



Workshop on Impurity Problems in Quantum Mixtures: from Ultracold Gases to Electron Matter | (SMR 4208)

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Unsupervised Learning of Effective Models for Quantum Impurity Systems

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Quantum impurity models are essential for describing nanoscale electronic systems, but their simulation becomes difficult when strong interactions generate complex low-energy behavior. We present a nonperturbative unsupervised learning approach that automatically constructs simple yet accurate effective impurity Hamiltonians. By minimizing the quantum relative entropy between the bare system and an effective model, our method identifies optimal parameters that reproduce key thermodynamic observables without requiring full low-temperature solutions of the original model. Benchmark tests on the Anderson impurity model demonstrate that the learned effective models capture both the low-energy physics and renormalization effects with high fidelity. This framework provides a general and scalable route to modeling complex correlated systems and offers a powerful tool for quantum materials and nanoelectronics research.

Polarons in Interacting Many-Body Systems: Unobserved Theoretical Predictions

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I will theoretically analyze a few cases of polaron spectra in interacting many-body baths, featuring BCS pairing [1,2], charge density waves [3,4], Mott insulator phases [4], topological edge states [5], BKT transitions [6], etc. Crucially, the injection spectrum of the impurity carries the hallmarks of the properties and correlations present in the bath. However, many of these predictions are still awaiting for experimental confirmation, and I will try to explain the origins of this gap between theory and experiments for the case of excitons in 2D materials and cold atomic mixtures.

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Impurity physics with Bose-Einstein condensates

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An impurity particle embedded in a bosonic environment poses a fundamental quantum many-body problem. The impurity, effectively described as a quasiparticle called the Bose polaron, is dressed by the surrounding medium. We use Bose-Einstein condensates to quantum simulate impurity physics. Generally, we use a combination of spectroscopic and interferometric schemes to investigate the spectral and dynamical properties of the Bose polaron.

In this work, we utilize an interferometric Ramsey-like method to investigate the non-equilibrium dynamics in 39K Bose-Einstein condensates, letting a different Zeeman state act as an impurity embedded within. This experimental scheme grants access to the quantum coherence of the impurity state, and we can resolve the ultrafast dynamics. Due to the rich Feshbach structure in 39K, we can tune the coupling between medium and impurity – both for attractive and repulsive interactions.

In earlier experiments, we have extensively investigated the dynamics of the impurity state in the regime, where the interaction between medium and impurity is attractive [1,2]. Recently, we have extended these investigations to repulsive interactions, where the energy landscape is richer [3]. Interestingly, we observe quantum beating between competing coexisting polaronic states, and we demonstrate that the energy difference between these states can be extracted from the quantum beat frequency.

Furthermore, we identify several dynamical regimes in the formation of the repulsive Bose polaron, greatly improving our understanding of quantum impurities interacting strongly, repulsively with a bosonic environment.

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[3] A.M. Morgen et al., Phys. Rev. Research 7, L022002 (2025)

Spectral properties of Bose-Fermi mixtures in two dimensions

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Ultracold dilute Bose-Fermi (BF) mixtures are highly tunable and controllable systems, allowing for the investigation of substantially different conditions and quantum effects in matter. In such mixtures with a pairing interaction, one can study the competition between the formation of fermionic composite molecules and the tendency of bosons to condense. One possible application is a recent proposal to obtain a quantum simulator for p -wave superfluidity [1].

In previous work [2], we considered a 2D ultracold Bose-Fermi mixture at $T = 0$. We described the system applying to two dimensions an (imaginary-time) T-matrix many-body approach, which has also been successfully applied to 3D systems [3, 4].

In the present work, we focus on single-particle spectral properties, which could be relevant for future radio-frequency spectroscopy experiments (as done in 3D in [5]). To calculate dynamic quantities, we reformulate our theory for real-time and frequencies (as done in 3D in [6]). We study the evolution from the (Fermi) polaron regime to the case of a finite concentration of partially condensed bosons. In the literature, the Fermi polaron has been abundantly studied (e.g., in [7]), while the study of a finite bosonic density with arbitrary boson-fermion attraction is almost absent.

Our main results for the bosonic spectral weight function are:

- At small bosonic concentration, the dispersions of the attractive and repulsive branches are only slightly modified from the polaronic case, but acquire, however, a finite width and thus a finite lifetime even at small momenta;
- The presence of the condensate introduces at negative frequencies a new dispersion of poles of the T-matrix (first predicted in 3D mixtures in [8]). This, in turn, creates in the bosonic spectral weight function a new structure at negative frequencies, whose prediction could be verified by radio-frequency spectroscopy experiments;
- The polaronic picture is no longer valid going towards the density-matched case, where we observe the appearance of a third excitation branch.
- The bosonic Goldstone mode displays a non-trivial dependence on the Bose-Fermi and Bose-Bose interactions, with a peak in its stiffness at intermediate Bose-Fermi attractions.

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Realization of repulsive polarons in the strongly correlated regime

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Mobile impurities interacting with a quantum medium form quasiparticles known as polarons, a central concept in many-body physics. While the quantum impurity problem has been extensively studied with ultracold atomic gases, repulsive polarons in the strongly correlated regime have remained elusive. Typically, the impurity atoms bind into molecules or rapidly decay into deeper lying states before they can acquire an appreciable dressing cloud. Here, we report on the realization of polarons in a strongly repulsive quasi-two-dimensional quantum gas. Using a superfluid of ⁶Li dimers, we introduce impurities by promoting a small fraction of the dimers into higher levels of the transverse confining potential. These novel synthetic-spin polarons give access to the strongly repulsive regime where common decay channels are suppressed. We extract key polaron properties—the energy, quasiparticle residue, and effective mass—using trap modulation and Bragg spectroscopy. Our measurements are well captured by a microscopic T -matrix approach and quantum Monte Carlo simulations, revealing deviations from mean-field predictions. In particular, we measure a significant enhancement of the polaron mass, with values exceeding twice the free dimer mass. Our demonstration of a stable repulsive Bose polaron establishes a platform for studying impurity physics in low-dimensional and strongly correlated systems [1].

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Stability of Magnetization in Frustrated Heisenberg Lattices: A Linear Spin-Wave Approach With Duffy-Regularized Integrals

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It is shown a theoretical and computational study of the stability of the antiferromagnetic order in frustrated spin- $\frac{1}{2}$ Heisenberg models with competing nearest- and next-nearest-neighbor couplings J_2/J_1 . Motivated by recent high-precision work on the square-lattice $J_1 - J_2$ model, which shows a direct transition from Néel order to a valence-bond solid without an intermediate spin liquid [1], and by coupled cluster method and related studies of the triangular and cubic $J_1 - J_2$ models that map out where 120° and collinear orders are destroyed by frustration [2, 3], we aimed to compute the ground-state staggered magnetization across these phase diagrams within Linear Spin-Wave Theory (LSWT). First, it was considered the nearest-neighbor scenario, where the magnetization is calculated in the magnon ground state within the magnetic Brillouin zone, computing the integrals using Duffy-type coordinate transformations to regularize the infrared singularities at the Goldstone points [4]. This approach resembles accurately the known results for the unfrustrated 2D square [5] and 3D simple-cubic [6] antiferromagnets, obtaining magnetizations in excellent agreement with established values from more fancy methods as quantum Monte Carlo and series expansions broadly found in literature. Then, this framework LSWT + Duffy-type transformations is also extended to the frustrated $J_1 - J_2$ square, cubic, and triangular lattices, mapping where long-range magnetic order survives or collapses as frustration is increased, and thereby providing a novel and simpler method to approach the stability of the magnetization in these canonical frustrated quantum magnets.

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Impurity Effects and Polaronic Behavior in Ni-Doped SnO₂: Bridging Experiment and First-Principles Theory

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We investigated the effect of nickel (Ni) doping on the structural, morphological, and optoelectronic properties of SnO₂, combining experimental characterization and first-principles simulations. Ni was incorporated at concentrations of 1%, 2%, 3%, 4%, and 5% to systematically probe its role as an impurity in the SnO₂ lattice. Experimentally, X-ray diffraction and electron microscopy revealed modifications in crystallite size and surface morphology with increasing Ni content. Optical measurements indicated changes in the band gap and absorption properties, suggesting tuning of electronic states by Ni incorporation. These experimental results were validated and interpreted through density functional theory (DFT) calculations, which provided insights into the formation energies, electronic density of states, and potential polaronic effects induced by Ni impurities. Our combined approach elucidates how controlled Ni doping modulates the electronic structure and optoelectronic performance of SnO₂, offering guidance for designing oxide-based functional materials for applications such as electron transport layers in photovoltaic devices.

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[2] M. Al-Hattab, E. Oublal, M. Sahal, L. Moudou, O. Bajjou, and K. Rahmani. Simulation study of the novel ag₂mgsn(s/se)₄ chalcogenide tandem solar device employing monolithically integrated (2t) configurations. *Solar Energy*, 248:221–229, 2022.

Harnessing spin-qubit decoherence to probe strongly-interacting quantum systems

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Using a mobile qubit as a probe to study the properties of a larger quantum system is a novel technique that takes advantage of quantum properties of the probe, the system under study, and the interaction between them [1-3]. This allows to obtain accurate information about the physical characteristics of the system as well as to determine system properties which are impossible or hard to study by classical measurement schemes. The idea relies on treating the system as an environment from the perspective of the qubit and measure qubit decay or decoherence. Such indirect measurement is advantageous because the qubit is easily accessible experimentally while its position and the properties of the qubit and interaction can be tuned.

Extending this method to strongly correlated systems, which exhibit complex and challenging-to-measure properties, is particularly valuable. Here, we apply this method to investigate the anisotropic Heisenberg XXZ spin-1/2 chain, an archetypal example of strongly correlated system. By integrating the Time-Convolutionless (TCL) projection operator method with the Time Dependent Variational Principle (TDVP), we observe diverse dynamics in the qubit evolution, reflecting different parameters of the chain. This demonstrates that a spin qubit can probe both quantitative properties of the spin chain and qualitative characteristics, such as the quantum phase transitions, and perturbation propagation velocity within the system [4]. This approach reveals the power of small quantum systems to probe the properties of large, strongly correlated quantum systems.

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Kondo, Kagome, and Strain: Engineering High Thermoelectric Efficiency in Correlated Quantum Impurity Systems

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Understanding thermoelectric transport in materials with strong electronic correlations is crucial for designing high-efficiency devices. At low temperatures, the Kondo Effect drives the formation of the Abrikosov-Suhl Resonance, a sharp peak in the electronic density of states near the Fermi energy level (ϵ_F). This phenomenon is vital for optimizing the Seebeck coefficient (S), a key measure of thermoelectric conversion capacity. In this study, we apply the Single Impurity Anderson Model (SIAM), solved via the highly accurate Numerical Renormalization Group (NRG) method, to analyze the transport properties in a novel system: an impurity coupled to a Kagome lattice nanoribbon. The Kagome lattice, known for its unique geometry and the presence of flat bands, provides an excellent platform to enhance electronic interactions and improve electrical conductivity (σ). Furthermore, we introduce uniaxial strain as an external control tool to tune the electronic energy levels and, consequently, optimize the material's thermoelectric performance. Our results demonstrate that the combination of the Kagome structure, the asymmetric positioning of the impurity level (ϵ_d), and the application of uniaxial strain leads to remarkable improvements in the material's Figure of Merit (ZT). The crucial ability to break electron-hole symmetry, essential for maximizing the Seebeck coefficient, is achieved by carefully tuning the impurity energy level. In summary, the precise simulations performed using the NRG provide clear guidelines for the rational design of highly efficient thermoelectric materials, specifically aiming at the maximization of the power factor ($S^2\sigma$). This work opens up significant possibilities for applications in energy harvesting and solid-state refrigeration systems.

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Quantum-Monte Carlo study of electron-hole bilayer at low-density.

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Bilayer electron-hole systems provide a unique platform for investigating fundamental properties of excitons, particularly their condensation and superfluid behavior. By means of Quantum Monte Carlo we explore the formation and stability of interlayer excitons driven by Coulomb interactions as well as the appearance of the complexes made of excitons[1] such as bi-exciton or quadri-exciton, for the system with valley degeneracy[2], and their effect on the exciton condensation as well as possible signature in the the dispersion energy. Our focus will be on the low-density region of the system where the screening is reduced and the Coulomb interactions enhanced; if the repulsion between the well-formed elementary objects (excitons, biexcitons..) can become dominant over the kinetic energy, the spontaneous formation of a Wigner Crystal can occur, the possible coexistence with supefluidity order is discussed.

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Strongly-interacting impurities in 1D Bose gas: From emergent anyons to non-equilibrium polaron formation

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Anyons [1,2] are low-dimensional quasiparticles that obey fractional statistics, hence interpolating between bosons and fermions. One-dimensional (1D) anyons have been theoretically proposed, but their experimental realization has proven to be difficult. Here, we report the observation [3] of emergent anyonic correlations in a 1D strongly-interacting quantum gas, resulting from the phenomenon of spin-charge separation. A mobile impurity provides the necessary spin degree of freedom to engineer anyonic correlations in the charge sector and simultaneously acts as a probe to reveal these correlations. Starting with bosons, we tune the statistical phase to transmute bosons via anyons to fermions and observe an asymmetric momentum distribution, hallmark of anyonic correlations. Our work demonstrates how impurities can be used to create and probe emergent anyonic correlations in a strongly-interacting Bose gas.

In the second part [4], we inject a bare impurity with initial velocities ranging from subsonic to supersonic values, and subsequently track its dynamics. We observe the formation of a shock wave in the supersonic regime and identify a transition to a stationary regime past a remarkably short relaxation time. Contrary to conventional expectations of relaxation, we find that in the long-time limit, the impurity never comes to a full stop. Instead, the impurity forms a strongly correlated state with the quantum fluid and reaches a steady-state that propagates at a reduced velocity. For small initial velocity, this correlated state is akin to a dynamically generated moving Bose polaron and for a supersonic impurity our experiment qualitatively agrees with the phenomenon of quantum flutter [5].

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Mass-Gap Description of Heavy Impurities in Fermi Gases

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Single impurities immersed in a degenerate Fermi gas exhibit fascinating many-body phenomena, such as the polaron-to-molecule transition and Anderson's orthogonality catastrophe (OC). It is known that mobile impurities of finite mass can be described as quasiparticles, so called Fermi polarons. In contrast, Anderson showed in 1967 that the ground state of a static, infinitely heavy impurity in a Fermi sea is orthogonal to the ground state of the system without impurity - a hallmark of the OC and a fundamentally non-perturbative effect. As a result, conventional variational approaches or path integral methods fail to capture this phenomenon accurately. Despite decades of research, a unified approach connecting the quasiparticle description of Fermi polarons with Anderson's OC has remained elusive. In this work, we present a theoretical framework for arbitrary-mass impurities in a Fermi sea that incorporates Anderson's OC, the polaron-to-molecule transition and the quasiparticle picture. Our theory provides a simple yet powerful description of interacting quantum systems, with broad implications for ultra-cold atom experiments, atomically thin semiconductors, and future studies of strongly correlated matter.

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Mediated interactions in quantum mixtures

Anomalous diffusion and localization in a disorder-free atomic mixture

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The concept of random walk, in which particles or waves undergo multiple collisions with the microscopic constituents of a surrounding medium, is central to understanding diffusive transport across many research areas. However, this paradigm may break down in complex systems, where quantum interference and memory effects render the particle propagation anomalous, often fostering localization. Here we report on the observation of such anomalous dynamics in a minimal setting: an ultracold mass-imbalanced mixture of two fermionic gases in three dimensions. We release light impurities into a gas of heavier atoms and follow their evolution across different collisional regimes. Under strong interspecies interactions, by lowering the temperature we unveil a crossover from normal diffusion to subdiffusion. Simultaneously, a localized fraction of the light gas emerges, displaying no discernible dynamics over hundreds of collisions. Our findings, incompatible with the conventional Fermi-liquid picture, are instead captured by a model of an atom propagating through a (quasi-)static disordered landscape of point-like scatterers. These results highlight the key role of quantum interference in our mixture, which emerges as a versatile platform for exploring disorder-free localization phenomena.

Counterflow of impurities in harmonically confined optical lattices

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The progress in realising ultracold atomic mixtures has greatly revitalised the interest in studying impurities immersed in quantum mediums [1]. Following these developments, and motivated by the possibility of trapping ultracold atoms in optical lattices [2], the theoretical study of impurities in lattice configurations has emerged as a new platform for studying polaron physics. In this direction, recent studies of impurities interacting with bosonic baths have revealed intriguing features across the superfluid-to-Mott insulator transition [3,4].

In this work [5], we study an impurity interacting with a bosonic bath and immersed in a harmonically confined optical lattice. By means of DMRG simulations, we reveal that the impurity can form a correlated counterflow state with a bosonic bath. This counterflow state [6] shows long-range anti-pair order and displays non-trivial features, including a sudden orthogonality. These findings show that counterflow order appears even for large population imbalances in ultracold atomic mixtures.

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Interplay of Static and Photon-Mediated Interactions in Rydberg Lattices Inside an Optical Cavity

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Arrays of Rydberg atoms provide a platform for exploring many-body quantum physics with controllable long-range interactions. When such an array is placed inside a high-finesse optical cavity, the Rydberg spins couple collectively to quantized electromagnetic modes, giving rise to photon-mediated interactions that are intrinsically retarded in time. The coexistence of static van der Waals couplings and dynamically generated, frequency-dependent interactions opens a rich landscape of correlated light–matter phases.

Using an extended dynamical mean-field theory (EDMFT) framework, we study the steady-state properties of a two-dimensional lattice of Rydberg atoms coupled to the multimode cavity field. Our analysis captures on equal footing the instantaneous Ising-type interactions and the retarded exchange mediated by vacuum fluctuations of the photons. We identify competing regimes characterized by antiferromagnetic ordering, superradiant-like phases with collective photon coherence, and magnetically polarized states controlled by the effective longitudinal field. The resulting phase diagram reveals how cavity confinement and retardation qualitatively modify the nature of magnetic and superradiant transitions.

Our results demonstrate that cavity-embedded Rydberg arrays constitute a versatile platform where static and dynamic long-range couplings can be engineered and tuned, providing a route toward designing quantum phases of light and matter in and out of equilibrium.

Time resolved formation dynamics of a heavy Fermi polaron

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We study experimentally the decoherence of ^{133}Cs impurities embedded within a three-dimensional Fermi sea of ^6Li . As we show, this interacting system of impurities and a degenerate Fermi sea can be well described by the quasiparticle picture introduced by Landau's Fermi liquid theory [1]. The behavior of these emergent quasiparticles scales with the Fermi sea properties, which allows for complementary studies across different systems. While in metals – with a Fermi sea of electrons – the Fermi energy is on the order of a few electron volts and its corresponding shortest reaction time τ_F is about 100 attoseconds, ultracold atom experiments provide much more accessible timescales in the microsecond regime [2].

I will present our latest results on the formation dynamics of a Fermi polaron at a temperature of $T/T_F = 0.2$. Compared to previous work on the $^6\text{Li} - ^{40}\text{K}$ system in Innsbruck [2], our mass ratio of 22.2 is the highest achievable with alkali atoms, which significantly reduces the mobile character of the impurity. In the limit of a static impurity, the quasiparticle picture no longer describes the system, and the interacting many-body state is fully orthogonal to the initial Fermi sea. This phenomenon is known as the Anderson orthogonality catastrophe (AOC) [5] and our system explores a novel regime in the transition region close to the AOC, where first signatures of this behavior are predicted [3].

Additionally, it is worth mentioning that current theoretical models cannot fully describe our system, which makes it a perfect testbed for state-of-the-art polaron theories [3,4]. First comparisons show that the observed dynamics are similar to the predictions for the infinitely heavy polaron calculated with the functional determinant approach (FDA) for the given temperature [6], but also show significant differences, which indicate the remaining quasiparticle character of our many-body state.

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Strong optical nonlinearity of Fermi-polarons in monolayer MoSe₂**Shibalik Lahiri¹, Jonas Peterson², Monique Tie³, Tony Heinz,^{3,4,5} Valentin Walther^{1,2}, Libai Huang²**

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Strong few-photon nonlinearities are central to quantum photonics yet remain difficult to realize with bare excitons. In monolayer MoSe₂, an exciton dressed by a degenerate Fermi sea forms a Fermi polaron with dramatically enhanced interactions. While the attractive and repulsive polaron branches are well established spectroscopically, their spatial blockade has been unclear. Using femtosecond pump–probe microscopy, we directly image a polaron blockade: a single excitonic excitation couples collectively to tens of electrons and creating an extended blockade radius up to 40 nm in which additional excitations are suppressed—over an order of magnitude larger than the blockade associated with bare excitons. To identify its microscopic origin, we develop a variational model based on the Chevy ansatz, which truncates the hierarchy of particle–hole excitations while retaining essential correlations. The quantitative agreement between experiment and theory motivates a simple blockade framework that captures emergent spatial correlations, phase-space filling, and the resulting giant nonlinearity. Together, these results establish exciton–Fermi polarons in TMDCs as electrically gate-tunable, solid-state platforms for exploring strongly correlated optical quasiparticles and for realizing ultralow-power, few-photon nonlinear devices.

Semigroup Influence Matrices for Nonequilibrium Quantum Impurity Models

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I present a framework for describing the real-time dynamics of quantum impurity models (QIM) out of equilibrium which is based on the influence matrix approach [1, 2]. The method works by replacing the dynamical map of a large quantum environment with an effective semigroup influence matrix (SGIM) which acts on a reduced auxiliary space. This genuinely dissipative embedding enables stable simulations to long evolution times in both equilibrium and non-equilibrium settings. Technically speaking, the SGIM corresponds to a uniform matrix product state representation of the influence functional and can be obtained via tensor network algorithms. Our method performs excellent for computing dynamical quantities including quench dynamics and spectral functions, providing high resolution with low numerical effort. As an application we compute the numerically exact spectral function of a quantum impurity model with on-site two-fermion loss and confirm the emergence of Kondo physics at large loss rates.

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Bound states in the continuum realized in ultracold gases

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Quantum mechanical interaction potentials typically support either bound molecular states or unbound scattering states. An interesting exception are bound states in the continuum (BICs), localized quantum states with energies well above the molecular dissociation threshold. In 1985, Friedrich and Wintgen (FW) proposed a mechanism to realise such BICs in quantum systems through the interference of two Feshbach resonances [1]. Although since then BICs have been realised in classical systems [2], an unambiguous quantum-mechanical realisation based on the FW mechanism has so far remained elusive. In my contribution, I will present the experimental observations of the FW-BIC in an ultracold Li-6 atomic gas. The state is achieved through the interference of two tunable Feshbach resonances induced by Floquet engineering, implemented via high-frequency magnetic-field modulation that generates additional Feshbach scattering resonances with controllable positions and widths [3]. We support our observation by full coupled-channel calculations. Additionally, by an effective non-Hermitian Hamiltonian, we interpret the state as a dark-scattering state in analogy to electromagnetically-induced transparency.

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Competing few-body correlations in ultracold Fermi polarons

Raman-Driven Spin Noise Spectroscopy as a Real-Time, Non-Destructive Density Probe for Cold Atoms

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Raman-driven spin noise spectroscopy (RDSNS) allows for a non-invasive method for real-time measurement of local densities in cold atomic clouds with high spatial resolution and negligible perturbation. The technique is based on Faraday rotation noise due to Raman coupling between nearest-neighbor Zeeman sublevels, providing a way to probe spin dynamics that are intrinsic, while operating the probe beam in a strongly detuned regime, thus avoiding both atom loss and measurement back-action.

In order to demonstrate this process, we use cold potassium atoms, and the extracted density profiles show very good agreement with those calculated from inverse Abel transformation of fluorescence images in spherically symmetric systems, confirming the correctness of this approach [1]. In contrast to fluorescence-based methods, the RDSNS technique is non-destructive and very fast, with detection times on the order of microseconds. The RDSNS technique does not rely on symmetry assumptions, unlike the Abel transformation technique, and can therefore be used for asymmetric or time-dependent atomic distributions. Its non-destructive and real-time nature allows direct observation of density evolution during the atom capture and loading processes, complementing broadband spin-noise-based sensing and magnetometry methods.

Such features make RDSNS highly relevant for the study of transport phenomena, non-equilibrium dynamics, as well as impurity-induced phenomena in cold-atom experiments. More generally, it serves as a strong diagnostic tool for quantum simulation platforms where repeated measurements are important, providing a non-destructive alternative to standard imaging methods used in research involving cold atomic mixtures and impurity physics [3].

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What Lies Between A Fermi Liquid and a Mott Insulator? Mott Criticality as the Confinement Transition of a Pseudogap-Mott Metal

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The phenomenon of Mott insulation involves the localization of itinerant electrons due to strong local repulsion. Upon doping, a pseudogap (PG) phase emerges - marked by selective gapping of the Fermi surface without conventional symmetry breaking in spin or charge channels. A key challenge is understanding how quasiparticle breakdown in the Fermi liquid gives rise to this enigmatic state, and how it connects to both the Mott insulating and superconducting phases. Can a surface of zeros of the Greens function [1], rather than poles forming a Fermi surface, define an entirely new kind of metal? Could such an exotic state serve as the precursor to Mott localisation driven purely by repulsion, and without invoking magnetic order [2]? These questions necessitate a radical departure in understanding conduction in correlated electron systems beyond the quasiparticle paradigm [3].

I will take about a renormalization-based construction that we have developed for strongly correlated lattice models in order to capture the emergence of the pseudogap phase and its transition to a Mott insulator. Applying a many-body tiling (periodisation) scheme to the fixed-point impurity model uncovers a lattice model with electron interactions and Kondo physics. At half-filling, the interplay between Kondo screening and bath charge fluctuations in the impurity model leads to Fermi liquid breakdown. This reveals a pseudogap phase characterized by a non-Fermi liquid (the Mott metal) residing on nodal arcs, gapped antinodal regions of the Fermi surface, and an anomalous scaling of the electronic scattering rate with frequency. The eventual confinement of holon–doublon excitations of this exotic metal obtains a continuous transition into the Mott insulator. Our results identify the pseudogap as a distinct long-range entangled quantum phase, and offer a new route to Mott criticality beyond the paradigm of local quantum criticality.

While we demonstrate our approach for an extended Hubbard model, the underlying framework is broadly applicable to correlated quantum systems. The impurity-plus-tiling construction accommodates multi-orbital degrees of freedom, frustrated geometries, and nontrivial band topology. It thus provides a versatile and controlled route for engineering strongly correlated models, particularly in regimes where PG formation, NFL scaling, and Mott physics intersect.

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Dynamical Robustness of Quantum Droplets under Perturbations in Driven Low-Dimensional Bose Gases

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We investigate the dynamical behavior and robustness of quantum droplets in one-dimensional Bose mixtures under small perturbations, within the framework of an extended Gross–Pitaevskii equation (eGPE) including Lee–Huang–Yang (LHY) corrections. Starting from equilibrium droplet states, we apply controlled perturbations — e.g., density modulations or weak external excitations — and study the time evolution of the droplet’s shape, density, and phase. Our simulations demonstrate that the droplets remain self-bound and exhibit collective oscillations rather than dispersing or collapsing, highlighting their stability under realistic fluctuations. The results suggest that these droplets are robust beyond the static mean-field picture and can survive non-equilibrium disturbances, making them promising candidates for experiments aiming at exploring collective modes, droplet interactions, and quantum coherence in ultradilute Bose mixtures.

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Dopants in quantum spin lattices: quasiparticles and beyond

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The complex interplay of spin and charge degrees of freedom in doped quantum spin lattices is at the core of our understanding of strongly correlated quantum many-body systems. Indeed, dopant pairing mediated by magnetic interactions in Fermi-Hubbard systems is a potential origin of high-temperature superconductivity.

Recently, quantum simulators using ultracold atoms in optical lattices have emerged as a powerful platform to realize such physics, complementing decades of research in solid state physics. It has, e.g., enabled detailed experiments on spatial spin-dopant correlations and their non-equilibrium dynamics. It is generally believed that dopant motion leads to the formation of itinerant quasiparticles – i.e., magnetic polarons. This is consistent with experiments so far, and also supported at *zero temperature* with high-accuracy matrix-product-state (MPS) calculations in spin ladders and quasi one-dimensional cylindric geometries. However, for two-dimensional systems and/or nonzero temperatures, precious little is understood with high accuracy.

In these works [1, 2], we propose how to close this knowledge gap. On the one hand, we propose how to use radio-frequency spectroscopy in quantum simulated Fermi-Hubbard systems to accurately detect magnetic polarons [1]. In particular, we show how to use experiments on *dual* attractively and repulsively interacting systems to this end and characterise the best strategies for doing so.

On the other hand, we use high-accuracy MPS calculations in doped quantum spin ladders to calculate detailed dopant transport properties as a function of temperature [2]. While low temperatures lead to well-defined quasiparticles – consistent with previous results – we show that the high-temperature regime has a rich structure depending on the details of the spin interactions. Indeed, we show that Ising-type interactions leads to *localisation* of the dopant, arising due to a novel spin disorder-induced mechanism first characterised by the presenting author in systems exhibiting Hilbert space fragmentation [3, 4]. Moreover, in the presence of spin-exchange processes, transport shows *non-Gaussian* diffusive behaviour. I.e., while distance grows with the usual $\text{time}^{1/2}$ for diffusion, the spatial density profile has an unconventional non-Gaussian shape. This becomes particularly pronounced for highly anisotropic spin couplings towards the localised Ising coupling regime, and applies both to the dopant and spin dynamics. Moreover, we make it clear that one cannot understand the diffusive process as a usual scenario of quasiparticle scattering.

Together, these findings point towards accurately assessing the quasiparticle nature of dopants in quantum spin lattices, and its detailed and rich breakdown at nonzero temperatures.

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Quantum Gas Microscopy of Fermions in the Continuum

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Quantum gas microscopy has emerged in the last years as a powerful technique to probe and manipulate quantum many-body systems at the single-atom level. For over a decade, however, it has only been used to study lattice and spin chain physics, prominently to explore the Hubbard model and its generalizations. In this poster, we will present our recent work on quantum gas microscopy of ultracold fermions in continuous space and their characterization at previously inaccessible levels of resolution and precision. Firstly, we will report on the imaging of the in-situ density probability of deterministically prepared single-atom wave packets as they expand in a plane, and how we obtain a crucial benchmark for the reliability of our imaging protocol [1]. Secondly, we will report on quantum gas microscopy of 2D and quasi-2D ideal Fermi gases, where we measure spatially-resolved density correlation functions of the second and third order, and reveal their temperature dependence [2]. Finally, we will show how using single-atom resolved images, we extract the number fluctuations in the system and perform accurate fluctuation-thermometry over a large dynamical range, from nearly zero temperature to several times the Fermi temperature. By probing number fluctuations on small subsystems, we are able to find a regime where quantum fluctuations play an important role, leading to a significant deviation from the behavior predicted for fermions by the fluctuation-dissipation theorem in the thermodynamic limit [3]. These results represent the first application of quantum gas microscopy to continuous-space many-body systems. Our approach offers radically new possibilities for the exploration of strongly interacting Fermi gases at the single-atom level.

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Fermi polaron in highly elongated traps

We present recent results [1,2] on the theory of the Fermi polaron for atomic gases with contact attractive interactions under a strong radial confinement, resulting in a purely one-dimensional (1D) or quasi-1D configurations.

For the purely 1D case [1], we compare the exact Bethe ansatz predictions for the quasi-particle residue against diagrammatic Monte Carlo calculations, showing quantitative agreement. In particular the Monte Carlo faithfully reproduces the Anderson orthogonality catastrophe. We also find exact results for the excess bath charge Q around the impurity.

For the quasi-1D regime [2], we use the Chevy's ansatz to compute the energy, the effective mass and the quasi-particle residue of the Fermi polaron.

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A strong-coupling impurity solver for quantum materials

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We present a study of Hubbard-like fermionic models using a strong-coupling impurity solver within the dynamical mean-field theory framework. Our approach leverages the discrete Lehmann representation of the imaginary-time Green's function [1] to evaluate, deterministically and efficiently, diagrams in a bold-line strong-coupling expansion for generalized Anderson impurity models. The resulting algorithm [2] features logarithmic scaling with inverse temperature $\mathcal{O}(\log \beta)$, controllable high-order accuracy, and does not suffer from stochastic noise or sign-problem.

We benchmark the method on the single-band Hubbard model and on multi-orbital, realistic impurity models relevant to quantum materials. Across thermodynamic quantities and static and dynamic observables, we find excellent agreement with state-of-the-art continuous-time quantum Monte Carlo solvers, while reducing the computational cost by orders of magnitude. In addition, the expansion provides direct access to the impurity free energy and entropy, which are difficult to obtain accurately with Monte Carlo-based approaches, enabling a broader and more complete thermodynamic characterization of impurity problems.

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Boson-Fermion Pairing and Condensation in Two-Dimensional Bose-Fermi Mixtures

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We consider a mixture of bosons and spin-polarized fermions in two dimensions at zero temperature with a tunable Bose-Fermi attraction. By adopting a diagrammatic T-matrix approach, we analyze the behavior of several thermodynamic quantities for the two species as a function of the density ratio and coupling strength, including the chemical potentials, the momentum distribution functions, the boson condensate density, and the Tan’s contact parameter. By increasing the Bose-Fermi attraction, we find that the condensate is progressively depleted and Bose-Fermi pairs form, with a small fraction of condensed bosons surviving even for strong Bose-Fermi attraction. This small condensate proves sufficient to hybridize molecular and atomic states, producing quasi-particles with unusual Fermi liquid features. A nearly universal behavior of the condensate fraction, the bosonic momentum distribution, and Tan’s contact parameter with respect to the density ratio is also found [1].

[1] Leonardo Pisani, Pietro Bovini, Fabrizio Pavan and Pierbiagio Pieri, *SciPost Phys.* **18**, 076 (2025)

Self-binding of squeezed K-Rb quantum droplets with an impurity

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We investigate the effect of an impurity on a squeezed ^{41}K - ^{87}Rb quantum droplet using Quantum Monte Carlo and Density Functional Theory methods.

The study builds on the droplets explored by Cikojević [1] and the potassium impurity paper by Bighin [2]. We investigate the behaviour of the system under strong harmonic confinement in one direction, with varying impurity mass and interaction with rubidium, keeping the impurity-potassium interaction fixed.

Our preliminary results indicate a substantial increase in self-binding when a sufficiently attractive impurity is placed in a non-saturated droplet. The impurity localises at the droplet centre, concurrently reducing the droplet radius. These findings imply that the addition of impurities could facilitate the formation of smaller quantum droplets.

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Probing BCS Superfluid by Rydberg Atom Spectroscopy

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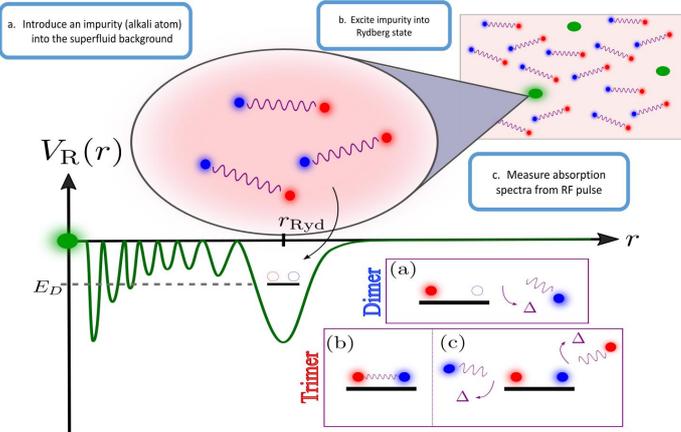
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0. Introduction and Motivation

The experimental research of the internal structure of **BCS superfluids** still remains a challenge. Key properties, such as the **superfluid gap**, are difficult to measure directly. **Rydberg atoms**, highly excited atomic configuration, offer a promising tool for probing the internal structure of BCS superfluids. When introduced as an impurity into the superfluid, a Rydberg atom can interact with the surrounding **Cooper pairs** through its extended electronic wavefunction, altering the local superfluid density. By studying the **radiofrequency (RF) spectrum** of the impurity, it is possible to extract information about the superfluid's gap and other microscopic parameters. This work presents a theoretical framework for using Rydberg impurities to probe the properties of BCS superfluids, utilizing the **Ramsey interference signal** and its RF absorption spectrum.

1. Immobile Rydberg Impurity in a Fermi Sea

- **Rydberg Impurity:** Atom with electron in highly excited state
- Low energy Rydberg-Fermi scattering potential: $V_R(\mathbf{r}) = \frac{2\pi a_e}{m_e} |\psi_{n_{\text{Ryd}}}(\mathbf{r})|^2$



2. Functional Determinant Approach

- **Many-body operator** for single particle: $\hat{X}_n = \sum_{ij} \langle i | \hat{x}_n | j \rangle \hat{c}_i^\dagger \hat{c}_j$

- **Klich formula** (fermionic operators):

$$\text{Tr} \left\{ \hat{\rho}_T e^{\hat{X}_1} \dots e^{\hat{X}_n} \right\} = \det \left(\hat{\mathbf{1}} - \hat{n}_F + \hat{n}_F e^{\hat{X}_1} \dots e^{\hat{X}_n} \right), \quad \hat{n}_F = \frac{1}{e^{\beta \hbar \omega} + \hat{\mathbf{1}}}$$

$$\text{Tr} \left\{ \text{Many-body} \right\} = \det \left(\text{Single particle} \right)$$

- **Ramsey signal and absorption spectrum:** (quench dynamics)

$$S(t) = \text{Tr} \left\{ \hat{\rho}_T e^{i\hat{H}_0 t} e^{-i\hat{H} t} \right\}, \quad A(\omega) = 2 \text{Re} \left\{ \int_0^\infty e^{i\omega t - 0^+ t} S(t) dt \right\}$$

- Obtain **many-body** observables by solving **single particle** Schrödinger equation with Rydberg potential

$$\hat{h}_{R,\sigma} |\alpha_\sigma\rangle = \omega_{\alpha\sigma}^{(\ell)} |\alpha_\sigma\rangle \quad \text{where} \quad \hat{h}_{R,\sigma} = -\frac{\nabla^2}{2m_\sigma} - \mu_\sigma + V_R(\mathbf{r})$$

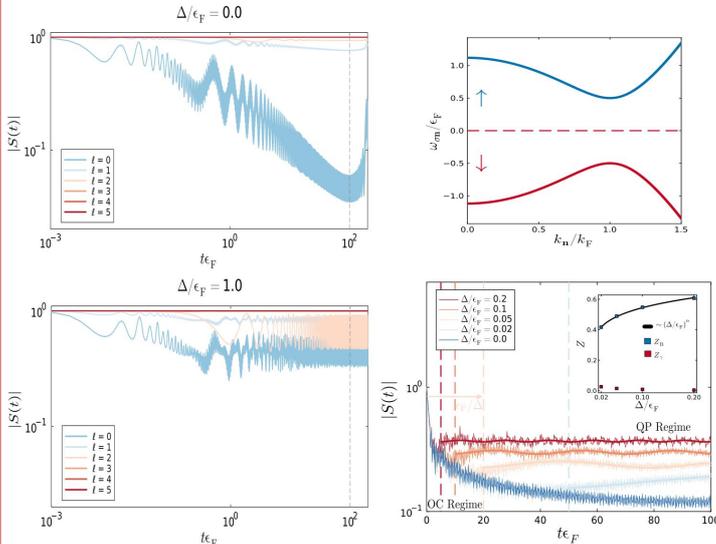
- Spherically symmetric potentials: $S(t) = \prod_\ell [S^{(\ell)}(t)]^{(2\ell+1)}$

3. Two Component Fermi Sea (BCS)

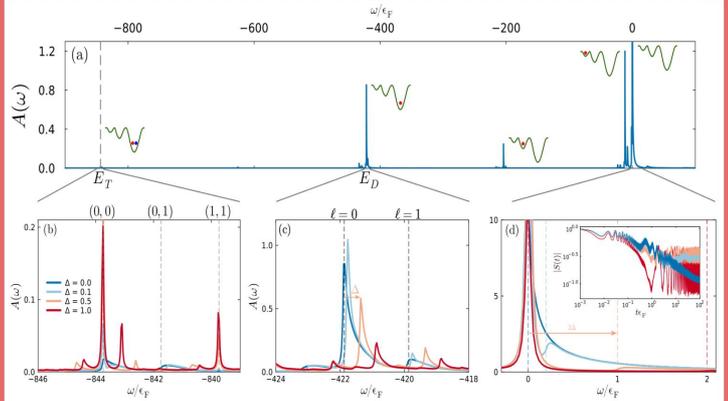
- Bilinear BCS hamiltonian for two component Fermi Sea:

$$\hat{H}_R = \sum_{\sigma,\alpha} \omega_{\alpha\sigma}^{(\ell)} \hat{c}_{\alpha\sigma}^\dagger \hat{c}_{\alpha\sigma} - \sum_{\alpha} \left[\Delta \hat{c}_{\alpha\uparrow}^\dagger \hat{c}_{-\alpha\downarrow}^\dagger + \Delta^* \hat{c}_{-\alpha\downarrow} \hat{c}_{\alpha\uparrow} \right] - \frac{\gamma}{g} |\Delta|^2$$

- Cooper pairing mechanism (Bogoliubov-de-Gennes) interacting with Rydberg atom
- Rydberg atom breaks Cooper pairs \rightarrow Formation of bound states (dimer, etc.)
- Energy of bound state depends on the superfluid gap \rightarrow Shift in spectrum



4. Absorption Spectrum



- **Outlook:**

- Probing of microscopic properties of BCS superfluid (⁸⁷Rb, ¹³³Cs) and (⁶Li, ⁴⁰K)
- Future Work:
 - Explore temperature variations, different interaction strengths, density imbalanced systems, etc.
 - Mobile impurity dynamics
 - Rydberg spectroscopy of strongly correlated systems

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Revealing the structure of the heavy Fermi polaron

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We present our latest spectroscopic measurements on the structure of the heavy Fermi polaron. In our experiment, this system is realized by a few heavy Caesium (¹³³Cs) impurities immersed in a deeply degenerate Fermi gas of much lighter Lithium (⁶Li) atoms.

While Fermi polarons – quasiparticles formed by impurities dressed by the excitations of a surrounding Fermi sea – are interesting in their own right, the large mass ratio in the Li-Cs system additionally enables addressing questions about the fate of quasiparticles close to the infinitely heavy impurity limit. At this point, Landau’s quasiparticle picture [1] breaks down and the system is best described by a new state that is fully orthogonal to the Fermi sea without the impurity – a phenomenon dubbed “Anderson orthogonality catastrophe” (AOC) [2].

Using tuneable impurity-bath interactions close to a magnetic Li-Cs Feshbach resonance, we can investigate both ground and excited states of the polaron as a function of impurity-bath interactions using spectroscopy between two Cs hyperfine states. A careful comparison to different theoretical models sheds light onto the effects of finite temperature and finite mass of the heavy Fermi polaron and how it compares to the limiting case of the AOC.

While the above-mentioned spectra are recorded using a weak spectroscopy pulse and timings adjusted to keep transferred fractions small, we can also continuously drive the impurities between their interacting and non-interacting states. The decrease of the Rabi frequency in the presence of the surrounding bath with respect to the bare Cs Rabi frequency for a weak drive would be attributed to the quasi-particle weight in a Chevy-type picture [3]. On the other hand, a non-trivial dependence of this reduction as a function of the driving strength has been derived for an infinitely heavy impurity governed by the AOC [4].

From a preliminary analysis, neither of the two models seems to adequately describe our measurements. A more flexible theoretical framework is thus required to describe how the Rabi frequency of the interacting system approaches the bare Rabi frequency as we increase the driving strength until the drive becomes the largest energy scale, clearly exceeding the Fermi energy, analogous to the scenario studied in [5].

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Lattice Bose polarons at strong coupling and quantum criticality

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We study the physics of a mobile impurity confined in a lattice, moving within a Bose-Hubbard bath at zero temperature. Within the Quantum Gutzwiller formalism [1], we develop a beyond-Fröhlich model of the bath-impurity interaction. Results for the properties of the polaronic quasiparticle formed from the dressing of the impurity by quantum fluctuations of the bath are presented throughout the entire phase diagram, focusing on the quantum phase transition between the superfluid and Mott insulating phases [2]. In the case of strong bath-impurity interaction we develop a new diagrammatic approach based on the quantum Gutzwiller Hamiltonian and the results for the ground state energy is benchmarked via Quantum Monte-Carlo (QMC) calculations [3]. We find that the modification of the impurity properties is highly sensitive to the presence of the Mott-Superfluid phase transition and to the different universality classes of the transition. We show that the polaron energy show a finite size scaling with new critical exponents when the bath is critical [4]. Therefore, the polaron can be also seen as an unambiguous probe of the quantum criticality of the many-body environment.

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Engineering tunnel-coupled tweezer trap potentials for quantum microscopy using a digital micromirror device

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To gain understanding of complex quantum effects in condensed matter systems, quantum gas microscopes, enabling detection of single atoms in an optical lattice, are ideal test-beds to perform analogue quantum simulations of electronic quantum phenomena occurring in a crystal [1]. In recent years, spatial light shaping devices introduced a new tool to create attractive arbitrary potentials [2, 3] such as box traps or dynamically controlled repulsive potential barriers [4]. This capability opens up new research perspectives to investigate exotic phenomena appearing beyond lattice geometries.

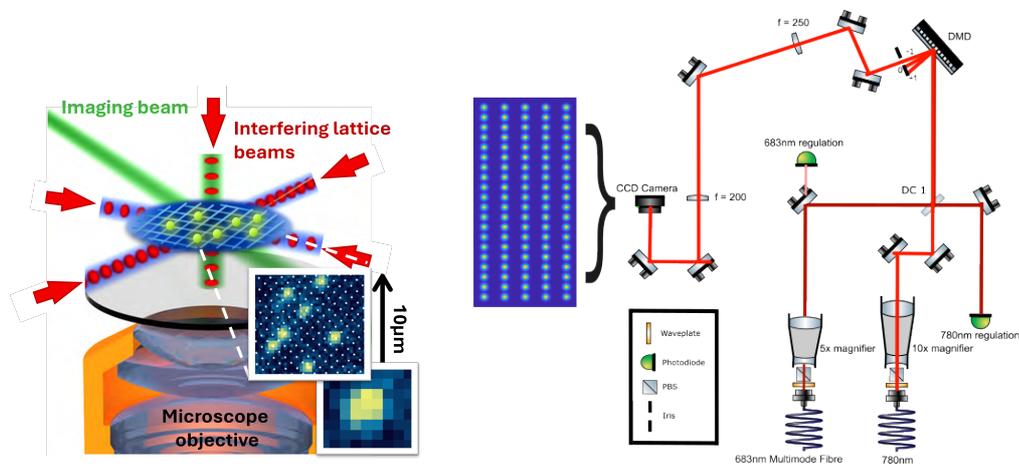


Fig. 1 (a) Drawing of a quantum gas microscope: atoms are located onto the grid made by interfering lattice beams and pictures of atomic fluorescence as insets. (b) Sketch of the DMD optical setup with a picture example of chains of microtraps used to test the feedback algorithm.

Here, we report on the development of an optical setup aiming at creating tweezer microtraps arranged in a custom geometry using a Digital Micromirror Device (ViALUX V-9001). The arbitrary-shaped intensity distribution of a 787 nm attractive laser light will be superimposed on the ^{40}K atoms through the 0.68 NA microscope objective of our fermionic quantum gas microscope. To perform tunnelling experiments with atoms in these microtraps, accurate control of the tweezer position, homogeneity and depths are required. We present the performance of our feedback algorithm for generating hundreds of microtraps and its convergence toward the target light pattern. We show that noise levels below 5% can be achieved by our camera feedback protocol.

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A study of the dimer-trimer crossover in a three-component Fermi gas

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We present a variational calculation for the binding energy between two and three distinguishable Fermions in vacuum and in the medium of a single Fermi sea. To obtain our results, we employ a new (separable) model which trades two short-range interactions for a single atom-dimer interaction, which in turn allows us to express our results analytically and avoid the typical Faddeev-style equations. We show that by varying the atom-dimer scattering length the system undergoes a transition between a dimer dressed by particle-hole excitations and a trimer, analogous to the polaron-molecule crossover present in systems with a single impurity. Our model is best suited to systems featuring three distinguishable Fermions where one of the underlying interactions is stronger than the others and a physical dimer can exist. Our results can also be interpreted as an extension to the study of a mass-imbalanced polaron-molecule crossover, where the impurity is a composite boson.

Promising properties of Ghost Gutzwiller Ansatz: from Mott insulators to correlated antiferromagnets

Antonio Maria Tagliente

January 7, 2026

The ghost Gutzwiller wavefunction is a recently proposed variational Ansatz that generalizes the traditional Gutzwiller wavefunction. It consists of a Slater determinant defined in an enlarged Hilbert space that is variationally projected into the physical one. This wavefunction is therefore naturally capable of describing Hubbard bands and coexisting quasiparticle peaks.

Here, we present several results obtained through this wavefunction treated with the so-called Gutzwiller approximation.

We begin by showing that the wavefunction can describe genuine paramagnetic Mott insulators, whose finite spin susceptibility has remained elusive using other methods. A metal lead in contact with such a Mott insulator can directly reveal the spinon excitations responsible for the paramagnetic behavior, which emerge at the interface as a heavy-fermion band.

We finally demonstrate that the ghost Gutzwiller wavefunction can stabilize a correlated antiferromagnet with spin-unpolarized Hubbard bands but polarized spinons. This solution contains much more entanglement than the conventional dynamical mean-field one, and might be more representative of an actual correlated antiferromagnet in finite dimensions.

Self-Consistent Spectra of the Strongly Correlated Bose-Fermi Gas

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Understanding the dynamical properties of mixtures of bosons and fermions at finite temperature is central to exploring new phases of quantum matter, but theoretical methods face major challenges, particularly for strong interactions. Most existing approaches rely on analytic continuation from imaginary-time data, a numerically unstable procedure that makes it difficult to obtain reliable real-frequency spectra. In this work, we showcase a real-time framework to compute the spectral properties of a three-dimensional Bose–Fermi mixture near the onset of Bose–Einstein condensation. Our method builds on recent advances for strongly interacting Fermi gases [1] and allows us to directly calculate real-frequency spectral functions in a fully self-consistent manner.

We find that self-consistency is crucial for capturing qualitative spectral features that simpler approximations miss. In addition, we investigate the phase diagram of the mixture and confirm the presence of a thermodynamic instability close to the condensation transition, as proposed in [2]. We present indications, that this instability arises from an effective attraction between bosons mediated by the fermionic component.

Beyond clarifying the interplay between bosons and fermions in strongly correlated regimes, our approach provides a versatile tool for studying spectral and transport properties in imbalanced mixtures, lower dimensions, and nonequilibrium quantum systems.

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Mobile Ion in a Bose-Einstein Condensate

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We consider a charged impurity moving in a Bose-Einstein condensate and its out-of-equilibrium properties. We study the stationary momentum of the ion at long times, which is nonzero due to the superfluid nature of the medium, and we calculate the effective mass of the impurity dressed with the atoms of the bath. The nonlinear evolution leads not only to emission of density waves, but also momentum transfer back to the ion, resulting in the possibility of oscillatory dynamics. The case of long-ranged interactions is of particular importance here, as it opens the possibility to leverage quantum correlations in controlling the system properties [1].

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Hybridization of Topological Defects and Repulsive Polarons in a Bose-Einstein Condensate

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The immersion of an impurity in a bosonic medium has enabled systematic exploration of the Bose polaron problem across the entire range of impurity–bath coupling strengths. Both attractive and repulsive polarons—arising from inherently attractive impurity–medium interactions, such as those involving Rydberg or ionic impurities in neutral ultracold gases—have been extensively investigated. While the attractive polaron represents the ground state of the many-body impurity–bath system, the nature of the metastable repulsive polaron remains less understood. Here, we present a unified framework for describing both attractive and repulsive polarons in one- and two-dimensional (1D and 2D) Bose gases. By obtaining ground- and excited-state solutions of the Gross–Pitaevskii equation for a finite-range impurity potential in a weakly interacting Bose medium, we demonstrate that repulsive polarons are adiabatically connected to topological defects supported by the condensate. In 2D, these defects correspond to vortices and dark ring solitons, while they manifest as distinct solitonic configurations in 1D. Furthermore, we uncover a crossover between the repulsive and attractive polaron branches as the impurity–bath coupling strength increases. The analysis identifies universal regimes characterized by the zero-energy impurity–bath scattering length and the condensate coherence length.

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Abstract for the workshop on Impurity Problems in Quantum Mixtures: from Ultracold Gases to Electron Matter (smr 4208)

Polaron formation in bosonic flux ladders

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Understanding how a mobile impurity interacts with a quantum many-body environment is an active area of research in condensed matter physics [1]. This work studies the dressing of a particle immersed in a weakly interacting Bose-Einstein condensate, forming a polaron. The host system is a quasi one-dimensional bosonic flux ladder, which serves as a minimal model for two-dimensional systems under magnetic flux [2, 3]. The system is described by the Bose-Hubbard Hamiltonian with Peierls substitution and is studied at zero temperature in the thermodynamic limit. It exhibits three phases: Meissner, vortex, and biased ladder, each characterized by distinct current patterns and symmetry-breaking properties [4]. The phase diagram is obtained using mean-field theory and is confirmed numerically by Gross-Pitaevskii evolution. Bogoliubov theory [5] is used to compute the collective excitations of the bath above the condensate, and the corresponding dynamical structure factor is computed in each phase.

An impurity is then introduced and treated within the Chevy approximation, a variational truncation of the many-body wavefunction [6]. The polaron spectral function is computed across all three phases. To isolate the role of flux, the spectral function is also computed for the one-dimensional Bose gas on a lattice. In this case, the impurity-boson correlation function is used to identify the nature of the dressed quasi-particles. The spectral functions show clear signatures of the underlying background. These are new results and are testable in cold-atom experiments.

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