the speed of optical photons inside (outside) the pulse results smaller (larger) than the pulse velocity: Seen from the reference frame comoving with the pulse, the leading (trailing) edge of the pulse appears then as the analog of a black(white) hole horizon. At the state of the art, the interpretation of the experimental results as Hawking radiation is still considered as controversial by many some authors.

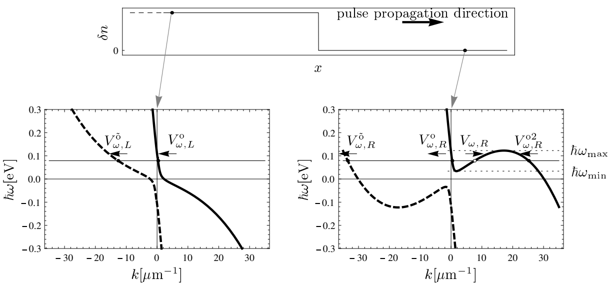

Figure 34: Simplified sketch of the propagating pulse and of the dispersion relation of light in fused silica highlighting the modes that are involved in the Hawking-like emission processes.

Different from previous studies that are strongly based on gravitational physics, the present work aims to develop a microscopical quantum optical model of light propagation in a nonlinear dielectric modulated by the passage of a high-intensity laser pulse where light is described in terms of the Lagrangian of the electromagnetic field coupled with three polarization fields. In this way, we are able to obtain quantitative predictions for the spectrum of spontaneously emitted photons.

One of the most important conclusions of our work is that the highly nontrivial dispersion relation makes the analogy with standard quantum field theory in curved space-time much weaker than in other analog systems considered in the literature, such as atomic BECs: For instance, in the present nonlinear optical context, an analog horizon can be defined only in a finite range of frequencies that does not extend to the long-wavelength limit where the analog geometry is generally defined. Nonetheless, the properties of the quantum vacuum emission in this frequency range still share several features of standard Hawking radiation.

Furthermore, in contrast to nondispersive media, where a necessary and sufficient condition to trigger emission processes à la Hawking is the presence of analog horizons, quantum vacuum radiation occurs in dispersive media even in the absence of any horizon as soon as the dispersion allows for modes with a negative norm but a positive frequency, as seen from the pulse comoving frame. With respect to the above-mentioned Hawking-like emission channel, this additional emission is however generally much weaker.

Phys. Rev. Lett. 110, 163901 (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

A typical strategy to study the physics of the planar whispering-gallery mode (WGM) resonators consists of exciting the cavity modes from an adjacent waveguide and collecting the transmitted light. The resonator- waveguide coupling (RWC) takes place via an overlap of the evanescent fields of the waveguide and the resonator optical modes. In an in-plane geometry, where the waveguide and the resonator lay on the same plane, the mode coupling is known to grow exponentially when the gap x between these two is decreased. This behavior has important implications in the amplitude and the linewidth of resonant dips that appear in the waveguide transmission spectrum $T(\omega)$ at cavity mode frequencies. As the gap x is reduced, the cavity mode linewidth Γ increases monotonically. The transmission T_{dip} at resonance, in turn, vanishes at a single critical coupling gap x^*.

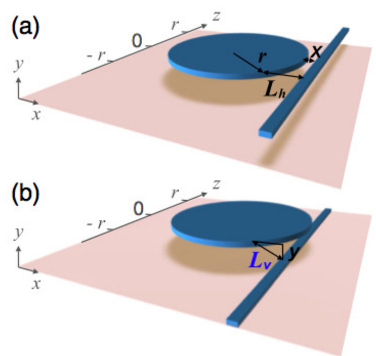

Figure 35: Sketch of the in-plane (a) and vertical (b) coupling geometries.

Besides, in present-day integrated optics a vertical coupling geometry for the RWC is also used, where the resonator and the waveguide lay on different planes. In contrast to lateral coupling, this approach does not require high-resolution lithography for the definition of narrow gaps and allows for an independent choice of materials and thickness's for the optical components. Such features offer a larger design flexibility that can be of great utility in a number of applications to high-speed integrated optoelectronics as well as to cavity optomechanics.

This work has been performed by a tripartite collaboration between groups active on the Povo hills: the BEC Center has provided the theory, the Nanoscience Lab of Trento University has performed the spectroscopical measurements, and the APP group of FBK has fabricated the samples. In particular, we have been able to show both theoretically and experimentally that the standard model of spatially localized RWC is actually wrong for a vertical geometry. In contrast to the monotonic exponential dependence of the effective RWC in the in-plane geometry, the vertical one is characterized by an oscillating effective coupling as a function of vertical gap y, with alternating under-and over-coupling regions, separated by several critical coupling points. Correspondingly, both the cavity mode linewidth Γ and the dip transmission T_{dip} show oscillating dependencies. An excellent qualitative agreement is found between the analytical model based on coupled mode theory and the experimental observations.

Experiments: work-flow, status and prospects

Work-flow and present status

The project of the new experimental laboratory of the BEC Center, proposed in 2009 and officially started in 2010, was expected to proceed in the three-year period 2010-12 according to the following steps: a) selection of the researcher that will lead the experimental team; b) identification of the spaces in which the laboratory will be hosted; c) definition of the research lines to be developed in the laboratory and consequent selection of the required equipment; d) planning and execution of the works to prepare the laboratory space according to the experimental requirements; e) purchase and test of the equipment; f) definition of a plan to recruit collaborators (researchers, PhD students, etc.); g) setting up of the equipment in the new laboratory and first test measurements; h) beginning of the measurements according to the laboratory's research lines.

By the end of year 2012 all steps were completed. In particular:

a) Several researchers were contacted and some of them were invited to the BEC Center to give seminars and to discuss on the project. At the end of this process, the team leader was identified in Dr. Gabriele Ferrari, an internationally distinguished physicist in the field of experimental studies on ultracold atoms, with previous experience in the setup of new and successful laboratories at the University of Pisa, at ENS in Paris, and at LENS in Florence. He accepted the position in June 2010 and started soon to elaborate the scientific project of the laboratory and the budget draft.

b) The Council of the Physics Department of the University of Trento, on November 10, 2010, decided unanimously its support to the birth of the experimental laboratory of the BEC Center, and the allocation of appropriate laboratory space. A specific formal agreement was signed by INO-CNR and the Department of Physics on 5 July 2011.

c) Since Dr. Ferrari took responsibility on the laboratory, the scientific project rapidly got defined in the details in order to attain some of the key objectives within 2012. The goal was to reach the full operativeness of the laboratory within the three-year period, to start the research on the properties of quantum gases of polar molecules, or in the presence of synthetic magnetic fields, by means of trapping and cooling to quantum degeneracy a mixture of sodium and potassium atoms. The experimental apparatus is conceived to study the dynamics of gases both in the usual three dimensional case and in lower dimensions, also while modifying the interaction properties of the system by taking advantage of collisional resonances. As regards the cases of reduced dimensionality, great interest will be put on the topic of transport in the presence of lattice potentials. A second topic that will be tackled is the interaction of cold atoms with ultrafast, phase-stabilized, and high repetition rate lasers. The project was defined with the advice of experts in the field specifically invited to Trento or met at conferences and workshops, as well as with the support of colleagues from LENS Florence. In addition, the complementarity between the new laboratory in Trento and LENS was also taken into account.

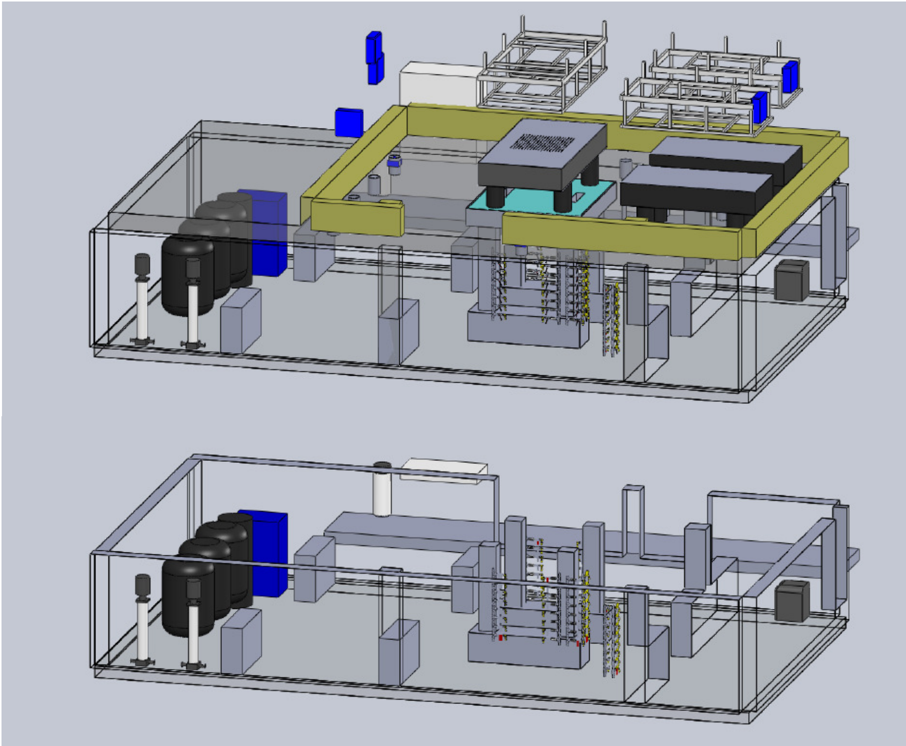

Figure 36: Framework of the main laboratory space. Upper picture: render of laboratory together with the space underneath. Lower picture: section view showing the distribution of space under the main laboratory. The pressurized chilled water system, together with three tanks for the additional passive temperature stabilization is present on the left of the picture. A concrete structure holds the main optical table directly form the room underneath the main laboratory, without a direct coupling to the main laboratory floor, to limit the propagation of the seismic and the building noise up to the ultra-cold sample.

d) After an initial delay, due to the time needed to find the appropriate space within the Physics Department, the works for the arrangement of the laboratory proceeded rapidly. The Department itself made an important effort to speed up the subsequent steps towards the arrangement of the laboratory in order to make up for the lost time. Since summer 2010, the new laboratory obtained a strong support from the local technical services, and both the Director of the Department and the chief responsible of the technical services did their best to obtain rapidly all the authorizations and help from the main University offices in order to complete the technical and financial arrangements (which includes the building, air conditioning, pressurized chilled water circuitry, electrical circuitry, etc). Two visits of Dr. Ferrari and engineers from the University of Trento were organized at the IQOQI in Innsbruck in order to optimize and shorten the design phase of the technical supplies of the laboratory. The room of the laboratory was fully refurbished, with the realization of an additional dedicated space under the laboratory to host a large fraction of the technical supplies, hence improving the overall environmental performances of the laboratory space, and providing a better access to the room devoted to the actual measurements. The works were completed within September 2011, when the optical tables were delivered. In addition, since December 2010 the Physics Department assigned to the laboratory two smaller rooms devoted to the setup and test of the equipment that then will be used in the main laboratory.

In figure 36 the structure of the main laboratory space is sketched. This is hosted in the basement of the Physics Department and it has a surface of about 50 square meters sufficient to host three optical tables, one devoted to the atomic source and the optical-dipole trapping lasers, and two devoted to the lasers required for laser cooling and the coherent transfer between molecular states. Underneath the main laboratory there is and additional space, of about 70 square meters, that hosts the technical equipment (such as the pumps and refrigerators required for the pressurized chilled water circuitry, the air conditioning system, UPS, etc) and the modules of laboratory equipment that, because of their noise or their their heat dissipation, may degrade the overall quality of the environment of the main laboratory.

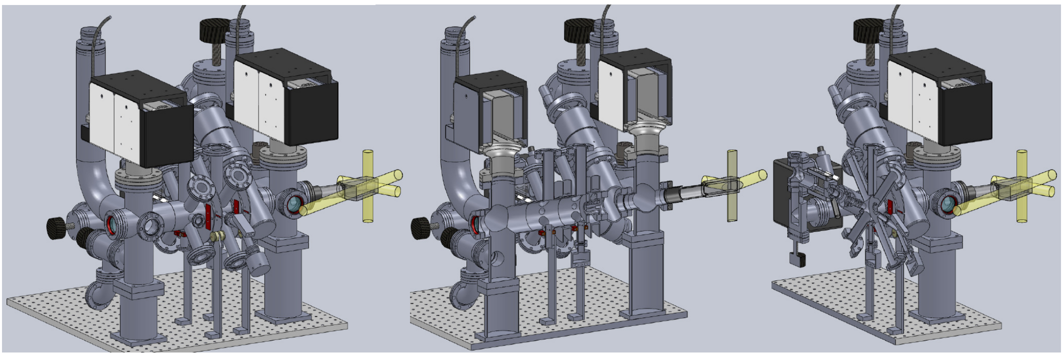

Figure 37: Vacuum system: left) the quartz cell is visible on the right of the apparatus together with the three orthogonal directions of the 3D MOT; center) vacuum system sectioned along the direction of the transfer between the region of intermediate and ultra-high vacuum; right) vacuum system sectioned along the direction of the transfer between the potassium 2D MOT and the sodium 2D MOT. The Na 2D MOT is overlapped to a second K 2D MOT that deflects the K towards the quartz cell.

e) The first step towards the realization of the project, once the project leader had been chosen and the laboratory space had been made available, consisted of starting the procedures for the purchase of the required equipment. These procedures, which are rather complex on their own, began in autumn 2010 with the expectation to spend the 350.000 euro foreseen in the budget for this year. Unfortunately in the same period CNR stopped most of the purchases at the national level in order to redefine the procedures in fulfillment of a recent law on money traceability (Law n. 136 of August 13, 2010). This resulted in an unavoidable delay on the spending schedule for the laboratory with a slow resumption of the orders starting from December 2010, when the administrative activity is usually slowed down because of the shift to the new financial year. Despite these bureaucracy problems, the equipment has been then supplied with a reasonable rate. Optical tables, lasers, vacuum system, and most of the things required at the start-up were installed in the laboratory within 2011, as it was foreseen in the initial planning. The purchase, installation and test of the equipment has proceeded regularly in 2012, according to the initial plans.

f) Particular care was taken for the creation of a dedicated team of researchers. The most important steps have been the following: i) the Physics Department appointed to the laboratory a mechanical technician, Michele Tomasi, during the full three-year period, who assisted Dr. Ferrari in the installation of the new equipment and in the realization of custom-made mechanical components; ii) on the basis of a competitive examination for the selection of a new CNR researcher, dr. Giacomo Lamporesi became a new permanent member of the experimental group, starting his activity in Trento since December 2011; iii) two master students, Simone Donadello and Simone Serafini joined the group at the beginning of 2012 to carry on their thesis work and actively participating to the set-up of the experiment. Simone Donadello graduates in September 2012 with Laude and soon after he was selected as a PhD student in the Doctorate School of the Department of Physics, to continue his activity in the lab. Simone Serafini graduated in March 2013, also with maximum grade and Laude. A new master student has started the thesis in the lab at the beginning of 2013.

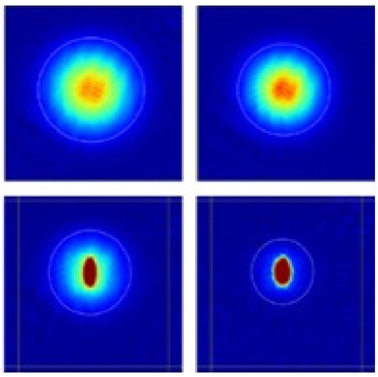

Figure 38: The first observation of the BEC transition of Sodium atoms in Trento.

g) The set-up of most of the equipment was completed in the second half of 2012. A series of tests have been performed in order to optimize the trapping and cooling techniques for Sodium atoms. The source of Potassium atoms have been also prepared.

h) In December 2012 the first condensate of Sodium atoms is observed. The laboratory is fully operational.

Overview of the long term scientific program

The main topic of the laboratory is chosen considering the present state-of-the-art in the field of ultra-cold and quantum degenerate gases, and the perspective of being in the forefront of research on quantum gases. Since the first demonstration of Bose-Einstein condensation with dilute gases in 1995, ultra-cold atoms have been studied in many different conditions and to mimic many different systems of fundamental interest. Nowadays the technical complexity of the experimental setups required in this field imposes a careful choice of the topics to be studied because

- the building of the experiment takes time, and once this is ready the state-of-the-art may be changed,
- the choice on the topic has a profound impact on the apparatus required in the laboratory, which may be difficult or expensive to modify after the first decision.

The production of ultra-cold ground-state polar molecules, and the realization of light-induced effective gauge fields for neutral atoms are among the most striking results published during the last three years within the quantum gas community. While ultra-cold atoms are becoming quite popular worldwide, today there are few groups active in these new fields and it is likely that the scenario will not change dramatically within the next couple of years. In addition, the specific features of these systems (that, for instance, allow an exquisite control on the parameters of the systems, or the flexibility on the modification of the configurations and the dimensionality), and the broad applicability that they collect in many different domains of fundamental and applied physics will ensure them a central role within the quantum gas community for the years to come.

The scientific objectives of the laboratory were chosen following the above considerations, and hence the experimental setup and equipments to adopt were decided. Specifically, after the pioneering results obtained by the Jun Ye and Debbie Jin group in JILA, Colorado, today we know how to produce ultra-cold ground-state polar molecules and we took the awareness of the importance of the chemical stability of the molecules across collisions. While the JILA group demonstrated an effective method to produce the cold polar gas, using Feshbach resonances in a quantum degenerate mixture of rubidium and potassium atoms followed by a stimulated transfer of the molecular weakly bound state to the absolute ground state, they also realized the importance of losses induced by chemical reactions of the type $2\,\mathrm{RbK}\rightarrow \mathrm{Rb}_2+\mathrm{K}_2$ which in their case it is energetically allowed. In our case we plan to follow a similar experimental approach but replacing the Rb-K mixture, which turned out to be chemically unstable, with the sodium-potassium mixture for which, according to calculations by Żuchowski and Hutson, the atom exchange reaction is energetically forbidden. Besides the chemical stability of the molecular state, both atomic sodium and atomic potassium already proved to be excellent choices for the experimental study of quantum degenerate atoms. Sodium is extremely stable in the Bose condensed phase and it is an excellent refrigerator for

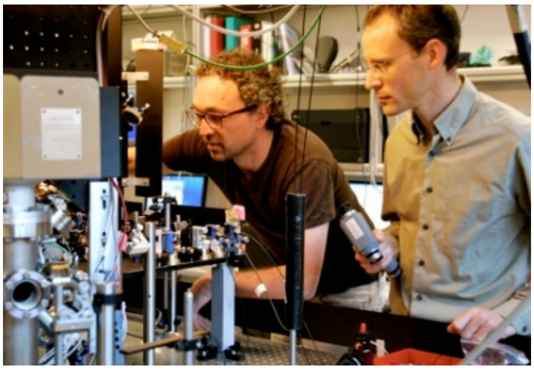

Figure 39: Gabriele Ferrari (right) and Giacomo Lamporesi (left) in their lab.

other species, and potassium is rich in isotopes, with both bosonic and fermionic ones, and collisional resonances. This makes the Na-K mixture very promising even beyond the application to the production of polar molecules.

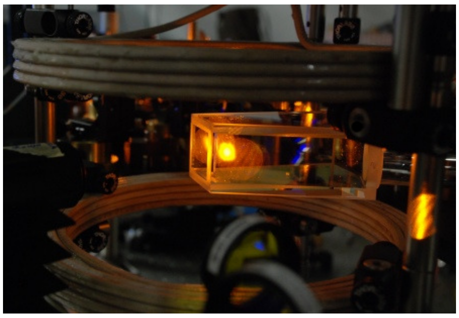

Figure 40: Sodium atoms in the magneto-optical trap.

Experimentally, the mixture will be produced using standard tools of laser cooling and manipulation. Both atom sources are based on two dimensional magneto-optical traps: potassium being loaded from background vapor following the usual scheme, and sodium being loaded from an effusive oven employing a generalized version of the 2D MOT demonstrated for lithium by the Walraven group in Amsterdam which, by incorporating a short Zeeman slower stage, provides an improved flux of atoms, of the order of the present state-of-the-art in the field. The vacuum system, which is sketched in the figure 37, allows the superposition of the two atomic species on the 2D MOT of sodium, which also acts as atomic deflector for potassium atoms previously collected and cooled from background vapor in a different region. The flux of the two species is hence overlapped and directed towards the ultra-high vacuum region, where the atoms are captured in a 3D MOT and then brought to ultra-low temperatures by means of laser cooling, and evaporation in magnetic and optical-dipole potentials. The final cooling stage takes place within a quartz cell that ensures a high optical access both for the atomic and molecular manipulation, and for imaging. Electric fields, which are required for the polarization the molecular gas, will be produced using four wire electrodes placed within the quartz cell. The electric field will be varied in intensity, and in direction within a plane, by varying individually the potential applied to each electrode.

All the components of the vacuum system were installed and are now operational with ultimate performances, as certified by the background pressure limited lifetime of the ultracold sample at the level of 5 minutes in the ultra-high vacuum region. All the sub-systems and instruments required to cool the atoms down to quantum degeneracy were installed (in many cases build in-house), tested individually, and optimized for the final configuration, based on the feedback directly provided by the atom behaviour. Following this procedure, we completed:

- both laser sources for the trapping and cooling cooling of sodium and potassium from thermal atomic sources,
- the magnetic trap, where the Na-K mixture are transferred after the magneto-optical cooling stage and further cooled to quantum degeneracy via evaporative cooling, and which is based on coils of wounded copper tubing driven by currents of the order of 200 amperes,
- the computer control system for the experiment, which includes digital, analog and radio-

frequency (DDS-based),

- the acquisition system based on resonant absorption imaging on CCD cameras, including the synchronization with the experiment control system, and integration with a versatile platform for on-line analysis of the collected data.

With this setup both sodium and potassium atoms were collected and cooled in a 3-dimensional magneto-optic traps, as shown in figure 40, and quasi-pure Bose-Einstein condensates containing 20 million atoms were routinely produced since December 2013. With this regard, figure 38 reports the atomic distribution after ballistic expansion of the sample while crossing the Bose-Einstein transition.

First results

The first results of the experimental team are summarized in two articles. The first one, "A compact high-flux source of cold Sodium atoms", by G. Lamporesi, S. Donadello, S. Serafini, G. Ferrari, has been published in the Review of Scientific Instruments. The second article, "Spontaneous creation of Kibble-Zurek solitons in a Bose-Einstein condensate", by G.Lamporesi, S.Donadello, S.Serafini, F.Dalfovo, and G.Ferrari, has been submitted for publications in April 2013 and is under review. A summary of each paper is given in the next pages.

Review of Scientific Instruments 84, 063102 (2013)

A compact high-flux source of cold sodium atoms

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

The growing interest in cold atoms led to the development of specific atomic sources. Sources capable of high fluxes have been developed for many atomic species addressing issues of compactness, atomic yield, and ease of use. In fact the availability of essential experimental tools as the atomic source, in many circumstances proved to drive the choice of the atomic species to study and, eventually, the physical domain to address.

In this article we present a novel type of compact atomic source delivering cold sodium atoms with state-of-the-art fluxes. This sodium source has a novel design that combines high-flux performances with the compactness and simplicity of the experimental setup. It is based on a thermal sodium atomic beam coming out from an oven that is slowed down through a 5 centimeters long Zeeman slower, and two-dimensionally trapped in a magneto-optic trap (2D MOT, see figure 41). An additional laser beam aligned along the non-trapped direction pushes the atoms hence obtaining a collimated and slow atomic beam that is finally captured and cooled in a three-dimensional magneto-optical trap (3D MOT) in a nearby ultra-high vacuum (UHV) region.

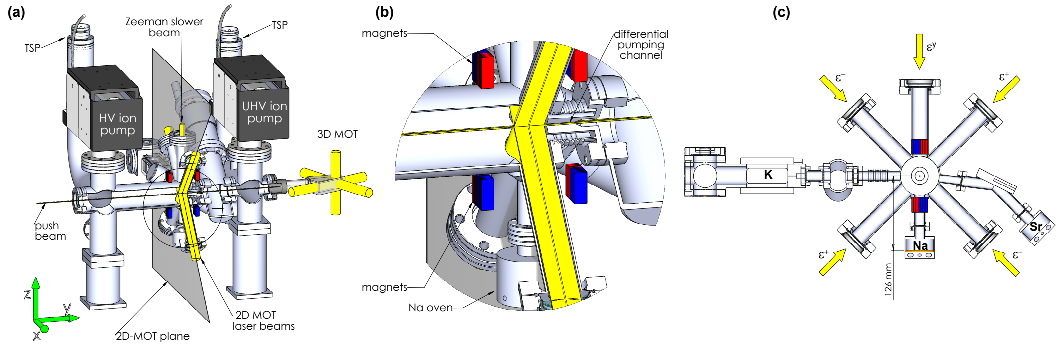

Figure 41: (a) 3D view of the vacuum system of the atomic source. HV region on the left side contains the atomic source and the optical access for the pre-cooling stage. The differential pumping channel connects this to the UHV region where the experiment is performed in a clean environment. Light beams (yellow) and magnets (red-blue) are shown. (b) Magnification of the compact slowing/cooling region. (c) 2D view of the pre-cooling plane showing atomic sources and beams configuration.

Our design presents many advantages compared to ordinary sodium atomic sources. Atoms from the oven cannot pass directly to the UHV chamber through the connecting channel, therefore no extra stages, such as mechanical shutters, are needed in the vacuum chamber to reduce background hot atoms in the UHV region. The transfer of atoms to the 3D MOT can be optically modulated by switching off 2D MOT's laser beams, and in our case no atoms are detected in the final 3D MOT in absence of these beams.

In addition to the simplification of the apparatus, our approach offers the possibility to deal with more atomic species at the same time. Thanks to its radial symmetry the sodium 2D MOT can be transversely loaded from different sources (see Fig. 41(c)). Our setup is already set for collecting also potassium from a vapor-cell 2D MOT and strontium from an oven. For both additional atomic species the corresponding cooling lights are superposed to the sodium one by means of dichroic mirrors. In fact, this multi-atomic species approach was readily demonstrated by the loading of both sodium and potassium atoms in the final 3D MOT.

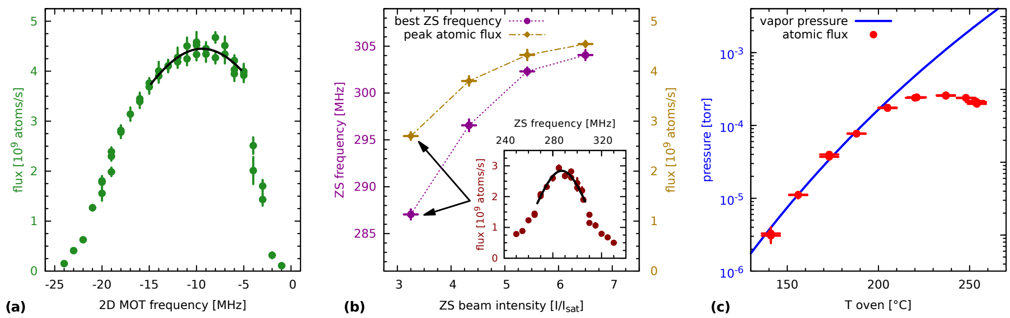

Figure 42: (a) Measured flux of atoms (green circles) captured in the 3D MOT as a function of the frequency detuning of the 2D MOT beams. Central data are fit to a Gaussian (black line) to find the best frequency. (b) Best Zeeman slower frequency (red) and maximum flux recorded (yellow) for different Zeeman slower intensities. The inset shows a typical dependence of atomic flux on the Zeeman slower frequency at fixed intensity. (c) Comparison between the vapor pressure of sodium (blue line) and the 3D MOT loading rate (red circles) as a function of the oven temperature.

The performances of the atomic sources were fully characterized, in terms of sodium atoms delivered to the UHV region and captured in the 3D MOT, as a function of the most relevant experimental parameters such as the intensity and frequency of the laser cooling light, the temperature of the effusing oven where sodium atoms evaporate from the liquid metal, and the magnitude of the magnetic field gradients. Figure 42 depicts some few graphs produced in this characterization process, showing the relatively low sensitivity of the performances to fluctuations and drifts of the parameters.

This atomic source proved to be very effective in the laser cooling of sodium and potassium in an environment perfectly suited for the subsequent evaporative cooling towards quantum degeneracy. Beside this, we believe this novel approach represents a valid alternative for the realization of a high-flux atomic sources, especially in case of multi-species experiments where complexity and encumbrance are relevant issues.

Preprint (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.

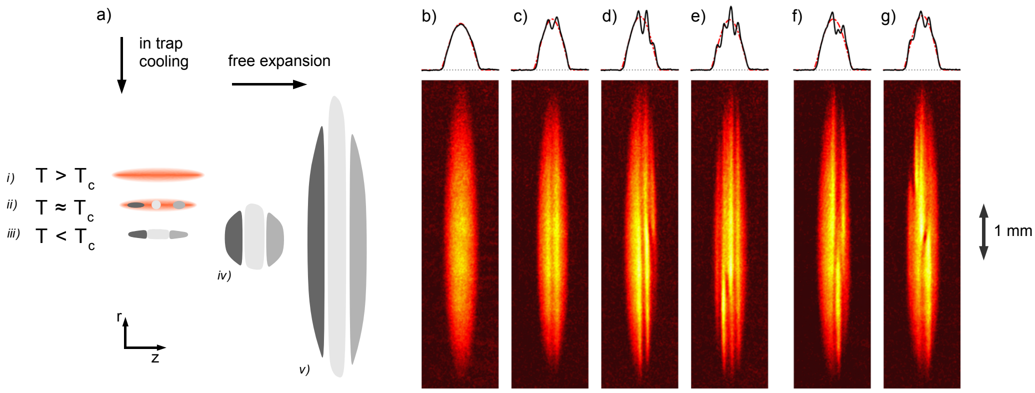

Figure 43: **a** Formation after a quenched cooling on a thermal gas (*i*, red) across the BEC transition, BEC is locally achieved forming several isles (*ii*) each with its own phase (grey). Further cooling makes them grow and get close (*iii*) forming solitons. The sample is released from the trap 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 manuscript we report on the observation of solitons 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 solitons 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 solitons 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. 43a *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. 43a *iii*). We characterize this process by counting the solitons 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. 43a *iv*-*v* and Fig. 44). Typical density distributions after time-of-flight (TOF) are shown in Fig. 43b-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 soliton. 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.

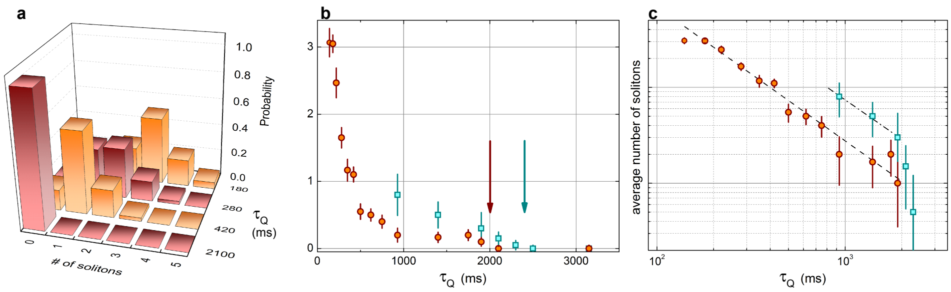

Figure 44: **a**, Counting statistics of the number of solitons observed in each shot for four different quench times and for the data set with 25 million atoms at T_c. Lin-lin (**b**) and log-log (**c**) plots of the average soliton number observed as a function of the quench time τ_Q. Red circles and 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.

Full list of publications

The following list includes the papers published or submitted for publication starting from January 2010 having at least one of the authors with the Trento BEC affiliation.

Articles

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,
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A compact high-flux source of cold sodium atoms, G. Lamporesi, S. Donadello, S. Serafini, and G. Ferrari,
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Localization in momentum space of ultracold atoms in incommensurate lattices, M.Larcher, M.Modugno, F.Dalfovo,
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Current-Phase Relation of a Bose-Einstein Condensate Flowing Through a Weak Link, F. Piazza, L. A. Collins, A. Smerzi,
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Supercurrent and dynamical instability of spin-orbit coupled ultracold Bose gases, Tomoki Ozawa, Lev P. Pitaevskii, and Sandro Stringari, arXiv:1305.0645

Spontaneous Peierls dimerization and emergent bond order in one-dimensional dipolar gases, M. Di Dio, L. Barbiero, A. Recati, M. Dalmonte, arXiv:1304.5200

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Dipolar-Induced Resonance for Ultracold Bosons in a Quasi-1D Optical Lattices, N. Bartolo, D.J. Papoular, L. Barbiero, C. Menotti, A. Recati, arXiv:1303.3130

Non-equilibrium quasi-condensates in reduced dimensions, Alessio Chiocchetta and Iacopo Carusotto, arXiv:1302.6158

Bloch oscillations in a periodic lattice under a strong (artificial) magnetic field, Marco Cominotti and Iacopo Carusotto, arXiv:1302.3165

A study of coherently coupled two-component Bose-Einstein Condensates, M. Abad and A. Recati, arXiv:1301.6864

First and second sound in a highly elongated Fermi gas at unitarity, Yan-Hua Hou, Lev P. Pitaevskii and Sandro Stringari, arXiv:1301.4419

Anyonic braiding phases in a rotating strongly correlated photon gas, R. O. Umucalilar, I. Carusotto, arXiv:1210.3070

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Polar molecules in bilayers with high population imbalances, Michael Klawunn and Alessio Recati, arXiv:1110.2336

Meetings, seminars, conferences

Group meetings and seminars at the BEC Center

- Wednesday, May 22th 2013, 14:00-19:00, Aula A207
  Mini-Workshop on *Non-equilibrium Bose-Einstein Condensation*
  Speakers: I. Carusotto (BEC Trento), A. Gambassi (SISSA), A. Chiocchetta (SISSA), S. Diehl (Univ. Innsbruck), L. Sieberer (Univ. Innsbruck) program

- Monday, May 20nd 2013, at 14:30, Aula Seminari Teorici
  Enrique Rico Ortega (Univ. 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 (Univ. 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
  Lectio Magistralis at the Opening of the Academic Year of the PhD School in Physics

- Monday, February 18th 2013, at 16:30, Aula A212
  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
  Marco Larcher (PhD defense)
  Localization and spreading of matter waves in disordered potentials

- Monday, February 11th 2013, at 14:30, Aula Seminari
  Pierre-Elie 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
  BEC Journal Club, T. 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

- Monday, January 7th 2012, at 14:30, Aula Seminari
  Hannah Price (Cambridge, UK)
  Measuring the Berry Curvature of Optical Lattices in Ultracold Gases

- Tuesday, December 18th 2012, at 11:00, Aula Seminari
  Tommaso Macr (Dresden, Germany)
  Quantum phases of soft core bosons with Rydberg gases

- Monday, December 10th 2012, at 14:30, Aula Seminari
  Marta Wolak (INLN, Nice and CQT-NUS, Singapore)
  Pairing in population imbalanced Fermi gas in one and two dimensions

- December 13th, 2012
  BEC Journal Club
  Riccardo Rota - *Supersolidity*

- Tuesday, November 13th 2012, at 14:30, Aula Seminari
  Martin Kroner (ETH Zurich, Switzerland)
  Quantum dot spins: an optical investigation

- Friday, October 19th 2012, at 15:30, Aula Seminari
  Iacopo Carusotto (BEC Center)
  Anyonic braiding phases in a rotating strongly correlated photon gas

- Friday, October 12th 2012, at 14:30, Aula Seminari
  Abhishek Mukherjee (ECT*, Trento)
  Quantum Monte Carlo methods for finite systems

- Wednesday, 26 September 2012, at 17:00, Aula A207
  Final Laurea exam of Alessio Chiocchetta (Univ. Trento and BEC)
  Bose-Einstein condensation out of equilibrium

- Wednesday, 26 September 2012, at 16:00, Aula A207
  Final Laurea exam of Alberto Sartori (Univ. Trento and BEC)
  Mixtures of atomic Bose gases: ground state and dynamics

- Wednesday, 26 September 2012, at 15:00, Aula A209
  Final Laurea exam of Marco Cominotti (Univ. Trento and BEC)
  Berry curvature effects on the semiclassical dynamics of a particle in a lattice under the effect of electric and magnetic fields

- Wednesday, 26 September 2012, at 14:00, Aula A209
  Final Laurea exam of Simone Donadello (Univ. Trento and BEC)
  A compact high-flux source of cold sodium atoms

- Tuesday, 11 September 2012, at 14:30, Aula Seminari
  Tomoki Ozawa (BEC Trento)
  Ultracold bosons with Rashba-Dresselhaus spin-orbit coupling

- Thursday, 6 September 2012, at 14:30, Aula Seminari di Fisica (ground floor)
  Shunji Tsuchiya (Tokyo Univ. of Science, Japan)
  The Higgs mode in superfluids of Dirac fermions

- Wednesday, 5 September 2012, at 14:00, Aula Seminari
  Marcello Dalmonte (Univ. Innsbruck, Austria)
  Confinement phenomena and the cold atom lattice gauge toolbox

- Friday, 20 July 2012, at 11:00, Aula Seminari
  Paolo Zanardi (Univ. Southern California)
  Entanglement susceptibility, area laws and beyond

- Friday, 20 July 2012, at 9:30, Aula Seminari
  Chris Vale (Swinburne University, Australia)
  Precision studies of Fermi gases using Bragg spectroscopy

- Tuesday, 03 July 2012, at 14:30, Aula Seminari
  Gianluca Bertaina (EPFL Lausanne, Switzerland)
  Quantum Monte Carlo study of a resonant Bose-Fermi mixture

- Monday, 11 June 2012, at 14:30, Aula Seminari
  Dario Poletti (Univ. Geneve, Switzerland)
  Dynamics of strongly repulsive Bosons in an optical lattice

- Monday, 28 May 2012, at 14:30, Aula Seminari
  Yun Li (BEC Trento)
  Sum rules, dipole oscillation and spin polarizability of a spin-orbit coupled quantum gases

- Friday, 25 May 2012, at 14:30, Aula Seminari
  Jan Chwedenczuk (Univ. Warsaw, Poland)
  Parameter Estimation using Spatial Correlation Functions of Bose-Einstein Condensates

- Monday, 7 May 2012, at 15:00, Aula Seminari
  Federico Becca (SISSA, Trieste)
  Localization and glassy dynamics of many-body quantum systems

- Friday, 20 April 2012, at 14:00, Aula Seminari
  Carlos Lobo (Univ. Southampton, UK)
  Collision of two spin-polarised Fermi clouds

- Wednesday, 18 April 2012, at 14:00, Aula Seminari
  Tomasz Karpiuk (CQT-NUS, Singapore)
  Spontaneous solitons in the thermal equilibrium of a quasi-one-dimensional Bose gas

- Wednesday, 4 April 2012, at 15:00, Aula Seminari
  Sebastiano Pilati (ICTP, Trieste, Italy)
  Ultracold atoms in optical lattices: beyond the Hubbard model

- 19-20 March 2012, room A105
  Joint meeting Trento-Florence
  speakers: A.Georges, M.Inguscio, F. Schaefer, M.Abad, E.Lucioni, S.Giorgini, P.Lombardi, R.Scott.

- Wednesday, 14 March 2012, at 15:00, Hall A101
  Physics Colloquium
  Antoine Georges (Collège de France)
  From hot superconductors to cold atoms (and back): quantum matter with strong correlations

- Monday, 12 March 2012, room A105
  Joint meeting Trento-Munich
  speakers: A.Georges, I.Bloch, U.Schneider, I.Carusotto, S.Fölling, Li Yun, C.Gohle, D.Papoular, C.Gross.

- Wednesday, 7 March 2012, at 15:00, Hall A103 (Povo 1)
  Christophe Salomon (ENS, Paris, France)
  From ultracold Fermi Gases to Neutron Stars
  (Talk at the PhD School in Physics)

- Wednesday, 7 March 2012, at 11:00, Aula Seminari
  Christophe Salomon (ENS, Paris, France)
  Thermodynamics of Quantum Gases

- Wednesday, 29 February 2012, at 15:00, Hall 106 (padiglione nord FBK)
  Stefano Gandolfi (LANL, USA)
  Properties and similarities of Fermions in nuclear physics, cold atoms and neutron stars
  (Lectio Magistralis at the Opening of the Academic Year of the PhD School in Physics)

- Monday, 27 February 2012, at 14:30, Aula Seminari
  Mikhail Baranov (Univ. Innsbruck, Austria)
  Many-body physics in dipolar mono- and bilayer fermionic systems

- Monday, February 20th 2012, at 14:00, Aula A210
  Manuele Landini (PhD defense)
  A tunable Bose-Einstein condensate for Quantum interferometry

- Thursday, Feb.16th 2012, at 14:30, Aula Seminari
  G. Lamporesi, BEC Journal Club:
  Quantum degenerate Bose-Fermi mixture of chemically different atomic species with widely tunable interactions

- Friday, February 10th 2012, at 14:30, Aula Seminari
  Alessandro Zenesini (Univ. Innsbruck, Austria)
  Universality in ultracold cesium gases: more resonances, more atoms, less dimensions

- Friday, 3 February 2012, at 14:30, Aula Seminari
  Zeng-Qiang Yu (Tsinghua University, Beijing, China)
  Spin-Orbit Coupled Fermi Gases

- BEC Journal Club on Thursday, Feb. 2nd, 2012 at 15:00, Aula Seminari
  Onur Umucalilar (BEC Trento)
  1/2-Anyons in Small Atomic Bose-Einstein Condensates

- Monday, 30 January 2012, at 14:30, Aula Seminari
  Hui Zhai (Tsinghua University, Beijing, China)
  Classification and Detection of Non-Abelian Phases in Bose-Einstein Condensate with High Spins

- BEC group meeting on Thursday, January 26th 2012 at 14:30, Aula Seminari
  William Simpson (University of St. Andrews, UK)
  The Casimir-Lifshitz Effect in Inhomogeneous media

- BEC group meeting on Friday, January 13th 2012 at 14:30, Aula Seminari
  Dario Gerace (Univ. Pavia)
  Analog Hawking radiation in an out-of-equilibrium superfluid

- BEC Journal Club: Thursday 15/12/2011, 14:00, Aula 101 IRST
  Alessio Recati
  Introduction to Tan's relations

- Joint BEC-LISC-ECT* meeting on Tuesday, December 13th 2011 at 16:30, Aula LISC
  Iacopo Carusotto (INO-CNR BEC Center and Dip. Fisica, Univ. Trento)
  Atoms and photons in artificial gauge fields

- BEC Journal Club on Wednesday, December 7th 2011 at 14:30, Aula Seminari
  Giovanni Martone
  Spin-orbit coupled Quantum Gases (H. Zhai, arXiv:1110.6798)

- BEC group meeting on Friday, November 18th 2011 at 14:30, Aula Seminari
  Chiara Menotti
  Bose-Hubbard model and beyond

- BEC group meeting on Friday, November 11th 2011 at 14:30, Aula Seminari
  Franco Dalfovo
  Swallow tails in superluid Fermi gases in optical lattices

- Friday, November 4th 2011, at 14:30, Aula Seminari
  Ulf Leonhardt (University of St Andrews, UK)
  Transformation optics

- BEC group meeting on Friday, October 28th 2011 at 14:30, Aula Seminari
  Alessio Recati
  Dipolar bilayer system in the highly unbalanced regime

- Joint BEC-LISC-ECT* meeting on Friday, October 21th 2011 at 11:00, Aula LISC
  Pietro Faccioli (LISC and Dip. Fisica, Univ. Trento)
  Investigating biological matter with theoretical physics methods

- Tuesday, October 4th 2011, at 15:00, Aula Seminari
  Jean Dalibard (Laboratoire Kastler Brossel, CNRS and ENS, France)
  Artificial gauge potentials for neutral atoms

- Tuesday, September 13th 2011, at 15:00, Aula Seminari
  Sam Rooney (University of Otago, New Zealand)
  Finite temperature dynamics of persistent current formation

- Tuesday, September 13th 2011, at 15:30, Aula Seminari
  Russell Bisset (University of Otago, New Zealand)
  The Dipolar Bose Gas: Stability at Finite Temperature

- Monday, July 18th 2011, at 14:30, Aula Seminari
  Martin Zwierlein (MIT)
  Universal Thermodynamics and Spin Transport in a Strongly Interacting Fermi Gas

- Monday, July 11th 2011, at 15:00, Aula Seminari
  Doerte Blume (Washington State University)
  Thermodynamics of two-component Fermi gas with large scattering length: Fourth- and higher-order virial coefficients

- BEC group meeting on Thursday, July 7th 2011 at 14:30, Aula Seminari
  Michael Klawunn
  The Fermi-polaron in two dimensions: Importance of the two-body bound state

- Thursday, June 23rd 2011, at 14:00, Aula Seminari
  Stefano Giovanazzi (Univ. Heidelberg)
  Entropy production in acoustic black holes

- Friday, June 3rd 2011, at 14:30, Aula Seminari
  Mohammad Hafezi (JQI, University Maryland and NIST)
  Quantum Hall physics with photons and its applications

- Monday, May 30th 2011, at 14:30, Aula Seminari
  Roland Combescot (LPS-ENS, Paris)
  Normal state of highly polarized Fermi gases: full many-body treatment

- Friday, May 27th 2011, at 14:30, Aula Seminari
  Rudi Grimm (Universitaet Innsbruck)
  Strongly Interacting Fermi-Fermi Mixture: Creation and First Experiments

- Thursday, May 19th 2011, at 15:00, Aula Seminari
  Riccardo Rota (Universitat Politecnica de Catalunya)
  Microscopic approach to the supersolid state of matter

- Thursday, May 5, 2011, at 14:30, Aula Seminari LISC
  Joint seminar with LISC
  Stefano Baroni (SISSA Trieste)
  Powering Computational Spectroscopy into the Hundreds-of-Atoms Size Range and Beyond

- Wednesday, April 20th 2011 at 14:30, Aula Seminari
  I. Carusotto
  How to measure the superfluid fraction of a two-dimensional Bose gas

- Monday, April 18th 2011 at 14:30, Aula Seminari
  Li Yun
  Universal contact and collective oscillations of a strongly interacting Fermi gas

- Thursday, April 7th 2011, at 14:30, Aula Seminari
  Gora Shlyapnikov (LPTMS, Orsay, France)
  Fermionic dipolar gases. Overview and recent results.

- Monday, April 4th 2011, at 14:30, Aula Seminari
  Stefano Finazzi (SISSA)
  Analogue Gravity: a bridge from gravity to condensed matter

- Friday, March 25th 2011 at 14:30, Aula Seminari
  Sandro Stringari
  New collaborations with the IASTU center at the Tsinghua University

- Wednesday, March 2nd 2011, at 11:00, Aula Seminari
  Mauro Antezza (Univ. Montpellier 2)
  Quantitative study of two- and three-dimensional strong localization of matter waves by atomic scatterers

- Tuesday, March 1st 2011, at 14:30, Aula Seminari
  Luis Santos (Univ. Hannover)
  Spinor and polar lattice gases

- Monday, February 28th 2011, at 16:30, Aula A108
  Francesco Piazza (PhD defense)
  Ultracold bosonic gases: superfluidity and quantum interferometry

- Wednesday, February 23rd 2011, at 15:00, Aula Seminari
  Grigori Astrakharchik (Univ. Politecnica de Catalunya, Barcelona)
  Coulomb gases in 1D

- Friday, February 18th 2011 at 14:30, Aula Seminari
  Informal discussion with Andrea Pugliese (Maths Depart., Trento University)
  Maximum Likelihood, Bayesian estimation and Cramer-Rao lower bound

- Monday, February 14th 2011, at 14:30, Aula Seminari
  Alexander Pikovski (Univ. Hannover, Germany)
  Interlayer superfluidity and scattering in bilayer systems of molecules

- Friday, February 11th 2011 at 14:30, Aula Seminari
  Sandro Stringari
  Number fluctuations in quantum gases at finite temperature

- Tuesday, February 8nd 2011, at 14:30, Aula Seminari
  David Papoular (LPTMS, Orsay, France)
  Microwave-Induced Feshbach Resonances

- Friday, February 4th 2011 at 14:30, Aula Seminari
  Onur Umucalılar
  Artificial magnetic fields for photons

- Wednesday, February 2nd 2011, at 14:30, Aula Seminari
  Carlos Lobo (Univ. of Southampton)
  Metastability in spin polarised Fermi gases and quasiparticle decay

- Tuesday, February 1st 2011, at 16:00, Aula Seminari
  Marco Larcher (BEC) and Marco Moratti (LENS, Firenze)
  Informal discussion on disordered quantum gases

- Monday, January 24th 2011, at 15:00, Aula Seminari
  Carmen Invernizzi (Univ. Milano)
  The discrimination problem: application to the quantum Ising model and to lossy channels

- Wednesday, January 19th 2011, at 11:00, Aula Seminari
  Tilman Esslinger (ETH Zuerich)
  Synthetic Quantum Many-Body Systems

- Friday, January 14th 2011 at 14:30, Aula Seminari
  C. Menotti
  Excitations of the Bose-Hubbard model

- Wednesday, December 15th 2010, at 14:30, Aula Seminari
  Angela White (Newcastle)
  Properties of Quantum Turbulence in Atomic Bose-Einstein Condensates

- Monday, December 13rd 2010, at 14:00, Aula Seminari
  Markus Oberthaler (Heidelberg)
  News from Heidelberg: Squeezing and entangling of matterwaves

- Friday, December 10th 2010 at 14:30, Aula Seminari
  Fabrizio Logiurato
  Is the Born rule a theorem?

- Thursday, November 25th 2010, at 15:00, Aula Seminari
  Marta Abad Garcia (Universidad de Barcelona)
  Josephson effects in dipolar self-induced double-well potentials

- Monday, November 22th 2010, at 14:30, Aula Seminari
  Jan Chwedenczuk (University of Warsaw)
  Phase estimation with interfering Bose-Einstein-condensed atomic clouds

- Friday, November 12th, at 14:30, Aula Seminari
  Francesco Piazza
  Critical Velocities for Superfluid Flow Instability

- Friday, November 5th, at 14:30, Aula Seminari
  Natalia Matveeva
  Dipole mode of collective oscillations in two cloud of dipolar gases

- Friday, October 29th, at 14:30, Aula Seminari
  Philipp Hyllus
  Entanglement in recent spin squeezing experiments with BECs

- Friday, October 22th, at 15:00, Aula Seminari
  A. Recati
  Bogoliubov theory of analog Hawking radiation in atomic BECs

- Friday, October 15th, at 15:00, Aula Seminari
  Luca Barbiero
  Homogeneous and inhomogeneous phases of constrained dipolar bosons

- Friday, October 8th, at 15:00, Aula Seminari
  Micheal Klawunn
  Two-dimensional scattering and bound states of polar molecules in bilayers

- UniTN Public Lecture, September 30th, at 16:00, Aula Magna, Povo
  Wolfgang Ketterle (MIT)
  Superfluid gases near absolute zero temperature

- Friday, September 24th, 2010, at 15:00, Aula Seminari
  I. Carusotto
  Complex-wavevector Bogoliubov modes in acoustic black/white hole configurations

- Friday, September 17th, 2010, at 15:00, Aula Seminari
  Sandro Stringari
  Second sound in ultracold gases

- Friday, September 3rd, 2010, at 15:00, Aula Seminari
  Stefano Giorgini
  Disordered Bose gases

- Wednesday, September 1st, at 15:00, Aula Seminari
  Rıfat Onur Umucalılar (Bilkent, Turkey)
  Quantum Gases in Rotating Optical Lattices

- Monday, July 19th 2010, at 15:00, Aula Seminari Round table with Alice Sinatra and Yvan Castin (LKB-ENS, France) on
  Problems in the theory of ultracold atomic gases

- Tuesday, July 13th 2010, at 14:00, Aula Seminari
  Li Yun (LKB-ENS, France and East China Normal University)
  Spin squeezing in Bose-Einstein condensates

- Friday, June 21th 2010, at 9:30, Aula 106 (III padiglione IRST)
  Carlo Sias (Cambridge)
  Impurities in a Bose gas

- Friday, June 11th 2010, at 15:00, Aula seminari
  Carsten Klempt (Hannover)
  A parametric amplifier of matter waves

- Tuesday, June 8th 2010, at 14:00, Aula 207 (III padiglione IRST)
  Gabriele Ferrari (LENS and INO-CNR, Firenze)
  Coherent transport in amplitude and phase modulated optical lattices

- Monday, May 31st 2010, at 16:00, Aula seminari
  Daniele Sanvitto (UAM Madrid)
  Polaritons in microcavities, observation of condensation and related quantum phenomena

- Thursday, May 20th 2010, at 15:00, Aula seminari
  Artur Widera (Universitaet Bonn)
  Probing Quantum Physics with Single Neutral Atoms

- Wednesday, May 5th 2010, at 14:30, Aula seminari
  Matteo Zaccanti (LENS and Univ. Firenze)
  Experiments with a tunable 39K BEC: from few-body to many-body physics

- Friday, April 23th 2010, at 14:30, Aula seminari
  Tom Montgomery (Univ. Nottingham)
  Angular momentum tunneling in degenerate Bose gases

  March-April 2010, Aula seminari
  Wilhelm Zwerger (Technische Univ. Muenchen)
  Series of lectures on
  Many-body theories with applications to ultracold gases
  Tue/Wed 16/17 March, 9:30-11:30
  Tue/Wed 23/24 March, 9:30-11:30
  Tue/Wed 30/31 March, 9:30-11:30
  Tue/Wed 13/14 April, 9:30-11:30

- Monday, March 29th 2010, at 16:00, Aula seminari
  Wilhelm Zwerger
  Fermionic Superfluids in One Dimension

- Monday, March 15th 2010, at 16:00, Aula seminari
  Bruno Galvan
  Generalization of the Born rule

- Friday, March 12th 2010, at 16:00, Aula seminari
  Wilhelm Zwerger (Technische Univ. Muenchen)
  The search for a perfect fluid: is string theory relevant for ultracold atoms?

- Friday, March 5th 2010, at 16:00, Aula seminari
  Corinna Kollath (Ecole Polytechnique, Palaiseau, France)
  Strongly correlated ultracold gases in optical lattices

- Thursday, March 4th 2010, at 16:00, Aula n.20
  Michael Koehl (Cambridge, UK)
  A trapped single ion inside a Bose-Einstein condensate

- Tuesday, February 16th 2010, at 16:00, Aula seminari
  Carlos Lobo (Cambridge, UK)
  BCS pairing with unequal masses

- Tuesday, February 9th 2010, at 16:00, Aula seminari
  Julian Grond (Graz)
  Optimal control of squeezing and many-body effects when splitting a BEC

- Monday, February 8th 2010, at 16:00, Aula seminari
  Carlo Nicola Colacino (Univ. Pisa and INFN)
  Stochastic gravitational background and fundamental noises in interferometric detectors of gravitational waves

- Monday, February 1st 2010, at 16:00, Aula seminari
  Daniele Faccio (Univ. Insubria, Como)
  Direct observation of analogue Hawking radiation?

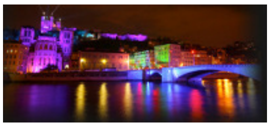
- Monday, Jan 25, 2010, at 16.00, Aula seminari
  Nicolas Pavloff (LPTMS Orsay)
  Density correlations as probes of Hawking radiation in BECs

- Monday, Jan 11, 2010, at 16.00, Aula seminari
  Philipp Treutlein (LMU Munich)
  Atom chip based generation of entanglement for quantum metrology

Conferences and Summer Schools organized or co-organized by the BEC Center

International Conference on
Quantum Gases of Polar Molecules and Magnetic Atoms
August 28-30, 2012 , Beijing, China

This conference brought together experimental and theoretical researchers working on quantum gases of polar molecules and magnetic atoms, discussing new opportunities and challenges. The conference included long and short invited talks as well as several discussion sessions. The conference was organized by the Institute for Advanced Study of Tsinghua University together with the Trento BEC Center. Organizers: Tin-Lun Ho (Ohio-State), Sandro Stringari (Trento), Hui Zhai (Tsinghua)



6th International Workshop on
Theory of Quantum Gases and Quantum Coherence
5-8 June 2012, ENS-Lyon, France

This workshop was dedicated to the theoretical challenges in the field of quantum gases, with a strong connection to condensed matter physics - including strongly correlated systems, low-dimensional systems, disorder effects etc.. One of the main goals of this workshop was to bring together young researchers coming from Europe and overseas. The program included 5 overview lectures by leading senior scientists in the field of cold atoms and condensed matter, about 20 lectures by junior scientists selected by the advisory committee, and a poster session open to all the participants. A special invited session was organized this year on the subject of Bose-Einstein condensation in condensed matter systems. Organizers: T. Roscilde (ENS, Lyon), E. Orignac (ENS, Lyon), A. Minguzzi (LPMMC, Grenoble), R. Citro (Salerno), F. Chevy (ENS, Paris), A. Recati (CNR-INO/BEC Center, Trento)

POLATOM ESF Physics School on
Cold atoms, excitons and polaritons
Toledo, Spain, 21-23 May 2012

The goal of the school was to give a background of the basic aspects of cold-atom, exciton and polariton physics so that students from related fields will be able to follow the most recent and exciting developments of these communities. Additional aims were to promote cooperation between the students and to produce synergy among these fields. The topics included: Atom-

, ion- and polariton-tronics; Photon and polariton condensation; Excitons in nanostructures; Superfluid properties; Nonlinear effects. Organizers: Luis Viña (Univ. Aut. Madrid), Carlos Tejedor de PAz(Univ. Aut. Madrid), Iacopo Carusotto (INO-CNR BEC).

International Workshop on
New trends in the physics of the quantum vacuum: from condensed matter, to gravitation and cosmology
ECT*, Trento, 27 June-1 July 2011

The main topics of this workshop are the following: Artificial Black Holes and Hawking radiation in BEC and in nonlinear optics, the quantum vacuum of many-body systems, Dynamical Casimir effectc, Ultra-strong light-matter coupling regime, surface waves in water tanks, quantum effects in cosmology and the dark energy, mini black holes at LHC, quantum quenches, radiation friction effects. Organizers: I. Carusotto (INO-CNR BEC), R. Balbinot (Università di Bologna and INFN), C. Ciuti (MPQ, Paris), A. Fabbri (Universidad de Valencia-CSIC).

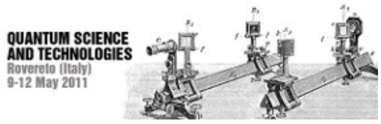
International Workshop on
Workshop on Frontiers in Ultracold Fermi Gases
ICTP, Trieste, 6 June -10 June 2011

This workshop aims to provide an overview of the recent progresses in the field of research of ultracold Fermi gases. This area attracted in the last years an increasing attention, also due to the impressive progresses in the experimental manipulation of such systems. It is foreseeable that in the near future of years new important results will be obtained, ranging from the study of Fermi gases in optical lattices to the use of ultracold fermions for simulating strongly correlated systems. Organizers: W. Ketterle (MIT Boston), M. Koehl (Cambridge, UK), G. Mussardo (SISSA, Trieste), S. Stringari (Trento), A. Trombettoni (SISSA, Trieste).

Symposium in honour of Allan Griffin and his contributions to physics
GriffinFest
Toronto, May 13 and 14, 2011

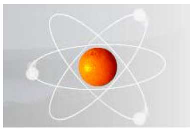
Organizers: Joseph Thywissen (University of Toronto), Jason Ho (Ohio State), Arun Paramekanti (University of Toronto), Sandro Stringari (Trento), Eugene Zaremba (Queen's University). Web:

http://ultracold.physics.utoronto.ca/GriffinFest.html



International Workshop on
Quantum Science and Technology
Rovereto (Trento), May 9-12, 2011

In the last few years we have witnessed impressive theoretical and experimental progresses in our understanding and control of entanglement. These have advanced our fundamental understanding of quantum science and the design of new technologies. Applications range from the creation of new devices for the ultrasensitive interferometric measurements to applications for secure communication, quantum control, quantum information processing. The workshop brings together the leading experts in these fields along with younger scientists in a pleasant environment aimed to encourage discussions and brainstorming. Participants: about 170. Organizers: Augusto Smerzi (INO-CNR BEC, Trento) and Tommaso Calarco (Ulm University). Web: http://events.unitn.it/en/qst



School on
Frontier topics on BEC in Solids and Atomic Gases
Turunc/Marmaris (Turkey), September 10-19, 2010

The program of the School was designed as an advanced training of young researchers on the frontiers of Bose-Einstein Condensation in Atoms and Semiconductors. The lectures covered detailed presentation of several important topics including advanced lectures, in class tutorials and applications stressing the theory-experiment relations aiming at the understanding of the material in depth by the participants. Organizers: I.Carusotto (BEC Center and Trento Univ., Italy) T. Hakioglu (Bilkent Univ. and ITAP, Turkey). Lecturers: Franco Dalfovo, Selim Jochim, Werner Krauth, Michiel Wouters, Marcos Rigol, Ady Stern. Web: http://www.itap-tthv.org/iars/thisyear/poster/2010/Carusotto_2010.htm

International Workshop on
Theory of Quantum Gases and Quantum Coherence
Nice (France), June 2-4 April, 2010

This is the fifth in a series of workshops dedicated to the theoretical challenges in the area of quantum gases (including strongly correlated systems, disorder, spinors), with a strong connection to condensed matter physics. In this conference the speakers and the participants are mainly young researchers from Europe and overseas, with some overview lectures delivered by leading Senior Scientists. The BEC center has co-organized the series of workshops (Salerno 2001, Levico 2003, Cortona 2005, and Grenoble 2008, Nice 2010). The Nice edition has been organized by R. Citro (Salerno), F. Hébert (INLN, Nice), G. Labeyrie (INLN, Nice), A. Minguzzi (LPMMC, Grenoble), A. Recati (INO-CNR BEC, Trento), S. Tanzilli (LPMC, Nice), P. Vignolo (INLN, Nice). Web: http://nicebec.inln.cnrs.fr/

International Workshop on
New Frontiers in Graphene Physics
ECT*, Trento, 12-14 April 2010

The main objective of the workshop "New Frontiers in Graphene Physics" held at the ECT* in Trento (Italy) in April 2010 was to favor the establishment of an interdisciplinary community of scientists interested in the physics of graphene from different points of view. The issues that were addressed can be classified as follows: Experiments in graphene, Many-body theory of graphene, Lattice gauge theories applied to graphene, Analogs of graphene in condensed-matter systems, in ultracold atomic gases, and with light. Participants: 46. Chairman: I. Carusotto (BEC INO-CNR); Co-organizers: S. Hands (Swansea University, UK), A. Richter (TU Darmstadt, DE - ECT*), B. Trauzettel (Univ. Wuerzburg, DE), S. Stringari (Trento University and BEC INO-CNR).