SuperFluctuations 2022 – Book of Abstracts

Fluctuations and Highly Non Linear Phenomena in Superfluids and Superconductors

July 6-8, 2022
Padova, Italy

Hybrid On-line and On-Site Conference

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

Venue

Aula Magna "Rostagni",
Dipartimento di Fisica e Astronomia "Galileo Galilei", Università di Padova, Italy

Main Topics:

Fluctuations and BCS-BEC crossover: multicomponent and low dimensional systems,
spin-orbit coupling, FFLO states.
Novel Quantum Phenomena with Bose and Fermi Mixtures.
Highly nonlinear phenomena: Josephson effects, topological defects, vortex states.
Electron-hole and Excitonic superfluidity and supersolidity
Innovative numerical methods: Machine Learning, its synergies with QMC.
Quantum technologies and quantum devices based on novel quantum systems.

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Conference Proceedings of SuperFluctuations 2022 will be published by Condensed Matter.

Spinning superfluid droplets

Francesco Ancilotto

Department of Physics and Astronomy of the University of Padova, Italy.

I will present theoretical results [1] on the properties of spinning quantum droplets [2] made of K-Rb bosonic mixture [3].
The structure and energetics of vortex formation in the self-bound mixture show that the formation of linear vortices in the heavier species is energetically favoured over other configurations. A fake, partially filled core develops as a consequence in the other species, resulting in a density depression which might be imaged in experiments.
The interplay between vortices and capillary waves, which are the two ways angular momentum can be stored in a rotating superfluid, is studied by computing the relation between angular momentum and rotational frequency. The results show intriguing similarities with the case of a prototypical superfluid, i.e. He-4 droplets when set into rotation.
A two-branches curve in the stability diagram, qualitatively similar to the one found for classical (incompressible and viscous) rotating liquid droplets, is obtained when vortices are present in the droplets, while prolate (i.e. non axi-symmetric) shapes are only permitted in vortex-free droplets.

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Stability of quantum degenerate fermionic polar molecules with and without microwave shielding

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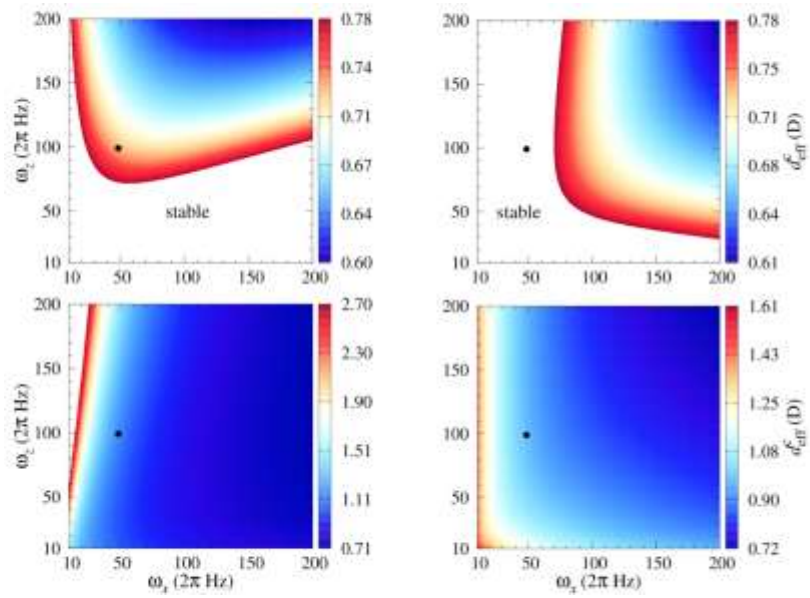
A stabilization of a fermionic molecular gas towards collapse in attractive head-to-tail collisions and its evaporative cooling below the Fermi temperature has so far been achieved in two ways. Either a strong dc electric field is applied to confine the molecular motion to 2D [1] or inelastic collisions in 3D are strongly suppressed by applying a circularly polarized microwave field [2]. Here we use a Hartree-Fock mean-field theory [3,4] in order to determine the 3D properties of quantum degenerate fermionic molecules. In particular, we compare the stability diagrams occurring with and without microwave shielding, where a dipole-dipole interaction with negative and positive sign is present. In case when the orientation of the electric dipoles with respect to the trap axes is unknown, we outline how to reconstruct it from time-of-flight absorption measurements.



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Proximity-driven ferromagnetism and superconductivity in the triangular Rashba-Hubbard model

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Poster / Video talk abstract

Bilayer moiré structures are a highly tunable laboratory to investigate the physics of strongly correlated electron systems. Moiré transition metal dichalcogenides (TMDs) at low energies, in particular, are believed to be described by a single narrow band Hubbard model on a triangular lattice. Motivated by recent experimental evidence for superconductivity in twisted bilayer materials, we investigate the possible superconducting pairings for TMDs deposited on a substrate by studying a two-dimensional single-band Rashba-Hubbard model. Using a random-phase approximation in the presence of nearest- and next-nearest-neighbor hopping, we analyze the structure of spin fluctuations and the symmetry of the superconducting gap function. We show that Rashba spin-orbit coupling favors ferromagnetic fluctuations which strengthen triplet superconductivity. If parity is violated due to the absence of spatial inversion symmetry, singlet (d-wave) and triplet (p-wave) channels of superconductivity will be mixed. Finally, we show that time-reversal symmetry can be spontaneously broken, leading to a chiral superconducting state.

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An impurity in a heteronuclear two-component Bose mixture

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We study the fate of an impurity in an ultracold heteronuclear Bose mixture, focusing on the experimentally relevant case of a 41K-87Rb mixture, with the impurity in a 41K hyperfine state. Our work provides a comprehensive description of an impurity in a BEC mixture with contact interactions across its phase diagram. We present results for the miscible and immiscible regimes, as well as for the impurity in a self-bound quantum droplet. Here, varying the interactions, we find novel, exotic states where the impurity localizes either at the center or at the surface of the droplet.

Reference:

[1] G. Bighin, A. Burchianti, F. Minardi, T. Macrì, *"An impurity in a heteronuclear two-component Bose mixture"*, to appear in Phys. Rev. A

Superfluidity in ordered phases

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We have explored the emergence of superfluidity in different ordered systems. In particular, in dipolar systems and in quasi-two-dimensional Helium adsorbed on graphite using ab initio Quantum Monte Carlo methods. In the case of dipoles, we have found that tilted dipoles in a plane show a stable stripe phase with superfluid signal across the stripes. This system, also known as superstripes, experiences a BKT transition that we have characterized with the PIMC method. In the case of dipolar droplets, harmonically confined, we observe the formation of droplets starting from a homogeneous phase and observe how the one-body density matrix show compatibility with a finite condensate fraction within a small window of interaction. Finally, we predicted that a supersolid registered phase could exist in the second layer of Helium on graphite and a recent torsional oscillator experiment seems to confirm this finding.

Multi-component Mott systems: (A little) more is different

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Mott localization has become a central paradigm in condensed-matter physics after the discovery of high-Tc superconductivity in doped Mott insulators. While a long time has been devoted to the single-orbital Hubbard model, the last decade has demonstrated that multicomponent Mott insulators reveal a much richer physics which is also crucial to understand a variety of materials, including iron-based superconductors [1,2].

In this talk I will present a few examples highlighting some distinctive phenomena which are characteristic of multi-component system.

I will first introduce selective Mott physics, where only a part of the fermionic fluid becomes Mott localized, showing its relevance for materials [1] and a clean realization in a multi-flavor cold-atom platform [3,4], where I will also address the role of Mott physics on chiral currents in the presence of synthetic gauge fields [5]

Then I will discuss the role of electron-phonon interaction, connecting former results on alkali-doped fullerides [6] with recent model calculations showing a rich phase diagram where phonons and electron-electron interaction can either cooperate or compete [7].

The presents results from the collaborations with the authors of the references [1-7]

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Filamentary superconductivity in systems with competing charge density waves

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In a previous work [1], from a systematic analysis of high pulsed magnetic field resistance data of $La_{2-x}Sr_xCuO_4$ thin films, we extracted an experimental phase diagram for several doping values ranging from the very underdoped to the very overdoped regimes, highlighting the competition between charge density waves and superconductivity. This competition is ubiquitous between $x = 0.08$ and $x = 0.19$ and produces the previously observed double step transition. When suppressed by a strong magnetic field, superconductivity is resilient for two specific doping ranges centered around $x \approx 0.09$ and $x \approx 0.19$, and the characteristic temperature for the onset of the competing charge density wave phase is found to for $x > 0.19$. At $x = 1/8$ the two phases coexist exactly at zero magnetic field. In a subsequent publication [2], we accounted for this phenomenology introducing a negative-U generalized Hubbard model and a coarse-grained semiclassical pseudospin model. In the presence of disorder, the charge density wave phase breaks apart in domains with topologically protected filamentary superconductivity at the interfaces. Assuming that superconductivity and charge density waves phases have similar energies, at intermediate temperatures, the magnetic field drives the system from a fluctuating superconductor to a charge density wave state, as expected in the clean limit. Lowering the temperature, the clean quantum critical point is avoided, and a filamentary phase appears. Within our scenario, the filamentary superconducting phase is parasitic, while charge density wave and bulk superconducting phases play the role of primary competing orders. A systematic study by means of Monte Carlo simulations is currently underway [3].

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Formation and fate of quantum droplets in a quasi-1D dipolar Bose gas

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We theoretically investigate the formation of quantum droplets in a tightly trapped one-dimensional dipolar gas of bosonic atoms. By using a variational approach based on the Bethe ansatz wave function of the Lieb-Liniger gas[1], we calculate the density profile and show that when the strength of the dipolar interaction becomes sufficiently attractive compared to the contact one, a solitonic-like density profile forms evolving into a liquid-like droplet for sufficiently large number of particles. The incipient gas-liquid transition is also signaled by a steep increase of the breathing mode [2] and a change in sign of the chemical potential. Upon a sudden release of the trap the numerical solution of a time-dependent generalized Gross-Pitaevskii equation shows that either the droplet evaporates or forms a single self-bound droplet or fragments in multiple droplets, depending on the number of trapped atoms and the scattering length [3]. These results can be probed with lanthanides atoms and allow to characterize the effect of the dipolar interaction in a quasi-one-dimensional geometry.

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Saturation of the Superconductivity in p>0.5 Cuprates: A Novel Mechanism

Steven D. Conradson[a,b], Linda Sederholm[j], Victor Velasco[c] Marcello B. Silva Neto[c,], Theodore H. Geballe[d,e,f,], Chang-Qing Jin[g,h], Wen-Min Li[g,h], Li-Peng Cao[g,h], Andrea Gauzzi[i], Maarit Karppinen[j], Andrea Perali[k], Sandro Wimberger[l,m], Alan R. Bishop[n], Gianguido Baldinozzi[o], Edmondo Gilioli[q]

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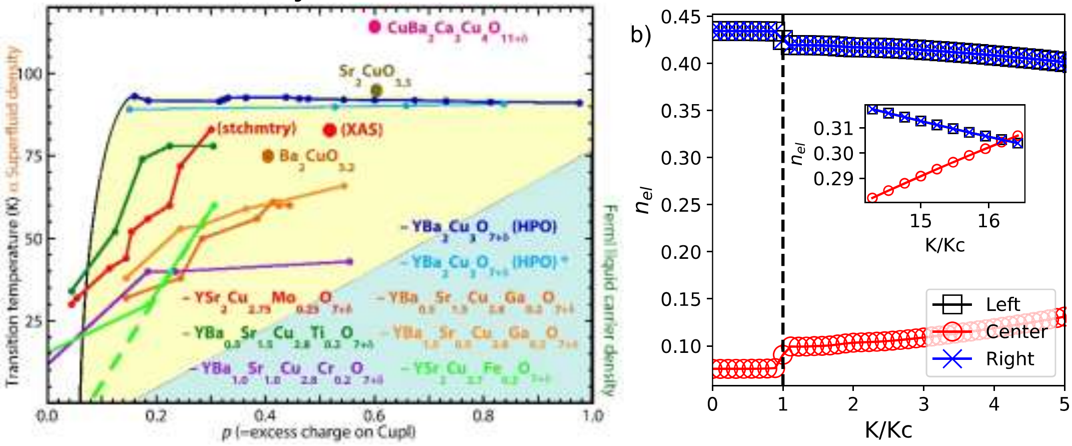
Thirty-five years and of the order of 10^5 papers after the initial discovery of high temperature superconductivity in cuprates its mechanism remains a mystery. A principal obstacle in this regard has been the intentional neglect by the mainstream community of a subset of these materials, the superconducting overdoped compounds prepared with high pressure oxygen (HPO) in multianvil presses. These demonstrate that the superconducting "dome" of the standard phase diagram, far from its assumed universality, in fact only applies to samples equilibrated with up to a few atmospheres of oxygen. The unfortunate results are that not only that the majority of effort has been focused on the very narrow doping range on its underdoped side, but also there are serious misunderstandings of the coupling of disorder and charge density to the superconductivity. The HPO synthesis of cuprates of the $YBa_2Cu_3O_7$ structural class inserts the excess or adventitious oxygen into a specific site with no reduction of their transition temperatures or superfluid densities. Intriguingly, we have already noted HPO synthesis of La_2CuO_4-type materials gives quite different structures concomitant with a 2-1/2 times higher T_c. The phase diagram including the HPO materials shows that, far from peaking at p=0.16 and ending at p=0.27, the superconductivity in fact persists through p=1 in $YBa_2Cu_3O_7$. In addition, and most radically, the superconductivity saturates with T_c and the volume fraction remaining essentially constant beyond the optimum doping level and excess carriers shunted into a Fermi liquid phase. Insofar as this behavior is incompatible with a superconducting mechanism involving pairing of metallic carriers as a condition of superfluid formation, we alternatively utilize two other properties of cuprates. The numerous ones we have studied with EXAFS show changes in their spectra in proximity to their superconducting transitions, demonstrating strong coupling of their dynamic structure to their superconductivity. These changes in particular oxygen positions are assigned to the internal dynamics of the charge inhomogeneities in these systems, thus Internal Quantum Tunneling Polarons (IQTPs). Anharmonic coupling between these causes a transition of the dynamic structure into a synchronized phase. Condensation of the IQTPs of this phase into the superfluid would dictate that the limiting factor would be the structure of the condensate directly coupled to the crystal lattice, i.e., the constituent particles would be the synchronized IQTPs.



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Local lattice distortions and dynamics in extremely overdoped superconducting $YSr_2Cu_{2.75}Mo_{0.25}O_{7.54}$. Steven D. Conradson, Theodore H. Geballe, Andrea Gauzzi, Maarit Karppinen, Chang-qing Jin, Gianguido Baldinozzi, Wen-min Li, Li-peng Cao, Edmondo Gilioli, Jack Mingde Jiang, Matthew Latimer, Oliver Mueller, Venera Nasretdinova. *Proc. Nat. Acad. Sci. USA* **117**, 4559 (2020). https:/doi.org/ 10.1073/pnas.1918704117

Local structure of $Sr_2CuO_{3.3}$, a 95 K cuprate superconductor without CuO_2 planes. Steven D. Conradson, Theodore H. Geballe, Chang-qing Jin, Li-peng Cao, Gianguido Baldinozzi, Jack Mingde Jiang, Matthew Latimer, Oliver Mueller. *Proc. Nat. Acad. Sci. USA* **117**, 4565 (2020). https:/doi.org/ 10.1073/pnas.1918890117

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Extremely Overdoped Superconducting Cuprates via High Pressure Oxygenation Methods. Linda Sederholm, Steven D. Conradson, Theodore H. Geballe, Chang-qing Jin, Andrea Gauzzi, Edmondo Gilioli, Maarit Karppinen, Gianguido Baldinozzi. *Condens. Matter* **6** (2021). https://doi.org/10.3390/condmat6040050

Evolution of Charge-Lattice Dynamics across the Kuramoto Synchronization Phase Diagram of Quantum Tunneling Polarons in Cuprate Superconductors. ,Victor Velasco, Marcello B. Silva Neto, Andrea Perali,Sandro Wimberger, Alan R. Bishop, and Steven D. Conradson. *Condens. Matter* **6**, 52 (2021). https://doi.org/10.3390/condmat604005

Kuramoto synchronization of quantum tunneling polarons for describing the dynamic structure in cuprate superconductors. Victor Velasco, Marcello B. Silva Neto, Andrea Perali, Sandro Wimberger, Alan R. Bishop, and Steven D. Conradson. *Phys. Rev. B* **105**, 174305 (2022).

https://doi.org/10.1103/PhysRevB.105.174305

Chester supersolid of spatially indirect excitons in double-layer semiconductor heterostructures

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A supersolid, a counter-intuitive quantum state in which a rigid lattice of particles flows without resistance [1], has to date not been unambiguously realised. Here we reveal a supersolid ground state of excitons in a double-layer semiconductor heterostructure over a wide range of layer separations outside the focus of recent experiments. This supersolid conforms to the original Chester supersolid [2] with one exciton per supersolid site, as distinct from the alternative version reported in cold-atom systems of a periodic modulation of the superfluid density [3]. We provide the phase diagram augmented by the supersolid. This new phase appears at layer separations much smaller than the predicted exciton normal solid [4], and it persists up to a solid-solid transition where the quantum phase coherence collapses. The ranges of layer separations and exciton densities in our phase diagram are well within reach of the current experimental capabilities [5].

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Anomalous normal and superconducting states in the nematic $FeSe_{1-x}S_x$

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$FeSe_{1-x}S_x$ is unique among unconventional superconductors because of superconductivity that emerges from a pure electronic nematic state. Substituting Se for S leads to a progressive suppression of the nematic transition which is believed to terminate as a quantum critical point (QCP) at $x \approx 0.17$. Highly unusual transport properties have been detected in the normal (non-SC) state in high magnetic fields (*H*) down to low temperatures (*T*): i) *T*-linear resistivity within a fan-like region centered at the QCP, ii) quadrature scaling with *H*-linear magnetoresistance at high *H* that peaks close to the QCP and iii) non-monotonous Hall response that also peaks close to the QCP. Here we focus on the SC state of $FeSe_{1-x}S_x$, especially on the mixed (vortex) regime and follow its evolution with *T*, *H* and *x*. Our high-field magnetoresistance measurements reveal an unusually broad field range with finite resistivity in the SC state that persists down to extremely low *T* across the nematic QCP [1]. Such behavior points towards the melting of the vortex lattice even in the zero-temperature limit, i.e. the emergence of a robust quantum vortex liquid (QVL) regime, which is ascribed to intense quantum fluctuations, of both nematic and magnetic origin. Further expansion of the QVL beyond the QCP is associated with a reduction in pinning strength along with a possible approach towards Bose-Einstein condensation. Additional thermal conductivity measurements on pure FeSe provide compelling evidence for the stabilization of the Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) state at high *H* [2].

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link to the individual web page: http://www.ifs.hr/en/people/matija-culo/

Phonon-limited transport and Fermi arc lifetime in Weyl semimetals

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Weyl semimetals harbor topological Fermi arc surface states that determine the nontrivial charge current response to external fields. In this talk I will discuss the quasiparticle decay rate of Fermi arc states arising from their coupling to acoustic phonons and the phonon-limited conductivity tensor for a clean Weyl semimetal slab [1]. I will show that the temperature dependence of the quasiparticle decay rate depends on the position along the arc. Then, using the Boltzmann approach in a slab geometry, I'll determine the dependence of the linear-response conductivity on key parameters such as the temperature, the chemical potential, the geometric shape of the Fermi arcs, or the slab width. The chiral nature of Fermi arc states causes an enhancement of the longitudinal conductivity along the chiral direction at low temperatures, together with a $1/T^2$ scaling regime at intermediate temperatures without counterpart for the conductivity along the perpendicular direction.

Reference:

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Excitonic condensation, pairing gap and quadri-excitons in an electron-hole bilayer with twofold valley degeneracy

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We study a model of symmetric electron-hole bilayer, encoding the key features, valley degeneracy and many-body correlations, of coupled graphene bilayers separated by a thin insulating material. Using Quantum Monte Carlo simulations we map the phase diagram of our model in the plane carrier density/bilayer separation. We found an excitonic phase (bound pairs of opposite charges) sandwiched between a plasma phase and a quadriexcitonic phase (characterised by complexes of eight-particles) [1]. We calculate the condensate fraction, pair correlation functions and the pairing gap to characterise the phases of the model.
Only the intermediate excitonic phase undergoes Bose-Einstein condensation, possibly explaining why anomalous tunnelling conductivity, interpreted as signature of condensation, is observed only between two finite values of carrier density in graphene bilayers [2].

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Pair-Density Wave in anisotropic strongly coupled pairing systems

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In weakly coupled BCS superconductors, only electrons within a tiny energy window around the Fermi energy form Cooper pairs. This may not be the case in strong coupling superconductors, where the pairing scale becomes comparable or even larger than the Fermi energy. In this talk I will discuss an analytically solvable model to examine possible pairing phases in the strongly coupled regime in the presence of anisotropic interactions [1]. I will illustrate the properties of a novel finite temperature phase where local pair correlations have non-zero center-of-mass momentum but lack long-range order. Below a critical temperature such a fluctuating pair-density wave phase can condense either to a uniform d-wave superconductor or to a pair-density wave phase depending on the strength of the pairing interaction.

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Fundings: EU H2020 Program MSCA-IF global Fellowship SuperCoop Grant number 838526, DOE grant number DE-FG02-05ER46236

https://laurafanfarillo.wordpress.com/

Hund-driven Correlations, Superconductivity and Nematicity

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Poster abstract

Iron-based superconductors represent the perfect playground to analyze a plethora of quantum phases including superconductivity and nematicity. Although a number of experiments call for a prominent role of local correlations and identify iron superconductors as Hund's metals, only recently we started to unveil the non-trivial effect of the electronic correlations on the superconducting [1] and nematic phase [2]. The key novelty of the study is the inclusion of the dynamical properties that make a Hund's metal substantially different with respect to both a weakly interacting metal and to an ordinary correlated metal with a large effective mass renormalization. This allows us to distinguish the specific nematic spectral features characterizing the Hund's metal with respect to a standard correlated metal and to unveil the crucial role of the redistribution of spectral weight of the Hund's metal to promote superconductivity.

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Chiral behavior of strongly interacting fermions under synthetic gauge fields

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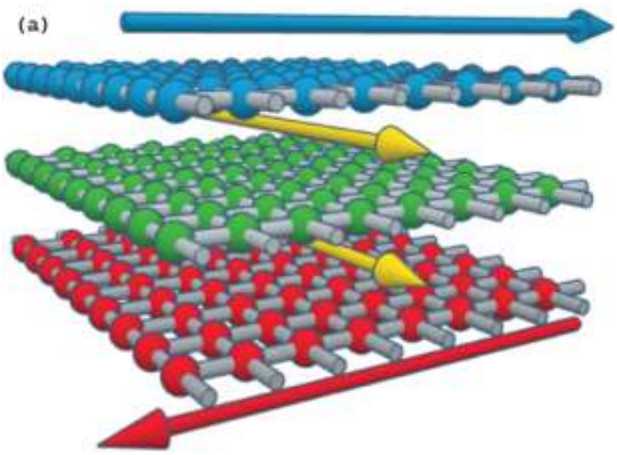
Video talk abstract



Experimental platforms of ultracold atoms trapped in optical lattices are a powerful tool to perform the quantum simulation of solid state systems, as well as to engineer novel quantum systems with no analogues. One of the major achievements in this field has been the realization of effective gauge fields coupled to the neutral atoms by means of the synthetic dimension approach, and the subsequent observation of chiral edge modes along the synthetic direction.
Moreover, taking advantage of the peculiar electronic structure of alkaline-earth like atoms, it is possible to realize a SU(N) symmetric atom-atom interaction, which in turn can be flexibly tuned from the weak to the strong coupling regime.
In this seminar we investigate the role of strong SU(N) atomic interactions on the chiral edge modes of the system, both in one and two real dimensions. We work in the regime of integer filling fraction, where interactions are expected to strongly influence the equilibrium properties, due to the interplay with the Mott metal-insulator phase transition. We find that the chiral current is rapidly enhanced by the interaction in the metal, while it is slowly suppressed in the insulator, resulting in a sharp peak located exactly at the phase transition, thus leading to the surprising result that the optimal chirality is reached close to the quantum critical state.
We explain this results and check their robustness by taking advantage of different techniques, including Hartree-Fock approximation, dynamical mean field theory (DMFT), exact diagonalization and an effective low energy spin model for the strong coupling regime.

The work will be posted on ArXiv soon.

Quantum Correction to Josephson Oscillations

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We theoretically investigate a bosonic Josephson junction by using the path-integral formalism with relative phase and population imbalance as dynamical variables. Starting from a Lagrangian of a Bose Josephson junction, we derive an action only in terms of relative phase by performing functional integration over the population imbalance. We then analyze the quantum only-phase action, which formally contains all of the quantum corrections. To the second order in the derivative expansion and to the lowest order in $\hbar$, we finally obtain the quantum correction to the Josephson frequency of oscillation in the Josephson regime [1]. The identical quantum correction is found also by adopting an alternative approach. While the estimated quantum correction to the Josephson frequency is relatively small based on current experimental setups, we expect that the correction can be significant by appropriately tuning some parameters such as the onsite interaction strength in an atomic Josephson junction or the capacitance in a superconducting Josephson circuit. Our predictions would be a useful theoretical tool for experiments with atomic or superconducting Josephson junctions.

Reference:

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Mott-Driven BEC-BCS Crossover in a Doped Spin Liquid Candidate

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Quantum spin liquid (QSL) is an exotic state possibly having quantum entanglement and fractionalization in excitations. Further intriguing is superconductivity that possibly emerges by doping QSL. In this presentation, I briefly review the present status of the QSL research on an organic triangular-lattice compound and present our recent experimental studies on the superconductivity in a 11% hole doped QSL candidate.

At ambient pressure, the ^{13}C NMR measurements suggest spin-singlet nodal pairing. The superfluid density evaluated by the penetration depth measurements is anomalously suppressed, indicating that the substantial part of the spectral weight is incoherent [1]. The transport and Nernst effect measurements suggest that the superconductivity at ambient pressure is a BEC-like condensate from a non-Fermi liquid and is driven to a BCS condensate from a Fermi liquid by pressure, which reduces the Coulombic interactions among electrons [2]. I also present the thermoelectric signature of quantum criticality and its possible relevance to superconductivity [3] as well as the variation of the electronic state under uniaxial distortion of the triangular lattice [4].

The present work is a collaboration with Y. Suzuki, K. Wakamatsu, Y. Ueno, J. Ibuka, H. Oike, T. Fujii, K. Miyagawa and H. Taniguchi.

References:

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Collective excitations of a Fermi superfluid in the BCS-BEC crossover

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This talk is devoted to our recent studies of collective excitations in a superfluid state of condensed Fermi gases [1 - 6], being particularly focused on charged superfluids and superconductors. The path integral Gaussian pair-density fluctuation approach (GF) is equivalent to the random phase approximation (RPA) and is capable to describe all branches of collective excitations in the crossover between the weak-coupling regime of the Bardeen – Cooper – Schrieffer (BCS) pairing and the strong-coupling regime of the Bose-Einstein (BEC) condensation of molecules.

The case of a particular interest occurs when the plasma frequency is of the same order as the pair-breaking continuum edge. In the BCS-BEC crossover, plasma and pair-breaking modes can interact with each other, because they are not, in general, purely amplitude or phase excitations. As a result, pair-breaking and plasma excitations exhibit anticrossing near the continuum edge and show an enhancement of the pair-breaking mode response at resonance. The plasma mode exhibits a non-monotonic behavior, passing through a minimum. The pair-breaking mode survives in a charged superfluid. The subtle structure of poles in the analytic continuation for the GF propagator is reflected in frequency behavior of pair-field and density response functions.

References:

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HELMI: a superconducting quantum computer

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CSC IT – Center for Science (Finland)

In the last few years there has been an increasing interest towards quantum computing even from non-expert communities. This is mostly due to the increasing number of open access platforms which are offered by several vendors. In my talk I introduce the VTT-IQM 5-(transmon) qubits quantum computer HELMI, its architecture and the software stack that software developers can use to program it.

HELMI belongs to the family of the so-called Noisy Intermediate-Scale Quantum (NISQ) devices and as such we need to tame noise to perform meaningful computation. The calibration and fine tuning of a quantum computer are operations that need to be performed on a regular basis to fight against the degradation of the performances induced by external factors such as thermal excitation and parasite currents. I will describe the calibration procedure which we use to guarantee that HELMI always runs to the best of its capabilities and discuss the challenges that we face.

I will also talk about how we are planning to deploy HELMI as a service via the pan-European supercomputer LUMI (Large Unified Modern Infrastructure). This will make our quantum computer available to all European users.

References:

[1] Finland's first 5-qubit quantum computer is now operational
[2] Large Unified Modern Infrastructure informations

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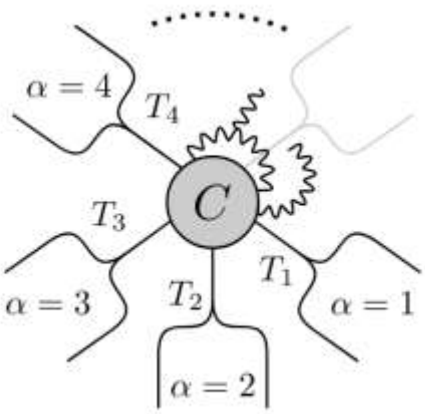
Non-equilibrium Green's function applied to transport non-equilibrium system

Nicolino Lo Gullo

VTT – Technical Research Centre of Finland and
CSC IT – Center for Science (Finland)

Poster / Video talk abstract



The non-equilibrium Green's function formalism is a powerful and versatile tool which allows to study the physical properties of quantum system in different physical scenarios. It finds applications in the study of the dynamics of closed quantum systems either autonomous or continuously driven, but it is also suited to study the response in the time domain following short perturbations. On the other hand, its power is best revealed when applied to real transport setups to compute currents and other transport properties.

In my talk I will give a brief review of the methods and then present some concrete applications of this method to the study of dynamics in closed systems and transport in quantum dots and chains. I will also present the numerical libraries which we made available recently which support researchers who want to start experimenting with these tools.

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Excitonic insulators in Coulomb-coupled atomic bilayers

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Cornell University, USA

Excitonic insulators (EIs) arise from the formation of bound electron-hole pairs (excitons) in semiconductors and provide a solid-state platform for quantum many-boson physics. Strong exciton-exciton repulsion is expected to stabilize condensed superfluid and crystalline phases by suppressing both density and phase fluctuations. Although spectroscopic signatures of EIs have been reported, conclusive evidence for strongly correlated EI states has remained elusive. In this talk, I will discuss the realization of strongly correlated EIs in Coulomb-coupled bilayers of 2D semiconductors. In particular, I will present direct thermodynamic evidence of the EI ground state and discuss the exciton phase diagram that reveals both the Mott transition and interaction-enhanced quasi-condensation. If time permits, I will also discuss the realization of a strongly correlated EI in a moiré lattice, effectively realizing the Bose-Hubbard model in a solid-state platform.

A FL* Solution to the FL /NFL Dichotomy in hole-doped Cuprates

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Using the terminology of [1] we denote by FL* an exotic FL satisfying a suitable version of Luttinger theorem related to topological order, in which, besides standard electrons (or better holes for hole-doped cuprates) carrying charge and spin, the quasi-particle excitations are the holons carrying only charge and the spinons carrying only spin. The electron is then a bound state, or in general a resonance, made of holon and spinon and the corresponding Landau quasi-particle is the true low-energy excitation, holon and spinon being well defined particle-like excitations only far away from the region of small energy close to the electron Fermi surface.

One amazing characteristic of hole-doped cuprates is that some of their physical quantities qualitatively behaves almost like in a Fermi liquid (FL), especially at sufficiently large doping and temperature, whereas in the same range of parameters other quantities behave in a completely non-FL (NFL) fashion.

We show that in our FL* formalism [2] for hole-doped cuprates, based upon a 2D t-J model expressed in terms of gapped spinons and semionic holons with Fermi surface smaller than that of the hole, many experimental dichotomies FL/NFL are qualitatively well reproduced [3] and the NFL features appear when the response is dominated by spinons whereas the FL features appear when the response is dominated by the hole resonance. In particular this approach can explain 1) why the Knight shift at moderate doping approaches an almost FL behaviour at high temperature whereas the spin-lattice relaxation rate on the Cu sites does not, thus violating Korringa law 2) why in spite of the gapless Fermi arcs in the pseudogap region of the phase diagram the in-plane resistivity exhibits a metal-insulator crossover and, suitably normalized, a universal behaviour 3) why in spite of a BCS-like behaviour of the superconducting gap in the nodal region for small dopings, the superfluid density is not BCS-like, violates Leggett rule, satisfies Uemura relation and, suitably normalized, exhibits a universal behaviour.

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Collective oscillations of an atomic Bose-Bose mixture

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We study the coupled dynamics of a two-species Bose-Einstein condensate with tunable interspecies interaction. With a degenerate mixture of 41K-87Rb in an optical trap we excite the dipole oscillations of both atomic species in the linear response regime. Varying the interspecies interaction from the weakly to the strongly attractive side, we measure the frequencies and the composition of the two dipole eigenmodes. We compare experimental results with numerical simulations performed by solving two coupled Gross-Pitaevskii equations, to obtain a detailed picture of the dipole excitations in asymmetric bosonic mixtures.

Website: https://quantumgases.lens.unifi.it/exp/krb

Superexchange liquefaction of strongly correlated lattice dipolar bosons

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Recently, a new class of ultradilute quantum droplets has been produced in ultracold atomic systems, both in bosonic dipolar systems and in bosonic mixtures. Such quantum droplets are characterized by being self-bound objects similar to the case of water droplets. The main difference is that the equilibrium density can be eight orders of magnitude smaller than in liquid water. Furthermore, the stability of these quantum droplets can be understood from a compensation between mean-field interactions and quantum fluctuations.

In this talk I will present a new type of quantum liquids and droplets which appear in dipolar bosonic systems loaded in one-dimensional optical lattices [1]. These appear in the strongly interacting regime and I will show how their formation can be understood from the appearance of superexchange processes. These processes liquefy the system when being close to the self-bound insulating state. I will discuss how such lattice quantum liquids can be produced in dipolar bosonic systems which could already be realized in current ultracold atomic laboratories by adding a one-dimensional optical lattice.

Reference:

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Shot noise indicating pairing at temperatures above T_c and energies above the gap in LSCO

D. Natelson[1], Panpan Zhou[1], Liyang Chen[2], Yue Liu[3], Ilya Sochnikov[4], Anthony T. Bollinger[5], Myung-Geun Han[5], Yimei Zhu[5], Xi He[6], Ivan Božoviç[5,6]

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Electronic shot noise is a means of experimentally examining the temporal correlations between charge carriers in a conductive structure, through the intrinsic fluctuations in a driven current caused by the statistical fluctuations in the arrival of charge carriers. In recent experiments[1] we have measured electronic shot noise in the tunneling current in high quality *c*-axis $La_{2-x}Sr_xCuO_4/La_2CuO_4/La_{2-x}Sr_xCuO_4$ heterostructures fabricated by atomic layer-by-layer molecular beam epitaxy. We examined four doping levels up to near-optimal doping (x = 0.1, 0.12, 0.14, 0.15) over a broad temperature range (100 K down to 5 K) spanning both the normal and superconducting states of the LSCO source and drain electrodes. In all devices, shot noise in excess of the expectation for simple single-electron tunneling was observed above T_c in the pseudogap regime. This enhanced shot noise persisted below T_c at biases large compared to the superconducting gap scale inferred from the zero-bias conductance suppression in the tunning differential conductance. This enhanced noise is indicative that some fraction of the tunneling current is through transport of pairs of carriers rather than individual quasiparticles. These observations constrain models of the pseudogap and broken symmetry states and suggest that the domain of superconductivity in this system is limited by phase fluctuations.

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https://natelson.web.rice.edu/group.html

Density correlation functions of the two-dimensional BEC-BCS crossover

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Video talk abstract

We consider the crossover between a Bose-Einstein condensate (BEC) state and a Bardeen-Cooper-Schrieffer (BCS) superfluid achieved by varying the effective interaction in a homogeneous balanced mixture of a two-component Fermi gas in two dimensions. We present analytical expressions for the density-density correlation functions between same and different components, which provide an explicit view of the two-body spatial distribution throughout the crossover. We also analyze the behavior of the variational pair wave function of the BCS-Leggett approach. Particularly, our expressions allow us to study the large-distance behavior of the two-body distributions, where they exhibit an exponential decay with an oscillatory behavior whose frequency is given by the Fermi wave number. The exponential decay is characterized by a large-distance correlation length, which can be written in terms of the chemical potential and the gap in such a way that its expression is valid in two and three dimensions. It is shown that within this mean-field approach the large-distance correlation length is associated to the threshold energy required to break a pair.

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[4] J. C. Obeso-Jureidini and V. Romero-Rochín, Phys. Rev. A **105**, 043307 (2022).

Link to web page:
https://www.fisica.unam.mx/personales/romero

Dimensional crossover in the three-dimensional attractive hubbard model

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The attractive Hubbard model (AHM) describes superconductivity driven by on-site pairing interactions. At half filling, the critical temperature, Tc, is zero for the square lattice by virtue of the Mermin-Wagner theorem, while it is finite in three dimensions. With the continuing development of optical lattices experiments, in which ultracold fermionic atoms are loaded and the interaction amongst them is controlled through an external magnetic field, the attractive Hubbard model has been experimentally studied in an unprecedented way. By adjusting the parameters of the counterpropagating laser beams one may be able to control the hopping amplitude between square planes, so that the crossover between two and three-dimensional behaviours could be followed. In solid state materials this could be achieved by applying uniaxial pressure, which would similarly introduce anisotropy in the hopping parameters. In view of this, a systematic study of the critical temperature as a function of the interplane hopping, t_z, is certainly of interest, especially due to the fact that the lowest temperatures achieved in the experiments are still somewhat higher than those predicted theoretically for the isotropic model. Any indication of routes towards increasing critical temperatures should therefore be of great help to experimentalists. With this in mind we have performed Quantum Monte Carlo simulations on the three-dimensional model with axially anisotropic hopping; we allow the ratio $\alpha = t_z/t$, where t is the planar hopping amplitude, to vary between $\alpha < 1$ and $\alpha > 1$. We have also studied the effect of next-nearest neighbour hopping. We discuss the behaviour of Tc thus obtained, as well as the thermal behaviour of correlation functions, double occupancy, and other experimentally measurable quantities.

Web site:

https://quantummatterufrj.wordpress.com

Josephson effect and BCS-BEC crossover in electron-hole superfluid heterostructures

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Poster abstract

We analyze the superfluid characteristics and crossover physics for Josephson junctions [1] in electron-hole bilayer TMD semiconductors [2, 3]. We determine the critical current across junctions of different potential barrier heights [4, 5]. We show that the crossover physics in the narrow barrier region controls the critical current throughout. We find that the ratio of the critical current divided by the carrier density exhibits an observable maximum at the density of the switchover from bosonic excitations to pair-breaking fermionic excitations [6]. This provides, for the first time in a semiconductor system, an experimental measure for the position of the boundary separating the BEC and BCS-BEC crossover regimes.

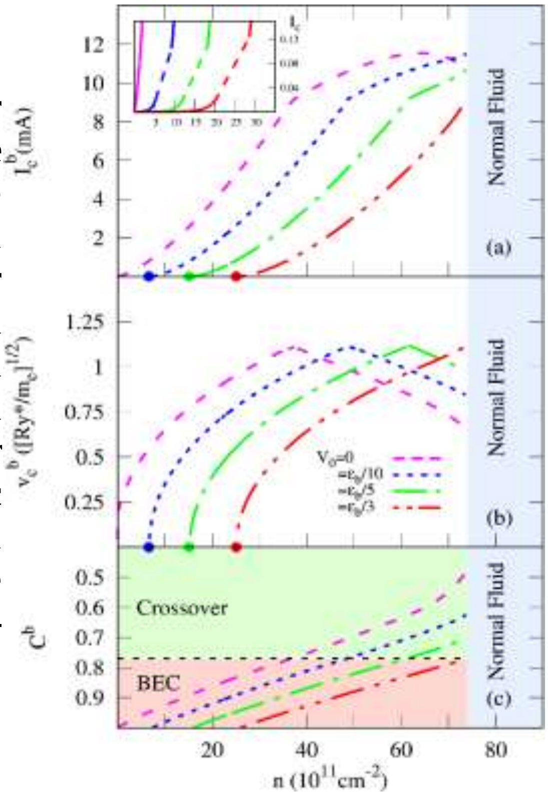

Figure 1: Critical current (a), critical velocity (b), condensate fraction (c) for different barrier heights V_0.

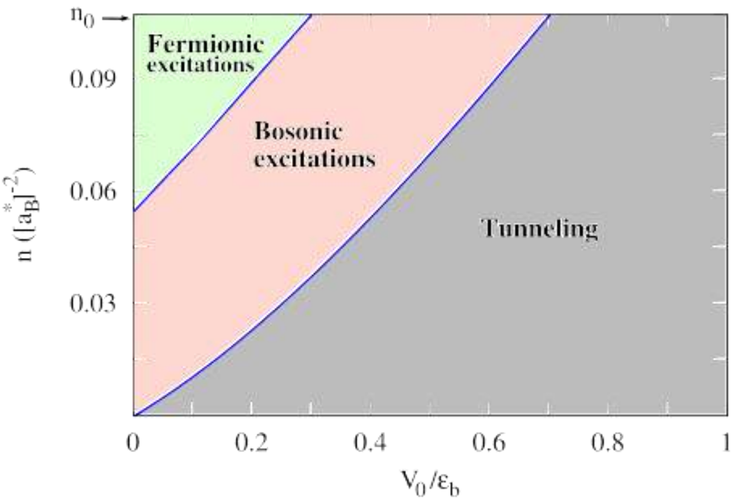

Figure 2: Critical current driving mechanism.

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On the Theoretical Description of Photon Bose-Einstein Condensates

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Since the advent of experiments with photon Bose-Einstein condensates in dye-filled microcavities in 2010 [1], many investigations have focused upon the emerging effective photon-photon interaction. Despite its smallness, it can be identified to stem from two physically distinct mechanisms [2]. On the one hand, a Kerr nonlinearity of the dye medium yields a photon-photon contact interaction, whose microscopic theoretical description is based on a Lindblad master equation [3]. On the other hand, a heating of the dye medium leads to an additional thermo-optic interaction, which is both delayed and non-local [4]. The latter turns out to represent the leading contribution to the effective interaction for the current 2D experiments.

A new experimental platform, which is currently built up in Kaiserslautern, will be devoted to analyse the dimensional crossover in trapped photon gases from 2D to 1D. As the photon-photon interaction is generically quite weak, they behave nearly as an ideal Bose gas. Moreover, since the current experiments are conducted in a microcavity, the longitudinal motion is frozen out and the photon gas represents effectively a two-dimensional trapped gas of massive bosons, where the anisotropy of the confinement allows for a dimensional crossover. A detailed investigation for such a system allows to determine its effective dimensionality from thermodynamic quantities [5].

Furthermore, we investigate how the effective photon-photon interaction changes on the meanfield level when the system dimension is reduced from 2D to 1D [6]. To this end, we consider an anisotropic harmonic trapping potential and determine via a variational approach how the properties of the photon Bose-Einstein condensate in general and both aforementioned interaction mechanisms in particular change with increasing anisotropy. We find that the thermo-optic interaction strength increases at first linearly with the trap aspect ratio and later on saturates at a certain value of the trap aspect ratio. And in the strong 1D limit the roles of both interactions get reversed as the thermo-optic interaction remains saturated and the contact Kerr interaction becomes the leading interaction mechanism.

Finally, we go beyond the mean-field theory and work out a quantum mechanical description of the effective photon-photon interaction [7]. At first we apply it in the perturbative regime to both a harmonic and a box potential for investigating its prospect for precise measurements of the effective photon-photon interaction strength. Then, by utilising an Exact Diagonalization approach, we reveal how the effective photon-

photon interaction modifies both the spectrum and the width of the photon gas. A comparison with a variational approach based on the Gross-Pitaevskii equation quantifies the contribution of the thermal cloud in the respective applications.

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Screening of fluctuations in multicomponent superconductors and superfluids

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The superconductivity in iron-based, magnesium diborides, and other high-Tc superconducting materials, including indications of high-Tc superconductivity in the organic potassium doped paraterphenyl, has a strong multi-band, multi-gap, and resonant character. Recent experiments support a BCS-BEC crossover induced by strong-coupling and proximity of the chemical potential to the band edge of one of the bands, with evidences for Lifshitz transitions associated with changes in the Fermi surface topology [1,2,3].

Here we study the BCS-BEC crossover, superconducting fluctuations, and complex pseudogap phenomena in a two-band / two-gap superconductor, considering tunable interactions, including mean-field and fluctuations effects. When the gap is of the order of the local chemical potential, superconductivity is in the crossover regime of the BCS-BEC crossover and the Fermi surface of the small band is completely smeared by the gap opening. In this situation, small and large Cooper pairs coexist in the condensate, which is the optimal condition for very high-Tc superconductivity, thanks to the screening of superconducting fluctuations generated by the deep band, showing in addition unexpected consequences on the pseudogap phenomenon above the critical temperature [4].

We discuss different physical systems in which the multigap and multiband BCS-BEC crossover can be realized, pointing toward very high-Tc superconductivity. As an example we consider here superconducting stripes in which shape resonances and multigap physics at the band edge play a cooperative role in enhancing superconductivity in the crossover regime of pairing [4,5,6,7]. A key prediction of the above discussed physics is recalled and discussed in comparison with experiments: the isotope effect of the superconducting critical temperature in the vicinity of a Lifshitz transition, which has a unique dependence on the energy distance between the chemical potential and the Lifshitz transition point [6].

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Evolution of an attractive polarized Fermi gas from the polaronic limit to the superfluid quantum critical point

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We analyze the evolution of an attractive polarized two-component Fermi gas at zero temperature as its polarization is progressively decreased from full polarization down to the critical value at which superfluidity sets in [1]. Within a fully self-consistent *t*-matrix approach [2,3], we determine the critical polarization and the nature of the superfluid instability which, depending on the coupling strength between the two components, can be either towards a Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) superfluid, or towards a more standard polarized BCS superfluid. We construct in this way the polarization-vs-coupling phase diagram at zero temperature throughout the whole BCS-BEC crossover. We find that the evolution with polarization of the quasi-particle parameters of the normal Fermi gas is strikingly different depending on the nature of the superfluid instability. When the superfluid instability is towards a polarized BCS superfluid, quasi-particles in the proximity of the two Fermi surfaces remain well defined for all polarizations. When the instability is towards an FFLO superfluid, the quasi-particle residues vanish and the effective masses diverge as the FFLO quantum critical point (QCP) is approached, with a complete breakdown of the quasi-particle picture that is similar to what is found in heavy-fermion materials at an antiferromagnetic QCP.

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Hydrides Superconductors in the Uemura diagram and the possible role of Nonadiabatic Superconductivity

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The Uemura diagram (below) provided a strong indication that all anomalous High Tc Superconductors are characterized by a very small Fermi energy (velocity). This stimulated the development of the Nonadiabatic Theory of Superconductivity (NTS) beyond Migdal's theorem. The possible location of the Hydrides in the same region has been conjectured for various reasons. Together with the high phonon frequency this may imply a possible role of NTS which we will discuss also in relation to the possible engineering of low pressure materials.

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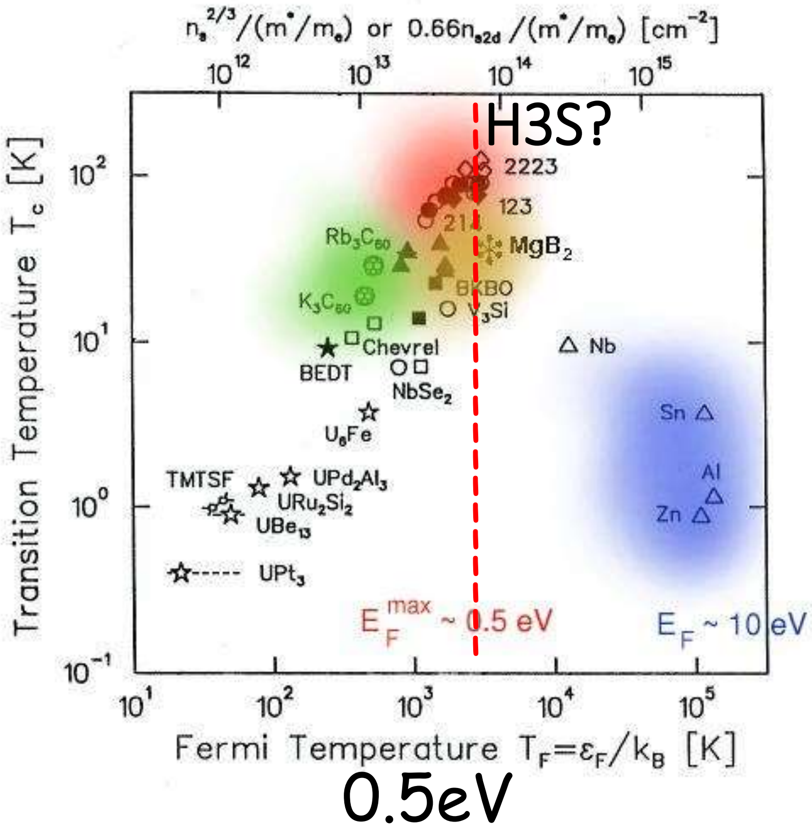

Dynamics of massive point vortices in a binary mixture of Bose-Einstein condensates

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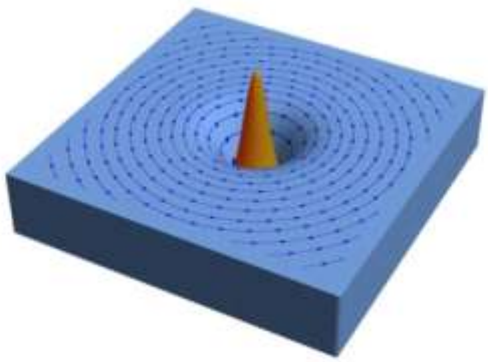
In quantum matter, vortices are topological excitations characterized by quantized circulation of the velocity field. They are often modelled as funnel-like holes around which the quantum fluid exhibits a swirling flow. In this perspective, vortex cores are nothing more than empty regions where the superfluid density goes to zero. In the last few years, this simple view has been challenged and it is now increasingly clear that, in many real systems, vortex cores are not that empty. In these cases, the hole in the superfluid is filled by particles or excitations which thus dress the vortices and provide them with an effective inertial mass.

In this talk, I will discuss the dynamics of two-dimensional point vortices of one species that have small cores of a different species. I will show how to derive the relevant Lagrangian itself, based on the time-dependent variational method with a two-component Gross-Pitaevskii (GP) trial function. The resulting Lagrangian resembles that of charged particles in a static electromagnetic field, where the canonical momentum includes an electromagnetic term. I will also show some interesting dynamical regimes. The simplest example is a single vortex within a rigid circular boundary, where a massless vortex can only precess uniformly. In contrast, the presence of a small core mass can lead to small radial oscillations, which are, in turn, clear signatures of the associated inertial effect.



The analytical model is then benchmarked against detailed numerical simulations of coupled two-component GP equations with a single vortex and small second-component core. The presence of such radial oscillations is confirmed, implying that this more realistic GP vortex acts as if it has a small massive core.

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Density induced BCS-Bose evolution in gated two-dimensional superconductors: The role of the interaction range in the Berezinskii-Kosterlitz-Thouless transition

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The evolution from Bardeen-Cooper-Schrieffer (BCS) to Bose superconductivity versus carrier density (n) in two-dimensional (2D) gated superconductors is discussed and the fundamental role that the interaction range plays in the Berezinskii-Kosterlitz-Thouless transition is addressed. [1] The density dependence of the critical temperature (T_c), superfluid density, order parameter, chemical potential and pair size are investigated. The most important finding is that it is essential to include classical and quantum phase fluctuations, as well as finite-ranged interactions to explain the non-monotonic behavior of T_c versus n and to guarantee that the upper bound on T_c is not exceeded in 2D superconductors, as experimentally observed in Li_xZrNCl [Science 372, **190** (2021)], a lithium intercalated layered nitride, and in magic-angle twisted trilayer graphene [Nature **590**, 249 (2021)]. Furthermore, it is shown that the effective mass of charge carriers, their interaction strength and range can be extracted from measurements of T_c and the order parameter.

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Collective excitations and quantum incompressibility in electron-hole fluids

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We have recently extended to electron-hole bilayers [1] the quantum continuum mechanics (QCM) formalism [2], which expresses excitation energies at $T = 0$ in terms of ground-state pair correlation functions and kinetic energy. The final formulas for the collective modes deduced from this approach coincide with the formulas obtained in the QLC approximation of Kalman and co-workers, as adapted to e-e bilayers [3], once the non-interacting kinetic energy is replaced with the interacting one. In the charged channell the theory [1] predicts the existence of gapped excitations, with the gap arising from electron-hole correlation, with the consequence that the static density-density response function vanishes as q^2 for $q \to 0$, rather than linearly in q, as commonly expected, pointing to an incompressibility of the system. This feature, which has no analog in the classical electron-hole plasma, is consistent with the existence of an excitonic ground state and implies the existence of a discontinuity in the chemical potential of electrons and holes when the numbers of electrons and holes are equal. It should be experimentally observable by monitoring the densities of electrons and holes in response to potentials that attempt to change these densities in opposite directions. I will first briefly review our findings for the electron-hole bilayers when using structure and kinetic energy from (i) accurate DMC simulations [4] or (ii) a BCS selfconsistent scheme. I will then turn to the application of the QCM to a 3-dimensional electron-hole homogeneous fluid at $T = 0$, stressing similarities and differences with the 2-dimensional counterpart. I will then present preliminary numerical results obtained using ground-state structure and kinetic energy computed within a BCS selfconsistent scheme.

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Granularity related superconducting properties in NbN ultrathin films

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Poster abstract

We have found and characterized the Berezinskii-Kosterlitz-Thouless (BKT) type superconducting transitions in NbN ultrathin films [1, 2]. Several NbN films having a thickness lower than 10 nm have been deposited on different type of substrates as MgO, Sapphire and SiO_2. All investigated samples have evidenced a BKT transition both in the temperature dependent resistivity curve and in the current-voltage (I-V) characteristics, outside the theoretical expectations. In general, thin films of NbN can be considered as a 2D strongly coupled type-II superconducting system characterised by a 3D to 2D BKT like transition, belonging to the same universality class of the 2D XY model [4]. In the studied NbN nanofilms, the observation of the BKT transition has been connected to the intrinsic granularity and possible in-homogeneities of the films, documented in the literature [3]. For the analysis and interpretation, the Cooper fluctuation model for 2D superconducting system has been implemented in order to understand the vortex-anti-vortex interaction and the specific properties of the BKT superconducting transition in the NbN ultrathin films explored in this work.

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How many heavy fermions can be bound by a single light atom in 1D?

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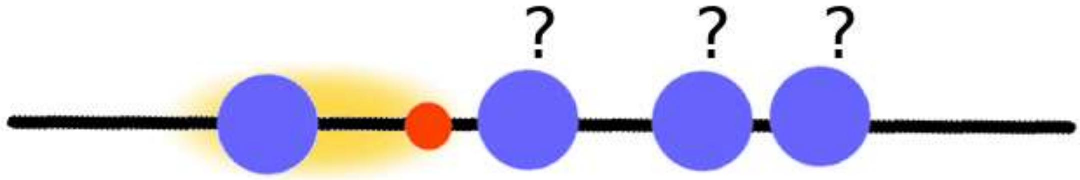

We analyze the problem of N identical fermions interacting via a zero-range attractive potential with a lighter atom in one dimension. We address the fundamental question of how many atoms can be bound in a cluster, analyzing the main scales that control the problem: the number of atoms and the heavy-to-light mass ratio. At small N, in particular, we employ an exact method to determine the critical mass ratios for the emergence of the tetramer, pentamer and hexamer. At large N, we solve the problem analytically with a mean-field theory based on the Thomas-Fermi approximation, and set up a Hartree-Fock approach that can be perturbatively improved and describes precisely the microscopic structure of the clusters. Our findings have implications for experiments with mass and density imbalanced fermionic mixtures.

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Chronological Development and Relevant Ideas of the Uemura Plot
--- personal accounts and views ---

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Soon after the discovery of high-Tc cuprates, which was shared among the research community in 1987, we performed muon spin relaxation measurements of the magnetic penetration depth in many cuprate and other unconventional superconductors (SCs). We reported a nearly linear relationship between the superfluid density n_s/m^* and Tc, and initiated discussions of these results using an energy scale argument of a plot of Tc versus the effective Fermi temperature T_F derived from the superfluid density. These two plots are often referred to as "Uemura plot" and has been updated by many subsequent experiments on various new unconventional SCs, including the twisted bi-layer and tri-layer graphene. Regarding its implications, however, different and sometimes conflicting views exist, especially in views originating from 2-dimensional (2-d) Kosterlitz-Thouless (KT) transitions, and 3-d Bose Einstein Condensation. In this talk, I would like to review these views, with their chronological developments, along the progress of experimental knowledge.

We will start with the pre-cuprate era results on superconductivity and superfluidity of thin films of BCS superconductors and syperfluid 4He adsorbed on various films, both of which exhibit KT transition. Then the results on layered cuprates and BEDT systems were first noticed for the linear relationship between Tc and the superfluid density, but soon followed by many of the more 3-d systems, such as A_3C_{60} and Fe-based SCs.

In 1994-95, with detailed results on the pseudogap becoming available, we had an opportunity to consider the overall framework: I was one of those advocating BEC-BCS crossover on 3-d concepts, while Vic Emery was stressing 2-d aspects.

For 3-d models, it was necessary to notice that the idealized BEC temperature, obtained from n_s and m*, is about 5 times or more higher than the actual Tc. To resolve this difficulty, I proposed a model in 2004 in which we developed an analogy between rotons in the superfluid 4He and the magnetic resonance mode in unconventional SC's, both as thermal excitations originating from fluctuations of competing order. These dynamic excitations thermodynamically determine Tc.

It is then important to find some actual physical phenomena which signify the "idealized BEC transition line", existing well above actual Tc. In 2004 I noticed that the onset temperature of the Nernst effect can be explained as this "idealized BEC" line which represents the point where the local phase coherence becomes conceivable in a simple density arguments with n_s and m* In 2017, I also realized that the transient optical spectral weight and the transient onset temperature of Cavalleri's photo excited experiments can be considered as representing the idealized BEC line, in a manner as if photo excitations eliminated the effect of competing order. In contrast, the concept of "local phase coherence" is missing in the KT type argument in 2-d SC systems.

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