SuperFluctuations 2021

Fluctuations and Highly Non Linear Phenomena in Superfluids and Superconductors

June 14-16, 2021

On-line Conference – **Book of Abstracts** (invited and video talks)

Jointly organized by: University of Camerino and University of Padova, *Italy*

in synergy with Columbia University, USA

Frontiers of Condensed Matter Physics lecture series

The Conference SuperFluctuations this year will be organized fully on-line. This is a way to overcome the impossibility for many of us to attend scientific events in presence because of the COVID-19 emergency, sharing in a highly interactive manner our recent scientific achievements and future research perspectives. During the on-line conference we will discuss opportunities to establish large collaboration efforts or empowering existing ones, as well as to plan joint participation to international projects. Young participants will be able to look and discuss opportunities for doctoral or post doc positions. Cross-fertilization, merging of capacities, and methods will be encouraged in a very interactive atmosphere.

This is year we are happy to announce the collaboration with Prof. Yasutomo Uemura, Columbia University - USA, to stream selected invited talks among the scientific community attending the lecture series on "*Frontiers of Condensed Matter Physics*" (FCMP).

Main Topics:

Fluctuations and BCS-BEC crossover phenomena in multicomponent and low dimensional systems.

Quantum Technologies and Novel Phenomena with Bose and Fermi Mixtures.

Highly nonlinear phenomena: Josephson and Andreev effects, topological defects, vortex states.

Novel quantum phenomena in multicomponent / multigap superconductors and superfluids.

Innovative numerical methods: Machine Learning and its applications.

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Transition from a BEC to supersolid to quantum droplets in dipolar condensates in a ring potential

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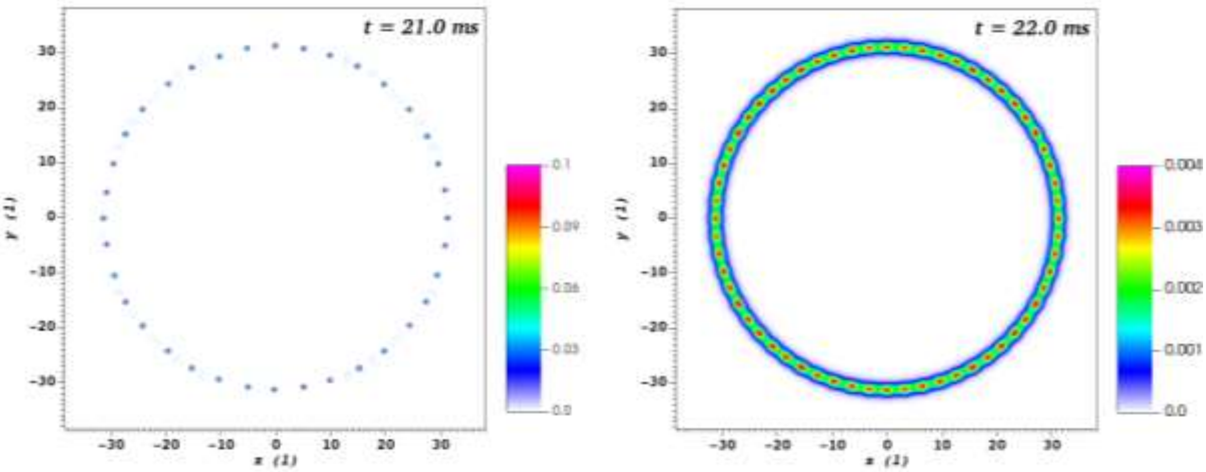
We study formation of quantum droplets in dipolar Bose-Einstein condensates in a ring-shaped geometry using numerical techniques. A condensate is initially prepared in a stable ground state of the system, and droplet formation is triggered by a sudden quench of the contact interaction. We investigate possible phases of the system and how the number of the obtained droplets depends on the total number of atoms in the system, as well as on the strength of the contact and the dipole-dipole interaction. These results can be used in experiments to fine-tune parameters of the system to produce droplets of desired size. Furthermore, we study the emergence of supersolidity in the system, when droplets are formed due to the contact interaction quench, but the common phase is still preserved among spatially separated droplets. The quasi-1D geometry imposes additional constraints in the system, in particular when the particle density is higher, such that quantum fluctuation effects become more prominent. We use the Bogoliubov-Popov theory for dipolar Bose systems, including the dipolar analogue of the Lee-Huang-Yang correction [1, 2], and take into account the condensate depletion due to quantum fluctuations.



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Multigap superconductivity and topological states in gallenene

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Structural simplicity combined with a rich variety of electronic properties are key signatures of elemental two-dimensional (2D) materials. 2D gallium structures, coined *gallenene*, are among the newest members of this family, first fabricated in 2018 [1]. By combining *ab initio* calculations with Migdal-Eliashberg theory we reveal that several gallenene structures are intrinsically superconducting through the electron-phonon coupling mechanism [2].

The first considered gallenene phase, so-called Ga-100 gallenene, is a planar monolayer isostructural with graphene (see figure). As such, it is the structurally simplest 2D superconductor known to date. What's more, we found that it hosts a Dirac-type band crossing among its excited states, with topologically non-trivial properties. This leads to topologically insulating behavior induced by spin-orbit coupling, accompanied by distinct edge states. These effects persist at a considerably higher temperature than in graphene, owing to the higher atomic mass of gallium compared to carbon.

Our fully anisotropic Eliashberg calculations show distinctly three-gap superconductivity in Ga-100 gallenene (see figure), in contrast to the alternative buckled Ga-010 gallenene phase, which exhibits a single anisotropic superconducting gap. Strikingly, the critical temperature (T_c) of the gallenenes is in the range of 7-10 K, exceeding the T_c of bulk gallium from which it is exfoliated. Finally, we explore chemical functionalization of Ga-010 gallenene with hydrogen, leading to *gallenane*. We show that this hydrogenation not only enhances the T_c to 17 K, but also induces two distinct superconducting gaps in gallenane, in contrast with the single gap of its pristine counterpart.

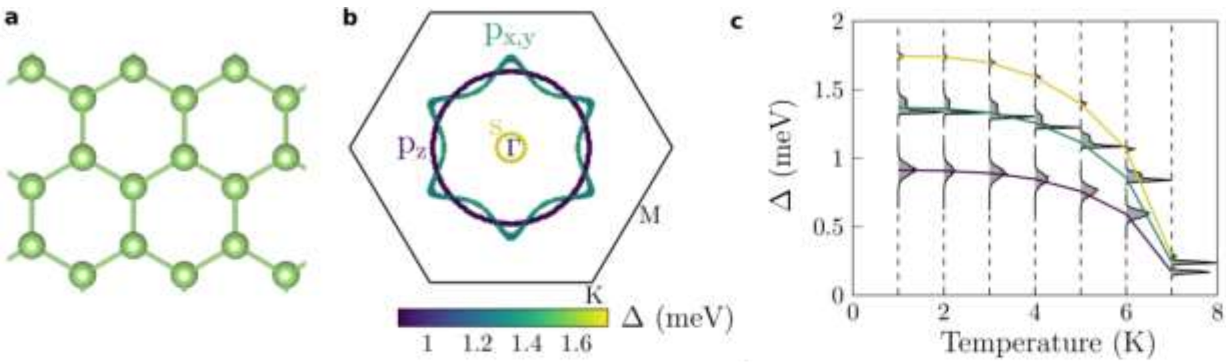

Figure: Structural and superconducting properties of Ga-100 gallenene. **a.** Honeycomb crystal structure, **b.** distribution of the superconducting gap Δ on the Fermi surface, showing three distinct superconducting gaps, **c.** evolution of the gap distribution with temperature, revealing T_c=7 K.

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The quantum mechanism for room temperature superconductivity

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We have recently shown [1] that room temperature superconductivity in CSH_x and related high T_c a superconductivity in pressurized hydrides like H_3S and LaH_{10} occurs near the BCS-BEC crossover in materials showing the nanoscale superstripes landscape made of weakly interacting quantum stripes made by lattice heterogeneity. Pressure moves the chemical potential near Lifshitz transitions in a multigap system giving a resonant superconductivity appearing in the many body quantum mechanics framework of Wentzel, Feynman, Dirac path integrals because of the mechanism driven by Fano Feshbach resonance for configuration interation between different open and closed pairing channels [1-6].

Room temperature superconductivity emerges at a Fano-Feshbach resonance where BCS pairing channels resonate with a strong coupling pairing channel in the BCS-BEC crossover like predicted by the Bianconi-Perali-Valletta theory for weakly interacting quantum stripes [2,3], in agreement with evidence of universal Uemura plot for high temperature superconductors and with the claims of the European patent for *High-temperature superconductors made by metal heterostructures at the atomic limit* [4] and the USA patent for the *Process of increasing the critical temperature Tc of a bulk superconductor by making metal heterostructures at the atomic limit* [5]. In the case of iron based superconductors made of superlattices of quantum wells we remind the key role of hopping between quantum wells to stabilize the strong coupling pairing channel in the BCS-BEC crossover at Fano-Feshbach resonances [6,7]. Finally for the superlattices of 2D quantum wells we report the recent results showing the novel amplification mechanism of the critical temperature in multigap superconductivity tuning the Fano-Feshbach resonance at unconventional Lifshitz transition in a three-dimensional Rashba heterostructure at the atomic limit driven by the internal or external transversal electric field [8].

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Spin and charge order in doped spin-orbit coupled Mott insulators

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We study a two-dimensional single-band Hubbard Hamiltonian with antisymmetric spin-orbit coupling. We argue that this is the minimal model to understand the electronic properties of locally noncentrosymmetric transition metal (TM) oxides such as Sr_2IrO_4. Based on exact diagonalizations of small clusters and the random-phase approximation, we investigate the correlation effects on charge and magnetic order as a function of doping and of the TM-oxygen-TM bond angle θ. For small doping and $\theta \leq 15^\circ$ we find dominant commensurate in-plane antiferromagnetic fluctuations, while ferromagnetic fluctuations dominate for $\theta \geq 25^\circ$. Moderately strong nearest-neighbor Hubbard interactions can also stabilize a charge density wave order. Furthermore, we compare the dispersion of magnetic excitations for the hole-doped case to resonant inelastic x-ray scattering data and find good qualitative agreement.

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Flavour-selective localization in interacting lattice fermions

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A large repulsion between particles in a quantum system can lead to their localization, as it happens for the electrons in Mott insulating materials. Mott insulators have been thoroughly investigated in the last decades, mostly because of their link with high-temperature superconductivity.

The Mott paradigm has recently spawned a new concept, the orbital-selective Mott insulator, where electrons in some orbitals are localize, while others remain itinerant. This idea has been proposed in simple models and it nowadays believed to be central for the understanding of iron-based superconductors [1,2].

We provide a direct experimental realization of this phenomenon, that we extend to a more general flavour-selective localization [2]. By using an atom-based quantum simulator, we engineer SU(3) Fermi-Hubbard models breaking their symmetry via a tunable coupling between flavours, observing an enhancement of localization and the emergence of flavour-dependent correlations [3]. Our realization of flavour-selective Mott physics opens the path to the quantum simulation of multicomponent materials, from superconductors to topological insulators.

This work is the result of collaborations with the authors of Refs. [1-4].

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Sound propagation in two-dimensional Fermi gases

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Sound propagation is a macroscopic manifestation of the interplay between the equilibrium thermodynamics and the dynamical transport properties of fluids. It then represents an intriguing diagnostics tool to test microscopic theories and their emergent features condensed matter systems.

Concerning quantum liquids in their superfluid phase, the renowned Landau's two-fluid theory successfully explained ^{4}He experiments, but it cannot be taken for granted in cold atoms platforms, which usually deal with weakly interacting and much more dilute physical systems.

In this talk, we present some recent results on atomic Fermi gases in two dimensions. Here, second sound measurements are a promising candidate to reveal the onset of the BKT transition, which is somehow more elusive than expected in cold atoms.

Based on:

A. Tononi, A. Cappellaro, G. Bighin and L. Salasnich, arXiv:2009.06491 (to appear in Phys. Rev. A)

Evolution of quantum droplets in a dipolar Bose gas in 1D

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We theoretically investigate collective excitations and the droplets formation in a one-dimensional dipolar gas of bosonic atoms in a trap. We model the dipolar gas with an effective quasi-one-dimensional Hamiltonian using a variational approximation based on the Lieb-Liniger gas Bethe ansatz wave function and perturbation theory [1]. We calculate the breathing mode frequencies while varying polarization angles by a sum-rule approach and find they are in good agreement with recent experimental findings [2]. Finally, using a generalized Gross-Pitaevskii equation we study the formation and the dynamics of quantum droplets as a function of the interaction and number of particles.

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Electron-hole superfluidity in strained Si/Ge type II heterojunctions

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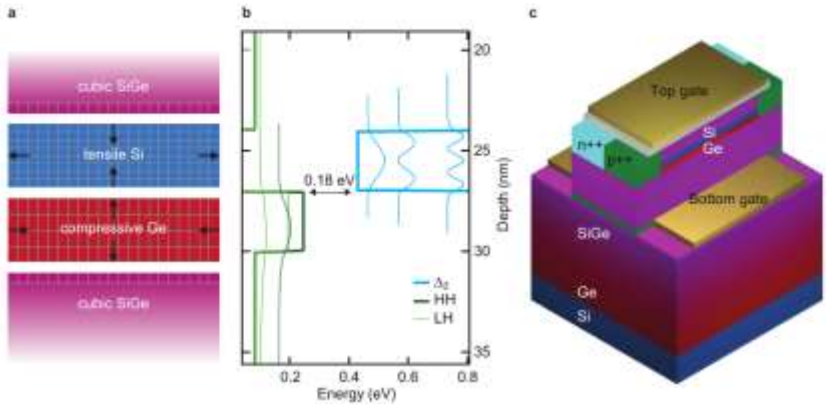
We predict that spatially indirect excitons in a lattice-matched strained Si/Ge bilayer embedded into a germanium-rich SiGe crystal will lead to mass-imbalanced electron-hole superfluidity and Bose-Einstein Condensation (BEC) at experimentally accessible densities and temperatures [1]. This opens the way to an enabling material platform with scaling compatibility with industrial semiconductor technology [2].



Holes would be confined in a compressively strained Ge quantum well and electrons in a lattice-matched tensile strained Si quantum well.

The device architecture requires no insulating barrier at the Si/Ge interface, because of the type II band alignment. This means that the electrons and holes can be kept very close, strengthening the electron-hole pairing attraction, but still kept separate, which strongly inhibits rapid electron-hole recombination.

An additional advantage is that the band alignment allows a one-step procedure for making independent contacts to the electron and hole layers, overcoming a significant obstacle in device fabrication for counterflow configurations [3].

We find superfluidity up to temperatures of a few Kelvin and carrier densities up to 6×10^{10} cm^{-2}. The large mismatch of the electron and hole effective masses may lead to exotic new superfluid phases [4].

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Two-dimensional supersolidity in a dipolar quantum gas

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Quantum physics often makes possible conceptual paradoxes, which appear ephemeral to our classical intuition. A recent example is the discovery of supersolid states in ultracold dipolar gases. Such states combine properties of superfluidity with those of a crystalline order.

This talk traces the fundamental steps for the observation of supersolidity from the perspective of the Innsbruck experiments. We will discuss how a quantum gas of erbium and dysprosium atoms spontaneously breaks its translational symmetry, creating a periodic modulation of its density, while maintaining a quantum phase coherence. We will show how in our experiments it is possible to drive the system to a supersolid phase transition either by cooling a thermal gas or by modifying the short-range interaction from an unmodulated dipolar condensate. Finally, we will report on the recent observation of extending the supersolid properties to two dimensions, and highlight the open questions which still remain to be understood.

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Damped Langevin dynamics in Josephson junctions

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Dynamics in Josephson junctions has been extensively investigated experimentally and theoretically so far. In particular, recently, it has been found that a Bose Josephson junction in a head-to-tail configuration exhibits damping in the dynamics [1] due to the intrinsic coupling between the Josephson mode and phonon bath modes, which occurs even without any external reservoir.

Based on these recent studies, in our presentation, we discuss the dynamics in an elongated bosonic Josephson junction [1, 2]. Starting from a microscopic Lagrangian for the Bose Josephson junction, we derive an intrinsic coupling between the Josephson mode and other phonon modes, which is different from the picture of the Caldeira-Leggett model. This coupling leads to damped Langevin dynamics in the Josephson mode. In addition to the thermal fluctuations in the phonon bath, we included the quantum fluctuations and investigate quantum effects on the dynamics of correlations.

In parallel, we also investigate the Langevin dynamics in a resistively and capacitively shunted Josephson (RCSJ) junction, which is governed by the current noise and damping because of the resistor in the junction [3]. This model corresponds to a system in contact with an external reservoir, which is distinct from the intrinsically coupled Josephson junction mentioned above. We observe the relaxation of the correlations of phase and voltage to finite values in the long-time limit due to the current noise that includes both thermal and quantum fluctuations. Compared to the low-temperature regime where quantum fluctuations are dominant, we also find an earlier decay of coherence at a higher temperature in which thermal fluctuations dominate.

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Quantum mixtures of ultracold gases

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I will review some recent results on the problem of quantum mixtures of ultracold gases, which have received great attention from the experimental point of view in connection with the miscibility transition and possible itinerant ferromagnetism as well as the formation of quantum droplets stabilized by beyond mean-field interaction terms. Concerning the theoretical treatment, I will discuss both perturbative approaches and quantum Monte-Carlo methods which are well suited to investigate regimes of strong correlations.

Dissipation and relaxation dynamics of mobile magnetic impurity with Rashba type spin-orbit coupling in an ohmic heat bath

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Spin-orbit coupling (SOC) is known to appear in various systems and is expected to open new physics. In recent years, SOC is realized in ultra-cold atom systems [1] with experimental controllability and has attracted much attention via its effect on Bose-Einstein condensates both from the theoretical and experimental sides. Spin relaxation, on the other hand, is an important phenomenon for spin dynamics and is applied in NMR technology. SOC can explain a spin relaxation mechanism [2] in such a way that momentum fluctuations due to collisions between a particle and another one lead to variation of the effective magnetic field through SOC. Concerning this mechanism, there are many phenomenological works. In the present work we try to describe the spin relaxation through a velocity dissipation from a microscopic model. We consider a single particle Rashba-type SOC system that interacts with an infinite number of harmonic oscillators and thus undergoes momentum dissipation. If the interaction is bilinear in coordinate space, the environment is equivalent to that in the Caldeira-Leggett model [3] that describes a Brownian particle moving in a medium with dissipation and noise. In this work, we eliminate the degrees of freedom of environmental oscillators by using a path integral method, a la Feynman-Vernon method [4], and obtain the effective action for the impurity particle. Then, we derive the quasi-classical equations of motion for the spin and momentum of the particle without noise in the quasi-classical approximation that is good when the time scale of decoherence is shorter than the dynamics. Finally, we show the resultant spin relaxation and momentum dissipation dynamics.

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Functional renormalization group for cold atom mixtures

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The functional renormalization group (FRG) is a modern non-perturbative formulation of Wilson's RG, where the aim is to compute the effective action by solving an RG equation [1,2]. The FRG has proved a promising tool to describe the long-distance properties of a variety of cold atom systems, particularly in strongly-correlated scenarios [3]. In this talk, I will give an overview of our recent work on bosonic mixtures with the FRG, including repulsive Bose-Bose mixtures [4] and the Bose polaron [5]. I will also outline current and future studies of other quantum mixtures.

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2D BCS-BEC crossover in a layered superconductor

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The Bardeen-Cooper-Schrieffer (BCS) condensation and the Bose-Einstein condensation (BEC) are the two extreme limits of the ground state of the paired fermion systems, which are theoretically predicted to continuously connected through an intermediate regime [1]. We report the two-dimensional (2D) BCS-BEC realized in a gate-controlled superconductor, electron doped layered material ZrNCl. To observe this phenomenon, we utilized an ionic gating method, which is well known as a powerful tool to control the carrier density in a large scale and induced 2D superconductivity [2].

We have succeeded in controlling the carrier density by nearly two-orders of magnitude, and established an electronic phase diagram through the simultaneous experiments of resistivity and tunneling spectra on the ionic gating devices. We found T_c exhibits dome-like behavior, and more importantly, a wide pseudogap phase in the low doping regime. In the low carrier density limit, T_c scales as $T_c/T_F = 0.12$, where T_F is the Fermi temperature [3], which shows fair agreement with the theoretical prediction of the upper limit $T_c/T_F = 1/8$ for the 2D BEC-BEC crossover [4, 5].

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Spatial structure of the density correlation functions and the pair wave function throughout the BEC-BCS crossover

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We analyze the spatial structure of a homogeneous mixture of a two-component Fermi gas, where the modulation of an effective interaction allows a crossover from a Bose-Einstein condensate (BEC) of composite bosons to a Bardeen-Cooper-Schrieffer (BCS) superfluid [1,2,3]. We study the large-distance behavior of three two-body distributions: the BCS pair wave function, the density correlation function of particles of different species and the density correlation function of like particles [4]. An exponential decay length and a spatial frequency of oscillation are calculated throughout the full BEC-BCS crossover. Good agreement is found with a postulated "pair-binding" wave function which has an exponential decay length given by a binding energy. The oscillatory behavior of the distributions gives rise to a qualitative picture of nested spin-shells that vary their separation throughout the crossover. Also, we report analytic expressions for the mean pair size and the correlation lengths of both density correlation functions. These distributions allow for a novel description of the spatial structure of the interacting Fermi superfluid along the crossover.

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BCS-BEC crossover and topological superconductivity in an Iron based superconductor

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$Fe_{1+y}Se_xTe_{1-x}$ is a nearly compensated semimetal, where both electron and hole pockets are very shallow, with Fermi energies, ε_F, of only a few meV. We realize the BCS-BEC crossover by tuning the Fermi energy via chemical doping, which permits us to systematically change Δ/ε_F from 0.16 to 0.50, where Δ is the superconducting gap. We use angle-resolved photoemission spectroscopy to measure the Fermi energy, the SC gap and characteristic changes in the SC state electronic dispersion as the system evolves from a BCS to a BEC regime.

The same compound has recently emerged as a promising candidate to host topological superconductivity. We show that the small Fermi energy combined with the strong electronic correlations in $Fe_{1+y}Se_xTe_{1-x}$ allows a unique situation where a relatively small spin-orbit coupling can lead to topological superconductivity with well isolated Majorana states in the vortex cores.

Exciton Condensation in van der Waals heterostructures

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A pair of electron and hole across the interface of semiconductor heterostructure can form a bound quantum state of the interlayer exciton. In a coupled interface between atomically thin van der Waals layers, the Coulomb interaction of the interlayer exciton increases further. Coulomb drag effect is a mesoscopic effect which manifests many-body interactions between two low-dimensional systems, which has served an extremely useful probe the strong correlation in quantum systems. In this presentation, we will first discuss observing interlayer exciton formation in semiconducting transition metal dichalcogenide (TMDC) layers. Unlike conventional semiconductor heterostructures, charge transport in the devices is found to critically depend on the interlayer charge transport, electron-hole recombination process mediated by tunneling across the interface. We demonstrate the enhanced electronic, optoelectronic performances in the vdW heterostructures, tuned by applying gate voltages, suggesting that these a few atom thick interfaces may provide a fundamental platform to realize novel physical phenomena. In addition, spatially confined quantum structures in TMDC can offer unique valley-spin features, holding the promises for novel mesoscopic systems, such as valley-spin qubits.

In the second part of the presentation, we will discuss magneto-exciton condensation. In this electronic double layer subject to strong magnetic fields, filled Landau states in one layer bind with empty states of the other layer to form an exciton condensate. Driving current in one graphene layer generates a near-quantized Hall voltage in the other layer, resulting in coherent exciton transport. In our experiment, capitalizing strong Coulomb interaction across the atomically thin hBN separation layer, we realize a superfluid condensation of magnetic-field-induced excitons. For small magnetic fields (the BEC limit), the counter-flow resistance shows an activation behavior. On the contrary, for large magnetic fields limit where the inter-exciton separation decreases (the BCS limit), the counter-flow resistance exhibits sharp transitions in temperature showing characters of Berezinskii-Kosterlitz-Thouless (BKT) transition. Furthermore, complete experimental control of density, displacement and magnetic fields in our graphene double layer system enables us to explore the rich phase diagram of several superfluid exciton phases with the different internal quantum degrees of freedom.

Linear and non Linear Terahertz Photonics based on Topological Matter

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The great potential of electrons (Dirac and Weyl) with linear energy/momentum dispersion for integrated photonics has been readily recognized after their discovery in graphene. Dirac carriers are also found in Topological Insulators (TI), quantum systems having an insulating gap in the bulk and intrinsic Dirac metallic states at the surface, while Weyl electrons appear in topological semimetals.

In this talk, after a brief panoramic of Topological Quantum Materials properties, I will discuss their applications in linear [1] and non-linear optics [2] and plasmonics [3,4,5]. In particular, I will review several experiments proving the exotic optical phenomena appearing in topological matter and its potential applications in quantum devices.

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FRAGILE GLASS TRANSITION IN THIN SUPERCONDUCTING FILMS

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The melting transition in two dimensions can occur in two steps via an intermediate phase called "hexatic" phase. The 2D vortex lattice forming in type-II superconducting films is a paradigmatic system to study this two-step melting transition. In a recent work [1], by combining transport and STS imaging in amorphous MoGe, it has been shown that the hexatic state carries additional signatures in transport, with a rather strong suppression of the vortex diffusivity in the hexatic state as compared to the isotropic liquid. Here we use Monte Carlo simulations on the XY model in transverse field to study the dynamical behavior of the vortex lattice and to simultaneously characterize the solid phase via the superfluid stiffness. We show that, in analogy with previous work in soft colloids, a so-called heterogeneous dynamics emerges at the verge of the isotropic to the hexatic transition. In our case this manifest through a strong suppression of the diffusivity well reproduced by a Vogel-Fulcher-Tamman (VFT) law. The temperature T_0 where vortex diffusivity vanishes coincides with the temperature where a true solid phase is established, as characterized by a finite superfluid stiffness. These theoretical results are compared to recent magnetotransport measurements in thin MoGe films.

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Solitons and polarons in ultracold bosonic mixtures

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The realization of multicomponent systems offers a natural playground to observe nonequilibrium effects in a more general framework. Restricting to two-component BECs, one notices already a rich variety of phases in the ground state. In purely repulsive mixtures, one observes a homogeneous superfluid or a phase separation when inter-species repulsion overcomes the intra-species interaction strength. In the attractive regime a series of recent experiments showed the formation of dilute self-bound droplet states in a two-component BEC both in a tight optical waveguide and in free space, closely following the theoretical predictions. In the quasi one-dimensional geometry, upon varying the mean-field interaction from the weakly to the strongly attractive regime, one observes a smooth crossover between bright soliton states and self-bound droplets. In the first part we investigate the quench dynamics of a two-component Bose mixture and study the onset of modulational instability, which leads the system far from equilibrium. Analogous to the single-component counterpart, this phenomenon results in the creation of trains of bright solitons. We also explain the significantly different soliton dynamics in a realistic experimental homonuclear potassium mixture in terms of different intraspecies interaction and loss rates. In the second part I will discuss the properties of impurities in a uniform and self-bound states of heteronuclear mixtures inspired by recent experiments, by tuning the interactions from the weakly to the strongly attractive regime.

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Soliton dynamics in spin-orbit coupled Bose-Einstein condensates

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Abstract

We analyze the dynamics of dark-bright and dark-dark type solitons of the Manakov model in Rashba spin-orbit (SO) coupled Bose-Einstein condensates confined in 1D boxlike traps at absolute zero temperature. For the sidewalls of the box potential, we consider two forms: one is a power-law type and another a Gaussian type. Depending on the Rashba, SO coupling and the interatomic interactions, three ground-state phases, namely, stripe, plane wave, and zero-momentum phases, are identified. We simulate the time evolution across these phases by varying the Rashba and SO coupling strengths, and the nonequilibrium dynamics of the system are studied. We also investigate the effect of trap parameters on the dynamics of the various phases of the system.

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Toward a complete T=0 phase diagram of coupled electron-hole conducting layers in solids

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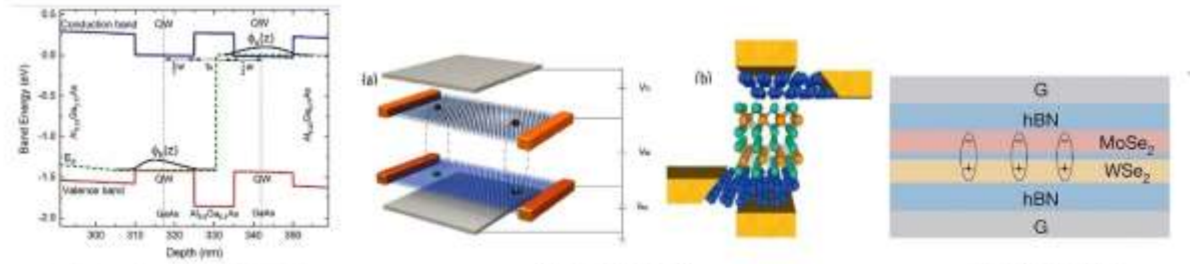
In recent years there have been a lot of theoretical and experimental studies in double electron-hole layers in heterostructures, Systems include GaAs double quantum wells (DQW)[1] and, more recently, double graphene bilayers (DBLG) with an hBN or WSe_2 barrier[2] and
double transition metal dichalcogenides (DTMD) such as $MoSe_2$-WSe_2 with an hBN barrier[3].



GaAs DQW D-BLG D-TMD

A big motivation for the studies has been that bound states of electron-hole pairs in these solids may condense into a superfluid/BEC at low temperatures, and there is now experimental evidence that this indeed happens. To maximise the strength of the electron-hole coupling, most attention has focused on minimising the layer separation *d* while keeping the layers electrically isolated from each other to inhibit electron-hole recombination[4].

However, the full zero temperature phase diagram that encompasses very large values of *d* also, is extraordinarily rich. Taking as the length scale the effective Bohr radius $a_B^* = 4\pi\varepsilon\hbar^2/m^*e^2$, the other significant parameter of the phase space is the average spacing between the electrons or holes within their layers r_0, which we take equal. The phases include coupled electron-hole plasma liquid, electron-hole superfluid, exciton supersolid, and coupled electron-hole Wigner crystals[5]. We present the unified phase diagram for these systems for densities $0<r_0 \lesssim 40$ and layer separations $0<d \lesssim 100$, and we map out the phase boundaries.

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Pair-exchange scattering in a BCS-BEC crossover in superconductors having dispersive and incipient heavy bands

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Crossover between BCS and Bose-Einstein condensation (BEC) regimes becomes especially interesting in two-band superfluid/superconductors, where pair-exchange scattering [1] across the two bands can dominate the physics. This is expected to be relevant to FeSe superconductors in the BCS-BEC crossover regime [2] as well as cold-atom systems such as Yb Fermi gases near an orbital Feshbach resonance [3].

In this contribution, we explore a situation where a dispersive band is accompanied by a heavy *incipient* (i.e., close to but away from the chemical potential) band. Superfluid/super-conducting (SF/SC) gap and the effective scattering length in each band are calculated within the mean-field approximation. We show how the individual SF/SC gap is enhanced by the pair-exchange scattering when the effective mass of the incipient band is increased (see Fig. 1). While the behaviour can basically be understood in terms of a Suhl-Kondo mechanism [1], the heavy incipient band situation dramatically affects the BCS-BEC crossover. We can also point out an analogy of this mechanism with a magnetic Feshbach resonance in cold-atomic physics.

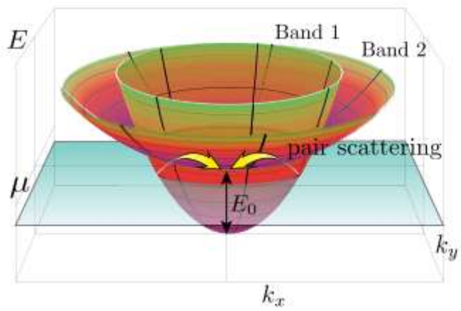

Fig. 1 Band dispersions (against (k_x, k_y) with a $k_z = 0$ projection here) of the two-band system having different effective masses with a band offset E_0. We consider a situation where the chemical potential μ is just below the bottom of the heavy band, making the band *incipient*.

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Non-equilibrium BCS-BEC crossover in a strongly interacting driven-dissipative Fermi gas

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We theoretically discuss the BCS-BEC crossover phenomenon, in the case when the system is *out of equilibrium*. We consider a model driven-dissipative two-component Fermi gas with an *s*-wave pairing interaction, where the main system is coupled with two reservoirs with difference values of the Fermi chemical potential. To include effects of pairing fluctuations in the whole BCS-BEC crossover region, we extend the *T*-matrix approximation (TMA) developed in the thermal equilibrium case to the non-equilibrium steady state, by employing the Schwinger-Keldysh Green's function technique.

We clarify how the BCS-BEC crossover behavior of the superfluid phase transition temperature T_c discussed in the thermal equilibrium case is altered, when the system becomes out of equilibrium. We show that, in addition to the expected result that T_c is suppressed by the non-zero quasi-particle lifetime caused by the two coupled reservoirs, the Fermi momentum distribution which is engineered by the reservoirs anomalously enhances pairing fluctuations with *non-zero* center of mass momentum. Although these pairing fluctuations are similar to those in the Fulde-Ferrell (FF) state discussed in (equilibrium) superconductivity under an external magnetic field, the present non-equilibrium case has no spin imbalance/supercurrent. We will also point out that, when the long-range order of this "FF-like" non-equilibrium Fermi superfluid can be realized, the so-called bi-stability phenomenon may occur, where both this novel pairing state and the ordinary BCS state may stably appear in the same parameter region.

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Dirac Hamiltonians for Bosonic spectra*

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Dirac materials are of great interest as condensed matter realizations of the Dirac and Weyl equations. This physics has been extensively studied in electronic systems such as graphene [1], Weyl, and Dirac semimetals. In contrast, recent studies have highlighted several examples of Dirac-like cones in collective excitation spectra, viz. in phonon, magnon [2], and triplon bands [3]. These cannot be directly related to the Dirac or Weyl equations as they are bosonic in nature with pseudo unitary band bases. We address this issue by constructing a generic deformation scheme that maps any fermionic Hamiltonian and its spectrum to that of a bosonic problem. In particular, we show that any Dirac-like equation can be deformed into a suitable bosonic form.

Our proposed bosonic Dirac structure appears in several known models. In materials, it is realized in $Ba_2CuSi_2O_6C_{12}$ [4] and possibly in $CoTiO_3$ [5]. Our results allow for a rigorous understanding of Dirac phononic and magnonic systems and enable concrete predictions, e.g., of surface states in magnonic topological insulators and Weyl semimetals.

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Quantum behavior of a heavy impurity in a Bose gas

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The scenario of an infinitely heavy impurity in a quantum medium is a fundamental problem in physics, with relevance ranging from electron gases to open quantum systems. Here I will consider the case of a heavy impurity interacting with a dilute Bose gas at zero temperature – the so-called Bose polaron. When the impurity-boson interactions are short ranged, I will show that boson-boson interactions induce a *quantum blockade effect*, where a single boson can effectively block or screen the impurity potential. This behaviour depends on the quantum granular nature of the Bose gas and thus cannot be captured within a standard classical-field description. Using a combination of exact quantum Monte Carlo methods and a truncated basis approach, I will expose how the polaron ground-state energy is linked to the spatial structure of the quantum correlations, spanning the infrared to ultraviolet physics.

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On the Dirty Boson Problem

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The notoriously difficult dirty boson problem amounts to understanding the emergence of coherence and order for ultracold bosonic atoms in the presence of a disorder potential. It appears either naturally like in current carrying wire traps, or artificially like in laser speckle fields. Theoretically it is intriguing because of the competition of localization and interaction as well as of disorder and superfluidity. Here we consider different generalizations of a perturbative approach to the dirty boson problem, worked out by Huang and Meng within a Bogoliubov theory [1].

At first, we consider a time-dependent extension by considering how switching on and off a weak disorder potential affects the equilibration of an initially homogeneous BEC and the emergence of a disorder-induced condensate deformation [2]. We find that in the switch on scenario the stationary condensate deformation turns out to be a sum of an equilibrium part, that actually corresponds to adiabatic switching on the disorder, and a dynamically-induced part, where the latter depends on the particular driving protocol. If the disorder is switched off afterwards, the resulting condensate deformation acquires an additional dynamically-induced part in the long-time limit, while the equilibrium part vanishes.

Afterwards, we implement an approach based on the cumulant expansion method [3] up to second order, that is non-perturbative with respect to disorder and also includes quantum fluctuations. We employ it within an experiment-theory collaboration to study static geometric properties of a harmonically trapped molecular BEC in laser speckle potential [4]. For weak disorder we find quantitative agreement with the Huang and Meng theory, while for strong disorder our theory perfectly reproduces the geometric mean of the experimentally measured transverse widths of the column density profiles.

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Simulating disordered quantum systems using artificial neural networks

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Artificial neural networks are finding increasing usage in computational condensed-matter physics to accelerate or to completely bypass otherwise prohibitive computational problems. In this talk, I will first review our recent investigations on how to exploit generative neural networks to accelerate classical and quantum Monte Carlo simulations of disordered spin models. Then, I will discuss how deep neural networks can be trained to directly predict ground-state energies of disordered atomic systems. In particular, I will present scalable models that accurately describe system sizes larger than those included in the training set, addressing larger linear sizes or larger particle numbers.

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Strong Fulde-Ferrell Larkin-Ovchinnikov pairing fluctuations in polarized Fermi systems

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We calculate the pair susceptibility of an attractive spin-polarized Fermi gas in the normal phase, as a function of the pair momentum. Close to unitarity, we find a strong enhancement of Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) pairing fluctuations over an extended region of the temperature-polarization phase diagram, which manifests itself as a pronounced peak in the pair momentum distribution at a finite pair momentum. This peak should be amenable to experimental observation at achievable temperatures in a box-like trapping potential, as a fingerprint of FFLO pairing. Our calculations rest on a self-consistent *t*-matrix approach [1,2] which, for the unitary balanced Fermi gas, has been validated against experimental data for several thermodynamic quantities.

Preprint: https://arxiv.org/abs/2105.00863

Group webpage: http://bcsbec.df.unicam.it/

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Pairing in 1D spin- and mass-imbalanced Fermi gases

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In this contribution we discuss spin- and mass-imbalanced mixtures of spin-1/2 fermions interacting via an attractive short-range potential in one spatial dimension. Specifically, we address the influence of unequal particle masses on the pair formation by studying suitable two-body correlation functions. To overcome the fermionic sign problem that plagues conventional quantum Monte Carlo algorithms, we employ the complex Langevin (CL) method, which has recently been successfully applied to other cold atomic systems. On the methodological side, this is the first determination of correlation functions within this approach.

Our central observable of interest is the so-called shot noise correlation function, which is experimentally accessible through time-of-flight imaging. At finite spin polarization, the quantity is known to show distinct maxima at momentum configurations associated with the Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) instability. Besides those maxima, we find that additional features emerge in the noise correlations upon increasing the mass imbalance, revealing the stability of FFLO-type correlations against mass imbalance and furnishing an experimentally relevant signature to probe this novel type of pairing.

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Are there Upper Bounds on the Superconducting Transition Temperature?

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Understanding limits on the superconducting transition temperature Tc is a question of fundamental and practical importance. I will begin by describing developments in quantum materials and the BCS-BEC crossover in Fermi gases that challenge conventional ideas on what controls Tc. I will then describe recent progress [1,2] on upper bounds on the superfluid phase stiffness in terms of the optical spectral weight. This in turn leads to upper bounds on BKT Tc of 2D systems irrespective of pairing mechanism or strength. The Tc bound is particularly simple for parabolic dispersion in 2D: Tc cannot exceed one-eighth the Fermi temperature. This bound has recently been realized in gate-tuned Li:ZrNCl [3]. I will next present results for arbitrary band structures and multi-band systems and discuss applications to monolayer FeSe/STO and magic-angle twisted bilayer graphene. I will then turn to the problem of flat bands in 2D where the optical spectral weight is induced by interactions. I will discuss bounds for both trivial and topological flat bands [2] that depend crucially on the quantum geometry of the Wannier functions. Finally, I will discuss the open question of deriving bounds on Tc in 3D.

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Quantum-torque-induced breaking of Josephson dynamics in ultra-cold gases

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In this work [1,2], we use a coherently-coupled mixture of ultracold bosonic gases to implement a system which is well described by dissipationless Landau-Lifshitz equations for ferromagnets. We prepare the system in a far-from-equilibrium fully polarized state and let it evolve. Depending on the local density the atomic spins can either show non-linear Rabi oscillations – at low density – also known as internal Josephson oscillations or being unable to change its polarization. The transition between the two regimes is characterised by a bifurcation in the spin equation of motion. While at very short time the local density picture holds, when magnetic interfaces form we observe the formation of short-wavelength magnetic waves, propagating from the spatial regions corresponding to the bifurcation points. The magnetic waves are generated by the so-called quantum torque and show strong spatial anticorrelations in the magnetization.

Our results suggest that cold gases can be used as a novel platform for the study of far-from-equilibrium (classical) spin dynamics, free from dissipation and in regimes that are not easily accessible in solid-state systems.

Moreover, they pave the way for studying the interplay between the density and the spin degrees of freedom. First results and near future perspectives are briefly discussed at the end of the talk.

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Websites:

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Interaction-resistant metals in multicomponent Fermi systems

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We analyze two different fermionic systems that defy Mott localization showing a metallic ground state at integer filling and very large Coulomb repulsion. The first is a multiorbital Hubbard model with a Hund's coupling (this physics has been widely studied, and the new metallic state is called a Hund's metal), and the second is a SU(3) Hubbard model with a patterned single-particle potential designed to display a similar interaction-resistant metal in a setup which can be implemented with SU(N) ultracold atoms. With simple analytical arguments and exact numerical diagonalization of the Hamiltonians for a minimal three-site system, we demonstrate that the interaction-resistant metal emerges in both cases as a compromise between two different insulating solutions which are stabilized by different terms of the models. This provides strong evidence that the Hund's metal is a specific realization of a more general phenomenon which can be realized in various strongly-correlated systems.

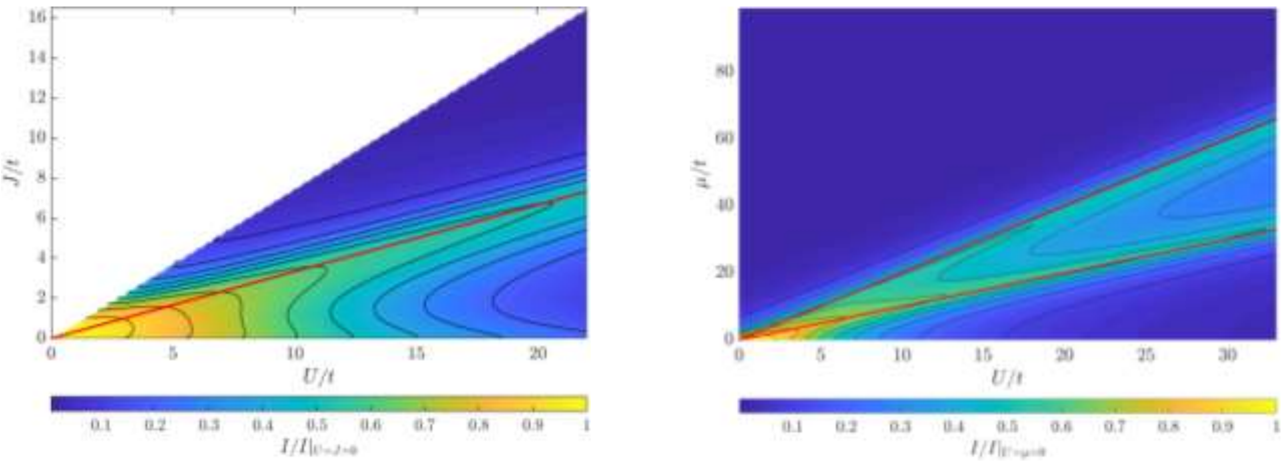

Figure: Degree of metallicity. Left panel: three-band Hubbard model with Kanamori interactions. Right panel SU(3) Hubbard model with patterned on-site potential. In both panels, red lines correspond to states featuring interaction-resistant metallicity.

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Quantum Simulation with Matter Waves in Engineered Optical Lattices

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A quantum simulator to simulate an extremely nontrivial task of another system is an essential requirement for quantum enhanced implementation of various novel phenomena [1]. Optical lattices are found to be the most favorable candidate for quantum simulation, envisaged from the high tunability of the system and the potential. Bose-Einstein condensate (BEC) under disordered optical lattices has become one of the most paramount fields and the underlying dynamics can exhibit various novel and complex quantum phenomena like Anderson-like localization, negative absolute temperature etc. [2-5].

Probing such researches through analytical approach is always a nontrivial task because one needs to solve the nonlinear system upon identifying the exact form of the external potential which can support a selfsimilar solution [6, 7]. BEC under a bi-chromatic optical lattice and engineered superlattices are being addressed through exact analytical methods [5]. Various unexplored matter-wave dynamics will be explicated along with their corresponding exact nonlinear excitations like solitons and rogue waves. A time dependent version of the model manifests precise control over the dynamics by tuning the solution parameters.

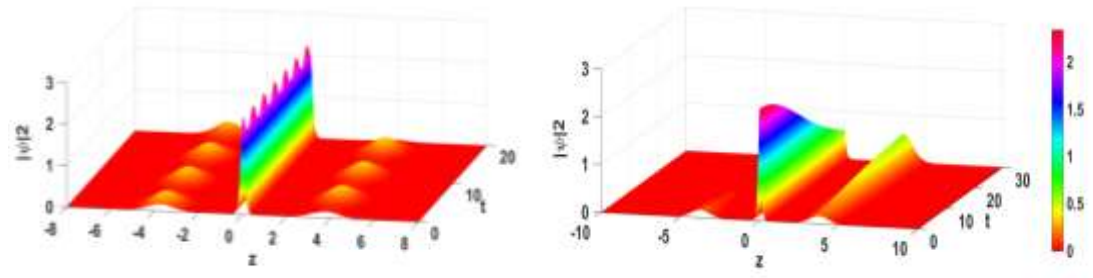

Figure: Time evolution of the condensate densities for sinusoidal (left) and linear (right) temporal variations under a bi-chromatic optical lattice

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Nematic-Orbit Coupling and Nematic Density Waves in Spin-1 Condensates

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We propose the creation of artificial nematic-orbit coupling in spin-1 Bose-Einstein condensates [1], in analogy with spin-orbit coupling. Using a suitably designed microwave chip, the quadratic Zeeman shift, normally uniform in space, can be made to be spatiotemporally varying, leading to a coupling between spatial and nematic degrees of freedom. A phase diagram is explored where three quantum phases with the nematic order emerge: easy axis, easy plane with single well structure, and easy plane with double-well structure in momentum space. By including spin-dependent and spin-independent interactions, we also obtain the low energy excitation spectra in these three phases. Last, we show that the nematic orbit coupling leads to a periodic nematic density modulation in relation to the period λ_T of the cosinusoidal quadratic Zeeman term. We make connections to supersolidity using both strict and broad definitions. Our results point to the rich possibilities for manipulation of tensorial degrees of freedom in ultracold gases without requiring Raman lasers, and therefore, obviating light-scattering induced heating.

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Hidden pseudogaps in the two-band BCS-BEC crossover

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The Bardeen-Cooper-Schrieffer (BCS) to Bose-Einstein condensation (BEC) crossover is of great interest in various fields such as ultracold atomic gases, high-T_c superconductors, semiconductors, and nuclear matter. Investigating the BCS-BEC crossover in these systems provides us with an opportunity to understand physics of strong correlations beyond the conventional mean-field picture. One of the most striking features in the crossover regime is a pseudogap effect induced by strong pairing fluctuations.

In this contribution, we focus on two-band superfluid/superconductors in the BCS-BEC crossover regime, where multi-channel pairing fluctuations play a crucial role. Such systems are relevant for iron-based superconductors locating in the BCS-BEC crossover regime [1-3]. We show unique features of the two-band BCS-BEC crossover such as the rise and fall of pseudogaps within the many-body *T*-matrix approach [4-6]. Moreover, we discuss the role of two-dimensional confinements, which is known to enhance fluctuation effects as observed in ultracold Fermi gases [7] and in gate-doped semiconductors [8].

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LINKS

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Pierbiagio Pieri https://www.unibo.it/sitoweb/pierbiagio.pieri

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Realizing a one-dimensional topological gauge theory in an optically dressed Bose-Einstein condensate

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Quantum gases constitute a versatile testbed for exploring the behaviour of quantum matter subjected to electric and magnetic fields. While most experiments consider classical gauge fields that act as a simple static background for the atoms, gauge fields appearing in nature are instead quantum dynamical entities that are influenced by the spatial configuration and motion of matter, and that fulfil local symmetry constraints. In my talk, I will discuss our recent realization of a chiral BF theory: a topological gauge theory for linear anyons in the continuum that corresponds to a possible one-dimensional reduction of the Chern-Simons gauge theory effectively describing fractional quantum Hall systems [1,2,3]. By using the local symmetry constraint of the theory, we encode the gauge field in terms of the matter field. The result is a system with chiral interactions, which we engineer in a ^{39}K Bose-Einstein condensate by synthesizing optically dressed atomic states with a momentum-dependent scattering length. When this dependence is linear, matter behaves as if minimally coupled to a density-dependent vector potential. Theoretically, we show that the system then realizes the chiral BF Hamiltonian at the quantum level [4]. Experimentally, we observe its two main features: the formation of chiral bright solitons - self-bound states of the matter field that only exist when propagating in one direction – and the back-action of matter into the gauge field [5]. Our results establish chiral interactions as a novel resource for quantum simulation experiments with ultracold atoms, and pave the way towards investigating linear anyon models [6] and implementing topological gauge theories in higher dimensions [7].

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Topological BKT transition in bubble-trapped condensates

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The external confinement has a profound influence on the equilibrium and nonequilibrium properties of a Bose-Einstein condensate. With the recent experimental advances, it is now possible to study two-dimensional bubble-trapped condensates, obtained by confining the atoms on a thin spherical or ellipsoidal shell. To analyze the superfluid properties, we discuss the vortex-antivortex physics of a bubble-trapped gas and derive its Kosterlitz-Nelson renormalization group equations. By solving them, we find universal scaling relations for the mean Berezinskii-Kosterlitz-Thouless (BKT) critical temperature and for the finite width of the superfluid transition. We also calculate the finite-temperature hydrodynamic modes which, being the equivalent of first and second sound of flat superfluids, are the main probe of the superfluid BKT transition. Our theoretical predictions are tailored on the typical parameters and regimes of NASA-JPL Cold Atom Lab experiments, a microgravity facility where these quantum systems are currently being investigated. In perspective, the tunable curvature of a quantum gas on a manifold can offer additional degrees of freedom for the simulation of quantum many-body systems with ultracold atoms.

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BEC-BCS crossover in unconventional superconductors with competing orders

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High-Tc cuprates, iron-based, A_3C_{60}, organic BEDT, heavy-fermion and some other unconventional superconductors exhibit behaviors distinctly different from those of BCS superconductors, such as Sn and Al. The unconventional behavior can be found in the following four different experimental results:
(1) Superfluid density at $T \rightarrow 0$ scales with Tc in a nearly linear relationship, both in underdoped and overdoped regions [1-3].
(2) Pseudogap behavior is observed in spin responses of NMR and charge responses of c-axis and ab-plane conductivity, and ARPES superconducting gap.
(3) Vortex Nernst effect observed in the underdoped region well above Tc (but well below T*).
(4) In transient responses of optical conductivity after photo-excitation, transient superconducting spectral weight emerges below an onset temperature very close to that of the vortex Nernst effect.

In this talk, we consider relevance of these behaviors with the BEC BCS crossover picture in the existence of competition with antiferromagnetic order. With a clear distinction among the three different processes of (a) pair formation (boson formation), (b) achievement of local phase coherence, and (c) superconducting transition with global phase coherence, we will try to come up with a coherent picture which is consistent with all the four behaviors (1)-(4) [4]. The effect of competing order can be found in the inelastic spin charge gapped soft mode, often referred to as the magnetic resonance mode in neutron scattering [4]. We will also discuss the appearance of this response in the charge sector, and a possible relationship of this mode and the 400 cm^{-1} (~ 12 THz) mode of the optical conductivity in YBCO cuprate systems observed in equilibrium and transient responses.

Recently BEC BCS crossover has been applied to the cases of magic angle twisted bi-layer and tri-layer graphene [5,6,7], and layerd ZrNCl with electro-gate tuning [8]. These systems exhibit behaviors possibly associated with BEC BCS crossover in 2-d systems. We also have new results on 3-d superconductors Fe(Se,S), $NeSe_2$ and other transition metal dichalcogenides, and some topological superconductors. Unlike the apparent behavior of 2-d single layer systems, many of the above mentioned 3-d superconductors exhibit nearly linear relationship between Tc and the superfluid density. We consider possible origins of this remarkable universal behavior.

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Current-induced self-organisation of mixed superconducting states

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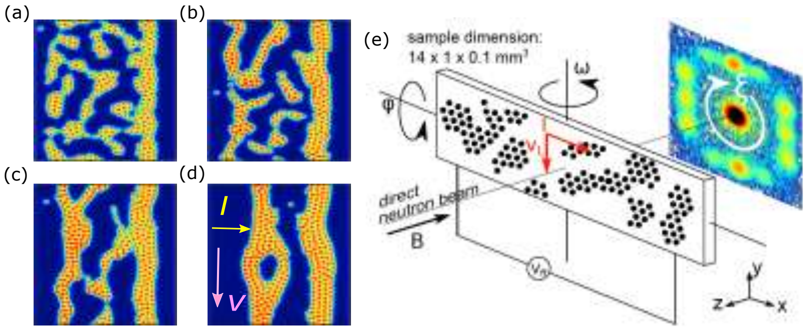

Fig. 1: (a) - (d) Snapshots of the time evolution of the vortex matter in the intermediate mixed state induced by the applied current *I*, here vortices move in the v direction. (e) A sketch of the neutron scattering experiment with the rocking angles ω and φ and the SANS image of the formfactor of the vortex pattern.

The intermediate mixed state in inter-type superconductors is characterised by special vortex interactions, repulsive at short but attractive at long distances while having a sig- nificant multi-vortex component [1]. The result is a two-phase domain structure, sensitive to smallest changes in external factors such as magnetic field and temperature [2,3]. En- hanced sensitivity facilitates a large variety of qualitatively different vortex patterns [4]. We report results of small angle neutron scattering (SANS) measurements supported by theoretical modelling that shed light on how the vortex matter changes when the current is applied [5]. Influence of the current is particularly interesting as it breaks the symmetry of the mixed state. We demonstrate that irrespective of its initial profile, the intermediate mixed state rearranges itself into a superstructure of stripes elongated perpendicular to the current flow. The rearrangement is facilitated by a peculiar way the current acts on vortices in an inter-type superconductor. In particular, vortices cannot be regarded isolated, and the action of the Lorentz as well as drag forces on them strongly depend on their spatial configuration. This creates a spatial gradient of vortex velocities leading to fast self-organisation of the vortex matter into a superstructure of parallel stripes.

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Kuramoto synchronization of quantum tunneling polarons for describing the dynamic structure in cuprate superconductors

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We describe the interplay between structural anharmonicity and charge/lattice dynamics in cuprates as evidenced by extended X-ray absorption fine structure (EXAFS) experiments[1,2]. By performing the exact diagonalization of a prototype, anharmonic many-body Hamiltonian on a relevant $6-$atom cluster we show that the EXAFS results can be understood as a Kuramoto synchronization between coupled internal quantum tunneling polarons, associated to deformations of the copper-apical-oxygen (Cu-O $_{ap}$) distances. Furthermore, we find that this first order, anti-phase synchronization transition can be fine tuned by temperature and/or anharmonicity, and promotes the pumping of charge, initially stored at the apical oxygen reservoirs, into the copper-oxide planes. Simultaneously, we also find that a novel (as of yet unobserved) planar internal quantum tunneling polaron appears, associated to deformations of the copper-planar-oxygen (Cu-O $_{pl}$) distance. All these findings support a description of the EXAFS data in terms of a simple, quantum mechanical triple-potential-well model, which accurately represents an anharmonic structural adiabatic passage (ASAP) promoting anti-phase synchronization and lattice-assisted charge transfer.

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