Istituto Nazionale per la Fisica della Materia

Consiglio Nazionale delle Ricerche

Research and Development Center on

Bose-Einstein Condensation

Trento, Italy

Scientific Report

June 2004 - May 2006

UNIVERSITÀ DEGLI STUDI DI TRENTO

Cover:

* Top: Density modulations of a Bose-Einstein condensate flowing with supersonic velocity through obstacles of various sizes. The profiles are calculated by means of a numerical integration of the three-dimensional Gross-Pitaevskii equation. Taken from I. Carusotto, S.X. Hu, L.A. Collins and A. Smerzi (to be published).

* Bottom (background): Density distribution of an expanding Bose-Einstein condensate subject to parametric amplification of longitudinal Bogoliubov phonons in a toroidal trap. Taken from M. Modugno, C. Tozzo and F. Dalfovo (to be published).

Contents

Overview

The mission of the Center

The aim of the INFM-CNR Research and Development Center on Bose-Einstein Condensation (BEC) is to promote theoretical research on the various phenomena related to Bose-Einstein condensation and to the physics of cold atomic gases in traps. Since the first observation of BEC in cold gases in 1995, the study of ultracold gases has become an emerging area of research at the crossing point of several disciplines, including atomic and molecular physics, quantum optics, statistical mechanics and condensed matter physics. BEC has been already achieved in many atomic species and an impressive number of experimental and theoretical groups worldwide is actively working in the field of ultracold atomic gases (about one thousand papers are published every year in the field). Before 1995 BEC had only been explored in strongly interacting systems, such as superfluid helium, where the effects of interactions mask some crucial features of quantum correlations. The dilute gas experiments have made it possible to compare in a systematic way experimental data with the predictions of first principle theory.

In the last few years the field has grown and developed in several important directions. On the one side the availability of advanced optical techniques has allowed to create new trapping configurations in the form of optical lattices. This has opened new frontiers of research where atomic physics meets important features of condensed matter and solid state physics, including the superfluid-Mott insulating transition, the implementation of new geometrical configurations where even the dimensionality of the system can be controlled, the study of disorder and localization effects, etc.. On the other side the availability of Fano-Feshbach resonances characterizing the interaction between several atomic species has opened the fascinating possibility of tuning the two-body interactions by simply changing the external magnetic field, with the consequence that the value and even the sign of the scattering length can be changed in controlled way, yielding the challenging and unique possibility of studying strongly correlated configurations with dilute atomic gases. Important achievements concern the study of ultracold Fermi gases. The initial cooling limitations due to Pauli blocking have been overcome and now the field of ultracold Fermi gases is growing in an impressive way with stimulating perspectives, also in view of the deep analogies between such systems and other Fermi systems, like high Tc superconductors and neutron stars. The Bose Einstein condensation of molecules formed starting from a Fermi sea and the superfluid phase have been already realized and the long sought BCS-BEC crossover is now object of intense theoretical and experimental investigations. Also the field of mixtures of different atomic species is becoming a rich area of research, with the perspective of generating new molecular configurations with permanent dipole moment and unexplored many-body quantum phases. Finally ultracold atomic physics is providing new perspectives of application to quantum information processes and precision measurements. These include, among others, the implementation of logical operations with the help of the new available trapping configurations, the advanced development of interferometric techniques based on matter waves and the study of the surface-atom force.

At the same time also the theoretical techniques have developed in a significant way and more sophisticated quantum many-body approaches have been proposed in order to study the complexity of the new configurations. The theoretical tools have been mainly based, in the first years, on the use of Gross-Pitaevskii theory for the order parameter and have proven quite successful, especially to predict the behaviour of trapped Bose-Einstein condensates at low temperature, both at equilibrium and out of equilibrium. More recent developments include, among others, quantum simulations based on Monte Carlo techniques, quantum models of solid state physics like the Hubbard model and new statistical approaches to study fluctuations and correlations. In general the theoretical approaches in the last few years have become more and more interdisciplinary. A significant example is given by the recent progress in the study of the Casimir-Polder force stimulated by the availability of highly precise measurements of the oscillations of Bose-Einstein condensates. At the same time many of the ideas of dilute quantum gases are becoming of central importance also in solid state physics and quantum optics.

The growth of the field has benefited in a crucial way by the cooperative efforts of experimental and theoretical groups in many laboratories. The aim of the BEC Center is to reinforce the interdisciplinary links of the theoretical research as well as the links between theoretical and experimental activities, establishing direct and systematic collaborations with the main laboratories in the world.

The first four years

The BEC Center was established by the Istituto Nazionale per la Fisica della Materia (INFM) in Trento in June 2002, following a selection made by an international panel. The Center is hosted by the Department of Physics. Scientists belonging to the BEC Center include INFM-CNR researchers as well as personnel from the University, together with a large number of PhD students and post-doctoral fellows, who are partly funded by INFM-CNR and partly by the University. At present the scientists active in the Center are about 20. The budget of the BEC Center is provided by INFM-CNR and by the Provincia Autonoma di Trento (PAT). The research activity of the Center is also supported by the European Union and by the Italian Ministry of Research. In the last years the Center has significantly strengthened the links with the Atomic Physics team of the European Laboratory for Non-Linear Spectroscopy (LENS) in Florence, by reinforcing the scientific collaborations and by promoting joint institutional initiatives.

The Trento BEC team has significantly contributed to the worldwide development of the field of ultracold gases through a long series of scientific publications, the reinforcement and the creation of international collaborations, the organization of workshops and conferences and through the training of young scientists. The impact of the scientific work carried out by the Trento team is recognized by the Essential

Science Indicators of Thomson Scientific where at the special topics "Bose-Einstein Condensates" (http://www.esi-topics.com/bose/) and "Superfluids" (http://www.esi-topics.com/superfluids/) the papers of the Trento BEC team rank at the top positions.

This is the second scientific report of the Center, following the one printed in 2004. Up-to-date information on the activity of the Center can be found at the website: **http://bec.science.unitn.it**

May, 2006

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Research

This report provides an overview of the main scientific activities on ultracold atoms and related topics, with reference to the period June 2004 - May 2006. The scientific work carried out at the Center can be naturally classified according to the following research lines:

- Rotating quantum gases
- Low dimensions
- Excitations in Bose-Einstein condensates
- Ultracold atoms in optical lattices
- Ultracold Fermi gases
- Quantum Monte Carlo methods
- Casimir-Polder force
- Quantum optics and solid state physics
- Quantum information processing
- Matter-waves interferometry

ROTATING QUANTUM GASES

One of the most important implications of superfluidity concerns the rotational behaviour of superfluids at low temperature. This problem, of historical importance in the physics of superfluid helium, has become popular also in the context of atomic gases. The implications of superfluidity are directly connected with the constraint of irrotationality imposed by the existence of an order parameter. The superfluid velocity field is in fact directly related with the gradient of the phase Φ of the order parameter

$$\boldsymbol{v} = \frac{\hbar}{m} \boldsymbol{\nabla} \Phi \ ,$$

with non trivial implications also at a topological level. Some important consequences imposed by the irrotationality constraint are:

- Superfluids cannot rotate in a rigid way and their moment of inertia consequently differs from the rigid value.
- Angular momentum can be carried through the creation of quantized vortices which, at high angular velocity, may arrange in regular arrays of singly quantized vortices.

In the last two years the Trento team has developed the activity in this important field along the following lines:

- study of Bose-Einstein condensates in annular configurations [1, 2, 3, 4];
- vortex lattices in the centrifugal limit [5, 6].

Bose-Einstein condensates in annular configurations

A fascinating experimental challenge in the field of rotating Bose-Einstein condensates consists in the achievement of very fast rotation rates, where the quantization of vorticity and the large amount of angular momentum present in the cloud lead to peculiar density patterns (vortex lattices, giant vortices, etc.).

The possibility of exploiting stronger than quadratic traps allows to consider situations where the condensate can be stirred to (in principle) arbitrarily high angular velocities. This is due to the fact that, at large distances, such steep potentials always overcome the effect of the centrifugal force, thereby keeping the system confined.

The repulsive centrifugal potential, however, strongly affects the shape of the density profile. In Ref. [1] the case of a two-dimensional harmonic plus quartic trap was considered. This configuration had already been studied in Ref. [7], where the equilibrium configurations as a function of the angular velocity were calculated. A particularly interesting stationary state found above a critical rotation rate is given by a 'vortex lattice plus hole' structure: the resulting density profile acquires an annular shape, due to the centrifugal effect which suppresses the atomic density in the cloud center. In Ref. [1] a detailed analytical characterization of the collective modes of this system has been provided, supported by numerical calculations (full solution of the two-dimensional time dependent Gross-Pitaevskii equation). In particular, for the ring-shaped structure mentioned before, once the Coriolis force due to rotation is correctly taken into account the collective frequencies turn out to admit a simple interpretation in terms of sound waves along the annulus, thereby yielding a valuable physical understanding of the system dynamics. Further details on the analytical calculations, based on the hydrodynamic theory and the sum rule technique, have been reported in Ref. [2].

In Ref. [3] the physics of annular Bose-Einstein condensates was explored also in the absence of rotation. In particular, a two-dimensional *anti-harmonic* plus quartic potential has been considered, which, for proper experimental parameters, gives rise to a ring trap. This setup is very well suited to study the effects of vorticity (see Fig. 1). Furthermore, the study of collective modes allows to investigate the energetic stability of the system, showing a remarkable application of the Landau criterion. The interest in the study of persistent currents naturally raises the question of performing unambiguous detections of the vorticity, also in view of possible applications of annular condensates as rotation sensors. To this purpose, in Ref. [3] various methods to detect the vorticity have been proposed. Indeed, the direct in-situ imaging of the density profile can hardly allow to discriminate between rotation rates which differ only by few quanta of circulation. In contrast, the change in the mode frequencies due to rotation, already successfully exploited in harmonically trapped Bose-Einstein condensates [8], can provide a more reliable measurement of the amount of vorticity present in the sample. A second possibility is given by the study of the condensate expansion after releasing the trap (see also [4]). Indeed, the survival of the central hole in the time-of-flight images implies the presence of vortices. Finally, the measurement of the momentum distribution can allow for a quantitative analysis of the rotation rate of the fluid even for very slow currents.

A recent line of research concerns the study of Bose-Einstein condensates trapped in curvilinear (e.g., elliptical) closed-loop traps, which generalize the annular configura-

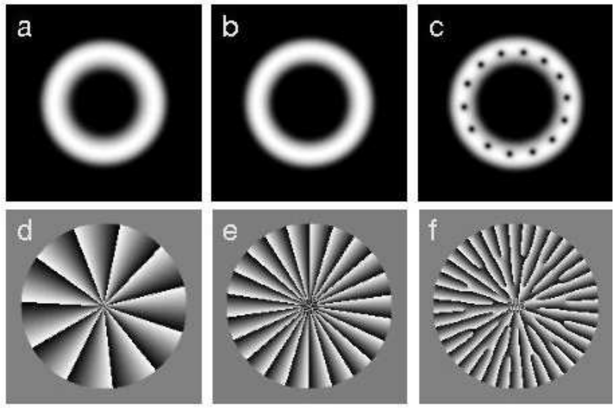

Figure 1: Density (a,b,c) and corresponding phase (d,e,f) profiles of a condensate in an antiharmonic plus quartic trap, found by numerical solution of the Gross-Pitaevskii equation. Taken from Ref. [3].

tions described above. A first step in this direction is being completed in collaboration with S. Schwartz and P. Bouyer (Orsay, Paris). In this project, a one-dimensional effective description of an atomic waveguide has been developed, valid in the presence of strong transverse confinement. The possibility of an experimental implementation of this system using the optical potential realized by optical tweezers has also been investigated.

The work [4], devoted to the detection of phonons and persistent currents in toroidal Bose-Einstein condensates by means of pattern formation, is discussed in the research line on Excitations in Bose-Einstein condensates.

Vortex lattices in the centrifugal limit

In the presence of a purely harmonic potential the highest possible rotation frequency is fixed by the trapping frequency $\omega_\perp$ in the plane of rotation. Indeed, when the angular velocity Ω equals $\omega_\perp$, the centrifugal force exactly compensates the attractive quadratic potential and the system is no more confined. This situation can however be considered from a theoretical point of view as the analogue of a uniform condensate in the non-rotating case. In such a situation, apart from a global phase term which can be treated separately, the vortex lattice becomes exactly periodic, allowing for a simplified (i.e., computationally 'cheap') numerical solution of the Gross-Pitaevskii equation. This is the subject of Ref. [5], where exact results for the density profile (see Fig. 2), the

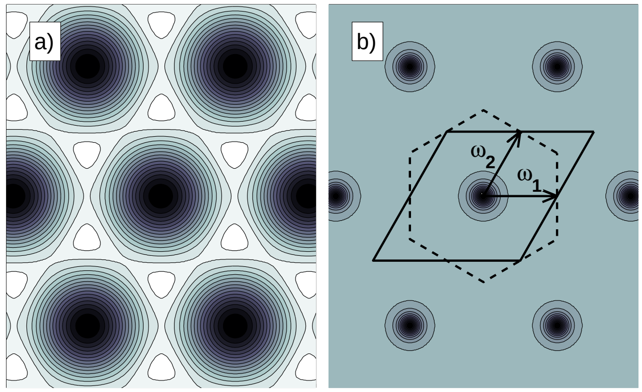

Figure 2: Density distribution of the condensate in the rotation plane computed by solving numerically the Gross-Pitaevskii equation: (a) lowest Landau level regime, (b) Thomas-Fermi regime. Darker regions correspond to lower density. Taken from Ref. [5]

equation of state, and the elastic properties of the vortex lattice are provided.

The shape of the density profile around a single vortex has been the subject of both theoretical [9] and experimental [10] investigations. The interest in the size of the vortex core is due to its relation with the angular velocity of the system. At slow rotation rates typical condensates are in the so called Thomas-Fermi regime $\mu/\hbar\Omega \gg 1$, where μ is the chemical potential. In this case the core radius is basically fixed by the healing length $\xi = \hbar/\sqrt{2m\mu}$, where m is the atom mass, and therefore grows with increasing angular velocity, as the chemical potential becomes smaller and smaller in the centrifugal limit. Conversely, once the angular velocity is so high that $\mu/\hbar\Omega \ll 1$ one enters the lowest Landau level regime, where the core size saturates at a certain fraction of the vortex cell radius, which is given by $\sqrt{\hbar/m\Omega}$. The transition from one regime to the other has been observed experimentally [10] and the predictions of Ref. [5] reproduce with good precision the experimental findings.

Of particular interest is also the study of the elastic properties of the vortex lattice, which determine the frequency of Tkachenko modes. In Ref. [5] it is shown how the shear modulus changes from the Thomas-Fermi [11] to the lowest Landau level regime [12]. A detailed comparison of the theoretical results for the Tkachenko frequencies with the available experimental data seem however to require more accurate measurements of the cloud parameters.

The physics of the lowest Landau level regime is also the subject of a collaboration with the team of the École Normale Supérieure [6]. In the centrifugal limit where $\mu \ll \hbar\Omega$ interactions can be treated as a perturbation and the condensate behaves in many aspects as an ideal gas. In the presence of thermal fluctuations, the distribution of vortices, which coincide with the zeros of the condensate wavefunction, turns then out to be related to the distribution of the zeros of random polynomials, an active field of study in statistical physics. Thus, a Bose-Einstein condensate in the centrifugal limit might provide a real physical system where one can observe the non trivial properties of such mathematical objects.

Another work related to rotations in quantum gases is devoted to hysteresis effects in rotating Bose-Einstein condensates [13].

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LOW DIMENSIONS

Degenerate low-dimensional gases are presently attracting considerable interest as model systems to investigate beyond mean-field effects and phenomena where many-body correlations, thermal and quantum fluctuations play a relevant role [1]. Particularly intriguing is the fermionization of a 1D Bose gas in the strongly repulsive Tonks-Girardeau (TG) regime, where the system behaves as if it consisted of noninteracting spinless fermions [2]. The Bose-Fermi mapping of the TG gas is a peculiar aspect of the universal low-energy properties which are exhibited by bosonic and fermionic gapless 1D quantum systems and are described by the Luttinger liquid model [3]. The concept of Luttinger liquid plays a central role in condensed matter physics and the prospect of a clean testing for its physical implications using ultracold gases confined in highly elongated traps is fascinating [4]. On the other hand, in 2D it is well known that thermal excitations destroy long-range order and Bose-Einstein condensation (BEC) can not exist in large bosonic systems at finite temperature [5]. Nevertheless, a defect-mediated phase transition from a high-temperature normal fluid to a low-temperature superfluid was predicted by Berezinskii, Kosterlitz and Thouless (BKT) [6] and has been observed in thin films of liquid ^{4}He [7]. The nature of the transition in confined 2D systems and whether it belongs to the BEC or BKT universality class is still an open problem both experimentally and theoretically [8, 9]. The research activity of the Trento BEC group in this field has been devoted to the study of various aspects of the physics of 1D and quasi-1D degenerate Bose gases and to the study of the ground-state properties of a Bose gas in 2D. Some of the most relevant contributions are discussed in more details below.

Heavy impurity through a Bose-Einstein condensate

We have investigated the problem of superfluidity of a 1D Bose gas at $T = 0$ [10]. There is no off-diagonal long-range order in this system and in order to solve the problem of superfluidity one must calculate the energy dissipation of a body moving in the gas. For a superfluid this dissipation is zero when the velocity of the body V is less than the Landau critical velocity and it is instead $\propto V^2$ for a normal fluid. The dissipation can be expressed in terms of the dynamic form factor S, which is calculated taking into account the long-wavelength phase fluctuations, which are responsible for destroying the long-range order. As a result the energy dissipation depends on the characteristic parameter $\eta = 2\pi n/c \geq 2$, where n is the 1D density and c is the speed of sound.

Finally the dissipation at small V is $\propto V^\eta$. In a gas at small density $\eta \to 2$. This corresponds to the Tonks-Girardeau limit, where the dynamic properties of the gas coincide with the ones of an ideal Fermi gas. Correspondingly the dissipation is the same as for a normal fluid. In the large density limit $\eta \to \infty$ the dissipation is very small and the gas behaves as a 3D superfluid. At finite $\eta > 2$ the properties of the gas are intermediate between normal and superfluid.

Correlation functions of a Lieb-Liniger Bose gas

Recent progress achieved in techniques of confining Bose condensates has lead to experimental realizations of quasi-1D systems [11, 12, 13, 14]. The quasi-1D regime is reached in highly anisotropic traps, where the axial motion of the atoms is weakly confined while the radial motion is frozen to zero point oscillations by the tight transverse trapping. These experimental achievements have revived interest in the theoretical study of the properties of 1D Bose gases. In most applications, a single parameter, the effective 1D scattering length a_{1D}, is sufficient to describe the interatomic potential, which in this case can be conveniently modeled by a δ-function pseudopotential. For repulsive effective interactions the relevant model is provided by the Lieb-Liniger Hamiltonian [15]. The interaction strength is measured in terms of the gas parameter $n|a_{1D}|$, where n is the 1D number density.

We use exact quantum Monte Carlo methods to investigate the behavior of correlation functions in the ground state of the Lieb-Liniger model [16]. Over a wide range of values for the interaction strength, we calculate the one- and two-body correlation function and their Fourier transform giving, respectively, the momentum distribution and the static structure factor of the system. Another important correlation function is the local three-body correlator $g_3(0)$ giving the probability of finding three particles at the same position in space

$$g_3(0) = \frac{N(N-1)(N-2)}{n^3} \frac{\int |\Psi_0(0,0,0,z_4,...,z_N)|^2 \, dz_4...dz_N}{\int |\Psi_0(z_1,...,z_N)|^2 \, dz_1...dz_N} \, . \tag{1}$$

The $z = 0$ value of g_3 was obtained within a perturbation scheme in the regions of strong and weak interactions [17]. It is very small in the Tonks-Girardeau (TG) limit ($n|a_{1D}| \ll 1$)

$$g_3(0) = \frac{(\pi n|a_{1D}|)^6}{60} \, , \tag{2}$$

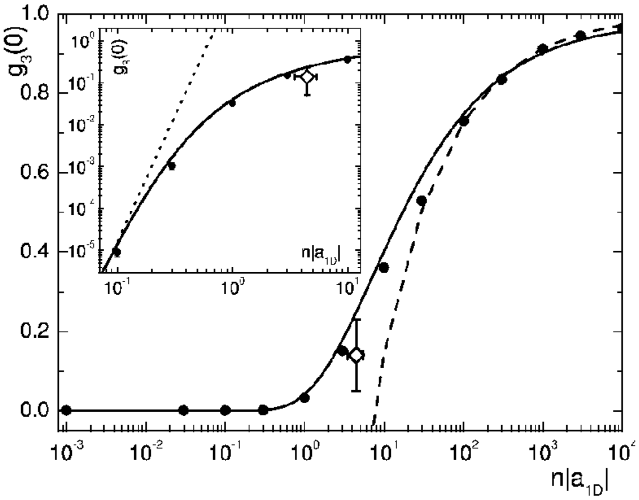

Figure 1: Value at zero distance of the three-body correlation function $g_3(0)$ (circles); MF limit, Eq. (3), dashed line; mean-field factorization, $g_3(0) = (g_2(0))^3$ solid line. Inset: small density region on a log-log scale: TG limit, Eq. (2), dotted line. Open symbol: measured value of $g_3(0)$ from three-body loss experiments [12].

and goes to unity in the opposite mean-field (MF) regime $(n|a_{1D}| \gg 1)$

$$g_3(0) = 1 - \frac{6\sqrt{2}}{\pi\sqrt{n|a_{1D}|}} \ . \tag{3}$$

In Fig. 1 we present results on the local three-body correlation function ranging from the weakly- up to the strongly-interacting regime. The value of $g_3(0)$ is related to the rate of three-body recombinations which is of great experimental relevance. The coefficient of three-body losses has been measured in quasi-1D configurations realized with deep two-dimensional optical lattices [12]. The value of $g_3(0)$ extracted from these measurements is also shown in Fig. 1.

Equation of state of a two-dimensional Bose gas at $T = 0$

In the work [18] we investigate the ground-state properties of a 2D homogeneous Bose gas using quantum Monte Carlo techniques. We calculate the equation of state as a function of the gas parameter na_{2D}^2, where n is the number density and a_{2D} is the effective scattering length in 2D. The investigation is carried out from the extremely dilute regime, $na_{2D}^2 \sim 10^{-7}$, to the strongly correlated regime, $na_{2D}^2 \sim 0.1$. The calculations of the energy per particle are performed using three different interatomic model potentials: two repulsive finite-ranged potentials [hard- (HD) and soft-disk (SD)] and a zero-range pseudopotential (PP) which supports a two-body bound state. The ground-state energy of a homogeneous dilute Bose gas in 2D has been first calculated by Schick [19] and is given by

$$\frac{E_{MF}}{N} = \frac{2\pi\hbar^2}{m} \frac{n}{\log(1/na_{2D}^2)} . \tag{4}$$

We investigate beyond mean-field corrections to the above equation of state and their dependence on the gas parameter na_{2D}^2 (see Fig. 2). In the case of the zero-range pseudopotential, from a study of the system compressibility as a function of the gas parameter we estimate that $na_{2D}^2 \simeq 0.04$ is the critical density at which the gas-like state becomes unstable against cluster formation (see Fig. 3). This result puts an upper limit to the value of density that can be reached in harmonic traps when one enters the regime of pure 2D scattering.

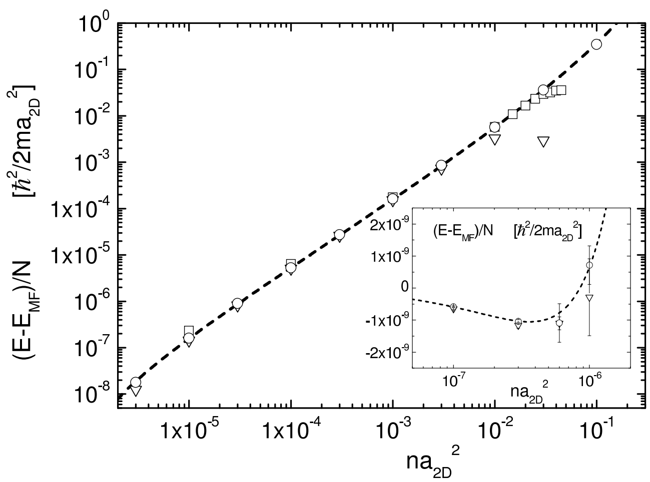

Figure 2: Beyond mean-field corrections to the equation of state. Circles, HD potential; triangles: SD potential; squares: PP potential. Dashed line: numerical fit to the results of the HD potential. Error bars are smaller than the size of the symbols. Inset: region of extremely dilute systems $na_{2D}^2 \leq 10^{-6}$.

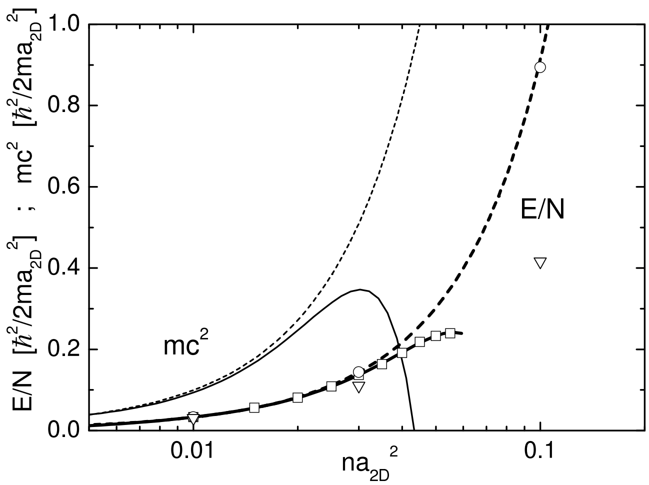

Figure 3: Energy per particle and inverse compressibility as a function of the gas parameter. Symbols are as in Fig. 2. Thick and thin dashed lines: best fit to the HD equation of state and corresponding mc^2, respectively. Thick and thin solid line: polynomial best fit to the PP equation of state and corresponding mc^2, respectively. Error bars are smaller than the size of the symbols.

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EXCITATIONS IN BOSE-EINSTEIN CONDENSATES

More than ten years after the first observation of BEC in dilute trapped gases the excitations of condensates are still a topic of very intense activity on both theoretical and experimental sides. Elementary excitations, collective modes, dynamic processes in general, provide precise and crucial information on the quantum many-body nature of these systems and on the role of interactions. In several experiments excitations are produced and probed by looking at the response of BEC to external perturbations and its dynamics in the linear and nonlinear regimes. Similar investigations have recently been done also with ultracold Fermi gases, as discussed elsewhere in this report.

Excitations in BEC represent a traditional line of research of the Trento team, started from the very beginning [1]. Different techniques have been used: superfluid hydrodynamic equations, linearized Gross-Pitaevskii (GP) theory, time dependent GP equation, sum rules. In our previous report (years 2002-2004) we gave some emphasis to the response of condensates to light (Bragg) scattering [2], in connection with the experiments carried out by Ketterle's group at MIT [3] and Davidson's group at the Weizmann Institute [4]. Most of the recent results, including the investigation of the multi-branch Bogoliubov spectrum [5, 6] and the expansion of condensates with phonons [7, 8] have been recently collected in a review paper by Davidson and collaborators [9].

The work done in Trento in this field in the last two years follows the same line, but focussing the attention to the problem of dynamic instabilities and parametric amplification of Bogoliubov excitations. Part of this work, namely the investigation of dynamical and energetic instabilities of condensates in optical lattices, are discussed elsewhere in this report. Here we present some results obtained on the parametric amplification of Bogoliubov phonons. Finally, another type of excitations which have been studied are the solitary waves. We will briefly summarize the main results on solitons at the end of this chapter.

Parametric amplification of Bogoliubov excitations

A parametric resonance corresponds to the exponential growth of certain modes of a system induced by the periodic variation of a parameter [10]. It is a very general phenomenon occurring in classical oscillators, in nonlinear optics, in systems governed by Non-Linear Schrödinger equations, and in Hamiltonian chaotic systems. Parametric resonances can also occur in Bose-Einstein condensates made of ultracold atomic gases. In [11, 12] we considered the case of an elongated condensate in an optical lattice when the intensity of the lattice is periodically modulated in time. We found parametric resonances corresponding to an exponential growth of the population of counter-propagating Bogoliubov excitations. In [11] we performed simulations by numerically integrating the Gross-Pitaevskii (GP) equation for a cigar-shaped condensate subject to a time-varying external potential. In [12] we made a deeper theoretical investigation by means of a suitable linearization of the GP equation, in order to find accurate approximated schemes for the calculation of the stability diagram and the growth rates of the unstable modes. We have shown that the main mechanism of instability is a coupling between pairs of counter-propagating Bogoliubov excitations. This coupling is caused by the modulation of the background in which the excitations live. This picture emerges quite clearly when a two-mode approximation is considered. In this case, one can derive semi-analytic results for the coupling between Bogoliubov modes in different bands and discuss the convergence to the tight binding regime. The results of this semi-analytic calculations were found to agree with the numerical GP simulations. When applied to realistic cases, the theory supports the idea that parametric resonances can be at the origin of the response observed by Stöferle *et al.* [13] with elongated condensates, when the depth of the axial optical lattice is small (i.e., in the superfluid regime).

An interesting aspect of parametric resonances is that they cause the amplification of initial fluctuations, which must be present in the system at the beginning of the external modulation. The seed excitations can be thermal and/or quantum fluctuations, or simply the effects of some uncontrolled dynamics when loading the condensate in the lattice. We have shown that the parametric resonances are indeed sensitive to the type and the amount of the initial seed, thus suggesting a way for measuring fluctuations. In the thermal regime this can provide a novel type of thermometry, while at very small temperature one can have access to beyond mean-field effects through the amplification of quantum fluctuations present in the quasiparticle vacuum. This process has interesting analogies in nonlinear quantum optics and with the dynamic Casimir effect.

Pattern formation in toroidal condensates

Bose-Einstein condensates have recently been obtained with ultracold gases in ring-shaped magnetic waveguides [14] and other groups are proposing different techniques to get toroidal condensates. These efforts are aimed to create a system in which fun-

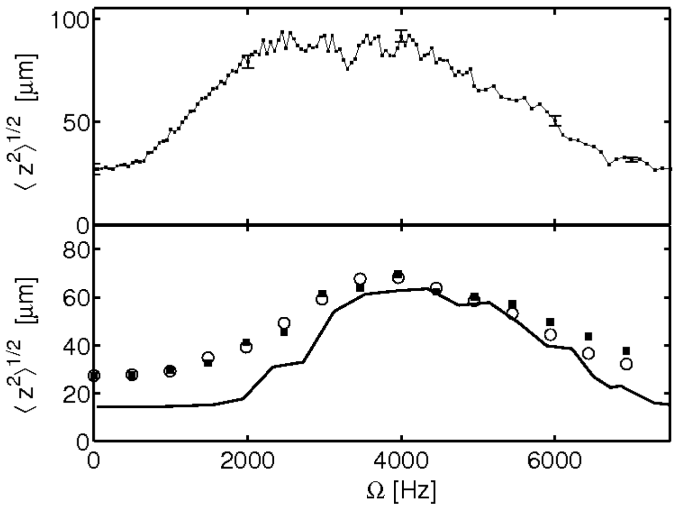

Figure 1: Axial width of an expanded array of elongated condensates, as in the experiment of Ref. [13], as function of the modulation frequency Ω. Top panel: experimental data. Solid line in bottom panel: our GP simulations starting from a small white noise. Empty circles and solid squares: same but with a larger white noise and thermal-like noise, respectively. Taken from [11].

damental properties, like quantized circulation and persistent currents, matter-wave interference, propagation of sound waves and solitons in low dimensions, can be observed in a clean and controllable way. An important issue concerns also the feasibility of high-sensitivity rotation sensors.

In [15] we have shown that key properties of condensates in toroidal traps can be measured by means of parametric amplification. We considered the modulation of the transverse confinement. The modulation is found to induce a longitudinal pattern formation [16] corresponding to a standing density wave along the torus. This occurs via the parametric instability of Bogoliubov phonons, with wavevector k, propagating along the torus in opposite directions. The process is analogous to the spontaneous pattern formation discussed in [17] for a 2D condensate. In our case the geometry is simpler, being essentially one-dimensional and similar to the case of Faraday's instability [16, 18] for classical fluids in annular resonators [19].

The spatial periodicity of the standing wave in the torus is fixed by the wavelength of the most rapidly growing modes, determined by the Bogoliubov dispersion relation $\omega(k)$ and the boundary conditions. The parametric amplification spontaneously selects modes with frequency close to the resonance condition $\omega(k) = \Omega/2$ and wave vector

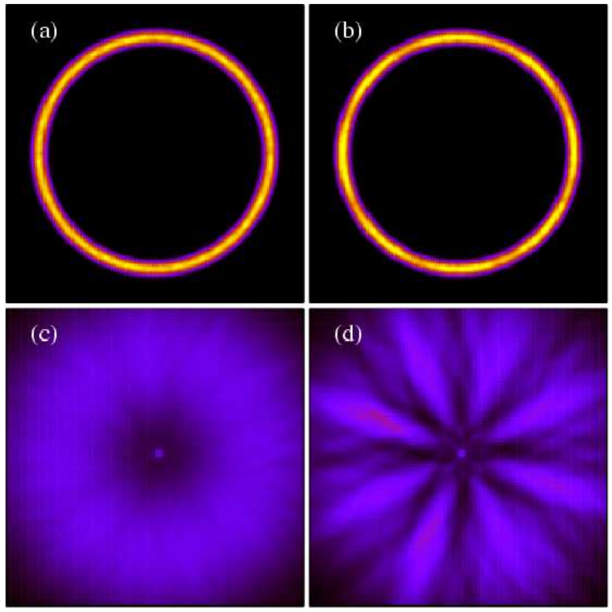

Figure 2: Top: a) density distribution of a condensate at equilibrium in the toroidal trap; b) same condensate after a transverse modulation of frequency $\Omega = 0.6\omega_\perp$, duration $t_{\rm mod} = 130.15$ ms and amplitude $A = 0.1$. Bottom: c) the condensate in (a) freely expanded for a time $t_{\rm exp} = 7$ ms; d) same expansion but for the condensate in (b). The quantity in all plots is the column density, i.e., the density integrated along the z-axis perpendicular to the torus. Taken from [15].

$k = 2\pi m/L$, where the integer m represents the azimuthal angular momentum of the excitation and $2m$ is the number of nodes in the density pattern. The position of the nodes changes randomly at each realization, being related to the phase of the initial fluctuations which are parametrically amplified. Since the GP equation contains a nonlinear mean-field term, the growth of the resonant modes is limited by the energy transfer to nonresonant modes due to nonlinear mode-mixing processes. Thus the $\pm k$ components eventually saturates around a maximum value for long times. Our analysis suggests the possibility to use the parametric amplification for spectroscopy: Each time a density pattern is observed, the wavevector k is simply obtained by counting the number of oscillations in the torus, while the frequency $\omega(k)$ is just $\Omega/2$.

The density pattern is accompanied by a pattern in the velocity distribution. The two patterns oscillate exactly out-of-phase in time. The occurrence of a periodic pattern in the velocity field of the atoms has spectacular consequences in the expansion after the release from the trap. In fact, the presence of $\pm k$-phonons gives rise to interference fringes of atoms expanding in preferred directions, similar to those observed in the expansion of an elongated condensate with Bragg excited phonons [7, 8]. In toroidal geometry these fringes produce a flower-like structure with m "petals" reflecting the periodicity of the initial pattern. Since these petals are much more visible than the in-trap density oscillations, the expansion significantly enhances the sensitivity of the spectroscopic measurement. Moreover the shape of the pattern is significantly affected, both in-situ and after expansion, by the presence of quantized circulation in the torus. If the condensate is initially rotating with angular momentum $L_z = \kappa\hbar$ per particle, where κ is the quantum of circulation, then the external modulation produces a density pattern which rotates along the torus at the same angular velocity of the condensate as a result of the frequency shift of counter-rotating phonons [20]. More strikingly, the interference structure observed in the free expansion exhibits a significant misalignment of opposite petals, proportional to κ. thus yielding a sensitive probe of rotations in the torus, which works down to a few quanta of circulation and is complementary to the techniques discussed in [21].

Solitons

Following the experimental observation of grey solitons (or more precisely, entities associated with quasi-1D grey solitons) in condensates [22], a great deal of attention has been paid to the theory of the phenomenon (see e.g. [23, 24] and references therein). It was found that a grey soliton in a parabolic trap displays a number of peculiarities. Among them, we mention the frequency of oscillations, which is $\sqrt{2}$ times less than the frequency of oscillations of the condensate as a whole [23], and the consequent beatings, which can be observed in the long-time dynamics of a soliton, an internal mode accompanying soliton dynamics, nontrivial phase changes in soliton evolution [24], etc. It turns out, however, that the mathematical treatment of the problem, based on the application of perturbation theory to dark solitons [25] and covering all the main effects, is rather involved, and more important, requires a small soliton velocity. The major problem is that a grey soliton even in the simplest one-dimensional (1D) parabolic trap is dramatically different from the standard grey soliton known from soliton theory.

In [26] we have studied the motion of a grey soliton over a wide range of velocities in a trapped condensate, whose longitudinal size is sufficiently large. The phenomenon has been described by the mean-field 1D Gross-Pitaevskii (GP) equation. We have shown that grey soliton dynamics in a 1D trap can be treated as Landau dynamics of a quasi-particle. A soliton of arbitrary amplitude moves in the trapping potential without deformation of its density profile as a particle of mass $2m$. The dynamics in the local density approximation is shown to be consistent with the perturbation theory for dark solitons. In the same paper we have also discussed qualitatively the dynamics of a vortex ring in a trap.

In [27] we have developed a theory for the dynamics of dark solitons based on the local density approximation. The approach is applicable for arbitrary polynomial nonlinearities of the mean-field equation governing the system as well as to arbitrary polynomial traps. In particular, we have derived a general expression for the frequency of the soliton oscillations in confining potentials. Special attention has been devoted to the study of the soliton dynamics in adiabatically varying traps. It has been shown that the dependence of the amplitude of oscillations *vs* the trap frequency (strength) is given by the scaling law $X_0 \propto \omega^{-\gamma}$ where the exponent γ depends on the type of the two-body interactions, on the exponent of the polynomial confining potential, on the density of the condensate and on the initial soliton velocity. Analytical results obtained within the framework of the local density approximation has been compared with the direct numerical simulations of the dynamics, showing a remarkable agreement. Various limiting cases have been addressed. In particular for the slow solitons we computed a general formula for the effective mass and for the frequency of oscillations.

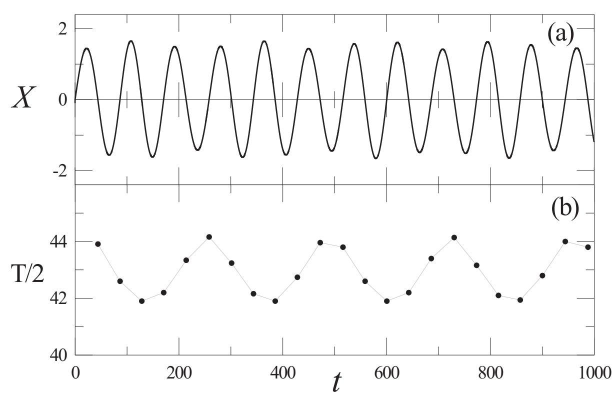

Figure 3: (a) Position of the center of a dark soliton as a function of time in a typical oscillation. (b) Time dependence of the half-period $T/2$. Taken from [27].

Other contributions to the field of excitations in bosonic systems involving members of the Trento BEC-INFM group are:

- Beyond the Landau criterion for superfluidity [28].

- Density pattern in supercritical flow of liquid ^{4}He [29].
- Oscillations in the expansion of solid 4He into vacuum [30].

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ULTRACOLD ATOMS IN OPTICAL LATTICES

The study of ultracold atoms in optical lattices has been one of the most intense areas of research in the last years both from the experimental and the theoretical point of view. Optical lattices allow the trapping of atoms in a huge variety of geometries, including one (1D), two (2D) and three (3D) dimensional periodic lattices with different symmetries, quasi-periodic and random potentials.

On the one hand, the study of ultracold atoms in lattices is very intriguing because it allows to reproduce with a much higher degree of control situations well known in condensed matter physics, ranging from quantum phase transitions to the issue of disorder. On the other hand, optical lattices become a tool for manipulating the properties of the atoms: a nice example in that direction is the realisation of a Tonks gas in a 2D lattice of 1D tubes, where an enhanced effect of interaction was achieved by superimposing a 1D lattice in the third dimension [1].

In the last two years, the long lasting research direction of the BEC center focused on the excitations and the instabilities arising in a Bose-Einstein condensate (BEC) due to the interplay between non linearities and periodic potential has been deepened, allowing the quantitative comparison with experiments. On the other hand, new research directions have opened. The main research themes on which the activity of the BEC center has been focused in the last two years are listed here below:

1) BEC in optical lattices, including the study of energetic and dynamical instabilities, sound propagation, BEC in 2D lattices and the effect of disordered potentials;

2) Berezinskii-Kosterlitz-Thouless transition in the presence of an optical lattice;

3) Effect of the lattice on the creation of molecules and on two-body collisions;

4) Study of the strongly correlated regime.

Bose-Einstein condensates in optical lattices

Role of the transverse confinement on the instability of BECs in 1D optical lattices.

It is well known that a condensate moving in a periodic potential may undergo a superfluid breakdown due to energetic or dynamical instabilities. Energetic instability sets in when, for instance, a uniform condensate flows with a velocity that exceeds the Bogoliubov's sound velocity. In the presence of an external defect the system can lower its energy by emitting phonons (Landau criterion of superfluidity) [3]. Dynamical instability occurs instead when the frequency of some modes in the excitation spectrum has a nonzero imaginary part. Then, if initially populated (*e.g.* due to quantum/thermal

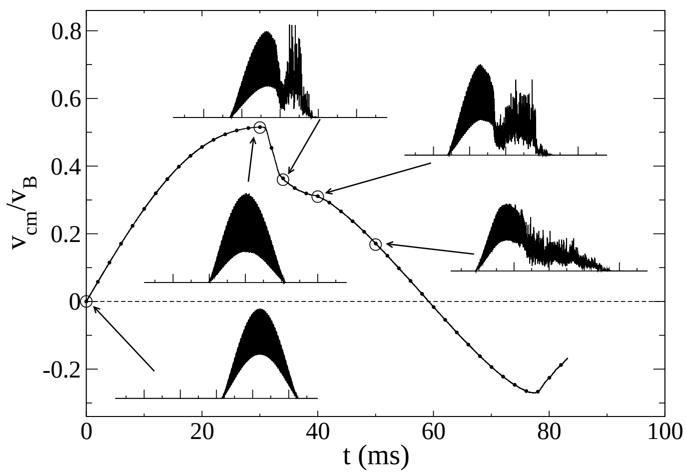

Figure 1: Center-of-mass velocity and density of the condensate in [8] during the its evolution in the harmonic trap after an initial displacement of 60 μm. The velocity initially increases, as expected for the harmonic dipole oscillation of the whole condensate, up to a critical value at which the condensate breaks up. The corresponding quasimomentum p lies in the dynamical unstable region.

fluctuations), the occupation of these modes grows exponentially in time and rapidly drives the system away from the steady state [4].

These features are already present in the 1D Gross-Pitaevskii (GP) theory [5], but a reliable framework for comparison with the experiments requires however the use of a 3D description that includes the radial degrees of freedom. The starting point is the linear analysis of the GP theory for a cylindrical condensate in a 1D optical lattice. In this case one can use Bloch functions and rigorously define the concept of quasimomentum k associated with the motion of the condensate in the lattice. The order parameter can be expanded as $\Phi(r,z,t) = e^{-i\mu t/\hbar}e^{ikz}[\Psi_{k0}(r,z) + \sum_{j\nu q} u_{kqj\nu}e^{-i\omega_{kj\nu}(q)t} + v^*_{kqj\nu}e^{i\omega_{kj\nu}(q)t}]$, where the functions $u_{kj\nu q}(r,z)$ and $v_{kj\nu}(r,z)$ are the Bogoliubov quasiparticle amplitudes of quasimomentum q, and quantum numbers j,ν representing the band index and the number of radial nodes respectively. For any given k and lattice height s (in units of the recoil energy), one can then calculate the excitation spectrum and the stability diagram by solving the equations of the linearized GP theory [6].

The description of the system can be simplified by using an effective 1D model, the Non-Polynomial Schrödinger Equation (NPSE) [7], which partially includes also the radial to axial coupling through a Gaussian Ansatz for the radial shape of the order parameter, with a z- and t-dependent width. With respect to strictly 1D models, which rely on a suitable renormalization of the mean-field coupling constant, the NPSE has the

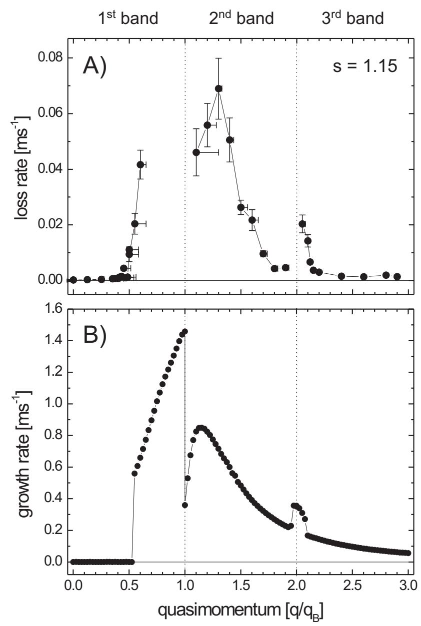

Figure 2: A) Experimental loss rates in [9] for a BEC loaded into the first three energy bands of a moving optical lattice with $s = 1.15$. B) Theoretical growth rates of the most dynamically unstable modes obtained from a linear stability analysis of the NPSE.

advantage that the true 3D coupling constant $g = 4\pi\hbar^2 a/m$ can be used, thus allowing for a direct comparison with experiments. Indeed it turns out that this model gives accurate predictions for the instability thresholds, the latter being mainly determined by the dispersion of the lowest branch of excitations, with no radial nodes. Higher branches, with one or more radial nodes, that are included in the GP theory but not in the NPSE, are shown to be important in characterizing the number and the type of excitations that become unstable above the instability threshold [6].

The predictions of the linear analysis discussed so far for the infinite cylinder can be compared with the direct solutions of the time-dependent 3D-GP equation for an elongated condensate. In particular we have considered the case of an elongated condensate of the experiments of Ref. [8], whose interpretation has been the object of a stimulating debate on the origin of the observed instability. Our analysis provides convincing evidence that the breakdown of superfluid flow observed in [8] is associated with the onset of a dynamical instability, triggered by the resonant coupling of Bogoliubov phonon and anti-phonon modes. The subsequent dynamics is shown to strongly involve radial motions.

This analysis is also relevant in connection with the experiments of Ref. [9] where the condensate is loaded adiabatically in a moving lattice. In this case, interesting results have been found by comparing the NPSE results with the experimental data for the nontrivial dissipative behavior of condensates loaded in higher Bloch bands. The remarkable similarity between the curves for the experimental loss rates and the theoretical growth rates indicates that the onset of the instability produces a significant imprinting on the subsequent dynamics of the system.

Velocity of sound in a BEC in the presence of an optical lattice and transverse confinement.

In [10], we have studied the effect of a 1D optical lattice on sound propagation. In addition to a decrease of the sound velocity due to the increased effective mass, we have shown that the optical lattice induces, on large sound signals, also a saturation-purification effect, which allows them to propagate without deformation at a maximal amplitude strongly decreasing with the lattice depth.

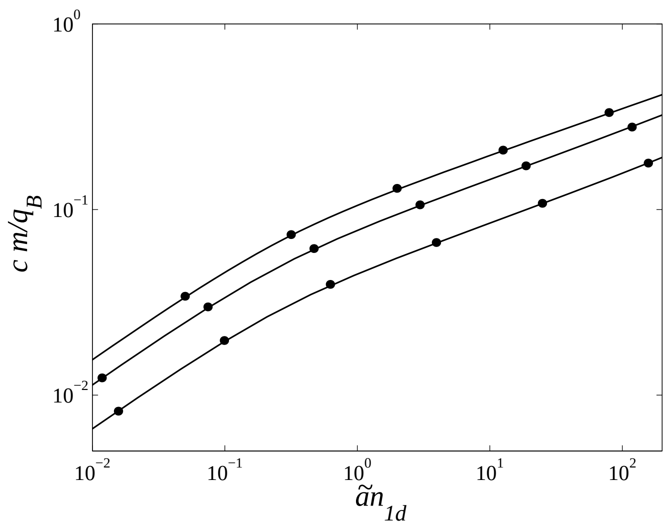

Figure 3: Velocity of sound as a function of $\tilde{a}n_{1D}$, for three values of the lattice intensity, $s = 0, 5, 10$. Results of full 3D numerical calculations (points) are compared with the prediction derived from the 1D equation of state (lines). Note that $\tilde{a}/1 = 1.49$ and $\tilde{a}/a = 1.98$ for $s = 5$ and $s = 10$ respectively.

Strictly 1D models, obtained through a renormalization of the coupling constant, take into account only partially the influence of the transverse confinement of the sound velocity. A more accurate description can be obtained by means of an effective 1D approach based on a factorization of the condensate wavefunction into a longitudinal and a radial part $\Psi(r,z) = \varphi(r)\psi(z)$ [11]. The physics underlying this assumption is that interactions mainly affect the radial wavefunction $\varphi(r)$, while the axial component $\psi(z)$ is that of a single particle in the periodic potential. This factorization is exact for $s = 0$, and quite accurate for the typical densities of current experiments with $s \neq 0$.

Under the factorization assumption, and using the normalisation condition for the wavefunction, one can write two coupled effective GP equations for the radial and axial components. This factorisation results in a renormalization of the scattering length $\tilde{a}$ in the radial equation due to the presence of the lattice, and of the number of atoms per well $\tilde{N}$ in the axial one due to the transverse confinement. As a consequence the effective mass, that is calculated from the lowest energy Bloch band $\epsilon(k)$ according to the general relation $1/m^* = \partial^2\varepsilon/\partial k^2|_{k=0}$, is affected by the radial confinement through its dependence on $\tilde{N}$. Then, the sound velocity c in presence of a 1D lattice and transverse harmonic confinement is completely accounted for by the expression $c = \sqrt{N\partial\mu(N)/\partial N/m^*}$, where $\mu(N)$ is equation of state resulting from the equation for the radial component $\varphi(r)$. This expression takes the analytic form $c = \sqrt{gn(0)/2m^*}$, $n(0)$ being the central density, both in the 1D mean-field (frozen radial dynamics) and Thomas-Fermi (TF) regimes.

The value for c obtained with this procedure can be compared with the exact 3D calculation from the slope of the lowest branch in the excitation spectrum $\omega_{j\nu}(q)$ (for $k = 0$), through the relation $c = \hbar\partial\omega_{10}(q)/\partial q|_{q=0}$ [6]. As shown in Fig.(3), the agreement is perfect in the full crossover from 1D mean-field to TF, for a wide range of lattice intensities [11].

Asymmetric Landau-Zener tunneling in optical lattices.

In the past years, one of the main activities of the BEC center has been to characterise the excitations of a Bose-Einstein condensate in an optical lattice [2]. In particular, the Bloch bands, describing the chemical potential of a condensate at a given quasi-momentum, have been investigated and it was shown that they strongly depend on interactions, giving rise for instance to a density dependent effective mass. A related effect of interactions is a change in the gap between first and second Bloch band, depending on which band is populated, giving rise to an asymmetric Landau-Zener tunneling. The gap has been calculated numerically in the two cases, in order to complement the theoretical analysis of the experimental observation of this effect [12].

BECs in random speckle potentials.

The investigation of Bose-Einstein condensates (BECs) in the presence of disorder is rapidly becoming a central topic in ultracold atom physics. Various interesting phenomena are expected to occur in these systems, among which the most fascinating are Anderson localization and the quantum transition to the Bose glass phase that originates from the interplay of interactions and disorder. Recently, effects of disorder created by optical speckles have been observed on the dynamics of an elongated BEC, including uncorrelated shifts of the quadrupole and dipole modes [13] and localization phenomena occurring during the expansion in a 1D waveguide [14, 15].

The main features observed in these experiments can be explained within the Gross-Pitaevskii (GP) theory. In the presence of a weak disorder the dipole and quadrupole modes of a harmonically trapped condensate turn out to be undamped in the small amplitude regime, whereas a superfluid breakdown may occur for larger oscillations. In the first case the two modes are characterized by uncorrelated frequency shifts, both in sign and amplitude, that depend on the particular realization of the perturbing potential. The origin of this behavior can be explained by using a sum rules approach, and considering the random potential V_R as a small perturbation of the harmonic confinement. The frequency shift can be expressed as $\Delta\omega \simeq \delta/2\omega_0$, with $\delta_D \simeq \langle \partial_z^2 V_R \rangle_0/m$ and $\delta_Q \simeq \langle z\partial_z V_R + z^2\partial_z^2 V_R \rangle_0/m\langle z^2 \rangle_0$ for the dipole and quadrupole modes respectively, ω_0 being the unperturbed frequency. These predictions nicely agree with the the direct solution of the GP equation and with the experimental observations in [13].

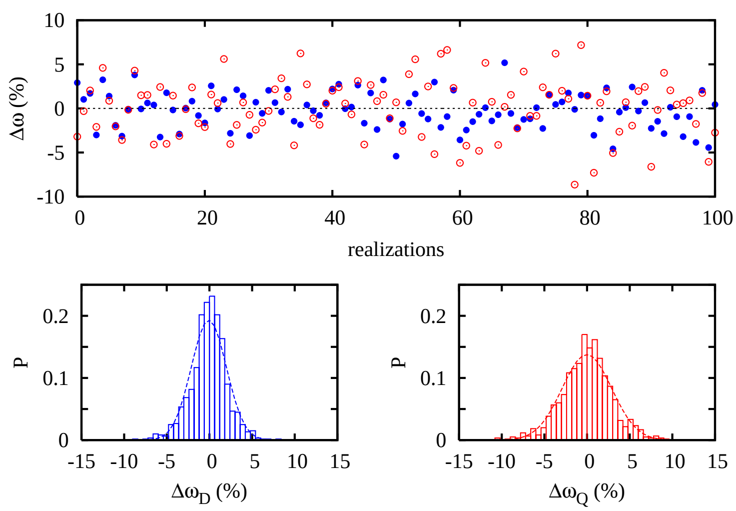

Figure 4: Top: dipole (filled circles) and quadrupole (empty circles) frequency shifts for 100 different realizations of the random potential as obtained from the sum rules. Bottom: probability distribution P.

It is interesting also to comment on the behaviour in the presence of a periodic lattice. When the wavelength of the lattice is much smaller than the axial extent of the condensate one can apply the Bloch picture obtaining the same renormalization for both the dipole and quadrupole frequencies $\omega = \sqrt{m/m^*}\omega_0$, m^* being the effective mass. Differently, in the case of a condensate that extends over only few wells (as for the speckles) the Bloch picture cannot be applied. In this case the sum rules predict correlated shifts, whose magnitude however still depends on the relative position between the condensate and the periodic potential, eventually yielding an uncorrelated renormalization of the two frequencies.

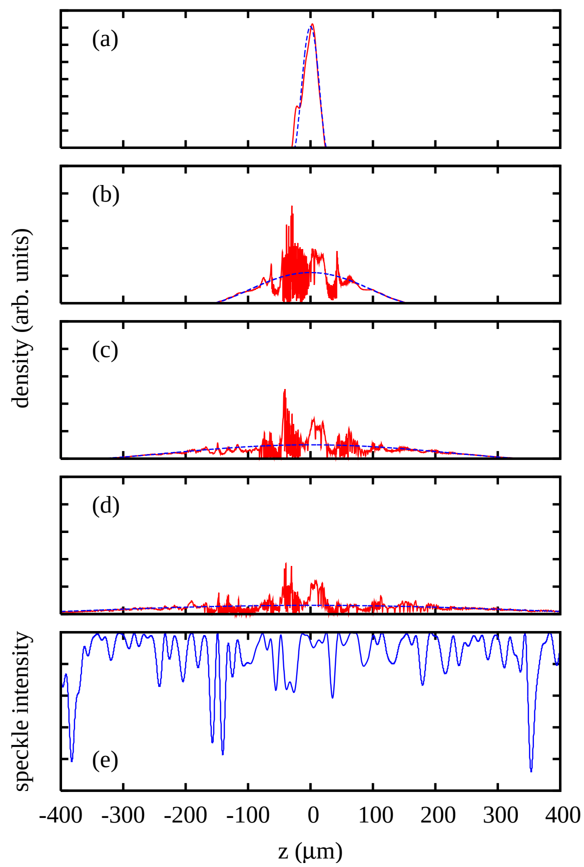

Figure 5: (a)-(d) Density profiles of the condensate (red continuous line) during the expansion in the waveguide in the presence of a red-detuned speckle potential (shown in frame (e)), for different times (t = 0, 25, 50, 75 ms, from (a) to (d)), compared with the free expansion case (blue dashed line).

The solution of the GP equation can be also used for characterizing the role of disorder on the expansion of BECs in a 1D waveguide. In case of speckles with correlation length $\simeq 10$ μm as in the experiments [14, 15, 16], the GP equation predicts localization effects mainly due to a *classical* trapping into single wells or between barriers of the random potential. These phenomena take place preferably near the trap center where the less energetic atoms reside. The outer part of the condensate instead expands almost freely, unless it encounters a high enough (reflecting) barrier. This behavior is qualitatively similar to that of a periodic system or even of a single well [15, 17], thus revealing that is not strictly an effect of disorder, but just of the actual shape of the potential. The analysis of the quantum behaviour of a single defect (well/barrier) of the potential confirms that quantum effects are negligible. In order to observe non trivial (Anderson-like) localization phenomena in a 1D system one should instead have interference of multiple *quantum* reflections of matterwaves. This regime could be achieved by reducing the correlation length of the random potential. This may be not straightforward for speckle potential due to the diffraction limit on the size of the defect [15], but could be easily obtained in case of super-lattices created by superimposing two standing waves of different wavelength.

Berezinskii-Kosterlitz-Thouless transition in an optical lattice.

The Berezinskii-Kosterlitz-Thouless (BKT) transition is a paradigmatic example of a phase transition in a 2D system. Indeed, according to the Mermin-Wagner theorem, two-dimensional systems with a continuous symmetry cannot sustain long-range order in the thermodynamic limit at finite temperature; however, a phase transition is still possible and it occurs via the unbinding of point defects like dislocations or vortices. The BKT theory associates this phase transition with the emergence of a topological order, resulting from the formation of bound pairs of vortices and antivortices. In the low-temperature phase, characterized by the presence of bound vortex-antivortex pairs, the spatial correlations exhibit a power-law decay; above a critical temperature T_{BKT}, the decay is exponential and there is a proliferation of free vortices. Very recently, the observation of a BKT-type crossover in a (continuous) 2D trapped gas of *Rb* atoms has been reported [18]. It is also interesting to explore the BKT transition in the presence of an optical lattice in the plane. In this way, it is possible to tune the strength of the coupling J between BECs in neighboring wells and, thus, to explore both correlated and mean field regimes depending on the ratio between the coupling energy J and the interaction energy U of the atoms in each well.

In [19] the finite-temperature properties of Bose-Einstein condensates loaded on a

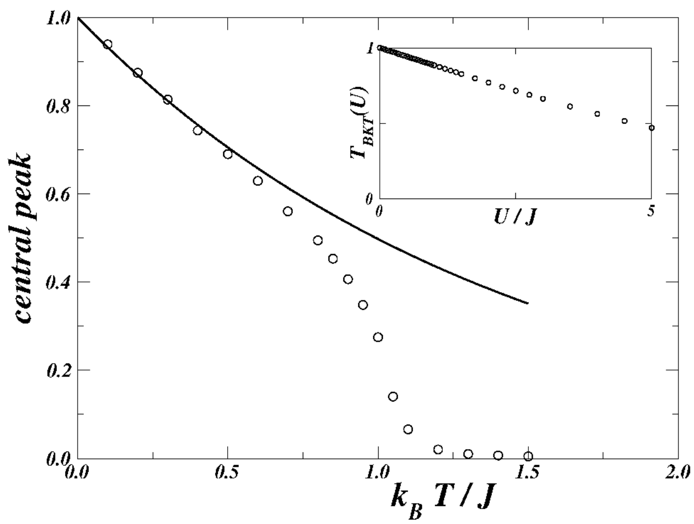

Figure 6: Intensity of the central peak of the momentum distribution (normalized to the value at $T = 0$) as a function of the temperature T (in units of the coupling energy J); empty circles: Monte Carlo simulations; solid line: low-temperature spin wave prediction. Inset: the BKT critical temperature $T_{BKT}(U)$ (in units of the critical temperature for $U << J$) as a function of U/J.

$2D$ optical lattice have been studied. The interference pattern of the expanding condensates provides the experimental signature of the BKT transition: near the critical temperature, the $\vec{k} = 0$ component of the momentum distribution sharply decreases. In Fig.6 we plot the intensity of the central peak of the momentum distribution (normalized to the value at $T = 0$) in a 2D lattice as a function of the temperature, evidencing the sharp decrease of the magnetization around the BKT critical temperature. By using a renormalization group analysis, it is possible to study the effect of interparticle interactions U on the critical temperature T_{BKT} at which the BKT transition occurs for Bose-Einstein condensates loaded at finite temperature in a $2D$ optical lattice [20]: T_{BKT} decreases as the interaction energy decreases and when $U/J = 36/\pi$ one has $T_{BKT} = 0$, signaling the possibility of a quantum phase transition of BKT type. In the inset of Fig.6, the BKT critical temperature T_{BKT} (in units of the critical temperature for $U << J$) is plotted as a function of U/J.

Effect of the lattice on the interaction properties

In the presence of a Feshbach resonance two interacting atoms can form a weakly bound state. In free space, diatomic molecules exist only for positive values of the scattering length a and the corresponding binding energy is given by $E_b = -\hbar^2/ma^2$, where m is the mass of each atom. These dimers have already been observed experimentally by several groups [21, 22, 23, 24]. An interesting problem is the formation of molecules and two-particle bound states in an optical lattice [25, 14, 27, 28].

Formation of molecules in 1D optical lattice.

In [29], we considered two atoms in the presence of a 1D periodic potential and free to move in the perpendicular directions. We calculated the binding energy and the tunneling properties of the weakly bound state as a function of the laser intensity and the scattering length a. In the presence of the lattice, the center-of-mass and the relative motion do not separate and the binding energy can be found solving an integral equation in the center-of-mass variable. Due to the periodicity of the lattice, the quasi-momentum Q of the molecule is a conserved quantity. For any value of Q, we solved this equation numerically.

In Fig.7 we show the binding energy as a function of the inverse scattering length for $Q = 0$ and different values of the laser intensity. For small and positive values of the scattering length, the bound state is weakly perturbed by the lattice (dotted line). Moving toward resonance and for sufficiently deep lattices, the molecule enters a quasi-2D regime where the two atoms are trapped at the bottom of a given well and experience an effective 1D harmonic potential. In this case the value of the binding energy is known analytically after Ref.[30] (dashed line). Going to negative values of scattering length, the binding energy becomes smaller than the atomic bandwidth $4t$ and the system enters an anisotropic 3D regime where the wavefunction is delocalized over many lattice sites. Finally, at a critical (negative) value of the scattering length, the binding energy vanishes and no solution exists beyond this point.

By solving the integral equation for different values of Q, we obtained the energy dispersion for the molecule. Due to the non separability of center-of-mass and relative motion, the tunneling properties of the molecule acquire a strong dependence on the value of the scattering length. In particular, going toward small and positive values of the scattering length, the molecule becomes heavier.

Two-body problem in periodic potentials.

In [31], we wrote the general equations for the binding energy and the scattering ampli-

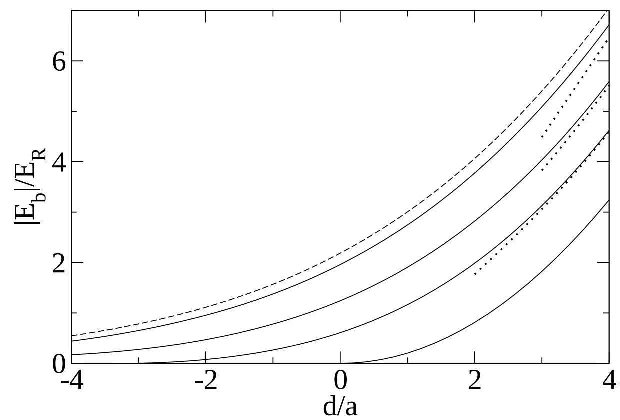

Figure 7: Binding energy versus inverse scattering length for different values of the laser intensity: from top to bottom $s = 20, 10, 5, 0$ (solid line). Also shown are the asymptotic behaviour for large d/a (dotted line) and the binding energy in harmonic approximation (dashed line) for $s = 20$.

tude in optical lattices of arbitrary dimensions. For deep lattices we showed that these equations can be solved analytically by a tight-binding Ansatz. This approach allowed us to describe the interplay between confinement and tunneling effects leading to the dimensional crossover mentioned above.

We first discussed in details the special case of a 1D lattice, by comparing our analytical predictions for the energy dispersion of the molecule with the exact numerics developed in Ref.[29]. We found a remarkably good agreement even for relatively low values of the laser intensity ($s \gtrsim 5$).

We then considered the case of 2D and 3D optical lattices. In the confined regime, where tunneling effects can be neglected and atoms feel an effective harmonic trapping, our predictions are consistent with known exact results [32, 33]. In the anisotropic 3D regime, closed to the critical point, the size of the molecule is large compared to the lattice period and the binding energy acquires a universal dependence on the scattering length.

Finally, we derived an asymptotically exact expression for the critical value of the scattering length needed to form a molecule in a tight lattice in terms of the atomic bandwidth $4t$.

Towards the strongly correlated regime

The enhancement of interactions with respect to tunneling and the control over the dimensionality of the system induced by the optical lattice open new possibilities of going into the strongly correlated regime.

Along the lines of the experiment in [34], we have proposed to use an optical lattice to enhance the beyond mean-field effects in a Bose-Einstein condensate. We have concentrated on the geometry given by a 2D optical lattice superimposed to a disc shaped condensate in a harmonic trap. By changing the physical parameters (laser intensity and atomic density), the system undergoes a dimensional crossover from a 3D regime to a quasi-1D regime. We have shown that the beyond mean field corrections to the equation of state are different in the two regimes and can therefore be observed through the measurement of collective oscillations. In particular we have calculated the frequency shift of the lowest compressional mode in the axial direction [35]. In the 1D regime we recover the result of [36] in the weakly interacting limit.

In [37], the momentum distribution of a 2D lattice of 1D tubes was studied to investigate the interplay between the correlations along the 1D tubes and the intertube tunneling. The momentum distribution is a relevant quantity since it is strictly linked to the interference pattern obtained in the experiments after release of the atomic cloud. It was shown that the disappearance of the interference pattern is a signature of the strong correlated Tonks-Girardeau regime inside the 1D tubes, rather than a signature of the Mott transition in the 2D lattice.

Recently, a new research line has started devoted to the study of the excitations in the Bose-Hubbard Hamiltonian, based on a Green's functions formalisms in the RPA approximation [38, 39]. We have studied the excitation spectrum, momentum distribution and depletion from the Mott insulating phase to the superfluid phase transition, till deep into the regime of large number of atoms per well and weak interactions, where the Bogoliubov results are recovered. This formalisms, usually applied in momentum space for the uniform system, has been extended to the case where an external trapping potential is superimposed, in one and two dimensional systems.

Presently on going is the study of the metastable states of dipolar bosons in a 2D optical lattice [40]. Due to the long-range of dipole-dipole interaction, the phase diagram is characterised by Mott-like insulating phases with average fractional filling factor, where the atoms arrange themselves in the lattice forming regular patterns. There are regions in phase space, where beyond the ground state configuration many metastable configurations are found. We are investigating controlled initialization and manipulation procedures between the different configurations.

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ULTRACOLD FERMI GASES

In the last few years impressive progress has been achieved in the physics of ultracold Fermi gases. Major experimental achievements have been the realization of molecular BEC [1] and of quantized vortices [2]. The tunability of the two-body scattering length and the possibility of realizing highly correlated configurations have stimulated much experimental and theoretical work, providing the exciting possibility of exploring the long sought BEC-BCS crossover, first proposed to understand the behaviour of high T_c superconductors. In particular in the so-called unitary regime, corresponding to values of the scattering length much larger than the interparticle distance, the many-body wave function of the system cannot be described neither in terms of a simple condensate of molecules, corresponding to the BEC regime, nor using standard BCS theory. At unitarity the system actually exhibits a new challenging universal behaviour. Some significant contributions of the Trento team to this active field of research are summarized below. Other works are presented in the Research Line on “Quantum Monte Carlo methods”.

Collective oscillations

The collective oscillations of a superfluid are described by the equations of irrotational hydrodynamics. In the case of Bose-Einstein condensed gases the predictions of hydrodynamics [3] have been accurately tested experimentally both concerning surface and compressions modes. The frequency of the compression modes depends explicitly on the equation of state which, in the case of dilute Bose gases, is characterized by a simple linear density dependence in the chemical potential. Viceversa, surface modes are independent of the equation of state, but differ from the predictions of the non interacting model. In a Fermi gas the equation of state varies significantly along the BEC-BCS crossover and consequently the study of these oscillations can provide unique experimental information on its behaviour. A first theoretical prediction [4] was addressed to the behaviour of the compressional frequencies in the relevant asymptotic regimes characterizing the crossover, including the unitary point. In particular in this paper it was pointed out that, due to the emergence of beyond mean field effects associated with quantum correlations [5], the frequency should be enhanced on the BEC side with respect to the mean field value predicted by Gross-Pitaevskii theory. Several experimental and theoretical efforts have later focused on a more systematic study of the collective oscillations. In particular in [6] we have compared the predictions for the collective frequencies obtained using the equation of state of standard BCS theory with the ones given by the Monte Carlo equation of state [7]. Very recent experiments [9] (see Fig. 1) remarkably agree with the predictions of the Monte Carlo equation of state. In particular these new data show an enhancement of the collective frequencies with respect to the mean field value on the BEC side of the crossover, thereby providing first clear evidence for the occurrence of beyond mean field effect.

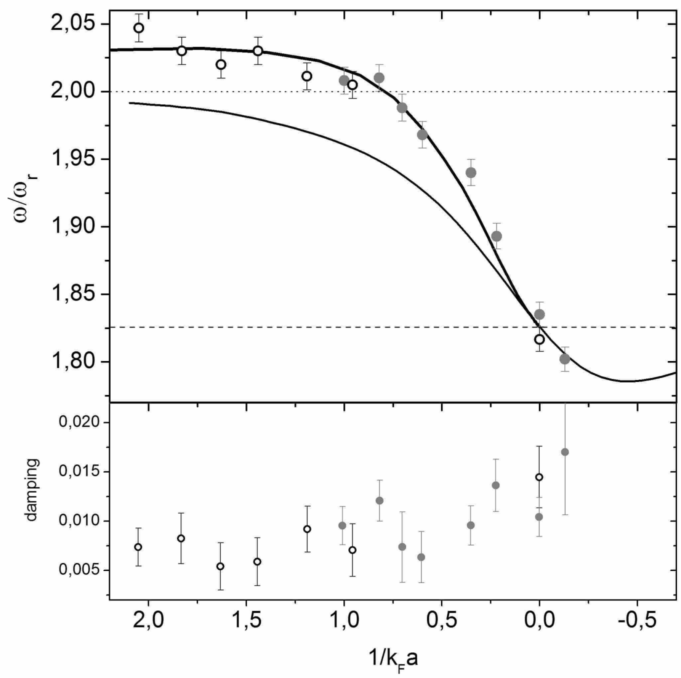

Figure 1: Experimental results (R. Grimm, private communication) for the frequency of the radial breathing mode in a trapped gas of ^6Li atoms at very low temperature. The data well agree with the predictions obtained using the Monte Carlo equation of state (upper line), while they differ from the predictions of standard BCS theory (lower line). Both theories and experiments agree with the universal behaviour $\sqrt{10/3}\omega_\perp$ at unitarity.

Static and dynamic structure factor

The structure factor is a key quantity systematically investigated in condensed matter as well as in nuclear physics. In [8] we have studied the behaviour of the static and dynamic structure factor of an interacting Fermi gas along the BEC-BCS crossover at relatively large wavevectors (larger than the inverse interparticle distance) where the response is sensitive to the elementary constituents of the system. The structure factor reveals rather intriguing features, mainly associated with the occurrence of strong correlations responsible for the formation of molecules on the BEC side of the resonance. In particular we find that when the wave vector is larger than the inverse of the (positive) scattering length the static structure factor approaches the value $S(k) = 1$ typical of the regime of incoherent scattering from individual atoms. Viceversa, when the wave vector is smaller than the inverse scattering length, but still larger than the inverse interparticle distance, one finds the value $S(k) = 2$ reflecting the excitation of individual molecules. Even at unitarity, where free molecules cannot form, one finds a pronounced dependence of $S(k)$ as a function of k, reflecting the occurrence of molecular like correlations (see figure 2). In the same paper we have also investigated the dynamic structure factor $S(k, \omega)$ and shown the emergence of a peak at $\omega \sim \hbar^2 k^2/4m$ characterizing the excitation of molecules. This peak is visible also close to unitarity while it disappears when we approach the BCS side of the crossover (see figure 3).

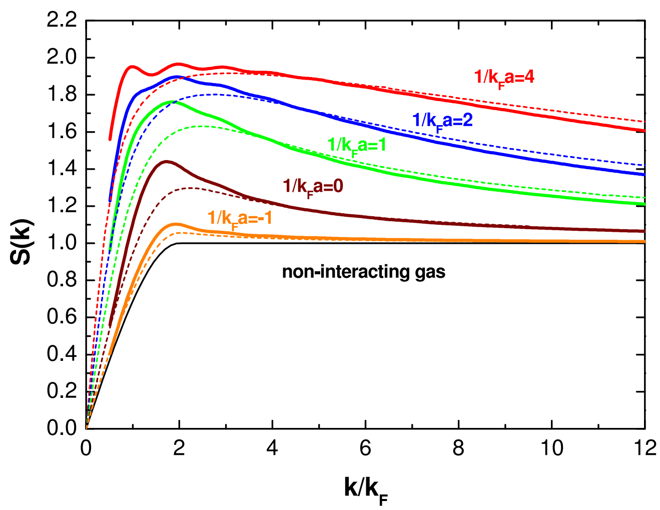

Figure 2: Static structure factor as a function of the wavevector k in units of the Fermi wavevector k_F for different values of the interaction strength. Solid lines correspond to Quantum Monte Carlo calculations and dashed lines to BCS results. The black line refers to the non interacting Fermi gas.

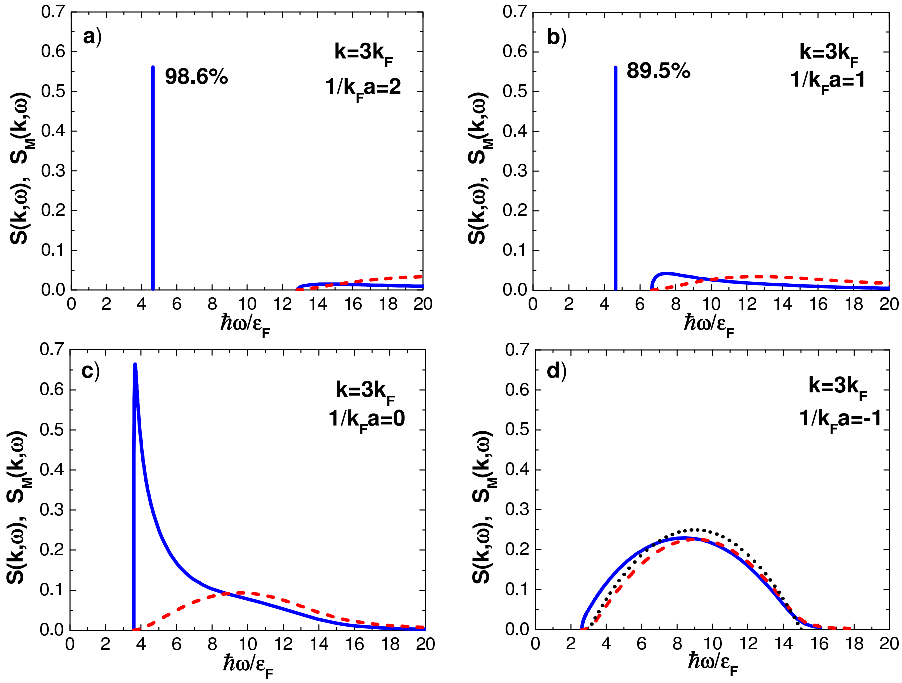

Figure 3: Dynamic structure factor calculated within BCS theory, as a function of ω for fixed momentum transfer $k = 3k_F$ and for various interaction strengths. Blue solid lines refer to the total structure factor $S(k,\omega)$ and red dashed lines to the magnetic one $S_M(k,\omega)$. The black dotted line in panel d) corresponds to the non-interacting gas. In panels a) and b) the weight of the sharp peak to $S(k)$ is also indicated. The units of the dynamic structure factor are $N/(2\epsilon_F)$.

Bragg scattering and spin structure factor of two-component gases

The inclusion of the atomic spin degrees of freedom has opened interesting new perspectives in the physics of radiation-matter interactions in ultracold atomic gases. In particular, the light polarization degrees of freedom can be exploited in novel imaging techniques which are able to get information on the spin state of the atoms in the cloud.

A recent experiment [10] has implemented a technique proposed by us a few years ago [11] to image in a non-destructive way the magnetization profile of a spin 1 Bose cloud. The same spin-dependent light-matter Hamiltonian has been then used to investigate [12] polarization-sensitive Bragg scattering processes: in particular, we have shown that these processes can be used to measure the correlation functions of the fluctuations of both the density and the magnetization, i.e. the density and the spin structure factors of an atomic gas. This quantity play in fact a central role in the characterization of the microscopic state of a quantum fluid, in particular the one of a Fermi superfluid.

Stimulated Bragg scattering probes the response function of the gas to the optical potential created by the interference pattern of the two laser beams: one can act on either the total or the spin density simply by changing the light polarizations. The fluctuation-dissipation theorem then relates the absorbed energy to the structure factor of our interest. On the other hand, the static density and spin structure factors can be directly probed in a spontaneous scattering experiment: the intensity of scattered light in a given polarization state is in fact proportional to a combination of the density and the spin structure factors, whose weights depend on the relative angle between the incident and scattered beam polarizations.

Expansion and pair correlation function

Recent experimental studies of two-body correlations in an expanding atomic cloud have pointed out for the first time the Hanbury-Brown and Twiss (HBT) effect in a dilute Bose gas, both concerning spatial [13] and temporal [14] correlations. The HBT effect consists of an enhancement in the value of the pair correlation function $g^{(2)}(s)$ at short distances due to bosonic statistical effects. In [15] we have studied the behaviour of the spin up-down correlation function of an interacting Fermi gas, with special attention to the most challenging unitary regime and proposed a simple hydrodynamic ansatz to predict its behaviour during the expansion after release of the trap. The result for the spin correlation function is shown in fig. 4 and reveals a typical $1/s^2$ behaviour at short distances. At unitarity the pair correlation function approaches the uncorrelated value $g^{(2)}(s) = 1$ value at distances of the order of the interparticle distance d which is the only length scale available at unitarity. This behaviour should be compared with the one in the molecular BEC regime ($d >> a$) where the pair correlation function approaches the uncorrelated value at shorter distances, of the order of the scattering length a.

During the expansion one expects that the superfluid will be governed by conditions of local equilibrium which ensure the isotropy of the pair correlation function even if the trap confining the gas before expansion is anisotropic. This differs from the case of the expansion of a non interacting gas where the pair correlation function gets an anisotropic dependence on the relative variable s after expansion. In particular at unitarity, where $g^{(2)}(s)$ depends only on the combination $k_F s$ where $k_F \sim 1/d$ is the Fermi wavevector, the expansion acts like a microscope, the value of k_F being reduced as a function of time. The expansion of the pair correlation function from an anisotropic trap exhibits rather peculiar features with respect to the one of the density distribution. In a non interacting gas (above T_c) the density distribution approaches an isotropic shape while the pair correlation function becomes anisotropic. In a superfluid the opposite takes place. In fact while the density distribution approaches an anisotropic shape (changing its shape from a cigar to a disc or viceversa), the pair correlation function keeps its isotropy. This behaviour is expected to hold on the BEC side of the resonance, including the unitary point, where superfluidity is robust and it is likely preserved during the expansion. Viceversa superfluidity is more fragile on the BCS side of the crossover, the superfluid gap becoming exponentially small as the density decreases during the expansion.

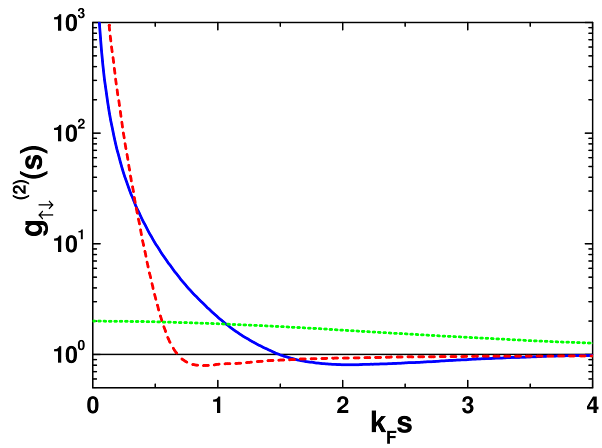

Figure 4: Spin up-down pair correlation function of a homogeneous system. Red line: Fermi gas in the deep BEC regime ($1/k_F a = 4$); blue line: Fermi gas at unitarity ($1/k_F a = 0$); green line: ideal Bose gas with density $n = k_F^3/(6\pi^2)$ at the Bose-Einstein critical temperature; black line: uncorrelated gas with $g^{(2)}(s) = 1$.

Spin polarizability and superfluidity

The study of polarization effects in Fermi superfluids has recently become a challenging subject of research in the community of ultra cold atoms. In particular new configurations have been experimentally achieved by populating two hyperfine states with different atomic numbers, yielding different Fermi wavevectors. Challenging questions concern the equilibrium structure and the dynamic and superfluid features of these configurations. First experiments carried out at MIT [16] and at Rice [17] have already produced a stimulating debate in the community. The scenario emerging from these experiments seems to indicate that at unitarity, where $k_F a \gg 1$, the polarization produces a phase separation between an unpolarized, superfluid component and a polarized phase located at the periphery of the atomic cloud. Instead of investigating a globally polarized system, as done in all previous approaches, in [18] we have investigated the effect of a local polarization produced by a position dependent magnetic field. This can be in practice produced by shifting the trapping potentials confining the two atomic species in opposite directions by a certain distance d. In the absence of interactions the effect of the displacement is very simple. The two atomic cloud will move rigidly in opposite directions giving rise to a spin dipole moment per particle equal to the displacement distance. In the presence of superfluidity the behaviour will be quite different. In fact it is well known that a superfluid cannot be polarized by a magnetic field, unless the field overcomes a critical value. This is due to the energy cost associated with pair breaking which makes the linear polarizability vanishingly small at zero temperature. We have calculated the induced spin dipole moment as a function of the displacement distance d. At unitarity, where the calculation is based on the knowledge of the equation of state of the superfluid phase and on the assumption of a phase separation between the superfluid and the spin polarized phases, we predict large deviations from the non interacting value even for large displacements, of the order of the size of the cloud (see Fig. 5). This should be compared with the behaviour on the BCS side where superfluidity is more fragile and the spin polarizability is quenched with respect to the non interacting value only for very small displacement distances.

Superfluid 3D Fermi gas in 1D optical lattice

The observation of a weak-coupling BCS superfluid transition remains a challenging goal in the studies of ultracold Fermi gases. It was recently suggested [19] that gases restricted to low dimensions are promising candidates for achieving superfluidity as the confinement enhances interaction effects. Adding a tunable periodic potential allows one to combine the benefits of the reduced dimensionality with the advantage of working with large yet coherent samples. In particular, it was shown in Ref.[20] that the study of the center of mass oscillations of the cloud in a superimposed weak harmonic potential could be a useful tool to detect the superfluid transition.

In our investigations we have mainly considered 3D Fermi gases with attractive

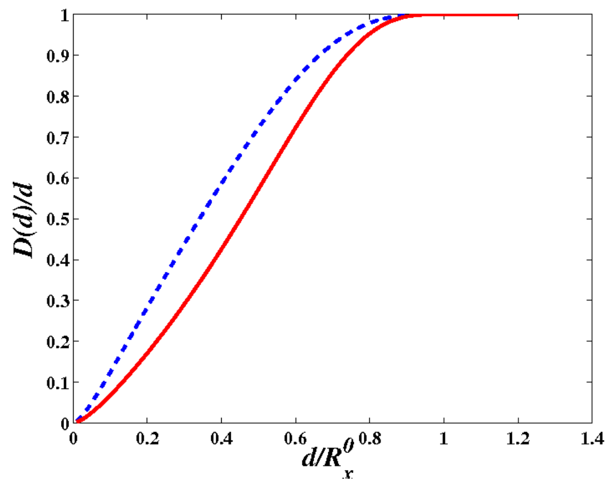

Figure 5: Normalized induced spin dipole moment vs the displacement d of the trapping potential. The solid and dashed lines correspond, respectively, to the Monte Carlo and BCS predictions for the equation of state at unitarity.

interactions in the presence of a 1D optical lattice. This model is particularly interesting because the Fermi energy ϵ_F can be larger or smaller with respect to the Bloch band width $4t$: in the first case the system retains an anisotropic 3D behaviour with an open Fermi surface whereas in the second case the gas is kinematically 2D. Hence, by increasing the atom density, the system undergoes a dimensional crossover.

Transition temperature

In Ref.[21] we calculated the critical temperature of the gas starting from BCS mean field theory. In the presence of the lattice, the density of states and the scattering properties of atoms at the Fermi surface change considerably. We showed that the signature of the dimensional crossover is that the coupling constant for Cooper pairs becomes density-dependent approaching the quasi 2D regime, while the density of states reaches a constant value. We found that the enhancement of the transition temperature in optical lattices advocated in Ref.[22] is mainly due to the confinement induced renormalization of the coupling constant.

The mean field theory neglects many-body effects. In Fig.6 we show the calculated Gorkov correction to the mean field estimate T_c^0 for the transition temperature as a function of the ratio $\epsilon_F/4t$.

Sound propagation

In Ref.[23] we developed the hydrodynamic theory of Fermi superfluids in the presence

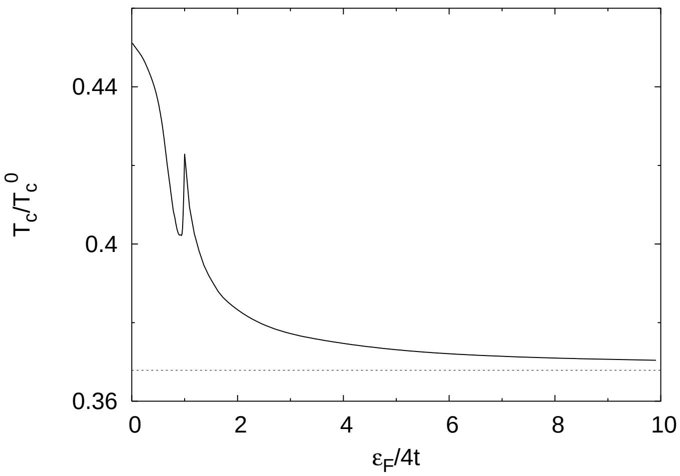

Figure 6: Gorkov's correction versus $\epsilon_F/4t$. The limiting value $T_c/T_c^0 = e^{-1}$ at $\epsilon_F/4t \gg 1$ is shown by a dotted line. The spike at $\epsilon_F/4t = 1$ signals the Van Hove singularity.

of the periodic potential. The relevant parameters governing the propagation of sound (compressibility and effective mass) have been calculated in the weak-coupling BCS limit. With respect to the case of atomic Bose-Einstein condensates (BEC) in optical lattices investigated in Ref.[24, 25, 26], we found two important differences. First, the effective mass of the superfluid gas is density dependent and reduces to the BEC value only for sufficiently low atom densities. Second, in weak coupling Fermi superfluids in the BCS regime the compressibility is fixed by the quantum pressure and not by the interparticle interactions.

The presence of sound waves implies that the gas can tunnel coherently between neighboring wells. In the presence of a shallow harmonic trap, one therefore expects that the gas perform complete oscillations which are undamped at zero temperature [27]. We generalized the hydrodynamic theory to describe collective modes of the trapped gas. In particular we calculated the frequency of the center of mass oscillations as a function of the atom density and the trap parameters.

Finally, in Ref.[23] we also investigated the conditions of stability of the superfluid motion with respect to the creation of phonons.

Superfluid-Mott Insulator quantum phase transition

In Bose-Einstein condensates this transition has already been observed experimentally in a tight 3D lattice [28]. In [21], we have considered a 1D lattice and we have assumed that atoms are also trapped in the directions perpendicular to the lattice. The system is then equivalent to a chain of weakly coupled discs and its low-energy physics is described by the Quantum Phase model. If the tunneling rate between the discs becomes smaller than a critical value, fluctuations in the atom number per disc are suppressed and the coherence properties along the chain are lost [29].

We have also shown that the relevant parameters (charging energy and Josephson energy) can be obtained starting from the hydrodynamic theory developed in Ref.[23]. We have found that the Josephson energy in our system is typically much smaller than in BEC because here phase coherence is guaranteed by tunneling of Cooper pairs instead of single atoms. As a consequence, the critical tunneling rate for the Mott transition turns out to be much larger in Fermi superfluids rather than in BEC. Moreover, in the case of Fermi superfluids we have found that inelastic losses are quenched by Fermi statistics, so the Mott transition can be observed also for the case of a large ($10^3 - 10^4$) number of atoms per disc.

Momentum distribution

The study of the momentum distribution of a quantum degenerate Fermi gas carries a wealth of information on the role played by interactions.

Recent experiments aiming to measure the momentum distribution are based on the ballistic expansion of the cloud after the scattering length has been quickly set to zero by a fast magnetic-field ramp [30, 31]. These experiments exploit a peculiar feature of ultracold gases which are characterized by a clear separation of energy scales. The energy scale associated with the two-body physics as fixed for example by $\hbar^2/mr_0^2 \sim 10mK$, being $r_0 \sim 100a_0$ the typical interaction length of the Van der Waals potential, and the energy scale associated with the many-body physics as determined by the typical Fermi energy $\epsilon_F \sim 1\mu K$. This separation of energy scales provides a very large range of timescales for which the dynamical process can be safely considered *fast* (*diabatic*) as the many-body dynamics is concerned and *slow* (*adiabatic*) with respect to the two-body dynamics. Provided the timescale of the magnetic-field ramp satisfies these conditions, the measured momentum distribution does not depend on the detailed structure of the interatomic potential, being in this sense universal, but it does depend on the timescale of the ramping process. The non-equilibrium quantity accessed in these experiments is the released momentum distribution, defined as the momentum distribution of the system after the scattering length has been rapidly ramped to $a = 0$.

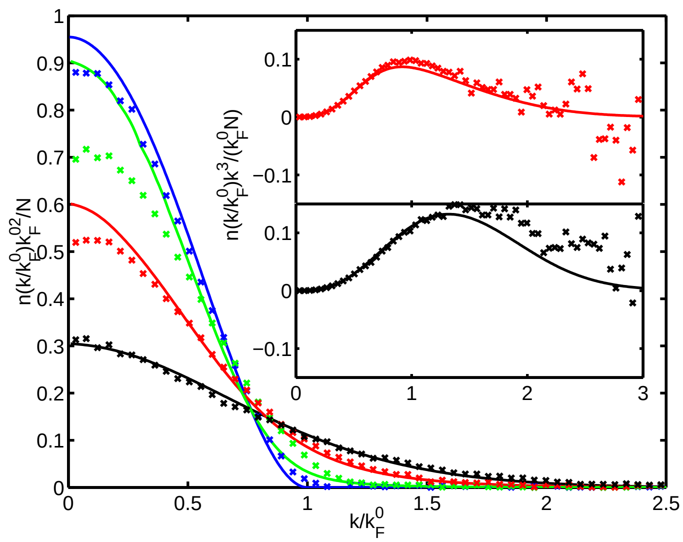

Figure 7: Column integrated released momentum distribution of a harmonically trapped gas. From top to bottom, the lines correspond to $1/(k_F^0 a(0)) = -71$ (blue), $1/(k_F^0 a(0)) = -0.66$ (green), $1/(k_F^0 a(0)) = 0$ (red) and $1/(k_F^0 a(0)) = 0.59$ (black). The magnetic-field ramp rate is 2μs/G. The symbols correspond to the experimental results of Ref. [31]. Inset: Results for $1/(k_F^0 a(0)) = 0$ (top) and 0.59 (bottom) weighted by k^3.

We have investigated the behavior of the released momentum distribution of a Fermi gas at $T = 0$ along the BCS-BEC crossover [32]. The dynamical effects of the magnetic-field ramp are accounted for within a time-dependent mean-field approach where the instantaneous value of the scattering length $a(t)$ enters as a boundary condition for the short-range behavior of the anomalous Green's function. The inputs of the calculation are the initial value $a(t = 0)$, corresponding to the equilibrium state before the magnetic-field ramp, and the value of the ramp rate (2μs/G in the experiments of Ref. [31]). The results for a harmonically trapped gas are shown in Fig. 7, where they are compared with experiments. Notice the good agreement between theory and experiments at unitarity and on the BEC side of the resonance. On the BCS side our model underestimates the effects of interactions due to the absence of the Hartree mean-field term. One should also notice (see inset of Fig. 7) that the large-k $1/k^4$ behavior of the equilibrium momentum distribution is greatly suppressed by the magnetic-field ramp and the second moment of the released $n_{\mathbf{k}}$ is a convergent integral. In Fig. 8 we compare the second moment of the released momentum distribution with the experimental results from Ref. [31]. Given that there are no adjustable parameters, theory

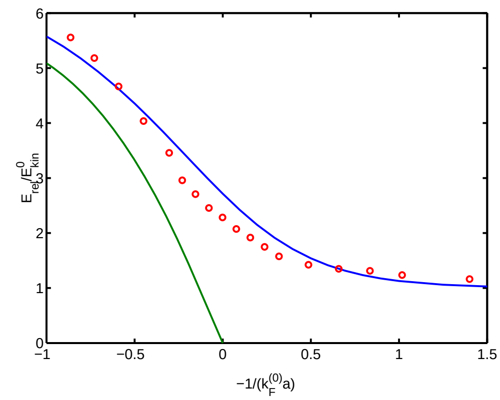

Figure 8: Released energy of a harmonically trapped gas as a function of the interaction strength $1/(k_F^0 a(0))$ for a ramp rate of 2μs/G (upper blue line). The lower (green) line is the corresponding result solving the two-body problem associated with the molecular state. The symbols are the experimental results from Ref. [31]. The energy is normalized to the kinetic energy of the non-interacting gas $E^0_{kin} = 3\epsilon^0_F/8$.

and experiments are in remarkable agreement over the whole crossover region.

The equilibrium momentum distribution of a Fermi gas at $T = 0$ in the BCS-BEC crossover has been calculated by the Trento group using quantum Monte Carlo techniques. These results are discussed in the Research Line on "Quantum Monte Carlo methods".

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QUANTUM MONTE CARLO METHODS

Quantum Monte Carlo methods have become a widely used tool in the study of the properties of ultracold gases. These methods are particularly well suited when dealing with strongly correlated systems for which other approaches, such as mean-field and perturbative expansions, are often bound to fail. An important example, which is currently the subject of extensive experimental and theoretical investigations, is a Fermi gas with resonantly enhanced interaction strength. Such a system can not be treated by standard perturbative techniques because the only dimensionless parameter present in the problem, $k_F a$, where k_F is the Fermi wave-vector and a is the s-wave scattering length, is much larger than unity and the system lacks a small parameter to construct a well posed theory. Quantum Monte Carlo simulations of this system have been carried out with great success. At $T = 0$, the equation of state has been determined [1, 2, 3] and the structural properties have been characterized through the calculation of correlation functions [4, 5, 6]. At finite T, the superfluid transition temperature and the thermodynamic behavior have been calculated [7, 8]. The Trento group has given important contributions to the study of the ground-state properties of the system using the fixed-node diffusion Monte Carlo (FN-DMC) method. Some of these contributions are described below in more details.

In collaboration with the Barcelona group we have also developed a path-integral Monte Carlo algorithm (PIMC) to investigate the properties of ultracold gases at finite temperature. The first application of this algorithm to the study of the equation of state of interacting bosons is briefly described below. Another application of quantum Monte Carlo methods by the Trento group refers to one-dimensional Bose gases and is described in the Research Line on “Low dimensions”.

During the year 2006 the Trento group has benefitted from a long-term visit by Prof. Nikolay Prokof’ev, a leading specialist in the field of quantum Monte Carlo techniques. His research activity during this year has touched many different aspects of condensed matter physics, from the thermodynamics of ultracold Fermi gases at unitarity to the problem of the existence of a supersolid phase.

BCS-BEC crossover: equation of state

Using the FN-DMC method we have calculated the equation of state of a homogeneous Fermi gas at $T = 0$ in the BCS-BEC crossover [3]. We have considered a system of equal number of spin-up and spin-down particles, $N_\uparrow = N_\downarrow = N/2$, and we model the

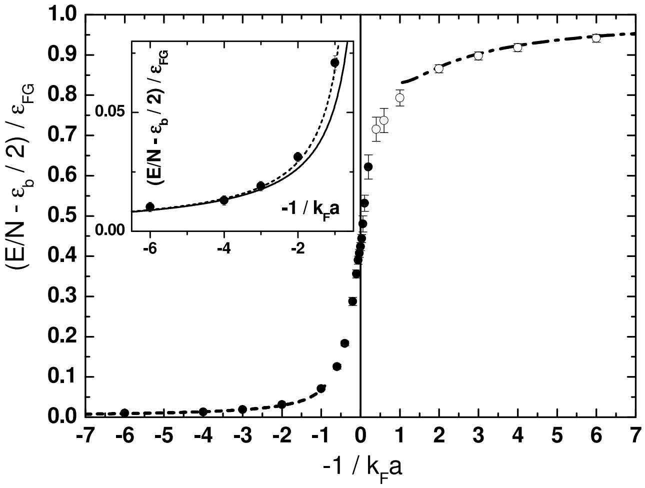

Figure 1: Energy per particle in the BCS-BEC crossover with the binding energy subtracted from E/N (solid and open symbols). The dot-dashed line is the expansion (1) holding in the BCS region and the dashed line corresponds to the expansion (2) holding in the BEC regime. Inset: enlarged view of the BEC regime $-1/k_Fa \leq -1$. The solid line corresponds to the mean-field energy [first term in the expansion (2)], the dashed line includes the beyond mean-field correction [Eq. (2)].

interspecies interatomic interactions using an attractive square-well potential: $V(r) = -V_0$ for $r < R_0$, and $V(r) = 0$ otherwise. In order to ensure that the results do not depend on the range R_0 of the potential we have chosen $nR_0^3 = 10^{-6}$, where $n = k_F^3/(3\pi^2)$ is the gas number density. By varying the depth V_0 of the potential one can tune the value of the s-wave scattering length a and therefore change the interaction parameter $1/k_Fa$.

In the BCS limit ($a < 0$ and $k_F|a| \ll 1$) one expects the perturbation expansion of a weakly attractive Fermi gas to hold [9]

$$\frac{E}{N\epsilon_{FG}} = 1 + \frac{10}{9\pi}k_Fa + \frac{4(11 - 2\log 2)}{21\pi^2}(k_Fa)^2 + ... , \tag{1}$$

where $\epsilon_{FG} = 3\hbar^2k_F^2/(10m)$ is the energy per particle of the non-interacting gas. In the opposite BEC limit ($a > 0$ and $k_Fa \ll 1$) molecules are created with binding energy ϵ_b

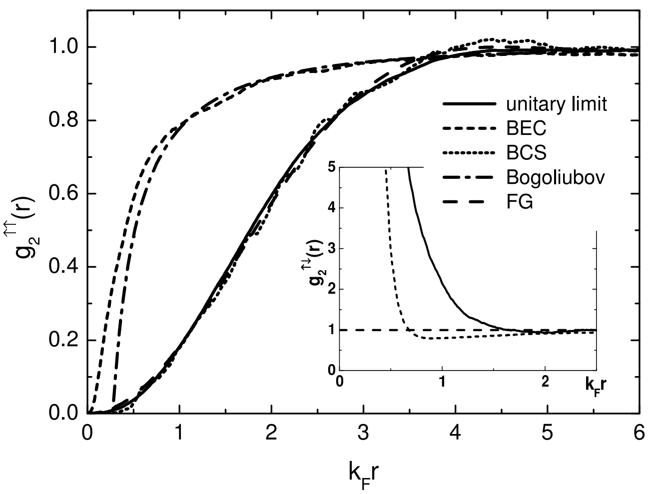

Figure 2: Pair correlation function of parallel, $g_2^{\uparrow\uparrow}(r)$, and (inset) of antiparallel spins, $g_2^{\uparrow\downarrow}(r)$, for $-1/k_F a = 0$ (unitary limit), $-1/k_F a = -4$ (BEC regime), $-1/k_F a = 4$ (BCS regime) and for a noninteracting Fermi gas (FG). The dot-dashed line corresponds to the pair correlation function of a Bose gas with $a_m = 0.6a$ and $-1/k_F a = -4$ calculated using the Bogoliubov approximation.

which form a repulsive gas governed by the equation of state

$$\frac{E/N - \epsilon_b/2}{\epsilon_{FG}} = \frac{5}{18\pi} k_F a_m \left[1 + \frac{128}{15\sqrt{6\pi^3}} (k_F a_m)^{3/2} + ... \right] . \tag{2}$$

In the above equation the first term corresponds to the mean-field energy of a gas of molecules of mass $2m$ and density $n/2$ interacting with the positive molecule-molecule scattering length a_m, and the second term corresponds to the first beyond mean-field correction [10].

The results are shown in Fig. 1. On the BCS side of the resonance we find agreement with the expansion (1) and on the BEC side with the equation of state (2) with the value $a_m = 0.6a$ as calculated in Ref. [11]. At unitarity we find $E/N = \xi\epsilon_{FG}$ with $\xi = 0.42(1)$ in agreement with the Green's function Monte Carlo result of Ref. [1].

A detailed knowledge of the equation of state of the homogeneous system is important for the determination of the frequencies of collective modes in trapped systems (see the discussion in the Research Line on "Ultracold Fermi gases")

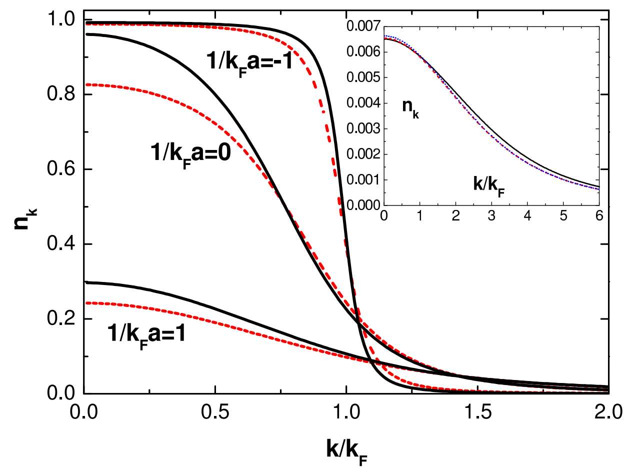

Figure 3: Momentum distribution $n_{\mathbf{k}}$ for different values of $1/k_F a$ (black solid lines). The red dashed lines correspond to $n_{\mathbf{k}}$ calculated using the BCS mean-field approach [12]. Inset: $n_{\mathbf{k}}$ for $1/k_F a = 4$. The blue dotted line corresponds to the momentum distribution of the molecular state $n_{\mathbf{k}} = 4(k_F a)^3/[3\pi(1+k^2a^2)^2]$.

BCS-BEC crossover: correlation functions

The pair correlation function of parallel, $g_2^{\uparrow\uparrow}(r)$, and antiparallel spins, $g_2^{\uparrow\downarrow}(r)$, and the momentum distribution $n_{\mathbf{k}}$ are important quantities which characterize the structural properties of an interacting Fermi gas. We have calculated these correlation functions using the FN-DMC method for a Fermi gas at $T=0$ in the BCS-BEC crossover. The results for the pair correlation functions are shown in Fig. 2. For parallel spins, $g_2^{\uparrow\uparrow}(r)$ must vanish at short distances due to the Pauli principle. In the BCS regime the effect of pairing is negligible and $g_2^{\uparrow\uparrow}(r)$ coincides with the prediction of a non-interacting Fermi gas. This result continues to hold in the unitary limit. In the BEC regime the static structure factor $S(k)$ of composite bosons can be estimated using the Bogoliubov result: $S(k) = \hbar^2k^2/[2M\omega(k)]$, where $\omega(k) = (\hbar^4k^4/4M^2 + gn_m\hbar^2k^2/M)^{1/2}$ is the Bogoliubov dispersion relation for particles with mass $M=2m$, density $n_m = n/2$ and coupling constant $g = 4\pi\hbar^2 a_m/M$. The pair distribution function $g_2(r)$ of composite bosons, obtained through $g_2(r) = 1 + 2/N\sum_{\mathbf{k}}[S(k)-1]e^{-i\mathbf{k}\cdot\mathbf{r}}$ using the value $a_m = 0.6a$, is shown in Fig. 2 for $-1/k_F a = -4$ and compared with the FN-DMC result. For large distances $r \gg a_m$, where Bogoliubov approximation is expected to hold, we find a remarkable agreement. For antiparallel spins, $g_2^{\uparrow\downarrow}(r)$ exhibits a large peak at short distances due to the attractive interaction. The short-range behavior of $g_2^{\uparrow\downarrow}(r)$ is discussed in detail in the Research Line on "Ultracold Fermi gases".

The momentum distribution $n_{\mathbf{k}}$ is shown in Fig. 3. In the inset we compare $n_{\mathbf{k}}$ corresponding to $1/k_F a = 4$ with the momentum distribution of the atoms in the molecular state $n_{\mathbf{k}} = 4(k_F a)^3/[3\pi(1+k^2a^2)^2]$ [12]. In the figure we also show the results of $n_{\mathbf{k}}$ obtained using the BCS mean-field theory [13], where the values of chemical potential and gap are calculated self-consistently through the gap and number equations [12]. The results of Fig. 3 show that the mean-field theory overestimates the broadening of $n_{\mathbf{k}}$ in the crossover region $-1 \leq 1/k_F a \leq 1$. Measurements of the momentum distribution of harmonically trapped systems have recently become available in the crossover [14]. The comparison carried out at unitarity, using the local density approximation, shows a good agreement with the observed distribution, but the experimental uncertainty is too large to distinguish between mean-field and FN-DMC results [14].

The released momentum distribution of a Fermi gas in the BCS-BEC crossover is discussed in the Research Line on "Ultracold Fermi gases".

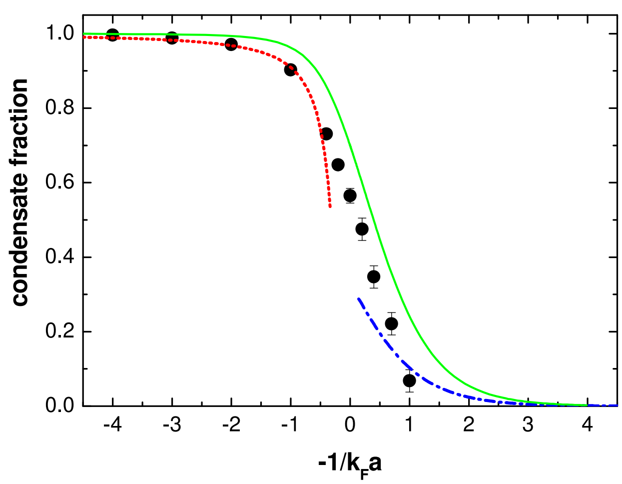

Figure 4: Condensate fraction of pairs α as a function of the interaction strength: FN-DMC results (symbols), Bogoliubov quantum depletion of a Bose gas with $a_m = 0.6a$ (red dashed line), BCS theory using Eq. (6) (blue dot-dashed line) and self-consistent mean-field theory (green solid line).

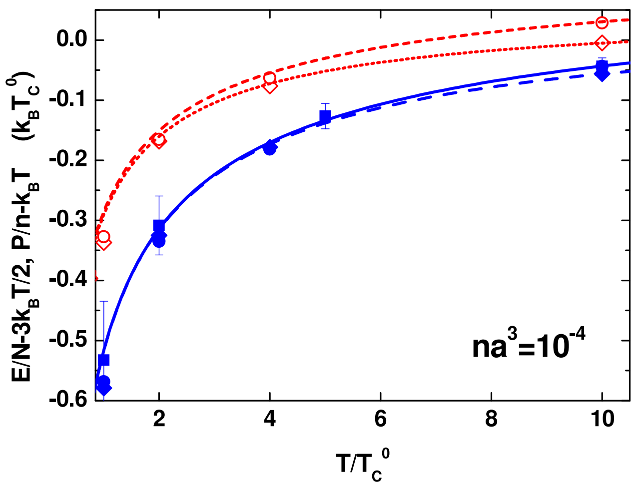

Figure 5: Energy per particle and pressure of a Bose gas in the normal phase as a function of temperature. The gas parameter is $na^3 = 10^{-4}$. Blue solid symbols refer to $E/N - 3k_BT/2$: HS potential (circles), SS potential (diamonds), NP potential (squares). Red open symbols refer to $P/n - k_BT$: HS potential (circles), SS potential (diamonds). For the HS and SS potentials statistical error bars are smaller than the size of the symbols. The virial expansion for the energy is represented by the blue lines: HS potential (solid line), SS potential (long-dashed line). The virial expansion for the pressure is represented by the red lines: HS potential (short-dashed line), SS potential (dotted line).

BCS-BEC crossover: condensate fraction

The occurrence of off-diagonal long-range order (ODLRO) in interacting systems of bosons and fermions was investigated by C.N. Yang in terms of the asymptotic behavior of the one- and two-body density matrix [15]. In the case of a two-component Fermi gas with $N_\uparrow$ spin-up and $N_\downarrow$ spin-down particles, the one-body density matrix (OBDM) for spin-up particles, defined as

$$\rho_1(\mathbf{r}_1', \mathbf{r}_1) = \langle \psi_\uparrow^\dagger(\mathbf{r}_1')\psi_\uparrow(\mathbf{r}_1)\rangle \ , \tag{3}$$

does not possess any eigenvalue of order $N_\uparrow$. This behavior implies for homogeneous systems the asymptotic condition $\rho_1(\mathbf{r}_1', \mathbf{r}_1) \to 0$ as $|\mathbf{r}_1 - \mathbf{r}_1'| \to \infty$. In the above expression $\psi_\uparrow^\dagger(\mathbf{r})$ ($\psi_\uparrow(\mathbf{r})$) denote the creation (annihilation) operator of spin-up particles.

The same result holds for spin-down particles. ODLRO may occur instead in the two-body density matrix (TBDM), that is defined as

$$\rho_2(\mathbf{r}'_1, \mathbf{r}'_2, \mathbf{r}_1, \mathbf{r}_2) = \langle \psi^\dagger_\uparrow(\mathbf{r}'_1)\psi^\dagger_\downarrow(\mathbf{r}'_2)\psi_\uparrow(\mathbf{r}_1)\psi_\downarrow(\mathbf{r}_2)\rangle \ . \tag{4}$$

For a homogeneous unpolarized gas with $N_\uparrow = N_\downarrow = N/2$, if ρ_2 has an eigenvalue of the order of the total number of particles N, the TBDM can be written as a spectral decomposition separating the largest eigenvalue yielding for $|\mathbf{r}_1 - \mathbf{r}'_1|$, $|\mathbf{r}_2 - \mathbf{r}'_2| \to \infty$ the asymptotic behavior

$$\rho_2(\mathbf{r}'_1, \mathbf{r}'_2, \mathbf{r}_1, \mathbf{r}_2) \to \alpha N/2 \varphi^*(|\mathbf{r}'_1 - \mathbf{r}'_2|)\varphi(|\mathbf{r}_1 - \mathbf{r}_2|) \ . \tag{5}$$

The parameter $\alpha \leq 1$ is interpreted as the condensate fraction of pairs, in a similar way as the condensate fraction of single atoms is derived from the OBDM. The complex function $\varphi(r)$ is normalized to the inverse volume $1/V$ and is proportional to the order parameter $\langle \psi_\uparrow(\mathbf{r}_1)\psi_\downarrow(\mathbf{r}_2)\rangle = \sqrt{\alpha N/2}\varphi(|\mathbf{r}_1 - \mathbf{r}_2|)$, whose appearance distinguishes the superfluid state of the Fermi gas. Equation (5) should be contrasted with the behavior of Bose systems with ODLRO, where ρ_1 has an eigenvalue of order N [16], and consequently the largest eigenvalue of ρ_2 is of the order of N^2.

We have calculated using the FN-DMC method ρ_1 and ρ_2 for a homogeneous interacting Fermi gas at $T = 0$ in the BCS-BEC crossover. From the asymptotic behavior of ρ_2, we extract the value of the condensate fraction of pairs α. The results are shown in Fig. 4. In the BEC regime, the results reproduce the Bogoliubov quantum depletion of a gas of composite bosons $\alpha = 1 - 8\sqrt{n_m a_m^3}/3\sqrt{\pi}$, where $n_m = n/2$ is the density of molecules and $a_m = 0.6a$ is the dimer-dimer scattering length [11]. In the opposite BCS regime, the condensate fraction α can be calculated from the result of the BCS order parameter holding for $r \gg a$ [17]

$$F_{\rm BCS}(r) = \frac{\Delta k_F^3}{\epsilon_F}\frac{\sin(k_F r)}{4\pi^2 k_F r}K_0(r/\xi_0) \ , \tag{6}$$

where $\xi_0 = \hbar^2 k_F/m\Delta$ is the coherence length and $K_0(x)$ is the modified Bessel function. If we include the Gorkov-Melik Barkhudarov correction for the pairing gap [18] $\Delta = (2/e)^{7/3}\epsilon_F e^{-\pi/2k_F|a|}$, we obtain for $\alpha = 2/n\int d^3\mathbf{r} F^2_{\rm BCS}(r)$ the dot-dashed line shown in Fig. 4. The condensate fraction α can also be estimated using the self-consistent mean-field approach [13] and the result for the order parameter: $F(r) = 1/V\sum_{\mathbf{k}} u_k v_k e^{i\mathbf{k}\cdot\mathbf{r}}$, where u_k and v_k are the usual quasiparticle amplitudes of BCS theory. The result is shown in Fig. 4 with a solid line (see also Ref. [19]).

Another work related to the superfluid order parameter in Fermi gases is presented in the research line on matter-wave interferometry.

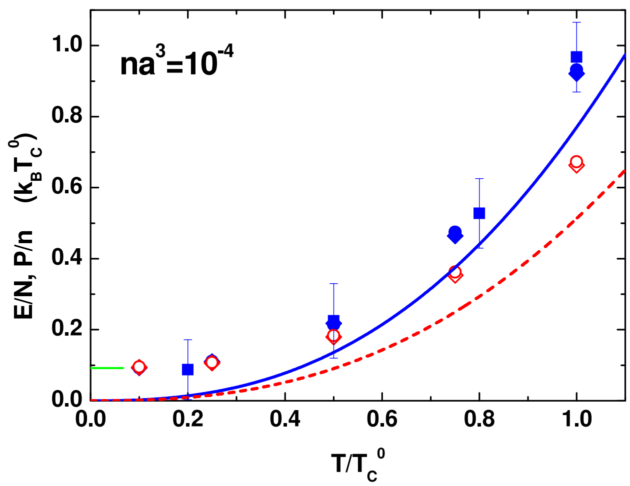

Figure 6: Energy per particle and pressure of a Bose gas in the superfluid phase as a function of temperature. The gas parameter is $na^3 = 10^{-4}$. Blue solid symbols refer to E/N: HS potential (circles), SS potential (diamonds), NP potential (squares). Red open symbols refer to P/n: HS potential (circles), SS potential (diamonds). For the HS and SS potentials statistical error bars are smaller than the size of the symbols. The horizontal green bar corresponds to the ground-state energy per particle E_0/N of a HS gas calculated using DMC. The lines correspond to a non-interacting gas: the blue solid line refers to the energy per particle and the red dashed line to the pressure.

Equation of state of an interacting Bose gas at finite temperature

Using the exact PIMC technique we have calculated the equation of state of an interacting Bose gas as a function of temperature both below and above the superfluid transition. The universal character of the equation of state for dilute systems and low enough temperatures is investigated by modelling the interatomic interactions with different repulsive potentials corresponding to the same s-wave scattering length. In particular we have used a hard-sphere (HS), a soft-sphere (SS) and a negative-power (NP) potential. The results for the value $na^3 = 10^{-4}$ of the gas parameter are shown in Figs. 5, 6. For temperatures above the transition we compare the results for energy

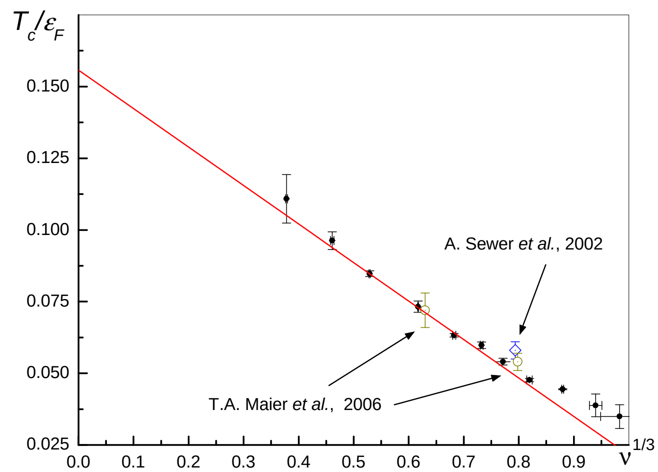

Figure 7: Scaling of the critical temperature with system density (lattice filling factor). Results of other groups at quarter filling and $\nu = 0.25$ are also shown for a comparison.

and pressure with the virial expansion finding good agreement. At low temperatures we recover the result for the ground-state energy obtained using the diffusion Monte Carlo technique.

BCS-BEC crossover: transition point at unitarity

To solve the problem of normal-to-superfluid transition temperature in the unitary regime a novel determinant Monte Carlo technique was developed [20, 21]. It is based on direct summation of all Feynman diagrams for the interacting fermion system in a finite volume, does not involve any approximations, and uses worm-type updates for efficient sampling of the two-body density matrix. Simulations were performed for the dilute system of lattice fermions (attractive Fermi-Hubbard model) with the coupling constant tuned to the point of resonance. For any given density ν of lattice fermions, the transition temperature can be deduced from finite-size scaling of the condensate fraction, n_0, using known scaling relations for the three-dimensional XY universality class, $n_0 L^{1.038} = f((T - T_c(\nu))L^{1.488})$, where L is the linear system size. The result is shown in Fig. 7.

The universal unitary point in this plot corresponds to the $\nu \to 0$ limit. From the analysis of the two-body scattering problem one can show that the leading finite-density correction to the T_c/ε_F ratio vanishes as $\nu^{1/3}$. The final answer for the universal ratio

T_c/ε_F at unitarity is then

$$T_c/\varepsilon_F = 0.152(7)\ . \tag{7}$$

Apart from T_c, all thermodynamic functions of the normal state at unitarity were determined. These results can be used to predict various properties of trapped systems (using the local density approximation) such as density profiles and temperature increase in the adiabatic ramp experiments.

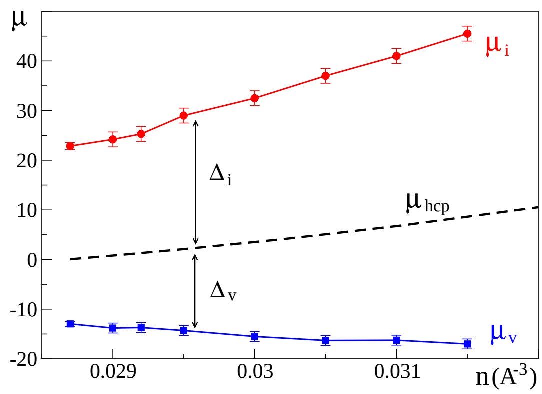

Figure 8: Chemical potential thresholds for creating a single interstitial (upper curve, $\mu_{\rm i}$) and vacancy (lower curve, $\mu_{\rm V}$) at different densities. $\mu_{\rm hcp}$ is the chemical potential of the hcp solid. The gaps $\Delta_{\rm V(i)}$ for activating a vacancy (or interstitial) are given by the difference in chemical potentials, $\mu_{\rm hcp} - \mu_{\rm V}$ (or $\mu_{\rm i} - \mu_{\rm hcp}$).

Supersolidity in ^{4}He

Previous path integral Monte Carlo (PIMC) simulations [22, 23, 24] have established that ideal commensurate *hcp* crystals of ^{4}He do not have ODLRO and thus are insulating. It appears that the only possibility left for understanding the body of experimental data on supersolidity in ^{4}He in terms of the genuine superfluid response is to consider imperfect helium solids. Using recently developed worm-algorithm approach to PIMC [25, 26] we have investigated various scenarios of how equilibrium and out-of-equilibrium vacancies can result in superfluidity of ^{4}He crystals. By calculating the Green function of the solid we have obtained accurate results for the vacancy and interstitial formation energies in the thermodynamic limit, see Fig. 8, and concluded that these defects are thermally activated at all pressures.

We have also looked at finite concentration of vacancies, to see if despite large activation energy Δ_v, a strongly correlated ground state with vacancies can be stable. We also explored the possibility of a (meta)stable gas of out-of-equilibrium vacancies. However, in all cases we find that a dilute homogeneous gas of vacancies in *hcp* ^{4}He crystal is thermodynamically unstable against phase separation at low temperature, due to anisotropic elastic interactions among vacancies. A cluster of vacancies in an otherwise perfect insulating crystal is formed and already three vacancies form a very tight bound state (binding energy for two vacancies is small, about $\sim 2-3\ K$). Our results rule out all proposals which are based on the vacancy-induced supersolidity and BEC in ^{4}He.

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CASIMIR-POLDER FORCE

The study of the fluctuations of the electromagnetic field and of their effects on the force acting on surfaces and atoms is a longstanding subject of research, starting from the pioneering works by Casimir, Polder and Lifschitz (see for example [1]). The resulting force, originating from the quantum and thermal fluctuations of the field, plays a crucial role at the micron scale. Recently ultracold Bose-Einstein condensates confined in magnetic traps and located close to the surface of a dielectric have proven to be a very promising alternative to more traditional methods of measurement based on solid state devices, in order to probe the Casimir-Polder force at relatively large distances. In the experiment with Bose-Einstein condensates one measures the effects of the force on the shift of the center of mass oscillation of the atomic cloud. These shifts can be measured with at least 10^{-4} precision, thereby providing a rather precise tool to detect the force at distances of a few microns, a region until now practically unexplored by previous experiments. The Trento team started a research activity in this direction almost three years ago in tight collaboration with the experimental team of Eric Cornell at JILA.

Casimir-Polder force and the shift of the collective frequencies

In [2] we have calculated the Casimir-Polder force, including the quantum and thermal fluctuations of the field, generated by the surface of a dielectric on an atom located at a certain distance from the surface. The calculation has permitted to describe continuously the transition from the van der Waals-London to the Casimir-Polder and eventually to the thermal Lifshitz force as one increases the distance form the surface. In the same paper we have also calculated the frequency shifts of the collective oscillations of an atomic cloud harmonically trapped close to the surface, accounting both for the finite size of the cloud, and for non linear effects in the oscillation which play a crucial role in actual experiments. The JILA team has measured the effects of the force [3] confirming with good accuracy the predictions of theory (see figure 1). This first Jila experiment, however, did not succeed in pointing out the thermal effect of the force which is too weak to be clearly detected in these experimental conditions. The thermal effect actually prevails on the quantum part of the force at distances larger than the thermal wave length $\lambda_T = \hbar c/k_B T$ of the photon, whose value is about 7 microns at room temperature. At such distances the surface-atom force is very weak and difficult to detect. A major motivation of such studies is given by the possibility of setting experimental bounds on the existence of exotic forces, violating gravity at the micron scale [4].

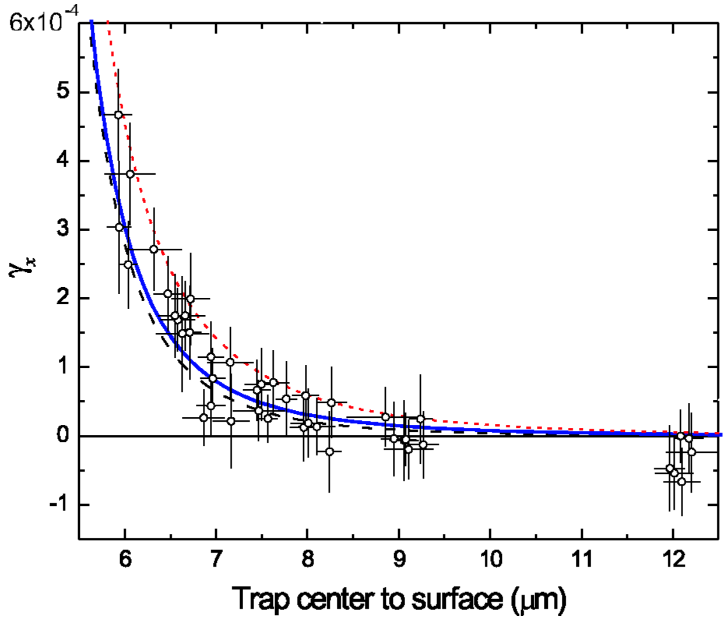

Figure 1: Relative frequency shifts of the center of mass oscillation of a Bose-Einstein condensate as a function of the distance from the surface of a dielectric measured at different temperatures. The continuous lines correspond to the theoretical predictions of [2] (from [3]).

Casimir-Polder force out of thermal equilibrium

The observation of thermal effects in the Casimir-Polder force has motivated several experimental efforts in the last years. As discussed in the previous paragraph the elusive nature of the thermal force follows from the fact that thermal effects becomes visible only at large distances, of the order of the photon thermal wave length. At such distances the force takes the so called Lifshitz form

$$F_{\rm th}^{\rm eq}(T,z)_{z\to\infty} = -\frac{3}{4}\frac{k_B T\alpha_0}{z^4}\frac{\varepsilon_0-1}{\varepsilon_0+1} \tag{1}$$

which increase linearly with the temperature of the system. Increasing the temperature is not however an easy task in the experiments with Bose-Einstein condensates which usually require extreme conditions of high vacuum. A more accessible strategy consists of heating only the substrate and leaving the environment at room temperature. In [5, 6,

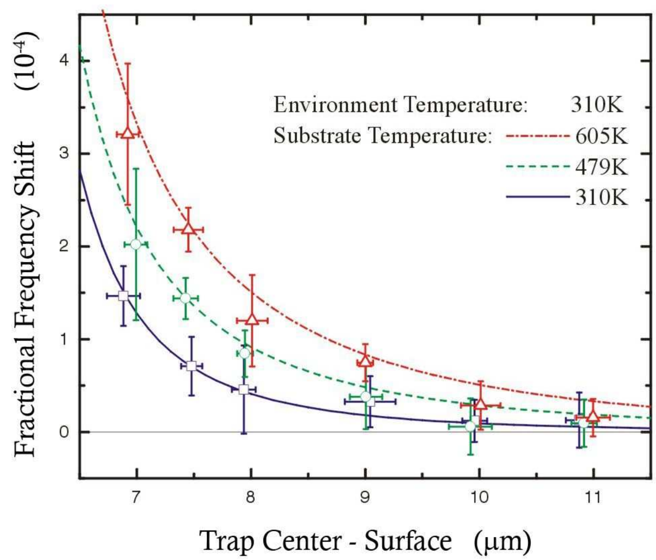

Figure 2: Relative frequency shifts of the center of mass oscillation of a Bose-Einstein condensate as a function of the distance from the surface of a dielectric measured out of thermal equilibrium. The environment temperature is $300K$, while the temperature of the substrate was varied from $300K$ to $600K$. The continuous lines correspond to the theoretical predictions of [5] (from [8]).

7] we have attacked the non trivial problem of calculating the force in such a stationary, but out of thermal equilibrium condition. The theoretical results of our investigations were very surprising. In fact we found that the force, in this non equilibrium conditions, changes its behaviour in a drastic way. At large distances and low temperatures we find the result

$$F^{neq}(T_S, T_E, z)_{z\to\infty} = -\frac{\pi}{6}\frac{\alpha_0 k_B^2 (T_S^2 - T_E^2)}{z^3\, c\hbar}\frac{\varepsilon_0 + 1}{\sqrt{\varepsilon_0 - 1}} \tag{2}$$

where T_S and T_E are, respectively, the temperatures of the substrate and of the environment. The above equation shows that, at large distances the force decays more slowly than the equilibrium Lifshitz force (1) and is attractive or repulsive depending on whether the substrate temperature is higher or smaller than the environment one. Furthermore it has a clear quantum nature since, differently from (1), it depends explicitly on the Planck constant. A major interest of the new result is that the value of the force can be significantly enhanced with respect to equilibrium, thereby providing new realistic perspectives for observing the consequences of the thermal fluctuations of the

Casimir-Polder force. Very recently the JILA team [8] has succeeded in measuring the effects of the new force, confirming in remarkable way the predictions of theory. This measurement provides the first conclusive experimental demonstration of the existence of thermal effects in the Casimir-Polder force.

Bloch oscillations and Casimir-Polder force

The study of the center of mass oscillations performed in [3, 8] corresponds to a *mechanical* probe of the Casimir-Polder based on the study the oscillations of the system in *coordinate* space. In [9] we have explored the alternative possibility of measuring the response of the system in *momentum* space using *interferometric* techniques as recently done at LENS [10]. This is realized by confining the system in a harmonic + periodic potential (the latter is generated by a laser field) and then exciting the Bloch oscillation by switching off the harmonic potential in the presence of gravity (see figure 3). In our paper we have considered a gas of polarized fermions where interactions are practically vanishing and the effects of dynamic instability can be safely neglected during the Bloch oscillations. This procedure, which actually measures directly the force rather than its gradient, as instead happens in the study of the center of mass frequency shift, is expected to become a very accurate sensor of weak forces. It might provide intriguing possibilities not only for future accurate measurements of the Casimir-Polder force, but also for deriving more precise bounds testing the possible violation of the Newtonian gravity force at the micron scale [4].

Figure 3: Sketch of the proposed experiment: an ultracold sample of atoms is trapped in a vertical optical lattice in proximity of a dielectric surface and performs Bloch oscillations under the combination of gravity and of the Casimir-Polder force.

Starting from the predictions recently obtained by Mauro Antezza on the Casimir force exerted on the atoms by a dielectric surface placed at a distance of a few microns [11], our study [12] has analyzed specific experimental configurations realistically achievable in the next future in Firenze, and a comparison has been drawn with analogous experiments presently in progress at JILA in Boulder. In particular, we have pointed out how the proposed technique for the case of a degenerate gas of polarized Fermi atoms should be able to detect Casimir forces in still unexplored regimes in which the dominant contribution to the force has a thermal origin.

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QUANTUM OPTICS AND SOLID STATE PHYSICS

In the last decade, a significant research activity has been devoted to the understanding of the analogy between the physics of the electromagnetic field in dielectric structures and the physics of ultracold atoms in external trapping potentials. This analogy has led to important exchanges of ideas between the two fields, and has been very useful to get deeper insight in both of them. To make the analogy more concrete, a pointwise summary of some among the most relevant issues of the analogy is shown in the table.

Atoms	**Light**
Quantum Bose field of matter	Electromagnetic field of QED
Gross-Pitaevskii eq. of mean-field theory	Maxwell eqs. of classical ED
Optical or magnetic potential	Linear refraction index
Optical lattice	Photonic Band Gap crystal
Atomic spin	Light polarization
Atom-atom interactions	Kerr Nonlinearity

The activity on these issues at the BEC center has taken full advantage of the local competences in many-body physics and quantum optics, and has been supported by the continuous collaboration with C. Ciuti of ENS (Paris), a specialist in the theory of semiconducting materials, as well as by contacts with leading experimental groups in the physics of semiconductor nanostructures.

Semiconducting materials combine in fact high quality and great flexibility of the structures that can be grown, with extremely large values of the nonlinearities, of mainly excitonic origin. Our activity has been to develop new techniques inspired by many-body physics and apply them to the study of the optical response of microcavities. As a result, this novel point of view has led to a powerful understanding of the microcavity physics in terms of a quantum fluid of light and has allowed us not only to account for many effects already observed, but also to predict new ones that should disclose interesting aspects of the many-body physics of light. The main achievements are summarized in the next sections.

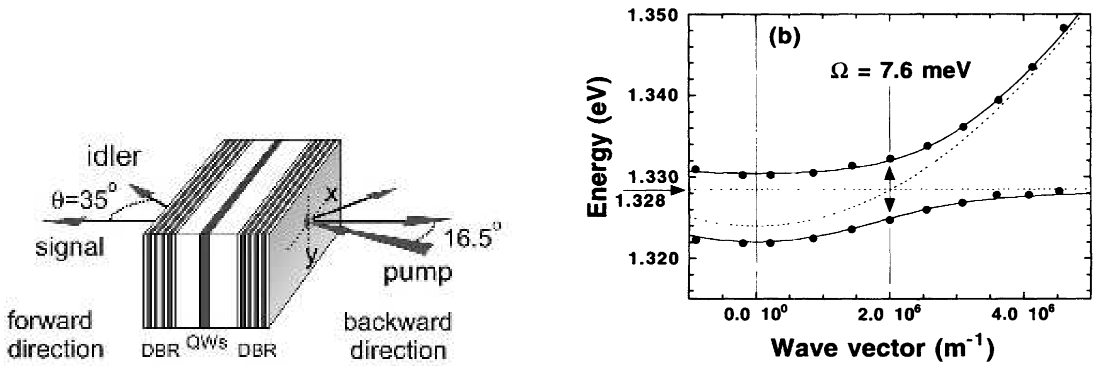


Figure 1: Left panel: sketch of a planar semiconductor microcavity. Light is confined by a pair of Distributed Bragg Reflectors (DBR), and a quantum well (QW) is present in the cavity layer. An QW excitonic resonance strongly coupled to the cavity mode is responsible for the peculiar polariton dispersion shown in the right panel, as well as for an extremely high value of the optical nonlinearity.

Many-body physics of non-equilibrium Bose gas: exciton-polaritons in semiconductor microcavities

Planar microcavities (fig.1a) constitute a very promising system in view of studies of the degenerate Bose gas in a completely new regime far from thermodynamical equilibrium. The elementary excitations of this system are the so-called *polaritons*, whose dispersion law is plotted in fig.1b. Polaritons are injected into the cavity in a very controlled as well as flexible way by a pump laser, and the properties of the resulting polariton Bose gas can be experimentally measured simply by collecting and analysing the emitted light.

As the state of the system is determined by a dynamical balance between driving and losses, the standard description in terms of equilibrium statistical mechanics can not be used, and different theoretical approaches have to be developed to account for the experimental observations.

Polariton superfluidity

As a first step, a generalized Gross-Pitaevskii equation has been derived to describe the dynamics of the coherent polaritonic field in the cavity, and has been used to characterize the superfluidity properties of a polariton fluid coherently injected by a laser field incident on the cavity mirror [1].

On one hand, a flowing polariton fluid shows most of the usual features of superfluidity, like a vanishing friction for subsonic flows, i.e. the disappearance of scattering on weak defects. This effect is experimentally observable in both the momentum and the real-space emission profiles from the cavity, which are respectively obtained in a far-field or a near-field image. In a far-field image, superfluidity shows up as a quenching of the so called resonant Rayleigh scattering, i.e. the emission in modes other than the pumped one, while in a near-field image the Cerenkov cone is reduced to a local screening of the defect (fig.2).

On the other hand, the additional degrees of freedom introduced by the non-equilibrium nature of the polariton fluid are responsible for a richer phenomenology which could not be observed in any quantum fluid at equilibrium.

The parametric threshold as a non-equilibrium phase transition

An issue presently of great interest from the experimental point of view is the characterization of the optical parametric threshold in planar microcavities: the peculiar dispersion of polaritons has allowed to observe triply resonant optical parametric oscillation (OPO), and the high value of the exciton-exciton interaction constant gives an extremely low value for the OPO threshold [2]. Differently from standard, few-mode, optical cavities, the planar geometry provides a continuum of modes into which the OPO process can occur, so that the spatial dynamics of the field has to be fully taken into account.

In order to quantitatively address the coherence properties of the parametric emission across the threshold, we have developed a Wigner Monte Carlo method for the study of the dynamics of the driven-dissipative polariton field [3]. This method is based on a stochastic Gross-Pitaevskii equation, and is the first one which is able to fully take into account the many-mode fluctuations of the spatially extended polariton field even in the vicinity of the threshold points where fluctuations are large.

The phenomenology that results from the numerical simulations is shown in fig.3 and supports the analogy with the physics of a Bose gas at equilibrium when the temperature is lowered across the condensation temperature: below the threshold, the parametric emission is incoherent: its coherence length is finite and strong intensity fluctuations are present. As the threshold is approached, the coherence length grows, and eventually reaches the sample size. Above threshold, the parametric emission is fully coherent, and intensity fluctuations are suppressed. It appears then natural to interpret the OPO threshold as a non-equilibrium analog of the Bose-Einstein conden-

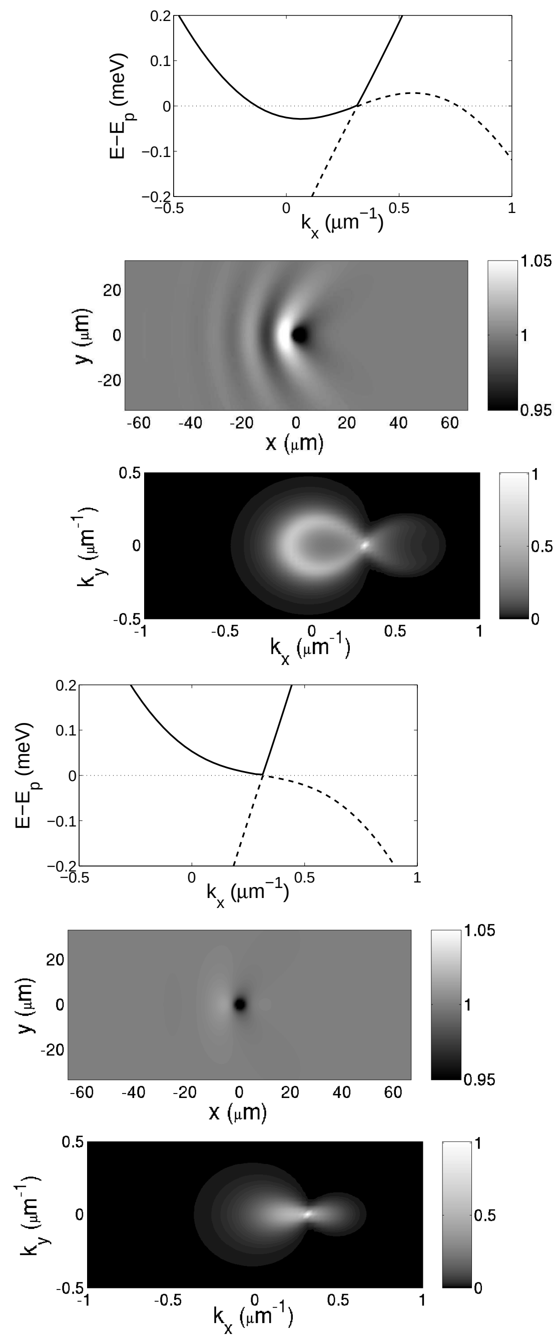
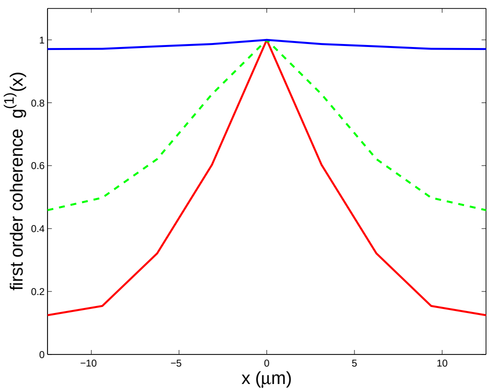


Figure 2: Top panel: collective excitation spectrum on top of a moving polariton fluid from richt to left. Middle and bottom panels: real- and momentum-space profiles of the normalized emission from a microcavity when the polariton fluid is flowing onto a defect (black spot in the real space pictures). By increasing the pump intensity (and consequently the sound velocity), one goes from a supersonic flow (left) to a subsonic flow where superfluidity effects are apparent (right).



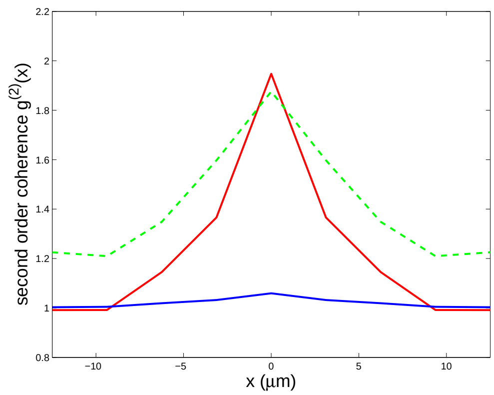


Figure 3: First (left) and second (right) order coherence function of the signal emission across the parametric threshold. Red, green, blue curves correspond to respectively below, close to, and above the threshold.

sation phase transition of equilibrium statistical mechanics.

Reduced dimensionality effects

As the field dynamics in microcavity systems takes place in dimension less or equal to two, a natural question to ask is whether true long-range order can be present in the parametric emission, or quantum fluctuations are able to destroy it. In equilibrium systems, a true long-range order appears in fact only in $d > 2$ at finite T and in $d \geq 2$ at $T = 0$.

So far, we have worked out the one-dimensional case of photonic wires, when the polaritons are transversally confined by a suitable etching of the microcavity and remain free to move along the longitudinal wire axis. Experiments showing parametric emission from such systems have been recently carried out [4], and it appears that these systems are promising from the technological point of view for vertically emitting OPO applications. This fact reinforces the importance of the question about the existence of long-range coherence, as this may limit the coherence degree of the parametric emission spot.

Numerical Wigner Monte Carlo simulations using realistic parameters from existing experiments suggest that long range order is destroyed on a length scale of the order of hundreds of microns, and this result has been quantitatively confirmed (see Fig.4) by analytical calculations based on a Bogoliubov-like linearization of the stochastic equations of motion of Wigner representation [5]. In particular, the long-distance decay of the correlation function of this polariton *quasi-condensate* turns out being exponential,

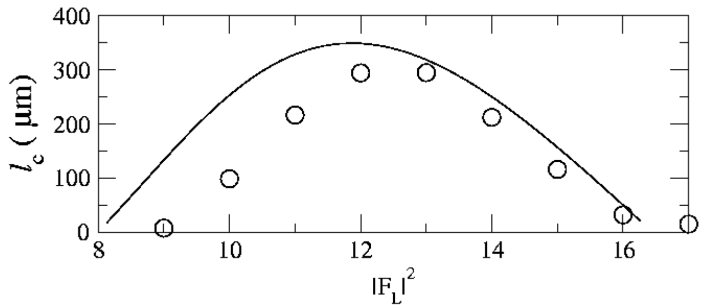


Figure 4: Coherence length of the signal emission from 1D photonic wires as a function of the pump intensity. Points: numerical Wigner Monte Carlo calculation. Line: approximate analytical results.

as in one-dimensional systems at equilibrium at a finite temperature.

Novel issues

Although the many similarities, the non-equilibrium phase transition discussed in the previous sections shows however several novel features as compared to the standard equilibrium case. An investigation of these novel issues in full detail has been the subject of our most recent activity.

As a U(1) signal/idler phase symmetry is spontaneously broken at the threshold, a Goldstone mode necessarily appears in the elementary excitation spectrum around the parametric oscillation steady-state [6]. Its main property is that both the real and the imaginary parts of its dispersion tend to 0 for $k \to 0$. However, differently from the equilibrium case, the Goldstone mode in non-equilibrium systems has a diffusive nature and corresponds to overdamped phase modulations, rather than sound propagation.

Another central difference is related to the shape of the condensate wavefunction [6]: at equilibrium, free-energy minimization forces the BEC to appear in the minimum energy state of the trap. In the non-equilibrium case, no free-energy is available, and the signal and idler wavevectors can be freely selected by the system dynamics and may depend on the details of the system, e.g. the boundary conditions. Although the numerical simulations can provide an answer to this question, an analytical insight is hard to obtain even at mean-field regime: the wavevector selection problem in planar OPOs is in fact related to the general problem of pattern selection in the theory of pattern formation in nonlinear dynamical systems, a problem which still challenges full understanding [7].

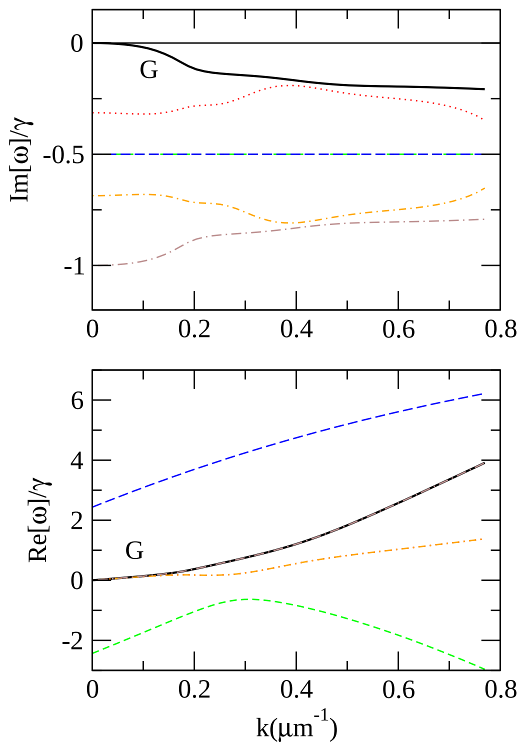


Figure 5: Dispersion of elementary excitations around the parametric oscillation steady-state. The soft Goldstone mode is plotted as a black line.

Optics of dynamical photonic nanostructures

Since 2005, a collaboration with the experimental group of photonics of the Università di Trento is in progress on the subject of dynamical photonic nanostructures, i.e. nanostructures whose optical properties (namely the refractive index) are rapidly changed in time while an optical pulse is propagating through them. As a specific example [8], we have studied the possibility of using a coupled resonator optical waveguide (fig.6) to shift the carrier frequency of an optical pulse without significant losses and without affecting the pulse shape or the coherence. Given the continuous tunability of the frequency shift, as well as its large amplitude, such a device could have important technological applications in laboratory optical setups as well as in optical telecommunications. All this research has been conducted with a special eye to porous silicon structures, a material presently under intense study in Trento.

Further steps will be the identification of new dynamic structures where purely quantum effects can be observed, in particular those one that originate from amplifi-

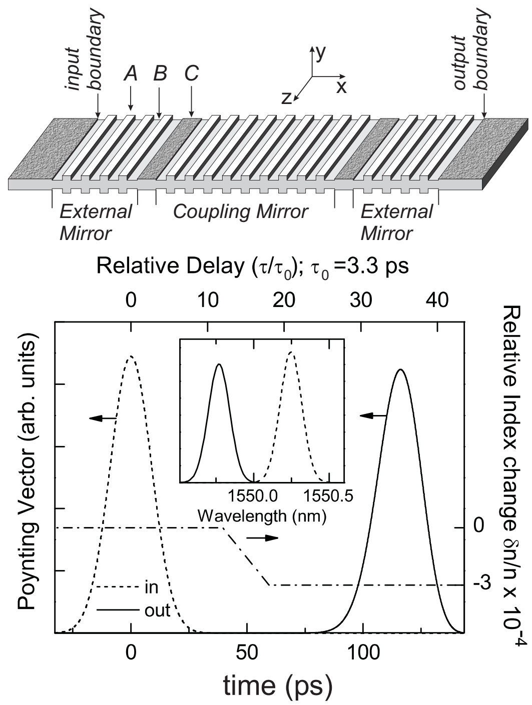


Figure 6: Upper panel: scheme of a coupled resonator optical waveguide (CROW). Lower panel: time and frequency shape of input and output pulses for the photon energy lifter.

cation of zero-point fluctuations such as the dynamical Casimir effect, as suggested in [9].

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QUANTUM INFORMATION PROCESSING

Neutral atoms are one of the most promising candidates for realizing quantum information processing devices. Sophisticated methods, widely applied in atomic clocks, have been developed over many decades to coherently manipulate the internal quantum states of an atom. For instance, neutral atoms in optical lattices and atom chips are unique for quantum information purposes, as they are so far the only physical system, in which both an outstanding degree of single particle control exists, while simultaneously large scale qubit systems can be realized.

Theory must continue to play a leading role in guiding and supporting experimental developments. The various implementations require continuous theoretical work especially finding physical solutions where mere technology is yet too cumbersome. The work of the Quantum Information group at the BEC center has focused mainly along this direction.

Fundamentals of atomic interactions

In [1], we present a zero-range pseudopotential applicable for all partial wave interactions between neutral atoms. For p- and d-waves we derive effective pseudopotentials, which are useful for problems involving anisotropic external potentials. Finally, we consider two nontrivial applications of the p-wave pseudopotential: we solve analytically the problem of two interacting spin-polarized fermions confined in a harmonic trap, and analyze the scattering of p-wave interacting particles in a quasi-two-dimensional system.

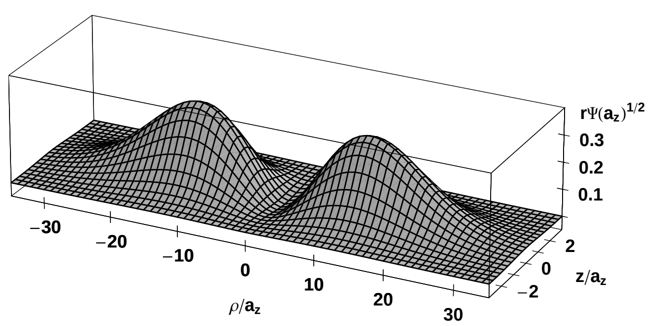

Figure 1: Exact wave function of the first excited state for two atoms interacting via s-wave pseudopotential and trapped in a quasi-two-dimensional harmonic potential.

In [2], we discuss exact solutions of the Schrödinger equation for the system of two ultracold atoms confined in an axially symmetric harmonic potential. We investigate different geometries of the trapping potential, in particular we study the properties of eigenenergies and eigenfunctions for quasi-one and quasi-two-dimensional traps. We show that the quasi-one and the quasi-two-dimensional regimes for two atoms can be already realized in traps with moderately large (or small) ratios of the trapping frequencies in the axial and the transverse directions. Finally, we apply our theory to Feshbach resonances for trapped atoms. Introducing in our description an energy-dependent scattering length we calculate analytically the eigenenergies for two trapped atoms in the presence of a Feshbach resonance.

Quantum gates with neutral atoms in real settings

In [3], we propose a scheme for quantum logic with neutral atoms stored in an array of holographic dipole traps where the positions of the atoms can be rearranged by using holographic optical tweezers. In particular, this allows for the transport of two atoms to the same well where an external control field is used to perform gate operations via the molecular interaction between the atoms. We show that optimal control techniques allow for the fast implementation of the gates with high fidelity, in a way which is robust against low-frequency noise.

In [4], we present new schemes for implementing an atomic phase gate using two degrees of freedom for each atom and discuss their realization with cold rubidium atoms in atom chips. We also investigate the performance of a collisional phase gate in a magnetic trap that is currently available in atom chips. Our results show that gate operations with high quality performance can be efficiently realized in atom chips.

In [5], we propose a scheme for controlling interactions between Rydberg-excited neutral atoms in order to perform a fast high-fidelity quantum gate. Unlike dipole-blockade mechanisms already found in the literature, we drive resonantly the atoms with a state-dependent excitation to Rydberg levels, and we exploit the resulting dipole-dipole interaction to induce a controlled atomic motion in the trap, in a similar way as discussed in recent ion-trap quantum computing proposals. This leads atoms to gain the required gate phase, which turns out to be a combination of a dynamic and a geometrical contribution. The fidelity of this scheme is studied including small anharmonicity and temperature effects, with promising results for reasonably achievable experimental parameters.

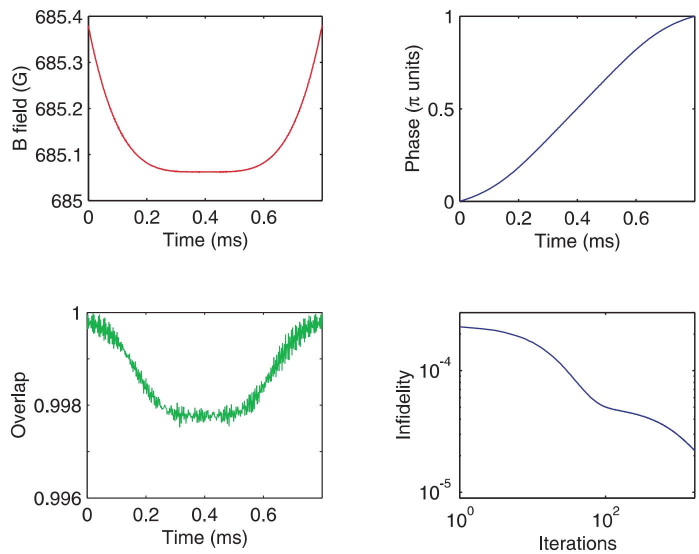

Figure 2: Two-qubit gate operation via optimal magnetic field control in a holographic dipole trap [3]: optimized magnetic field time dependence (top left); overlap between initial and evolved state (bottom left); accumulated two-particle phase (top right); decrease of the infidelity with increasing iterations (bottom right).

In [6], we present a detailed, realistic analysis of the implementation of a proposal for a quantum phase gate based on atomic vibrational states, specializing it to neutral rubidium atoms on atom chips. We show how to create a double–well potential with static currents on the atom chips, using for all relevant parameters values that are achieved with present technology. The potential barrier between the two wells can be modified by varying the currents in order to realize a quantum phase gate for qubit states encoded in the atomic external degree of freedom. The gate performance is analyzed through numerical simulations; the operation time is ~ 10 ms with a performance fidelity above 99.9%. For storage of the state between the operations the qubit state can be transferred efficiently via Raman transitions to two hyperfine states, where its decoherence is strongly inhibited. In addition we discuss the limits imposed by the proximity of the surface to the gate fidelity.

In [7], we analyze a theoretical proposal for performing a two-qubit phase gate via switching electromagnetic potentials on atom chips, and develop a version suitable for implementation with current atom-chip technology. The main features of our scheme are the use of microwave fields to modulate the state-dependence of the potential needed to achieve conditional dynamics, and the application of quantum control algorithms to

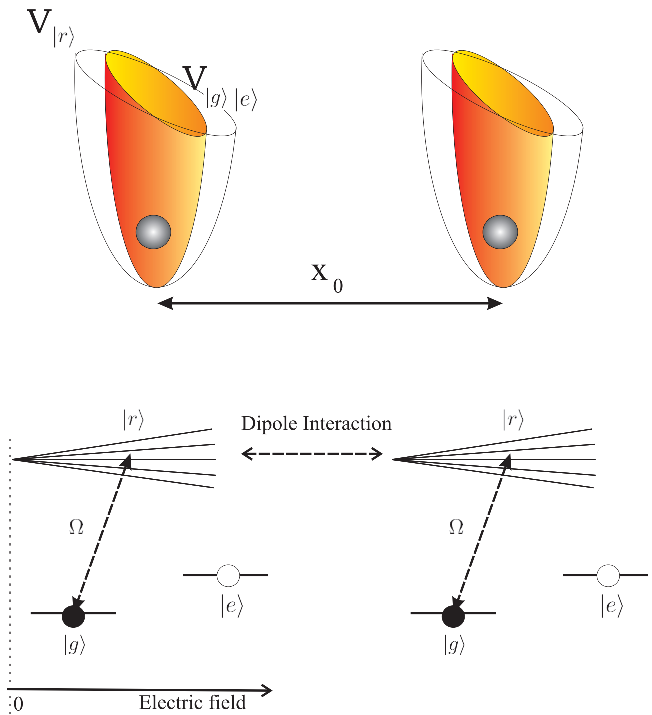

Figure 3: Schematic of the trapping potential and level scheme for the resonant Rydberg quantum phase gate without dipole blockade [5].

optimizing gate performance. We employ circuit configurations that can be built with current fabrication processes, and extensively discuss the sources of technical noise and imperfections that characterize an actual atom chip. We find an overall infidelity compatible with requirements for fault-tolerant quantum computation.

Controlling entanglement and decoherence in many-atom systems

In [8], we show that deterministic entanglement of neutral cold atoms can be achieved by combining several already available techniques like the creation/dissociation of neutral diatomic molecules, manipulating atoms with micro fabricated structures (atom chips) and detecting single atoms with almost 100% efficiency. Manipulating this entanglement with integrated/linear atom optics will open a new perspective for quantum information processing with neutral atoms.

In [9] we introduce, and determine decoherence for, a wide class of non-trivial quantum spin baths which embrace Ising, XY and Heisenberg universality classes coupled

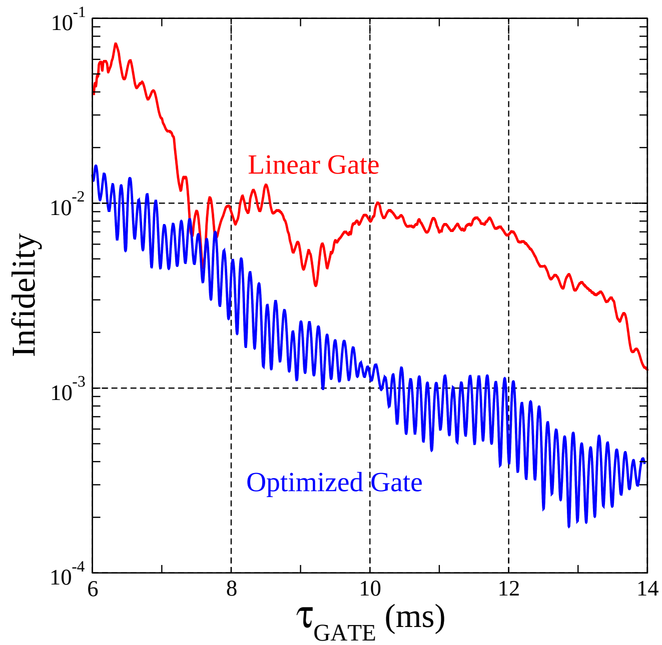

Figure 4: Infidelity of the vibrational phase gate described in [6] as a function of the gate duration. The red and blue lines correspond to the infidelities calculated for the linear and optimized gates respectively.

to a two-level system. For the XY and Ising universality classes we provide an exact expression for the decay of the loss of coherence beyond the case of a central spin coupled uniformly to all the spins of the baths which has been discussed so far in the literature. In the case of the Heisenberg spin bath we study the decoherence by means of the time-dependent density matrix renormalization group. We show how these baths can be engineered, by using atoms in optical lattices.

Strategic planning and networking at European level

In [10], we present an excerpt of the document "Quantum Information Processing and Communication: Strategic report on current status, visions and goals for research in Europe", which has been recently published in electronic form at the website of FET (the Future and Emerging Technologies Unit of the Directorate General Information Society of the European Commission, see also `http://www.cordis.lu/ist/fet/qipc-sr.htm`) under the joint coordination of the Trento group and of the Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences in Innsbruck. This

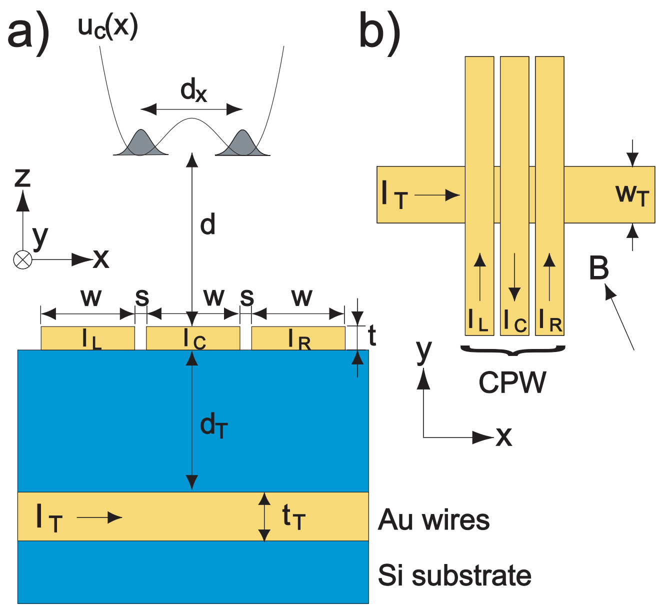

Figure 5: Chip layout for the microwave collisional phase gate analyzed in [7]. (a) Cut through substrate. (b) Top view of wire layout.

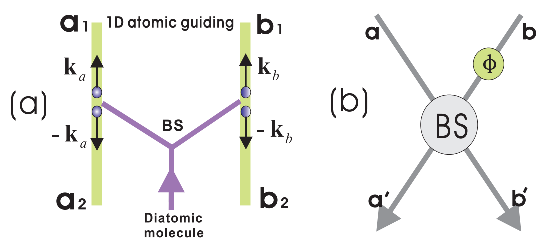

Figure 6: Generation and verification of two-atom entanglement [8]. (a) Correlated decay of a diatomic molecule which can be dissociated along either path a or path b. (b) Combining the path states of the dissociated atoms on the 50-50 atomic BS and applying phases to verify the entanglement.

document has been elaborated, following a former suggestion by FET, by a committee of QIPC scientists to provide input towards the European Commission for the preparation of the Seventh Framework Program. Besides being a document addressed to policy makers and funding agencies (both at the European and national level), the document contains a detailed scientific assessment of the state-of-the-art, main research goals, challenges, strengths, weaknesses, visions and perspectives of all the most relevant QIPC sub-fields.

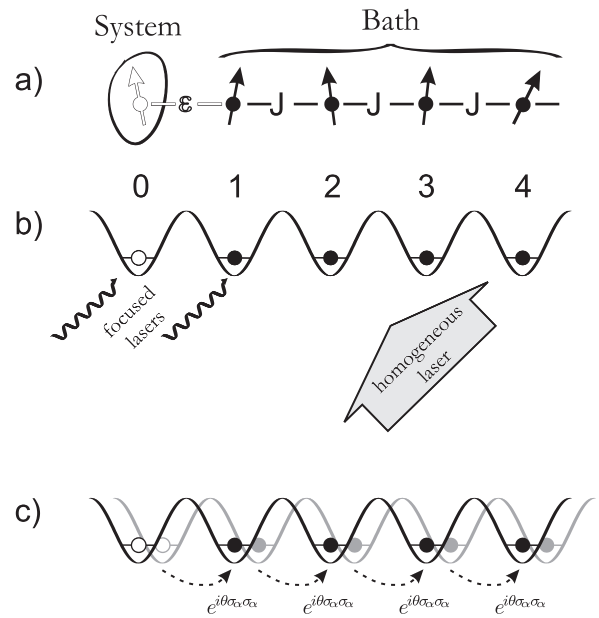

Figure 7: a) A sketch of the system plus bath model we consider in [9]. A two level system is coupled to the σ_z component of the first spin of the chain that acts as a spin bath. Atoms in an optical lattice can simulate this controlled decoherence by means of series of lasers (b) and displacements of the lattice (c).

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MATTER-WAVES INTERFEROMETRY

An interferometer is a fundamental apparatus in optical and matter wave physics whose output signal is sensitive to a phase shift between two fields traveling down separated paths. The phase shift is created by the interaction of the particles with some external force or by a difference in the length of the two paths of the interferometer. The problem is to estimate the phase shift and, therefore, retrieve information about the external force perturbing the system. Interferometry plays a central role in the development of basic science and technology. For instance, the Michelson-Morley interferometer was developed to test the ether hypothesis at the end of the 19th century. The same interferometric design is still used for testing General Relativity and for the detection of gravitational waves (Laser Interferometry Gravity Observatory, LIGO, and the European Laser Interferometer Space Antenna, LISA). A further application is the Satellite-to-Satellite laser interferometry proposed for the next generation of Gravity Recovery And Climate Experiment (GRACE II). From the point of view of technological applications, interferometers are used, to cite only two examples, to search for oil mineral reserves and for the realization of gyroscopes (Sagnac interferometers) for the passive navigation of submarines and satellites.

Phase sensitivity at the Heisenberg limit

The central goal of interferometry is, given a finite resource of atoms or photons, to estimate phase shifts with the highest precision. Several sources of noise conspire against such a goal. Classical noise can be created by micro-seismic geological activities, temperature fluctuations, poor detector efficiencies, or biased phase estimation protocols. Current interferometric technologies, however, can reduce the classical noise to the level where a second, irreducible source of noise becomes dominant: quantum fluctuations, which cannot be reduced beyond the limits imposed by the Heisenberg uncertainty relation.

A generic classical interferometer, characterized by a Poissonian distribution of particles has a standard quantum limit (or shot-noise) sensitivity that scales as $\Delta\Theta = 1/\sqrt{N}$, where N is the number of particles passing through the interferometer per unit time. To reach any desired sensitivity it would seem sufficient to increase the power of the matter/optical wave source. However, since the phase sensitivity scales slowly with N, the power needed for the most advanced scientific and technological applications would introduce large fluctuations and noise from the thermo-mechanical back-reaction of the interferometer components. This would eventually bound the sensitivity of the device.

In the last few years, it has been realized that quantum entanglement has the potential to revolutionize the entire field of interferometry. Quantum correlations in the optical/matter quantum state entering the arms of the interferometer can improve the sensitivity of the measurement up to the Heisenberg limit $\Delta\Theta = 1/N$, which is believed to be the highest sensitivity allowed by the Heisenberg uncertainty principle. This is a factor $\sqrt{N}$ improvement with respect to classical interferometers, with an increase of sensitivity of several orders of magnitude since the typical number of particles can be $\sim 10^8$ for atomic, and 10^{16} for optical systems.

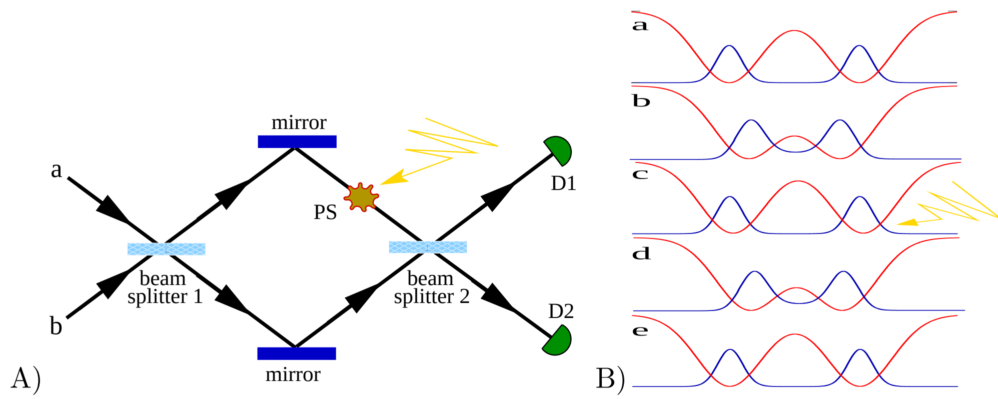

Figure 1: A) Schematic representation of the Mach-Zehnder interferometer. Atoms/photons enter the a and b input ports, mix and recombine in the beam splitters and are finally detected in D1 and D2. The phase shift (PS) is inferred from the number of atoms/photons measured in each output port. B) Cold atom Mach-Zehnder interferometer realized by tuning the height of a double well potential. a: The initial state is prepared by splitting an initial condensate in two spatially separated parts; b: The height of the interwell barrier is decreased to allow a $\pi/2$ phase shift among the condensates. This is the analog of the first half-transparent mirror of A); c: The two condensates are again separated. An external perturbation shift their relative phase; d: a second $\pi/2$ phase shift is induced among the condensates. This is the analog of the second half-transparent mirror of A); e: The number of atoms of the two condensates are finally measured.

The Mach-Zehnder interferometer.

Most of the interferometers described in the literature (like the Michelson-Morley and the Sagnac) belong to a class whose general properties are encompassed by the Mach-Zehnder (MZ), shown in Fig.(1). Schematically, the Mach-Zehnder interferometer consists of a two-mode state entering the input ports. The two waves are mixed in a beam splitter created with a half-transparent mirror. Therefore, the relative phase between the two waves is shifted by the interaction of the particles with some external perturbing force. A second half-transparent mirror eventually recombine the two waves. The detectors at the output ports count the number of particles, whose statistical distribution is governed by the conditional probability $P(N_c, N_d|N, \Theta)$ to measure N_c and N_d atoms given a phase shift Θ. The purpose of the interferometric experiment is: 1) to infer the value of the phase shift given a certain measured value of the number of particles at the output ports and 2) to rigorously calculate the confidence of the measurement.

How are phases and uncertainties estimated in the current literature? The common protocol involves performing several independent measurements of the relative, ΔN, and total, N, number of particles at the output ports. A certain combination of their moments (usually, the average $< \Delta N >$) is deterministically related with Θ, which can be therefore calculated by inverting the relation. In practice, the average can only be calculated over a finite number of experiments, introducing a statistical error into the estimated value of the phase: $\Delta\Theta = \sigma_{\Delta N}/|\partial < \Delta N > /\partial\Phi|_{\Theta}$. where $\sigma_{\Delta N}$ is the mean square fluctuation of the measured relative number of particles. This equation is based on a simple linear error propagation theory. Yet, there are several hidden assumptions in this approach, the most stringent requiring the validity of the central limit theorem, which is valid for an asymptotically large number of measurements. In our preliminary work [3], we have demonstrated that Eq. (1) fails to give a correct phase estimate of the Mach-Zehnder phase sensitivity in several important cases of Heisenberg limited interferometry.

Bayesian analysis

In our work, we combined a Bayesian calculation of phase distribution probabilities with an optimized measurement strategy based on multiple independent measurements done with a variable number of photons or atoms. In quantum interferometry, we measure the eigenvalues μ of a phase-dependent observable $\tilde{\mu}(\Theta)$ (which, in most cases, is the number of particles at the output ports). For simplicity of notation, in the following we consider input quantum states with a fixed total number of atoms. Quantum Mechanics provides the conditional probability $P(\mu|\Theta)$ to measure μ given the unknown phase shift Θ. Our aim, however, is to estimate Θ given a certain value μ measured at the output ports, $P(\Theta|\mu)$. In other words, we need to calculate the conditional probability for the possible values of the phase shift compatible with the measured result. This is provided by the Bayes theorem $P(\mu|\Theta)P(\mu) = P(\Theta|\mu)P(\mu)$, where $P(\mu)$ and $P(\Theta)$ take into account any a priori information about the real value of the phase shift and the output measurements. As a phase estimator, we choose the maximum of the distribution, and, as phase uncertainty, the 68% confidence. The Bayesian analysis is free of any statistical assumption, it does not requires statistical averaging and it provides rigorous phase sensitivities for an arbitrary number of independent measurements. In this case, indeed, the phase probability distribution is simply given by the product of the probabilities obtained for the single measurements.

Squeezed states

We study the sub-shot noise sensitivity of a linear Mach-Zehnder interferometer. The analysis assumes optical waves or BEC of non-interacting atoms. The effect of the BEC interatomic interaction will be discussed in the next Sections. We choose as input of the MZ the symmetric two-mode quantum state [1]

$$|\psi\rangle_{inp} = \frac{1}{\sqrt{2}}\big(|j+m\rangle_a|j-m\rangle_b + |j-m\rangle_a|j+m\rangle_b\big), \tag{1}$$

where $N = 2j$ and $2m$ are the total and the relative number of particles at the a and b input ports, respectively, cfr. Fig. (1).

We first considered the twin-Fock ($m = 0$) state introduced by Holland and Burnett [2]. The main results of our analysis can be summarized as follows: i) with a single measurement the MZ interferometer gives a sensitivity $\Delta\theta \sim 1/\log N$, worse than the shot noise, ii) the highest sensitivity is reached with *two* independent measurements, for the 68% confidence, and iii) with *three* measurements for the 95% confidence: $\Delta\theta_{68\%} = \frac{2.915}{N_T}$, $p = 2$, $\Delta\theta_{95\%} = \frac{6.654}{N_T}$, $p = 3$. The number of measurements needed to reach higher confidences is shown in Fig.(2,A). After considering various values of the parameter m of Eq. (1), we concluded that the best Mach-Zehnder performance is obtained when $m = 1$. This state can be created by constructing a twin-Fock state followed by the measurement of one particle. The sensitivity of the twin-m states is:

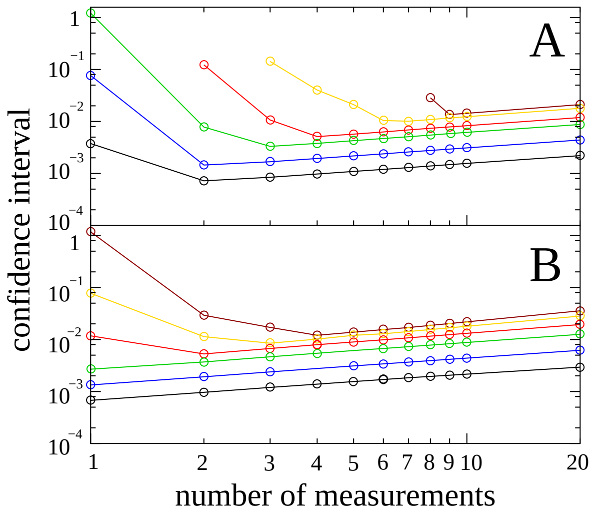

Figure 2: Confidence interval as a function of the number of independent measurements p for A) the twin-Fock $m = 0$ and B) the twin $m = 1$ states. Here $N_T = 2000$ particles. In both plots, from the bottom line to the top one, the black line is the confidence at 38.29%, the blue at 68.27%; the green at 95.45%, the red at 99.73%, the yellow at 99.994%, and the brown at 99.99994%. These correspond to $\sigma/2, \sigma, 2\sigma, 3\sigma, 4\sigma$ and 5σ when the distribution is Gaussian.

$\Delta\theta_{68\%} = \frac{2.67}{N_T}$, $p = 1$, $\Delta\theta_{95\%} = \frac{5.376}{N_T}$, $p = 1$. The main advantage is, beside the smaller prefactors, that the $1/N_T$ scaling is reached with a single ($p = 1$) measurement for both the 68% and the 95% confidence, as compared with the $p = 2$ and $p = 3$ measurements requested with Fock states, respectively. For higher confidences, the required number of measurements is shown in Fig.(2,B). The possibility to estimate a phase with a single measurement has some important advantages. Indeed, when the external perturbation has a short life-time, the need to perform several independent measurements might require the building of an equal number of interferometers.

Mach-Zehnder interferometry with BEC

A Mach-Zehnder interferometer can be realized in a double well potential by tuning the height of the potential barrier separating the condensates, see Fig. (1). The recent experimental creation of very stable double-well traps [3, 4, 5] bodes well for the future of matter-wave interferometry.

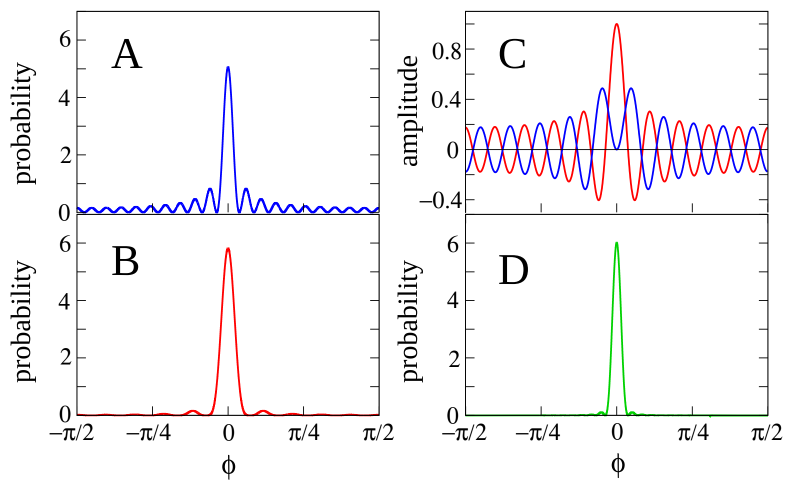

Figure 3: A,B: Probability distribution of the $m = 0$ twin-Fock state with A) $N = 40$ particles and a $p = 1$ measurement, (A); $N = 20$ particles and $p = 2$ measurements, (B). By combining the independent measurements it is possible to strongly reduce the weight of the tail of the distribution with respect to the central peak. C,D: Amplitude $d^j_{1,1}(\phi)$ (red line), and $d^j_{1,-1}(\phi)$ (blue line), for $N = 40$ particles ($j = 20$), (C). The tails of the amplitudes oscillate out of phase and interfere destructively, so to enhance the central peak of the probability distribution $P(\phi|j,0) \sim |d^j_{1,1}(\phi) + d^j_{1,-1}(\phi)|^2$, (D).

As already pointed out, the interferometric phase sensitivity depends on the specific quantum state entering the interferometer. If such state is created by splitting a single condensate in two parts, the MZ sensitivity would depend on the time scale of the splitting process. We studied both the adiabatic and dynamical splitting of the potential wells with a two-mode model and with a variational approach for the wave function [6]. In two-modes approximation, the Hamiltonian governing the BEC trapped in a double-well potential is:

$$\hat{H} = \frac{E_c}{4}\Big(\hat{a}^\dagger\hat{a}^\dagger\hat{a}\hat{a} + \hat{b}^\dagger\hat{b}^\dagger\hat{b}\hat{b}\Big) - K(t)\Big(\hat{a}^\dagger\hat{b} + \hat{b}^\dagger\hat{a}\Big). \tag{2}$$

where E_c is the "one-site energy' and $K(t) = K(0)e^{-t/\tau}$ is the "Josephson coupling energy". In WKB approximation, the effective ramping time $\tau = \frac{\Delta t_{\rm ramp}}{d\sqrt{V_0-\mu}}$ depends on the real ramping time $\Delta t_{\rm ramp}$, on the final distance d between the wells, the height of the potential barrier V_0, and the chemical potential μ . Such a time-dependent configuration has been realized by the MIT group [3]. We have studied Eq.(2) in a phase-states representation [7]. We write a general state in the Hilbert space of the two-mode system as $|\psi\rangle = \int_{-\pi}^{+\pi} \frac{\mathrm{d}\phi}{2\pi} \Psi(\phi,t)\,|\phi\rangle$, where ϕ is the relative phase between the two modes, and $|\phi\rangle$ are un-normalized phase states providing an overcomplete base for the relevant Hilbert space. In this representation the action of any two-mode operator applied to $|\psi\rangle$ can be represented in terms of differential operators acting on the associated phase amplitude $\Psi(\phi,t)$. For, the Hamiltonian of the system becomes$\hat{H}\,|\psi\rangle = \int_{-\pi}^{+\pi} \frac{\mathrm{d}\phi}{2\pi} \left[H_{eff}(\phi,t)\,\psi(\phi,t)\right] e^{\frac{2K(t)}{E_c}\cos\phi}|\phi\rangle$, where the H_{eff} is a Generalized Quantum Phase effective Hamiltonian: $H_{eff}(\phi,t) = \left[-\frac{E_c}{2}\frac{\partial^2}{\partial\phi^2} - K(t)N\,\cos\phi - \frac{K^2(t)}{E_c}\cos 2\phi \right]$. This phase representation allows the mapping of the two-modes quantum Hamiltonian to a partial differential equation, which is much easier to solve exactly with approximate time-dependent variational methods. Here we report the main results on the MZ phase sensitivity obtained for different splitting dynamical regimes. The sensitivity is calculated assuming that the interatomic interaction is turned off right after the input state in injected in the interferometer. This approximation will be released in the next section.

The main result of the analysis is the discovery of three different regimes, (see Fig.(4)), which, in analogy to three corresponding regimes existing in the dynamical Josephson effect [8], we call Rabi, Josephson and Fock. These three regimes are characterized by different scalings of the phase sensitivity $\Delta\theta$ with the total number of condensate particles N [10].

Rabi Regime. It is a semiclassical regime characterized by a strong tunneling between the two condensates. In this regime the phase sensitivity scales at the standard quantum limit $\Delta\theta \sim 1/N^{1/2}$.

Josephson Regime. This is the most interesting regime since it can be reached in a realistic experimental setting. With this state it is possible to reach a sub shot-noise sensitivity $\Delta\theta \sim 1/N^{3/4}$. We also find that the $1/N^{3/4}$ scaling is a rigorous upper bound in the limit $N \to \infty$, while keeping constant all different parameters of the bosonic Mach-Zehnder interferometer.

Fock Regime. In this regime, the initial condensate has been fragmented in two independent condensates. Once these feed the input ports of the MZ it would be possible to reach the Heisenberg limit $\Delta\theta \sim 1/N$. However, in a realistic dynamical BEC splitting, the $1/N$ limit would requires a quite long adiabaticity time scale, which is hardly reachable experimentally.

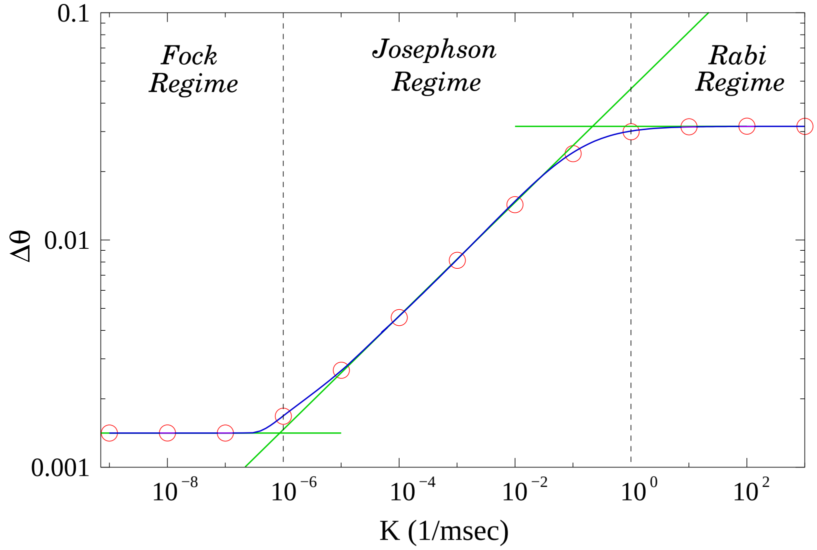

Figure 4: Mach Zehnder phase sensitivity $\Delta\theta$ as a function of the Josephson energy K. The green lines are the analytical predictions in three regimes: i) *Rabi Regime*, where $\Delta\theta \approx 1/\sqrt{N}$, ii) *Josephson Regime*, where $\Delta\theta \approx 1/N^{3/4}$, and iii) *Fock Regime*, where $\Delta\theta \approx 1/N$. Here $N = 1000$. The blue line is given by a variational approach, while the red circles are numerical exact solutions.

Non-linear Beam-splitter

The beam splitter is a central component of an atomic/optical Mach-Zehnder interferometer. We studied a Bose Einstein Condensate beam splitter, realized with a double well potential of tunable height [9]. We analyzed how the sensitivity of a Mach Zehnder interferometer is degraded by the non-linear particle-particle interaction during the splitting dynamics. We consider, as input, two independent condensates of $N/2$ particles (Twin Fock state [2]) an we simulate a matter wave beam splitter within the two-mode model introduce before. In our model, a beam splitter for interacting Bose-Einstein condensates is created through a three stage process:, A) we start from two independent condensates ($E_c(0) \neq 0$, $K(0) = 0$); B) we allow a tunneling between the potential wells by decreasing the height of the potential barrier separating them ($E_c(t) \neq 0$, $K(t) \neq 0$); and finally C) we suppress the tunneling by raising the potential barrier. We recover the 50/50 linear beam splitter when the interaction is switched off, $E_c(t) = 0$, and $\int_0^{+\infty} \mathrm{d}t\, K(t) = \pi/4$. In figure (5) we plot the phase sensitivity as a function of the separation time, for different values of E_c. As we see, the optimal separation time to realize a beam splitter, corresponding to the minimum of the phase sensitivity, depends on the particle-particle interaction. In the linear case this is equal to $\pi/(2K)$. By increasing E_c, the phase width reaches a minimum at smaller times and corresponding larger values.

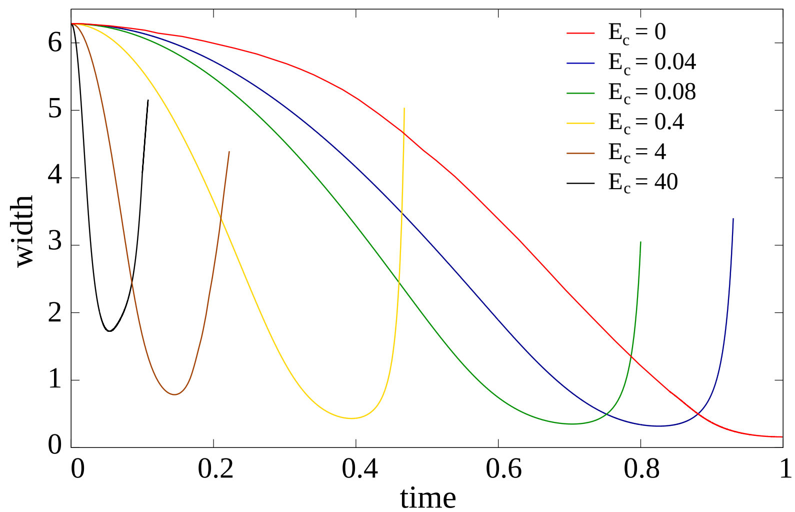

Figure 5: Width of the phase distribution as a function of time (in units $\pi/(4K)$) and for different value of the interaction energy E_c. The linear case ($E_c = 0$) is represented by the red line. By increasing E_c the minimum is attained at smaller times and at corresponding larger widths. We notice that, independently of E_c, at $t = 0$ we have a flat probability distribution corresponding to a phase width 2π and complete phase uncertainty. Here $K = 0.5$ and $N = 40$.

For different values of K and E_c, we calculate the minimum phase uncertainty and we indicate it as $\Delta\theta = \frac{\alpha}{N^\beta}$, where α is a prefactor, and β gives the scaling of the phase uncertainty with the total number of particles N. The main result of our analysis is presented in figure (6) where we plot β as a function of the ratio K/Ec. In analogy to what discussed in the previous Section, we highlight the existence of three different regimes, which we still call Rabi, Josephson and Fock.

Rabi Regime. This is the most interesting regime and is defined by $K/E_c \gg N$. The phase distribution is squeezed during the dynamics: the initial flat phase distribution developes a central peak with a width at the Heisenberg limit. In this regime, we have $\beta \sim 1$, corresponding to sub shot-noise sensitivity.

Josephson Regime. The Josephson regime is given by $1/N \ll K/E_c \ll N$. It is the dominant regime when we increase the number of particles, keeping fixed the ratio K/E_c. As shown in figure (6), the phase sensitivity decreases when $K/E_c < N$ and,

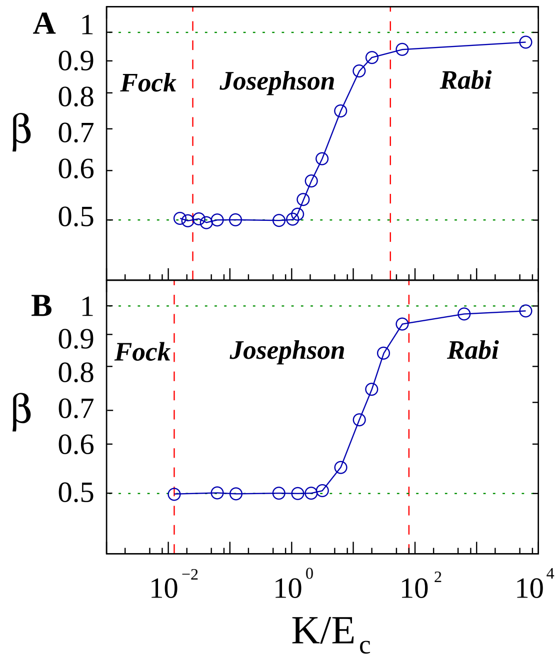

Figure 6: Scaling parameter β as a function of K/E_c. The circles are the results of numerical simulations, the blue line is a guide to the eye. The red vertical dashed lines delineate three regimes: Rabi, Josephson and Fock. Horizontal green dotted lines indicate the two relevant limits of quantum interferometry: the Heisenberg limit $\beta = 1$, and the Standard Quantum Limit $\beta = 0.5$. Note that the Heisenberg Limit is reached asymptotically in the number of particles. Here we considered A) $N = 40$ and B) $N = 80$. The Josephson regime becomes larger and larger while increasing the number of particles. In the Fock regime it is not possible to define a scaling of the phase uncertainty since the phase distribution is almost flat and the phase sensitivity is $\Delta\theta \sim 2\pi$.

in the Josephson regime, we recover the shot-noise limit $\beta = 1/2$. The prefactor α becomes progressively large.

Fock Regime. The Fock regime is characterized by $K/E_c \ll 1/N$ and corresponds to strong interaction. In the case $K/E_c \to 0$, the dynamics is slightly perturbed by the tunneling and the beam splitter becomes ineffective. The initial state is left almost unchanged by the beam splitter transformation, and the phase distribution remains flat.

The main result of our analysis of the beam splitter is that there is an interval in the values of the parameter $K/E_c \gg N$, the so called Rabi regime, where sub Shot-

Noise sensitivity can be achieved, despite the presence of a non linear coupling. This conclusion is of interest in view of recent experiments where both the particle-particle interaction (employing a Feshbach resonance) and the tunneling strength (tuning the potential barrier) can be appropriately controlled and changed, making the Rabi regime and sub-shot noise sensitivity achievable.

Quantum optics of Fermi matter waves and the superfluid order parameter in Fermi gases

A possible way of detecting a macroscopic long-range coherence in a gas of ultracold bosonic atoms below the Bose-Einstein condensation temperature consists in extracting two matter waves from distant points in the cloud and making them to overlap. If coherence is present between the two points, interference fringes show up in the overlap region as a spatial modulation in the density profile. In quantum optical terms, this is a one-particle interferometric measurement.

A similar experiment can be envisaged in order to detect a BCS state in a gas of fermionic atoms by looking at the long-range coherence in the BCS order parameter. The difficulty to overcome is that the long-range coherence involves in this case four-operator correlation functions instead of two-operator ones as in the bosonic case, so that a two-particle interferometric measurement is needed to reveal it.

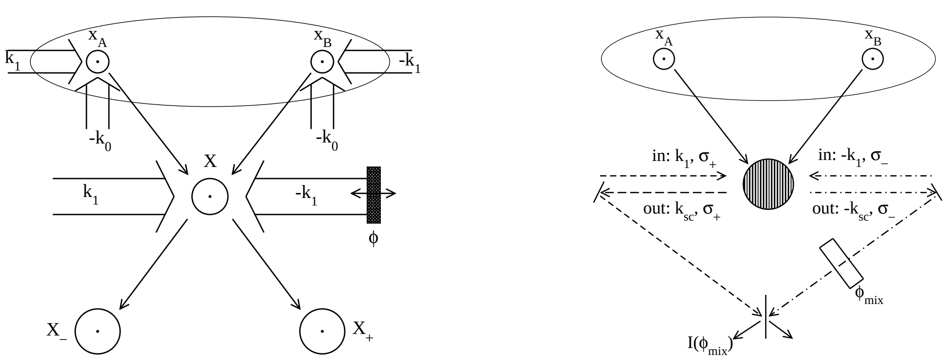

Figure 7: Sketch of the proposed experimental setups

In [11], we have extended the quantum optical techniques to the case of a Fermi field and we have identified a pair of two-particle interferometric schemes which are able to show the presence of a long-range order in a Fermi gas. In the first scheme, two wave packets are coherently extracted at two points of the cloud, and then mixed at a beam-splitter. The correlations between the atom numbers in the different spin states in the two output channels of the beam-splitter are then measured. This provides direct information on the two-particle correlations in the cloud. In the second scheme, the interference fringes formed by the two overlapping wavepackets are observed by light scattering techniques: information on the order in the Fermi gas is encoded in the second-order correlation functions of the scattered light field.

Experimental realization of these proposals not only would provide important informations on the microscopic state of the Fermi superfluid, but would also constitute a first example of quantum optical measurement on Fermi matter beams rather than Bose ones.

Noise correlations and measurement of the Green functions in Bose gases

The correlation functions of the Bose field and, in particular, the one-body Green functions play a central role in the physics close to the critical points of a phase transition, both at finite and at zero temperature. An important question is therefore to understand how these can be measured in an experiment. In [12], we have given a possible answer to this question, by proposing two-body interferometric schemes of the Hanbury-Brown and Twiss kind where the correlations of the Bose field show up as noise correlations in a single-shot experimental image of the density profile.

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Projects and scientific collaborations

Projects

During the period June 2004 - May 2006 the members of the BEC Center have been involved in national projects supported by the Italian Ministry of Research, by INFM-CNR and the European Union. Among them:

2003-2005 MIUR PRIN on "Superfluidity and Fermi atomic gases"

2005-2007 MIUR PRIN on "Ultracold Fermi gases and optical lattices"

2003-2006 IST-FET RTD project ACQP (Atom Chip Quantum Processor)

2005-2008 Marie-Curie Outgoing International Fellowship QOQIP (Quantum Optics for Quantum Information Processing)

2005-2009 IST-FET Integrated Project SCALA (Scalable quantum computing with Atoms and Light)

2005-2007 Coordination Action ERA-Pilot QIST (Quantum Information Sciences and Technologies)

2006-2009 Coordination Action QUROPE (Quantum Information Processing and Communication in Europe)

The BEC Center is also supported by the Provincia Autonoma di Trento (PAT) on the basis of an official agreement with INFM-CNR.

Scientific Collaborations

The scientific activity carried out at the BEC Center is the result of numerous national and international collaborations. Some of the most significant ones are briefly described below:

- *Florence* (European Laboratory for Nonlinear Spectroscopy, LENS). The Trento team has a long and fruitful experience of collaboration with LENS , also in the framework of national projects. Recent joint activities have concerned the study of the insulating behaviour of a trapped ideal Fermi gas [1] and the theoretical study of the Bloch oscillations in the presence of the Casimir-Polder force generated by the surface of a dielectric[2]. Iacopo Carusotto has collaborated with Gabriele

Ferrari on the development of a novel optical frequency synthetizer by means of DFG of a mode-locked laser[3]. Finally, Michele Modugno works at LENS but he is also a member of the BEC center; his activity is carried on in collaboration with both groups on the theory of condensates in disordered potential [4], in optical lattices [5] and in ring-shaped traps [6].

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- *Paris* (Ecole Normale Superieure, ENS). During the academic year 2004/2005 Sandro Stringari held the European Chair at the College de France where he delivered a series of lectures on "Bose-Einstein Condensation and superfluidity" [1]. During his visit at Paris he has collaborated with team of Yvan Castin and Jean Dalibard on the statistical distribution of quantized vortices in a rotating ideal Bose gas [2]. He also started a series of collaborations with the team of Roland Combescot on the study of the collective oscillations in a superfluid Fermi gas [3] and on the behaviour of the structure factor along the BEC-BCS crossover [4]. Iacopo Carusotto has spent the academic year 2003-04 in Paris as Maitre de Conferences Associe to Claude Cohen-Tannoudji's chair at College de France and during this time has been involved in several collaborations. Together with Yvan Castin (LKB-ENS), he has worked on the development of a quantum optical formalism for Fermi beams and on its application to interferometrical schemes that can be used to probe the effects of long range order in Fermi gases [5]. This collaboration is still in progress and presently deals with the application of semi-classical Monte Carlo schemes to the study of two-dimensional Bose gases at thermal equilibrium. Another collaboration is going on with Cristiano Ciuti (LPA-ENS), on subjects at the interface between many-body physics and nonlinear and quantum optics. This activity has started with the investigation of the physics of exciton-polariton in semiconductor microcavities from the point of view of a quantum fluid of light [6, 7, 8, 9]. More recently, this collaboration has been extended to a joint project on the study of novel semiconductor microstructures which appear as very promising in the quest for the experimental observation of the dynamical Casimir effect [10].

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- *Boulder* (JILA and University of Colorado, Boulder). The Trento team has fruitful collaborations with JILA since a long time. The collaboration with the team of Eric Cornell on the study of the Casimir-Polder force has been particularly fruitful during the last two years. The theoretical predictions [1] of the Trento group on the effects of this force on the collective frequencies of a Bose-Einstein condensate located close to the surface of a dielectric has been confirmed experimentally [2] with high precision. More recently the Cornell team has proven [3] the temperature dependence of the force confirming the theoretical predictions of the Trento team [4] and proving for the first time the existence of thermal effects in this elusive force. From September 2004 through August 2005 Stefano Giorgini has spent a sabbatical year at JILA. During this period Stefano has been involved in the study of the momentum distribution of ultracold Fermi gases in collaboration with the experimental group of D. Jin and the theoretical group of M. Holland. This joint project has been very fruitful and has provided a clear theoretical interpretation to the measurements of released momentum distribution and released energy after a fast magnetic-field ramp to zero scattering length [5, 6].

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- *Innsbruck.* The collaboration with the Institute for Theoretical Physics and with the new Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences in Innsbruck dates back to before the establishment of the BEC Centre. In particular, in the field of Quantum Information Processing, this has lead not only to the study of novel quantum gate implementations [1] in the tradition of this long-standing collaboration between T. Calarco and P. Zoller, but also to the development of a general overview of the whole field of QIP for the purpose of contributing to the European Commission's strategy in this field, via the so-called European QIPC Roadmap [2].

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- *Heidelberg.* The collaboration with the experimental group of J. Schmiedmayer has also a long history in Trento, having lead to the development of several projects on atom chips for quantum information processing. In this context, the research has been more recently diversified from the traditional studies of quantum gate implementations with different techniques on atom chips [1, 2] to embrace also fundamental studies of entanglement generation in atom optics [3].

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- *Los Alamos National Laboratory.* Augusto Smerzi spent a long sabbatical as a visiting staff member, developing projects in collaboration with Lee Collins and A.R. Bishop [1, 2, 3, 4, 5]. These collaborations include the study of a BEC interferometer and, in particular, the effects of the nonlinearity on the phase estimation sensitivity. A different line of research regarded the study of the thermal statistical properties of a DNA chain, by using a generalized Ising-like Hamiltonian. During these years, Smerzi has supervised the PhD thesis of Luca Pezzè, who spent the full PhD period at LANL, and the Laurea thesis of Sara Ianeselli, who spent two months at the LANL. Part of this activity has been done within a new collaboration with the experimental group of Bouwmeester at University of California, Santa Barbara, namely the study of an optical Mach-Zehnder with a new Bayesian phase estimation protocol [6].

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- *Barcelona.* During the last two years the collaboration with the quantum Monte Carlo group at the Universitat Politecnica de Catalunya (UPC) has been extremely fruitful. The main subject has been the investigation of the properties of ultracold gases using quantum Monte Carlo methods. The collaboration has produced a number of publications on international journals [1, 2, 3, 4]. A PhD student of the BEC center, Sebastiano Pilati, has benefitted of a long-term visiting position in Barcelona (from September 2004 through August 2005) developing a path-integral Monte Carlo algorithm to study the thermodynamic behavior of ultracold gases. Furthermore, a former PhD student and research associate of the BEC center, Grigori Astrakharchik, has been given a research associate position at UPC working also on joint scientific projects with our group. In Barcelona we have an active collaboration also with ICFO, Institut de Ciències Fotòniques, namely with the group of M. Lewenstein. The collaboration with Lewenstein started when he was in Hannover through the co-tutelle programme for the PhD Thesis of Paolo Pedri. Presently Chiara Menotti is visiting ICFO as Marie Curie Fellow, working on strongly correlated atoms in optical lattices. At the moment, she is involved in the study of a gas of dipolar bosons in a 2D optical lattice. In the near future, she plans to study non abelian-gauge fields in optical lattices and the effect of disorder and impurities on the insulating-superfluid transition.

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- *Trento* (Photonics group, Department of Physics). A collaboration with Francesco Riboli, Mher Ghulinyan, Zeno Gaburro and Lorenzo Pavesi is in progress since

2005 [1, 2]. The collaboration takes advantage of the mutual exchange of ideas between the physics of electrons in solids, light in photonic crystals, and ultracold atoms in optical lattices. So far it has been focused on the subject of dynamic photonic crystals, and their application as silicon-based opto-electronic devices for wavelength conversion. Other issues presently under active investigation are radiation-induced forces between parallel waveguides, and new concepts of optical nonlinearity-induced interfaces which move at superluminal speeds.

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Publications

The following list includes the papers published or submitted for publication starting from January 2004 having at least one of the authors with the Trento BEC affiliation.

2006

Measurement of the Temperature Dependence of the Casimir-Polder Force; J.M. Obrecht, R.J. Wild, M. Antezza, L.P. Pitaevskii, S. Stringari, E.A. Cornell, physics/0608074

Normal state of a polarized Fermi gas at unitarity; C. Lobo, A. Recati, S. Giorgini, S. Stringari, cond-mat/0607730

Equation of state of an interacting Bose gas at finite temperature: a Path Integral Monte Carlo study; S. Pilati, K. Sakkos, J. Boronat, J. Casulleras, S. Giorgini, cond-mat/0607721

The parametric oscillation threshold of semiconductor microcavities in the strong coupling regime; M. Wouters, I. Carusotto, cond-mat/0607719

Collective mode of homogeneous superfluid Fermi gases in the BEC-BCS crossover; R. Combescot, M.Yu. Kagan and S. Stringari, cond-mat/0607493

Quantum fluctuations and collective oscillations of a Bose-Einstein condensate in a 2D optical lattice; G. Orso, C. Menotti and S. Stringari, cond-mat/0607371

Strongly correlated 2D quantum phases with cold polar molecules: controlling the shape of the interaction potential; H.P. Büchler, E. Demler, M. Lukin, A. Micheli, N. Prokof'ev, G. Pupillo, P. Zoller, cond-mat/0607294

Casimir-Lifshitz force out of thermal equilibrium and asymptotic non-additivity; M. Antezza, L. P. Pitaevskii, S. Stringari, V. B. Svetovoy, cond-mat/0607205

Landau and dynamical instabilities of Bose-Einstein condensates with superfluid *flow in a Kronig-Penney potential;* Ippei Danshita and Shunji Tsuchiya, cond-mat/0607195

Stability and excitations of solitons in 2D Bose-Einstein condensates; S. Tsuchiya, F. Dalfovo, C. Tozzo, and L. Pitaevskii, cond-mat/0607160

Sub Shot-Noise interferometric phase sensitivity with Beryllium ions Schroedinger Cat States; L. Pezzè and A. Smerzi, quant-ph/0606221

The Goldstone mode of planar optical parametric oscillators; M. Wouters and I. Carusotto, cond-mat/0606755

Input-output theory of cavities in the ultra-strong coupling regime: the case of a time-independent vacuum Rabi frequency; C. Ciuti and I. Carusotto, cond-mat/0606554

One-dimensional description of a Bose-Einstein condensate in a rotating closed-loop waveguide; S. Schwartz, M. Cozzini, C. Menotti, I. Carusotto, P. Bouyer, S. Stringari, cond-mat/0606262

Spin polarizability of a trapped superfluid Fermi gas; A. Recati, I. Carusotto, C. Lobo and S. Stringari, cond-mat/0605754

Worm Algorithm and Diagrammatic Monte Carlo: A New Approach to Continuous-Space Path Integral Monte Carlo Simulations; M. Boninsegni, N. V. Prokof'ev, B. V. Svistunov, physics/0605225

The fate of vacancy-induced supersolidity in 4He; M. Boninsegni, A. Kuklov, L. Pollet, N. Prokof'ev, B. Svistunov, M. Troyer, cond-mat/0605627

Non-Linear Beam Splitter in Bose-Einstein Condensate Interferometers; L. Pezze', A. Smerzi, G.P. Berman, A.R. Bishop, and L.A. Collins, cond-mat/0605271

Detecting phonons and persistent currents in toroidal Bose-Einstein condensates by means of pattern formation; M. Modugno, C. Tozzo, F. Dalfovo, cond-mat/0605183

Decoherence by engineered quantum baths; D. Rossini, T. Calarco, V. Giovannetti, S. Montangero, R. Fazio, quant-ph/060551

Healing length and bubble formation in DNA; Z. Rapti, A. Smerzi, K. Ø. Rasmussen, A. R. Bishop, C. H. Choi, and A. Usheva, Phys. Rev. E 73, 051902 (2006)

Pair correlations of an expanding superfluid Fermi gas; C. Lobo, I. Carusotto, S. Giorgini, A. Recati, S. Stringari, cond-mat/0604282

Density Matrix Renormalization Group for Dummies; G. De Chiara, M. Rizzi, D. Rossini and S. Montangero, cond-mat/0603842, (open source version of the code)

Non-Positive α Rule for Continuous Phase Transition Lines; Nikolay Prokof'ev, Boris Svistunov, cond-mat/0603626

Dark solitons as quasiparticles in trapped condensates; V.A. Brazhnyi, V.V. Konotop, L.P. Pitaevskii, cond-mat/0603197

Deconfined criticality, runaway flow in the two-component scalar electrodynamics and weak first-order superfluid-solid transitions; A. Kuklov, N. Prokof'ev, B. Svistunov and M. Troyer, cond-mat/0602466

Critical Temperature and Thermodynamics of Attractive Fermions at Unitarity; E. Burovski, N. Prokof'ev, B. Svistunov, M. Troyer, cond-mat/0602224

Hysteresis effects in rotating Bose-Einstein condensates; B. Jackson, C. F. Barenghi, cond-mat/0602334

Imaging of critical correlations in optical lattices and atomic traps; Qian Niu, Iacopo Carusotto, and A. B. Kuklov, cond-mat/0601032, Phys. Rev. A 73, 053604 (2006)

Bragg scattering and the spin structure factor of two-component atomic gases; I. Carusotto, cond-mat/0512539

Off-diagonal correlations of the Calogero-Sutherland model; G.E. Astrakharchik, D.M. Gangardt, Yu.E Lozovik and I.A. Sorokin, cond-mat/0512470

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2nd Workshop Semiconductor Quantum Optics, Rügen (Germany), April 14-17, 2004

Stefano Giorgini: “Degenerate gases in quasi-1D harmonic traps”

Aspects of Large Quantum Systems Related to Bose-Einstein Condensation, Aarhus, April 15-18, 2004

Tommaso Calarco: "Entanglement: introduction"
XXII Convegno Fisica teorica e struttura della materia, Fai della Raganella (Trento), April 18-21, 2004

Murray Holland: "A theory of resonant interactions in dilute quantum gases"
Workshop on Ultra-Cold Fermi Gases, Levico (Italy), March 3-6, 2004

Tommaso Calarco: "QC with atoms in optical lattices: marker atoms and molecular Interactions"
2nd Workshop Quantum Information with atoms and photons, Torino, April 26-27, 2004

Sandro Stringari: "Expansion and collective oscillations in ultracold Fermi gases"
Conference on Frontiers in Quantum Gases, Santa Barbara, May 10-14, 2004

Murray Holland: "A theory of resonance superfluidity"
NASA Workshop on Fundamental Physics, Solvang (California), April 20-22, 2004

Iacopo Carusotto: "Many-Body Physics with Exciton-Polaritons in Semiconductor Microcavities"
Quantum Gases Program at KITP, Santa Barbara (California), May 2004

Chiara Menotti: "The role of boson-fermion correlations in the resonance theory of superfluids"
Quantum Gases Program at KITP, Santa Barbara (California), May 2004

Visitors

Long term visitors

Murray Holland (JILA, Univ. Colorado, Boulder), Sept 2003 - Aug 2004

Nikolai Prokof'ev (Univ. Massachusetts, Amherst), Dec 2005 - Aug 2006

Short term visitors

René Stock (IQIS, Univ. Calgary), June 26 - July 15, 2006

Murray Holland (JILA and Univ. Colorado, Boulder), June 26-30, 2006

Roland Combescot (LPS, ENS, Paris), May 29-30, 2006

Christophe Salomon (Laboratoire Kastler-Brossel, ENS, Paris), May 8-11, 2006

Raffaella Burioni (University of Parma), May 5th, 2006

Gershon Kurizki, (Weizmann Institute of Science, Israel), May 4th, 2006

Vukics Andras (Institut fuer Teoretische Physik, Innsbruck University), April 28th, 2006

Ingrid Bausmerth (University of Karlsruhe), April 19-21, 2006

Raul Santachiara (LPT Strasbourg), April 10-11, 2006

Giacomo Roati (LENS, University of Florence), April 3rd, 2006

Vitaly Svetovoy (University of Twelve, Enschede, The Netherlands), March 15-17, 2006

Andrea Trombettoni (Perugia), March 1-3, 2006

Markus Holzmann (Jussieu, Paris), February 27-28, 2006

Sergei Dickmann (Moskow), Febrary 21-23, 2006

Carsten Henkel (Uni. Potsdam), December 16, 2005

Cristiano Ciuti (ENS Paris), December 12-16, 2005

Alexander L. Fetter (Stanford University), December 12-14, 2005

Chiara Fort (LENS Firenze), December 12, 2005

Roland Combescot (ENS Paris) and Monique Combescot (Jussieu, Paris), October 3-8, 2005

Chris Pethick (NORDITA Copenhagen), September 14, 2005

Xiao-Hui Bao (Univ. Heidelberg), July 28 - August 3, 2005

Jörg Schmiedmayer (Univ. Heidelberg), July 28-29, 2005

Dimitri Gangardt (Univ. Paris-Sud), July 25-26, 2005

Adilet Imambekov (Harvard, USA), July 7-8, 2005

Sylvain Schwartz (Orsay), June 14-18 and July 3-17, 2005

Gabriele De Chiara (SNS Pisa), June 13-14, 2005

Philipp Treutlein (MPI and LMU, Munich), June 9-10, 2005

Luca Salasnich (INFM Milano), June 7, 2005

Meret Krämer (JILA, Boulder), May 22-28, 2005

Päivi Törmä and Sorin Paraoanu (Jyväskylä), May 19-20, 2005

Paolo Zanardi (ISI, Torino), April 28-29, 2005

Jordi Mur-Petit (Univ. Barcelona), March 7-11, 2005

Anna Minguzzi (Orsay), January 31 - February 1, 2005

Dimitri Gangardt (Orsay), January 31 - February 1, 2005

Rosario Fazio (SNS Pisa), January 31 - February 1, 2005

Mario Rasetti (Politecnico Torino), January 31, 2005

Gora Shlyapnikov (Orsay), December 15-16, 2004

Saverio Moroni (Roma), December 15, 2004

Riccardo Sturani (Univ. Geneva), November 4-5, 2004

Massimo Inguscio, Chiara Fort, Jessica E. Lye and Leonardo Fallani (LENS), October 19-20, 2004

Henrik Smith (Oersted Lab, Univ. Copenhagen), September 26 - October 6, 2004

Vyacheslav Yukalov (Dubna, Russia), June 21 - July 9, 2004

Marilù Chiofalo (Pisa), May 31 - June 4, 2004

Rafael Guardiola (Univ. Valencia), April 16, 2004

Nandini Trivedi (TIFR, Bombay), March 5-15, 2004

Alexander Fetter (Univ. Stanford), February 15 - March 6, 2004

Events and outreach

Conferences organized by the BEC Center

International Symposium on
Quantum Fluids and Solids
Trento (Italy) 5-9 July 2004

QFS2004 is an international symposium devoted to traditional topics of liquid and solid 4He, 3He, 3He-4He mixtures, Hydrogen, confined fermionic and bosonic gases, and other systems that exhibit long-range quantum order and quantum coherence. Emphasis is given to novel experimental techniques and recent theoretical advances. The meeting is a continuation of a long series of symposia, started in Sanibel (Florida) in 1975. QFS2004 has been hosted by the University of Trento. The BEC center has co-sponsored the event and has been strongly involved in the organization. The local organizing committee was composed by F.Dalfovo (Symposium chair), L.Reatto (Program chair), F.Pederiva (Publication chair), L.Pitaevskii, S.Stringari and S.Vitale. About 260 people attended the symposium. The proceedings appeared in 2 volumes of The Journal of Low Temperature Physics (Vol. **138**, 1/2, January 2005).

Third International Workshop on
Theory of Quantum Gases and Quantum Coherence
Cortona (Italy) October 29 - November 2, 2005

The third workshop on ”Theory of quantum gases and quantum coherence” (the first edition was held in Salerno in 2001 and the second edition in Levico in 2003) was particularly intended to get together ”young” researchers (at the level of PhD students, Postdocs and junior research associates). The workshop was attended by more than 90 scientists coming from Europe and overseas and the topic of discussion covered various theoretical aspects in the fields of Bose-Einstein condensation, degenerate Fermi gases and coherence properties in quantum many-body systems. The organizing committee was composed by: R. Chitra, Chiara Menotti, Anna Minguzzi and Patrizia Vignolo. Many contributions to the conference were collected in a special issue of the Journal of Physics B: Atomic, Molecular and Optical Physics (Vol. **39**, n.10, 2006).

Annual meeting
Fisica teorica e struttura della materia
Levico (Italy) 17 - 20 September 2006

Every year the group of Trento organizes a traditional three day meeting of the community of Italian theorists working in the field of condensed matter physics. The meeting is sponsored by INFM. Most of the participants are young researchers, presenting their last results on quantum mechanics, statistical mechanics, quantum field theory, computational physics, etc., with applications in condensed matter, soft matter, electron systems and others fields. The next edition will be held in Levico, in September 2006. The organizers are F.Dalfovo, I. Carusotto and S. Giorgini. The scientific advisory committee also involves R. Fazio, R. Livi, U. Marini Bettolo Marconi and R. Resta.

Group meetings and seminars at the BEC Center

2006

Monday 8th May at 11.00, Aula Seminari,
Christophe Salomon (Laboratoire Kastler-Brossel, ENS, Paris)
Experiments in the BEC-BCS Crossover with Lithium Atoms

Friday 5th May at 11.00, Aula Seminari,
Raffaella Burioni (University of Parma)
Quantum Particles on Inhomogeneous Networks

Thursday 4th May at 11.00, Aula Seminari,
Gershon Kurizki (Weizmann Institute of Science, Israel)
Can we protect Quantum Information from Decoherence?

Tuesday 2nd & Wednesday 3rd May, Aula Seminari di Matematica (first floor)
BEC Internal Meeting
talks:
Franco Dalfovo, Excitations in Condensates
Tommaso Calarco, Quantum Information
Lev P. Pitaevskii, Superfluidity in One Dimension
Augusto Smerzi (on-line from Los Alamos), Interferometry and Sensors
Iacopo Carusotto, Quantum Optics and Applications to Solid State
Sandro Stringari, Ultracold Fermions
Michele Modugno, Cold bosons Optical Lattices
Giuliano Orso, Cold fermions in Optical Lattices
Stefano Giorgini, Quantum Monte Carlo Methods

Friday 28th April at 15.00, Aula Seminari,
Vukics Andras (Institut fuer Teoretische Physik)
Cooling and Trapping of Atoms in Optical Resonators

Thursday 20th Apr. at 11.00, Aula Seminari,
Ingrid Bausmerth (University of Karlsruhe)
Atomic Quantum Dot Coupled to Trapped Bose Einstein Condensates

Monday 10th Apr. at 10.00, Aula Seminari,

Raul Santachiara (LPT Strasbourg)
Increasing of Entanglement Entropy from Pure to Random Quantum Critical Chains

Friday 7th April at 15.00, Aula Seminari Matematici
Group meeting: Chiara Menotti talks about
her recent activities in Barcelona

Wednesday 5th April at 15.00, Aula Seminari,
Francesco Riboli (University of Trento)
Optical Modes Induced Force between Coupled Waveguides

Monday 3rd Apr at 10.00, Aula Seminari,
Giacomo Roati (LENS, University of Florence)
Measurement of the Thermal Casimir-Polder Force with Degenerate Bosons

Monday 6th March at 15.00, Aula Seminari,
Joaquin E. Drut (University of Washington)
Spin 1/2 Fermions in the Unitary Regime at Finite Temperature

Monday 27th Feb., at 15.00, Aula Seminari,
Nikolai Prokof'ev
Worm Algorithm for Path-Integral Monte Carlo and new results for the supersolid He-4

Tuesday, 21st Feb., at 15.00 (Room 21),
Joint Colloquium
Lev P. Pitaevsky on
Surface-atom Casimir force out of thermal equilibrium

Monday, 20th Feb., at 15:00, Aula Seminari,
Nikolai Prokof'ev
Worm Algorithms for classical and quantum models

Friday 17th Feb., at 10.00 (Room 21),
Nathan L. Harshman (American University Washington, DC, USA)
Dynamical Entanglement in Particle Systems

Tuesday 14th Feb., at 17.00, Aula Seminari

Michiel Wouters presents some concepts of the
theory of pattern formation

Monday, 13th Feb., at 15:00, Aula Seminari,
Nikolai Prokof'ev
Diagrammatic quantum Monte Carlo: from polarons to fermions with contact interactions

Thursday 9th Feb., at 15:00, ECT* Seminar (Villa Tambosi),
Sebastian Diehl (Nuclear University of Heidelberg)
Universality in the BCS - BEC: Crossover in Cold Fermion Gases

Monday, 6th Feb., at 15:00, Aula Seminari,
Nikolai Prokof'ev
Quasicondensate mean-field for the weakly interacting Bose gas

Tuesday, 31st Jan., at 15:00, Room 21
Joint Colloquium
William A. Eaton (Laboratory of Chemical Physics NIDDK National Institute of Health, Bethesda, Maryland)
Ultrafast Protein Folding

Monday 30th January 2006, at 15:00, Aula Seminari,
Nikolai Prokof'ev
Weak first-order superfluid-solid quantum transitions: is deconfined criticality a self-consistent theory?

Monday 23rd January 2006, at 15:00, Aula Seminari,
Gabriele De Chiara
Density Matrix Renormalization Group: introduction and two applications in condensed matter physics

2005

Tuesday 20 - Wednesday 21 December 2005
*NEST-BEC meeting at ECT**

Participants: Gandolfi, Montangero, Nobile, Operetto, Zuccato, Binosi, Calarco, Fazio, Jones, Cecchini, Pupillo, Giovannetti, Recati, Tozzo, Cozzini, Idziaszek, Negretti, Cirone, Minardi, and others.
Topics: Meeting for the SuperComputer "Ben" at ECT*, Meeting for ERA-pilot QIST, Surface-acoustic-waves nanodevices for quantum information processing, Extended fermionization, Information Transfer in Quantum Chains, Casimir forces between defects in one-dimensional quantum liquids, Dynamics of Entanglement in the Heisenberg Model, Qubit-preserving ion-assisted cooling of atoms in lattices, Interfaces between solid state devices and optical-atomic systems for quantum information purposes, Optimal control for quantum information purposes, NEST-BEC project for quantum information.

Thursday 15 December 2005, at 15:00, Aula 14b,
C. Ciuti (Lab. P.Aigrain ENS, Paris)
Quantum vacuum properties of microcavities in the ultra-strong light-matter coupling regime

Monday 5 December 2005, at 15:00, Theory Seminar Room
M. Wouters
Coherence length of one-dimensional optical parametric oscillators

Wednesday 23 November 2005, at 17:30, Theory Seminar Room
F. Intravia (Lab. Kastler-Brossel, ENS, Paris)
Casimir effect and Interaction between Surface Plasmons

Thursday 17 November 2005, at 15:30, Theory Seminar Room
V. B. Svetovoy (MESA and Research Institute, University of Twente, The Nederlands)
The problem with the temperature dependence of the Casimir force between metals

Monday 14 November 2005, at 15:00, Aula 7
S. B. Kumar *Parity non-conservation in Singly Ionized Barium*

Tuesday 25 October 2005, ECT*
Theory Day Meeting, Joint initiative of ECT* and BEC Center

Thursday 6 October 2005, at 15.00, Theory Seminar Room,
Shunji Tsuchiya
Bogoliubov excitations in optical lattices

Tuesday 4 October 2005, at 15.00, Theory Seminar Room,
Monique Combescot (Jussieu, Paris)
Shiva diagrams for composite boson many body effects

Monday 3 October 2005, at 17.00, Theory Seminar Room,
Roland Combescot (ENS Paris)
Collective mode and structure factor in the BEC-BCS crossover from BCS model

Wednesday 21 September 2005, at 14.30, Aula 7,
Mauro Antezza
Surface-atom force out of thermal equilibrium

Wednesday 14 September 2005, at 14:00, Theo. Sem. Room,
Informal discussion with Chris Pethick (Nordita, Copenhagen)

Tuesday 30 August 2005, at 11:00, Theo. Sem. Room
Luca Pezzè
Phase Sensitivity of a Mach-Zehnder Interferometer

Thursday 28 July 2005, at 15.30, Theo. Sem. Room
Jörg Schmiedmayer (Univ. Heidelberg)
Ultra cold atoms in 1d Traps on Atom Chips: Coherent splitting of an Atom Cloud

Tuesday 26 July 2005, at 15.00, Theo. Sem. Room
Dimitri Gangardt (Univ. Paris-Sud)
Exact evolution of a Harmonically Confined Tonks-Girardeau Gas

Tuesday 19 July 2005, at 15.00, Theo. Sem. Room
Grigori Astrakharchik
Local density approximation for a perturbative equation of state

Thursdau 7 July 2005, at 15.00, Theo. Sem. Room
Adilet Imambekov (Harvard, USA)
Exactly solvable case of a one-dimensional Bose-Fermi mixture

Friday 1 July 2005, at 15:00, Theo. Sem. Room
Filippo Caruso (Catania)

Storing Quantum Information via Atomic Dark Resonances

Thursday 30 June 2005, at 15:00, Theo. Sem. Room
Grigori Astrakhartchik
Momentum distribution and condensate fraction of a Fermi gas in the BCS-BEC crossover

Monday 27 June 2005, at 15:00, Theo. Sem. Room
Fabio Anselmi (Hertfordshire Univ.)
Complementarity between extractable mechanical work, accessible entanglement, and ability to act as a reference frame, under arbitrary superselection rules

Friday 24 June 2005, at 15:00, Theo. Sem. Room
Joe Carlos (Los Alamos)
Dilute Atomic Fermi Gases near the Unitary Limit; Fully Paired plus (small) polarizations

Friday 17 June 2005, at 15:30, Theo. Sem. Room
Cesare Tozzo
Equilibrium properties of homogeneous vortex lattices in rotating Bose-Einstein condensates

Thursday 16 June 2005, at 17:00, Theo. Sem. Room
Sylvain Schwartz (Orsay)
Towards an active atom gyroscope

Monday 13 June 2005, at 15:00, Aula 1
Gabriele De Chiara (SNS Pisa)
Quantum Information in Spin Networks

Thursday 9 June 2005, at 15:00, Theo. Sem. Room
Philipp Treutlein (MPI and LMU, Munich)
Towards a collisional phase gate on an atom chip

Tueday 7 June 2005, at 15:30, Theo. Sem. Room
Luca Salasnich (INFM Milano)
Quantum Phases of an attractive BEC in a toroidal trap

Friday 27 May 2005, at 15:00, Theo. Sem. Room
Meret Krämer presents some ideas about the
Analogue of pn-junctions with ultracold bosons in a lattice

Friday 20 May 2005, at 11.30, Theo. Sem. Room
Sorin Paraoanu (Jyvsäkylä)
A view from the other side of the road to quantum computing: superconducting qubits

Thursday 19 May 2005, at 15.00, Theo. Sem. Room
Päivi Törmä (Jyvsäkylä)
Spectroscopy and finite size effects in superfluid atomic Fermi gases

Tuesday 17 May 2005, at 16.00, Theo. Sem. Room
Iacopo Carusotto
Many-body physics of exciton-polaritons in semiconductor microcavities: a quantum fluid of light

Friday 6 May 2005, at 16.30, Theo. Sem. Room
Mauro Antezza
New asymptotic behaviour of the surface-atom force out of thermal equilibrium

Friday, 29 April 2005, at 15:00, Theo. Sem. Room
Paolo Zanardi (ISI Torino)
Entanglement and Quantum Phase Transition in Low Dimensional Spin Systems

Tuesday, 28 April 2005, at 17:00, Aula 21
Colloquium di Facoltà, Sandro Stringari:
Verso lo zero assoluto

Tuesday, 19 April 2005, at 15:00, Theo. Sem. Room
Pietro Faccioli (Dipartimento di Fisica, Trento)
Collective phenomena and topological fluctuations in the QCD vacuum

Monday, 7 March 2005, at 15:45, Theo. Sem. Room
Jordi Mur Petit (Univ. Barcelona)
Ultracold multi-component gases

Friday, 18 Feb 2005, at 15:00, Theo. Sem. Room
Christian Trefzger
Quantum gates with fermions in static potentials

Thursday, 10 Feb 2005, College de France, Paris.
Stringari's inaugural lecture of his *course on Bose Einstein Condensation and superfluidity,* as Titulaire de la Chaire européenne 2004-2005

Tuesday, 1 Feb 2005, Theo. Sem. Room at 15:00
Dimitri Gangardt (Orsay)
Exact density matrix of trapped Tonks gas

Monday, 31 Gen 2005, Theo. Sem. Room at 17:30
Rosario Fazio (SNS Pisa)
Solid state quantum information

Friday, 14 Gen 2005, Aula seminari, first floor, at 15:45
Alessio Recati
BCS-BEC crossover in 1D trapped cold gases

2004

Monday, 20 december 2004

* Guido Pupillo (NIST, Gaithersburg):
  The Mott state in optical lattices: adiabatic realization, finite temperature effects and applications (Aula seminari teorici, second floor, at 10:30)
* René Stock (Albuquerque):
  Quantum logic in optical lattices via trap induced shape resonances in controlled atomic collisions (Aula seminari teorici, second floor, at 15:45)

Friday, 17 December 2004

* Maciej Lewenstein (Hannover):
  Atomic ultracold gases in trimerized Kagome lattice: from quantum spin liquid to quantum antiferromagnetic gel (Aula seminari, first floor, at 10:45)
* Paolo Pedri:
  PhD defence (Aula 20, at 15:30)

* Wolfgang Ertmer (Hannover):
  Atomic quantum sensors, a versatile tool for experiments in fundamental physics(Aula seminari, first floor, at 17:30)

Wednesday, 15 December 2004

* Saverio Moroni (Roma):
  Computational spectroscopy of doped He clusters (Aula seminari, first floor, at 10:00)
* Gora Shlyapnikov (Orsay):
  Two-dimensional Bose gas under extreme rotation (Aula seminari, first floor, at 10.45)
* Grigori Astrakharchik:
  PhD defence (Aula 3, at 14:30)

Friday, 26 Nov. 2004, at 15.45, Theo. Sem. Room
Zbigniew Idziaszek talks about
Two ultracold atoms in an anisotropic harmonic trap

Friday, 19 Nov. 2004, from 14.00 to 17.00:
ECT*-BEC meeting at Villa Tambosi.
Talk by Pitaevskii about
Coherence and superfluidity of BEC in optical lattices, followed by short talks (20 min) by Menotti, Jackson and Antezza.

Thursday, 4 Nov. 2004, at 10.30, Aula Sem. Matematica
Riccardo Sturani (Univ. Geneva) talks about
Matter-wave interferometers as gravitational wave detectors

Friday, 22 Oct. 2004, and Monday, 25 Oct., at 15.45, Theo. Sem. Room
Uffe Poulsen talks about
Entanglement in ground state condensates and quantum gates

Tuesday, 19 Oct. 2004, at 15.00, Aula 14A
Leonardo Fallani (LENS) talks about
BEC in random potentials: first experimental observations

Friday, 15 Oct. 2004, at 11.00, Theo. Sem. Room
2nd year PhD Seminars by Cesare Tozzo
Parametric excitation of a Bose-Einstein condensate in a 1D optical lattice
and Marco Cozzini *Vortex lattice in rotating Bose-Einstein condensates*

Monday, 11 Oct. 2004, at 15.45, Theo. Sem. Room
Iacopo Carusotto talks about
Interference of Fermi gases and atom-interferometrical detection of the superfluid order parameter in an ultracold Fermi gas

Monday, 27 Sept. 2004, at 15.45, Theo. Sem. Room
Lev Pitaevskii talks about
his recent work on Solitons

Tuesday, 28 Sept. 2004, at 15.45, Theo. Sem. Room
Henrik Smith (Oersted Lab, Univ. Copenhagen) talks about
Viscous relaxation and collective oscillations in a trapped Fermi gas near the unitarity limit

Monday, 6 Sept. 2004, at 15.45, Theo. Sem. Room
Sara Ianeselli talks about
Beyond the Landau Criterion for Superfluidity

Thursday, 26 Aug. 2004, at 15.45, Theo. Sem. Room
Laura Faoro (I.S.I. Torino)
Towards geometric and topological computation with network of Josephson junctions

Friday, 2 July 2004, at 15.45, Theo. Sem. Room
S. Yukalov (Dubna) talks about
Nonground-State Bose-Einstein Condensates of Trapped Atoms

Friday, 25 June 2004, at 15.45, Theo. Sem. Room
Meret Krämer talks about
Velocity of sound in a Bose-Einstein condensate in the presence of an optical lattice and transverse confinement

Friday, 18 June 2004, at 15.45, Theo. Sem. Room

Gianmaria Falco talks about
Atomic Fermi Gases at Feshbach Resonance

Monday, 14 June 2004, at 15.45, Theo. Sem. Room
Iacopo Carusotto talks about
Physics of a degenerate Bose gas of exciton-polaritons in a semiconductor microcavity

Monday, 26 Apr 2004, at 17.00, Theory Seminar Room
Giuliano Orso talks about
BCS critical temperature in dilute Fermi gases in optical lattices

Friday, 16 Apr 2004, at 15.45, Theory Seminar Room
Rafael Guardiola (Valencia) gives a talk on
Magic numbers in the production of helium drop

Monday, 5 April 2004, at 15.45, Theo. Sem. Room
Informal talk by Paolo Pedri on
Mott-insulator phase of coupled 1D atomic gases in 2D optical lattices

Monday, 22 March 2004, at 15.45, Theo. Sem. Room
Brian Jackson talks about
Expansion and entropy production of a zero temperature Fermi gas

Monday, 15 March 2004
Franco Dalfovo
Adiabatic and non-adiabatic phonon evaporation in expanding BEC

Monday, 8 March 2004
Nandini Trivedi (TIFR - Mumbay)
Superfluidity/ Superconductivity in strongly interacting systems: Some lessons from High Tc Superconductors

Friday, 27 Feb 2004
Meret Kraemer
BEC in rotating traps and optical lattices

Tuesday, 24 Feb 2004

Andrea Perali (Univ. Camerino)
BCS-BEC crossover in ultracold Fermi gases

Tuesday, 17 Feb 2004
Alexander Fetter (Univ. Stanford)
Annular Structures in Rapidly Rotating Bose-Einstein Condensates

Tuesday, 10 February 2004
Zbigniew Idziaszek
Microcanonical fluctuations of a Bose-Einstein condensate

Tuesday, 27 January 2004
Giovanna Morigi (Univ. Ulm)
Eigenmodes spectrum of a Coulomb chain in a harmonic potential

Friday, January 23, 2004
Trento-Tübingen meeting
Franco Dalfovo: *The fate of phonons in expanding condensates*
Giovanni Cennini: *All Optical Atom Laser*
Chiara Menotti: *Sound propagation in optical lattices*
Sebastian Slama: *Collective Atomic Recoil Laser*
Luciano Viverit: *Fermions in optical lattices for quantum computation*
Sebastian Guenther: *Degenerate mixtures of Rb and Li in tighly confining traps*
Stefano Giorgini: *Degenerate gases in quasi 1D traps*
Jozsef Fortragh: *Onchip laboratory for Bose Einstein condensates*

Monday, 20 January 2004
C. Salomon (ENS Paris)
Recent results on cold Fermi gases at ENS

Friday, 16 January 2004
John D. Reppy (Cornell University)
High Resolution Heat Capacity Measurements and Hyperuniversality

Tuesday, 13 January 2004
Lev Pitaevskii
Kinetic energy of a Bose condensate

Education and training

The BEC Center has contributed to the PhD programme of the Physics Department of the University of Trento, by funding several fellowships. Several students are presently preparing their doctoral thesis under the supervision of members of the BEC center and/or in the framework of international collaborations.