BOOK OF POSTER ABSTRACTS

Precision many-body physics 2023

Paris, June 12-14

SESSION 1

Monday June 12, 4:15pm - 6pm LOCATIONS: salle 1 (ground floor) & foyer (floor -1)

@ salle 1:

- **Oxygen vacancies at the origin of pinned moments in oxide interfaces: the example of tetragonal CuO/SrTiO$_3$**, B. Bacq-Labreuil, B. Lenz, S. Biermann
- **Realization of One-Dimensional Anyons with Tunable Statistical Phase**, B. Bakkali-Hassani, J. Kwan, S. Kim, P. Segura, Y. Li, M. Greiner
- **Superconductivity and stripes of strongly-correlated electrons in a magnetic field**, N. Baldelli, M. Fishman, A. Wietek
- **The Fermi polaron problem: 1D vs. quasi-1D**, L. Barišić, G. Orso, G. Dash, C. Salomon, F. Chevy
- **Edge state spectroscopy of Fractional Chern Insulators**, F. Binanti, N. Goldman, C. Repellin
- **Collective behaviour in Rabi-coupled two component Bose-Einstein condensates**, L. Lavoine, A. Hammond, R. Eid, S. Tiengo, T. Bourdel
- **Anomalous fluctuations of the condensate atom number in an interacting Bose gas**, J.-P. Bureik, G. Hercé, A. Tenarta, D. Clément
- **Quantum simulation of the Fermi-Hubbard model using optical superlattices**, T. Chalopin, D. Bourgund, P. Bojović, S. Wang, S. Hirthe, T. Franz, I. Bloch, T. Hilker
- **Superfluid fraction in an interacting spatially modulated Bose-Einstein condensate**, G. Chauveau, C. Maury, F. Rabec, C. Heintze, G. Brochier, S. Nascimbene, J. Dalibard, J. Beugnon, S. M. Roccuzzo, S. Stringari
- **Efficient reconstruction of quantum gas microscope images**, R. Journet, A. Molineri, C. Briosne-Fréjaville, M. Boffety, F. Goudail, C. Kulcsár, P. Trouvé, M. Cheneau
- **Advantages of Digital Qubit-Boson Hardware for Quantum Simulation of Lattice Gauge Theories**, E. Crane, A. Eickbusch, T. Tomesh, S. Kuhn, A. Schuckert, L. Funke, K. Smith, J. Martyn, M. Demarco, N. Wiebe, I. Chuang, S. Girvin

- **A comparative study of Neural quantum state architectures for quantum spin models**, S. Dash, M. Ferrero, A. Georges, J. Moreno, J. Carrasquilla
- **A Fermionic Quantum Gas Microscope for the Continuous Regime**, M. Dixmerias, J. Verstraten, K. Dai, S. Jin, B. Peaudecerf, T. de Jongh, T. Yefsah
- **Thermal fading of the $1k^4$-tail of the momentum distribution induced by the hole anomaly**, G. De Rosi, G. Astrakharchik, M. Olshanii, J. Boronat
- **Quantum simulation of the central spin model with a Rydberg atom and polar molecules in optical tweezers**, J. Dobrzyniecki, M. Tomza
- **Quantum transport of strongly correlated fermions**, T. Enss
- **Intensity correlations in the Driven-Dicke model**, G. Ferioli, S. Pancaldi, I. Ferrier-Barbut, A. Browaeys
- **Observation of Universal Hall Response in Strongly Interacting Fermions**, M. Filippone, T. Zhou, G. Cappellini, D. Tusi, L. Franchi, J. Parravicini, C. Repellin, S. Greschner, M. Inguscio, T. Giamarchi, J. Catani, L. Fallani
- **Universal van der Waals force between heavy polarons in superfluids**, K. Fujii, T. Enss, M. Hongo
- **Self-binding in one- and two-dimensional mass-imbalanced fermionic mixtures**, J. Givois, A. Tononi, D. Petrov
- **Dynamical mean field theory of the bilayer Hubbard model with Inchworm Monte Carlo**, D. Goldberger, E. Eidelstein, G. Cohen

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@ **foyer**:

- **Negative Absolute Temperatures in a Triangular Optical Lattice**, M. Hasan, L. Donini , S. Shanokprasith, D. Braund , T. Marozsak , M. Dydiowa , D. Reed , T. Harte, U. Schneider
- **Boundaries Changes Squeezing in a 1D Heisenberg Spin Chain**, Y. Hernández, G. Žlabys, M. Plodzien, D. Burba, S. Mackoit, G. Juzeliunas, E. Witkowska

- **Diffusion of underdamped single ultracold atoms in engineered environments**, S. Hiebel, S. Burgardt, J. Feß, F. Schall, D. Adam, A. Widera
- **Nuclear reactions and structure at the precision frontier**, G. Hupin and N. Pillet
- **Fermi Gas Microscopy in a Lattice with Tunable Geometry**, L. Kendrick, M. Xu, A. Kale, Y. Gang, G. Ji, R. Scalettar, M. Lebrat, M. Greiner
- **Attractive Fermi-Hubbard Model in a Magnetic Field**, E. Khatami
- **Benchmarks of Generalized Hydrodynamics for the Lieb-Liniger Gas**, K. Kheruntsyan, R. Watson, S. Simmons
- **Multifractality and transport in cavity-QED materials**, G. Pupillo

SESSION 2

Tuesday June 13, 4:15pm - 6pm LOCATIONS: salle 7, salle 8 & foyer (floor -1)

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- **A mathematical analysis of Density Matrix Embedding Theory (DMET)**, A. Kirsch, E. Cancès, F. Faulstich, E. Letournel, A. Levitt
- **Collective excitations of superconductors and Fermi superfluids in the BCS-BEC crossover**, S. Klimin, J. Tempere, H. Kurkjian
- **Hall conductivity in multiband systems and strained Sr_2RuO_4**, F. Kugler, L. van Munoz, S. Beck, J. Kaye, G. Kotliar, A. Georges
- **Diagrammatic Strong Coupling Lattice QMC: a cuprate case**, A. Lichtenstein
- **Multi-channel fluctuating field approach to competing instabilities in interacting electronic systems**, E. Linnér, A. Lichtenstein, C. Dutreix, S. Biermann, E. Stepanov
- **Collective excitations in mesoscopic Fermi gases**, P. Lunt , P. Hill, J. Reiter, P. Preiss, S. Jochim
- **Non-local correlations and criticality in the triangular lattice Hubbard model**, M. Malcolms Mario, S. Julian, H. Menke, M. Klett, G. Rohringer, T. Schäfer
- **Dynamics of massive superfluid vortices**, M. Caldara, A. Richaud, V. Penna, A. Fetter, P. Massignan
- **The Mott metal-insulator transition in the two-dimensional Hubbard model - a cellular dynamical mean-field study on large clusters**, M. Meixner , M. Klett , S. Heinzelmann , N. Wentzell , P. Hansmann , S. Andergassen, T. Schäfer
- **Triangular ad-atom surface lattices as a platform for correlated Hund's physics**, H. Menke, M. Bockstedte, P. Hansmann
- **Real space electronic structure quantum Monte Carlo for periodic systems: reaching the thermodynamic limit**, L. Mitas, H. Zhou, G. Zhang

- **Irreversible entropy transport between superfluids**, J. Mohan, P. Fabritius, M. Talebi, S. Wili, M.-Z. Huang, T. Esslinger

- **Experiment to Pinpoint the 3D Anderson Transition in Real Space with Matter Waves**, N. Myneni, X. Yu, Y. Guo, V. Josse, A. Aspect

- **Finite-size analysis in neural network classification of critical phenomena**, V. Chertenkov, E. Burovski, L. Shchur ;
  Dimensional crossover on multileg attractive-U Hubbard ladders, A. Potapova, I. Pile, T.-C. Yi, R. Mondaini, E. Burovski

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@ **salle 8**:

- **Observation of phase transitions in cavity QED**, B. Gábor, D. Nagy, A. Dombi, T. W. Clark, F. Williams, K. Adwaith, A. Vukics, P. Domokos

- **Thermal-induced Local Imbalance in Repulsive Binary Bose Mixtures**, G. Pascual, G. Spada, S. Pilati, S. Giorgini, J. Boronat

- **FFLO correlations in polarized ultracold Fermi gases**, P. Pieri, M. Pini, G. Strinati

- **Real-frequency quantum field theory applied to the Anderson impurity model**, A. Ge, N. Ritz, E. Walter, S. Aguirre, J. von Delft, F. Kugler

- **Separation of quadrupole, spin, and charge across the magnetic phases of a one-dimensional interacting spin-1 gas**, Felipe Reyes Osorio, Karen Rodríguez Ramírez

- **Antiferromagnetic fluctuations in copper oxide superconductors**, A. Sacuto, M. Mezidi, A. Alehkin,Y. Gallais, M. Cazayous, S. Houver, D. Colson, G. Gu

- **The strongly driven Fermi polaron**, A. Schuckert, F. Vivanco, S. Huang, G. Schumacher, G. Assumpcao, Y. Ji, J. Chen, M. Knap, N. Navon

- **Correlated insulator and supersolid phases in a one-dimensional $\mathbf{Z}_2$ lattice gauge theory**, V. Sharma, E. Mueller

- **Renyi entropy of quantum anharmonic chain at non-zero temperature**, M. Srdinsek, R. Vuilleumier, M. Casula

- **Orbital-selective metal-insulator transition: effect of non-local collective electronic fluctuations**, E. Stepanov, K. Held, S. Biermann, A. Lichtenstein
- **Finite density properties and crystalline phases in a quantum link ladder**, P. Stornati, P. Krah, K. Jansen, D. Benerjee
- **Acceleration of the auxiliary-field quantum Monte Carlo**, Z. Sukurma
- **Probing non-equilibrium dynamics across the BKT critical point by dynamical control of bilayer 2D Bose gases**, S. Sunami, A. Beregi, E. Chang, E. Rydow, C. Foot
- **Modern Quantum Field Theory of the Electron Liquid**, K. Chen

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@ **foyer**:

- **Magnetism and metallicity in moiré transition metal dichalcogenides**, P. Tscheppe, J. Zang, M. Klett, S. Karakuzu, A. Celarier, Z. Cheng, T. Maier, M. Ferrero, A. Millis, T. Schäfer
- **Equation of state of superfluid neutron matter with low-momentum interactions**, V. Palaniappan, S. Ramanana and M. Urban
- **Real-Time Diagrammatic Monte Carlo For Dissipative Impurity Model**, M. Vanhoecke, M. Schiro
- **Superfluid signatures in a dissipative quantum point contact**, M.-Z. Huang, J. Mohan, A.-M. Visuri, P. Fabritius, M. Talebi, S. Wili, S. Uchino, T. Giamarchi, T. Esslinger
- **Strongly-Coupled Fermions from Lattice Field Theory**, N. Warrington, E. Berkowitz, P. Bedaque, A. Alexandru
- **High-order diagrammatic expansion around BCS Hamiltonians: polarized superfluid phase of the attractive Hubbard model**, G. Spada, R. Rossi, F. Simkovic, R. Garioud, M. Ferrero, Van Houcke, F. Werner
- **Squeezing oscillations in a multimode bosonic Josephson junction**, T. Zhang, M. Maiwöger, F. Borselli, Y. Kuriatnikov, J. Schmiedmayer, M. Prüfer

- **Quantum Advantage in Simulating Floquet Thermalized Systems on a Cold-Atom Processor**, Y-G Zheng, W-Y Zhang, Y-C Shen, A Luo, Y Liu, M-G He, H-R Zhang, W Lin, H-Y Wang, Z-H Zhu, M-C Chen, C-Y Lu, S Thanasilp, D G Angelakis, Z-S Yuan, J-W Pan

SESSION 1

Oxygen vacancies at the origin of pinned moments in oxide interfaces: the example of tetragonal $CuO/SrTiO_3$

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Obtaining an accurate theoretical description of the emergent phenomena in oxide heterostructures is a major challenge. Recently, intriguing paramagnetic spin and pinned orbital moments have been discovered by x-ray magnetic circular dichroïsm measurements at the Cu $L_{2,3}$-edge of a tetragonal $CuO/SrTiO_3$ heterostructure [1]. Using first principles calculations, we propose a scenario that explains both types of moments [2], based on the formation of oxygen vacancies in the TiO_2 interface layer. We show the emergence of a paramagnetic 2D electron gas hosted in the interface CuO layer. It is invisible at the Ti $L_{2,3}$-edge since the valence of the Ti atoms remains unchanged. Strong structural distortions breaking both the local and global fourfold rotation C_4 symmetries at the interface lead to the in-plane pinning of the Cu orbital moment close to the vacancy. Our results, and in particular the pinning of the orbital moment, may have implications for other systems, especially monoxide/dioxide interfaces with similar metal-oxygen bond length and weak spin-orbit coupling.

[1] O. Hernandez, *et al.*, *Magnetic Order of Tetragonal CuO Ultrathin Films*, Phys. Rev. B **103**, 224429 (2021)

[2] B. Bacq-Labreuil, B. Lenz and S. Biermann, *Oxygen vacancies at the origin of pinned moments in oxide interfaces: the example of tetragonal* $CuO/SrTiO_3$, Phys. Rev. B **106**, 235155 (2023)

Realization of One-Dimensional Anyons with Tunable Statistical Phase

Brice Bakkali-Hassani, Joyce Kwan, Sooshin Kim, Perrin Segura, Yanfei Li, and Markus Greiner

March 6, 2023

Anyons are particles with exchange statistics that are neither bosonic nor fermionic, but that interpolate between these two limits. In this work, we realize a one-dimensional Anyon-Hubbard model (AHM) using ultracold Rubidium 87 atoms in an optical lattice. Our Floquet-engineering scheme effectively realizes a Bose-Hubbard model with an occupation-dependent Peierls phase that maps onto the AHM. We observe the Hanbury Brown-Twiss effect for anyons using the correlations emerging from two-particle quantum walks, and detect the formation of bound states in the absence of on-site interactions. We also observe asymmetric density expansion which arises from the interplay between interactions and fractional statistics. Our scheme can be readily extended to study many-body phases of anyons in one dimension.

Superconductivity and stripes of strongly-correlated electrons in a magnetic field

Niccolò Baldelli [a*], Matthew Fishman [b], and Alexander Wietek [c]

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We study the hole-doped 2D t-t' Hubbard model in a region of the phase diagram expected to show coexistence between a charge density wave or striped order (CDW) and d-wave superconductivity (SC), in presence of an uniform orthogonal magnetic field. We obtain the ground state for cylinders up to width six using DMRG and rely on the Penrose-Onsager criterion for the condensation of Cooper pairs to identify the SC+CDW phase. We show how the pairs form a fragmented condensate where the condensate are localized on the stripes of the system and how the behavior of fragmented superconductivity is dependent on the applied magnetic field. We finally discuss how the results can be explained by a space-dependent Ginzburg-Landau effective field theory.

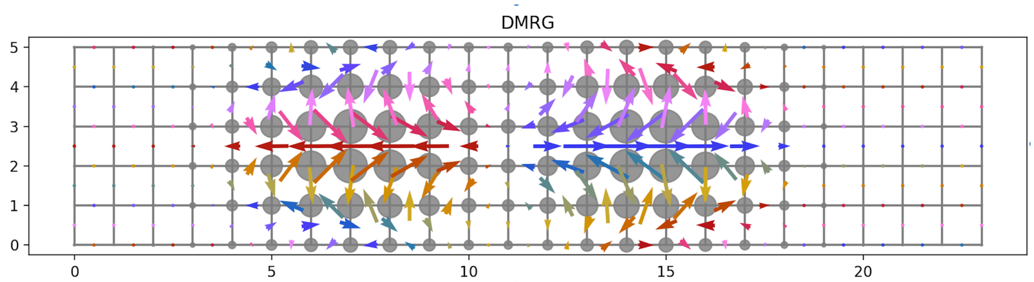

Figure 1 : Superconducting amplitude and phase (arrows) and hole density (circles) for a 24x6 cylinder, 4 holes and a 4π flux threading the system.

The Fermi polaron problem: 1D vs. quasi-1D

<u>L. A. Barišić</u>[1], G. Orso[2], G. Dash[1], C. Salomon[3], F. Chevy[1]

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[2]Université Paris Cité, Laboratoire Matériaux et Phénomènes Quantiques (MPQ), CNRS, F-75013, Paris

[3]Laboratoire Kastler Brossel, ENS-PSL, CNRS, Sorbonne Université, Collège de France, 75005 Paris

We study the system of one impurity (the polaron) in a quasi-1D quantum gas that is confined by a potential in two of the three directions. Such fermionic quasi-1D systems were studied in many different fields ranging from crystals in solid-state physics to cold atom gases. Quasi-1D systems are unique due to their link to the exact solution of 1D many-body systems when the confinement potential energy becomes much larger than all other energy scales of the system. While the polaron model studies the interaction of one impurity with a homogenous system, its solution is particularly interesting as it gives an insight into the phase diagram of strongly interacting population imbalanced quantum mixtures. In this work, we use a non-perturbative method to calculate the energy and behavior of one particle in a homogenous Fermi sea of opposite spin particles in the ground state of the confining potential. The variational calculation assumes that the polaron is dressed by a single particle-hole excitation and we study the breakdown of the one-dimensional approximation when the interaction with the Fermi sea is strong and leads to significant transitions towards excited states of the transverse potential. By calculating the effective mass of a quasi-1D polaron, we observe that it diverges in the strongly interacting limit. This divergence does not exist in the purely one-dimensional case but is characteristic of the polaron-to-molecule transition in 3D systems.

Edge state spectroscopy of Fractional Chern Insulators

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Fractional Chern Insulators (FCIs, which are lattice analogs of fractional quantum Hall states) have been the subject of intensive research in the last decades, not only for the interest we have in understanding the nature of topological phases of matter, but also thanks to the possible applications in quantum computing. Cold atoms in optical lattices can host these topologically ordered phases, and hallmark signatures have already been detected experimentally in two-boson systems [1]. The question that we want to address in this work is: is it possible to probe the edge spectrum of FCIs in experimentally accessible systems ? We propose to subjet the atomic FCI ground state to a Laguerre-Gauss laser, creating edge excitations through a transfer of angular momentum and energy, following a similar proposal in integer Chern insulators [2], and to subsequently measure the excitation fraction through local density measurements. We numerically test this protocol in a model of strongly-interacting bosons in the Hofstadter lattice, which is known [3] to host a $\nu = 1/2$ FCI phase. Whenever we excite a topological edge state, we observe the migration of particles from the bulk to the edges of the lattice (see Fig. 1). We use this variation of density profile to extract the transition frequencies and consequently rebuild the excitation spectrum. We find a chiral edge branch, indicative of topological order in systems with as few as 2 bosons. Finally, we use our tool to show the progressive opening of an edge gap in the limit of very dense systems.

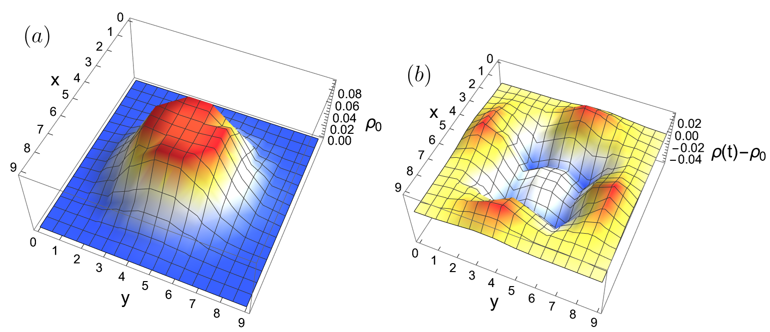

Figure 1: (a) Density profile of the FCI ground state. (b) Variation (at time t of the evolution) of the 2-particle ground state particle density when an edge state is excited.

[1] J. Léonard, S. Kim, J. Kwan, P. Segura, F. Grusdt, C. Repellin, N. Goldman, and M. Greiner, *Realization of a fractional quantum Hall state with ultracold atoms*, arXiv:2210.10919 (2022)

[2] N. Goldman, J. Beugnon, and F. Gerbier, *Detecting Chiral Edge States in the Hofstadter Optical Lattice*, Phys. Rev. Lett. 108, 255303 (2012)

[3] E. D. M. Hafezi, A. S. Sørensen and M. D. Lukin, *Fractional quantum Hall effect in optical lattices*, Phys. Rev. A 76, 023613 (2007)

Collective behaviour in Rabi-coupled two component Bose-Einstein condensates

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Mixtures of Bose-Einstein condensates offer situations where the usually dominant mean-field energy in weakly interacting systems can be reduced such that higher-order (for example beyond-mean-field) terms may play a dominant role in the equation of state. In this context, the case of two-component coupled Bose-Einstein condensate will be specifically addressed. First, large attractive effective three-body interaction or even saturating interaction can be engineered because of the mean-field induced frequency shift of the dressing field [1]. Second, the beyond-mean field energy is precisely measured and is shown to be modified as compared to the uncoupled case [2].

[1] A. Hammond, L. Lavoine, and T. Bourdel, *Tunable three-body interactions in driven two-component Bose-Einstein condensates*, Phys. Rev. Lett. **128**, 083401 (2022)

[2] L. Lavoine, A. Hammond, A. Recati, D. S. Petrov, and T. Bourdel, *Beyond-Mean-Field Effects in Rabi-Coupled Two-Component Bose-Einstein Condensate*, Phys. Rev. Lett. **127**, 203402 (2021).

Anomalous fluctuations of the condensate atom number in an interacting Bose gas

Jan-Philipp Bureik[a*], Gaétan Hercé[a], Antoine Tenart[a],and David Clément[a]

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In phases with a broken continuous symmetry, the order parameter is predicted to exhibit fluctuations that increase more than linearly with the number of particles N. This manifests the presence of gapless excitations, Goldstone modes, that dominate the low-energy properties of phases with a broken continuous symmetry. Such a property is expected in condensed Bose gases below the critical temperature where the fluctuations of the atom number in the Bose-Einstein condensate (BEC) reflect those of the order parameter [1,2]. Despite the fact that many quantum gas experiments routinely produce BECs, the observation of these fluctuations was only recently reported for weakly-interacting Bose gases [3]. Indeed, technical noise masks the expected anomalous fluctuations of order $\sqrt{N}$ in most cases, preventing systematic investigations of the population statistics of BECs. Here we study the BEC number fluctuations in a regime of strong interactions and we establish that these are a universal feature of broken continuous symmetries, present also in strongly-correlated systems. More specifically, we measure the BEC number fluctuations in strongly-interacting lattice superfluids. Our unique approach exploits single-atom detection in 3D coupled with precise post-selection of data to achieve the experimental stability necessary to reveal the fluctuations. Furthermore, we are currently conducting a detailed analysis to reveal the anomalous scaling of these fluctuations with the atom number N.

[1] S. Giorgini, L. P. Pitaevskii, and S. Stringari, *Anomalous Fluctuations of the Condensate in Interacting Bose Gases*, Phys. Rev. Lett. **80**, 5040 (1998)

[2] F. Meier and W. Zwerger, *Anomalous condensate fluctuations in strongly interacting superfluids*, Phys. Rev. A **60**, 5133 (1999)

[3] M. A. Kristensen, M. B. Christensen, M. Gajdacz, M. Iglicki, K. Pawlowski, C. Klempt, J. F. Sherson, K. Rzazewski, A. J. Hilliard, and J. J. Arlt, *Observation of Atom Number Fluctuations in a Bose-Einstein Condensate*, Phys. Rev. Lett. **122**, 163601 (2019)

Quantum simulation of the Fermi-Hubbard model using optical superlattices

T. Chalopin[a,b*], D. Bourgund[a,b], P. Bojović[a,b], S. Wang[a,b], S. Hirthe[a,b], T. Franz[a,b], I. Bloch[a,b,c] and T. Hilker[a,b]

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In the past few years, quantum gas microscopy has proven to be a valuable tool for the experimental exploration of the low-energy quantum many-body states of the Fermi-Hubbard model. More recently, a number of experiments have shifted their interest towards lattice geometries which go beyond the simple square lattice, extending the scope of quantum simulation towards more exotic states.

Here, I will present our recent implementation of bichromatic optical superlattices in our ^{6}Li quantum gas microscope. The phase stability and tunability granted by our design provide the necessary tools to implement novel cooling protocols and preparation techniques in tailored geometries. In particular, the superlattice allows us to prepare the doped t-J model in a mixed-dimensional geometry in 2D, where the tunneling t along one direction is suppressed while the superexchange J is maintained. Such a geometry allows us the explore the pairing of dopants in 2D, extending our recent work on the formation of hole pairs in mixed-dimensional ladders [1].

[1] S. Hirthe *et. al.*, *Magnetically mediated hole pairing in fermionic ladders of ultracold atoms*, Nature **613**, 463-467 (2023)

Superfluid fraction in an interacting spatially modulated Bose-Einstein condensate

G. Chauveau [a], C. Maury [a], F. Rabec [a], C. Heintze [a], G. Brochier [a], S. Nascimbene [a], J. Dalibard [a], J. Beugnon [a*], S. M. Roccuzzo [b] and S. Stringari [b†]

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b. Pitaevskii BEC Center, CNR-INO and Dipartimento di Fisica, Università di Trento, I-38123 Trento, Italy and Trento Institute for Fundamental Physics and Applications, INFN

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At zero temperature, a Galilean-invariant Bose fluid is expected to be fully superfluid. Here we investigate theoretically and experimentally the quenching of the superfluid density of a dilute Bose-Einstein condensate due to the breaking of translational (and thus Galilean) invariance by an external 1D periodic potential. Both Leggett's bound [1] fixed by the knowledge of the total density and the anisotropy of the sound velocity provide a consistent determination of the superfluid fraction. The use of a large-period lattice emphasizes the important role of two-body interactions on superfluidity.

[1] A.J. Leggett, "Can a solid be "superfluid"?" Phys. Rev. Lett. 25, 1543–1546 (1970)

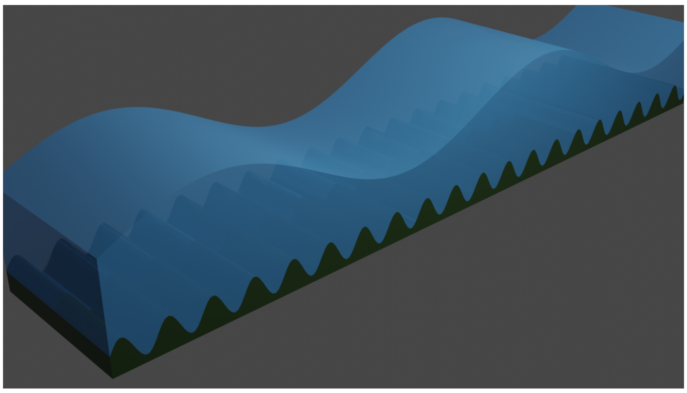

Figure 1: We measure the sound propagation, sketched in blue, in a periodically modulated 2D bose gas. The modulation is depicted in green.

Efficient reconstruction of quantum gas microscope images

Romaric Journet[a], Anaïs Molineri[a], Clémence Briosne-Fréjaville[a], Matthieu Boffety[a], François Goudail[a], Caroline Kulcsár[a], Pauline Trouvé[b], Marc Cheneau[a *],

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Quantum gas microscopy is a powerful tool to probe the many-body state of atomic gases in optical lattices. When designing new experimental apparatuses equipped with a microscope, most of the effort is usually put on the resolving power of the optical system, rather than in the efficiency of the algorithm used to reconstruct the occupancy of the lattice sites from the raw images. This approach, however, becomes increasingly difficult as the lattice spacing or the amount of fluorescence is reduced. We present here an efficient reconstruction algorithm able to faithfully reconstruct microscope images under such harsh conditions. Our algorithm outperforms the standard method based on Wiener deconvolution and completes within a few seconds on a standard desktop computer for images containing tens of thousands of lattice sites.

Advantages of Digital Qubit-Boson Hardware for Quantum Simulation of Lattice Gauge Theories

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K. Smith[2], J. Martyn[6], M. Demarco[6], N. Wiebe[7], I. Chuang[6], S. Girvin[2]
1. Joint Quantum Institute, QuICS, NIST, University of Maryland
2. Yale Quantum Institute, Yale
3. Max Plank Institute for Particle Physics, Hamburg
4. Department for Computer Science, Princeton
5. Deutsches Elektronen-Synchrotron
6. MIT-Harvard Center for Ultra-Cold Atoms, Massachusetts Institute of Technology

Quantum simulation of lattice gauge theories (LGTs) has been a subject of intense interest in high energy and condensed matter physics because computing dynamics and ground states is classically hard. However, the infinite Hilbert space bosonic sectors, which cannot be integrated out in higher dimensions, lead to extremely high qubit gate counts, threatening the ability of quantum simulation to address these theories.

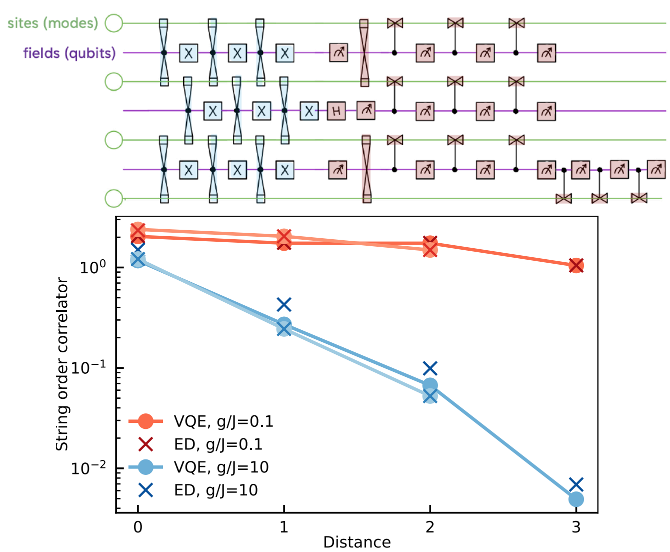

FIG. 1. (Top Panel) Trotterized and/or VQE ansatz for the 4 site bosonic Z2 model in native qubit-boson gates. Two cavity blue gates represent qubit-controlled beamsplitters. Cavity-qubit red gates represent selective number dependent arbitrary phase gates used during Fock state readout. (Lower Panel) Phases in the confined regime and near the deconfined critical point of the bosonic Z2 model, measured with an experimentally realisable technique for detection of the string order parameter measured on ground states of three and four site systems determined with variational quantum eigensolver method (VQE) compared to exact diagonalisation (ED).

Extensive progress has recently been made in the fabrication and control of microwave cavity resonators - which naturally host a bosonic Hilbert space - coupled to transmon qubits, however it is unclear whether the currently available hardware would outperform all-qubit hardware. Here, we provide an example of an experimental architecture which could be scaled to higher dimensions, for a 1+1D mixed boson-fermion system which efficiently performs ground state preparation for both the Z2 gauge theory coupled to bosonic matter and the Schwinger model.

First, due to the lack of compiler, we must design the fermion-boson gates in the mixed qubit-boson hardware. We do this in the context of creating a variational quantum eigensolver (VQE) for the bosonic Z2 and Schwinger lattice gauge theories, keeping the gauge fields. We find that the trotterised form of the Hamiltonians are extremely native in this platform and lead to low depth circuits in the VQE, as can be seen in Fig. 1. Our simulations of the VQE, which include realistic hardware noise, lead to hardware VQE runtimes on the order of hours with a single shot for any system size being on the order of microseconds. We use 'Bosonic Qiskit', a package we previously developed, which includes noisy simualtions of circuit QED coupled to microwave cavity resonators.

Second, we must demonstrate the ability to detect interesting order in the ground states with VQE. To do this we theoretically demonstrate an experimentally realistic methods to detect the first order phase transition caused by vacuum fluctuations in the Schwinger model and the bosonic Z2 confined and deconfined phases, see Fig. 1.

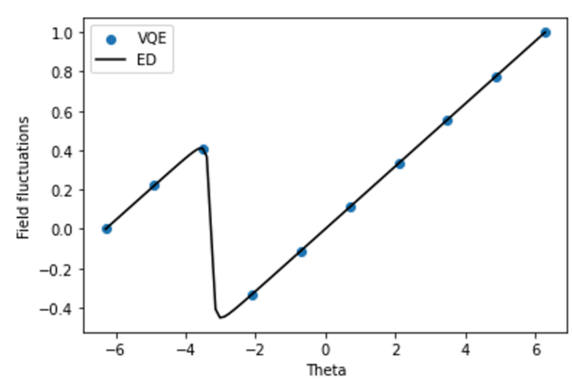

FIG. 2. First order phase transition in the Schwinger model seen in the ground state of a three site system with variational quantum eigensolver method (VQE) compared to exact diagonalisation (ED).

Third, of relevance to condensed matter physics, we add a Hubbard onsite term to the bosonic Z2 model, which has not to our knowledge been investigated before. Using matrix product states we find that the confined regime leads to an extended Mott-insulating state in the addition energy spectrum. We replicate these results in VQE.

Fourth, we study dynamics of a non-equilibrium initial state in the strongly confined regime. The dynamics of a single boson can be captured using hard-core bosons which can be mapped to qubits. However, the dynamics of two bosons starting in one of the sites cannot easily be mapped to qubits. We find a strikingly different behavior, in that the two bosons are no longer confined. Using a Schrieffer-Wolf transformation we find that the effective Hamiltonian is bosonic and allows hopping of pairs.

Finally, we calculate the relative complexity of simulating bosonic operations with qubit-boson hardware vs qubit-only hardware, and find that it would dramatically outperform all-qubit systems as can be seen in Fig. 3, featuring lower gate counts by three orders of magnitude which lead to far higher circuit fidelities and fewer total shots to successfully capture the essential physics of these fermion-boson theories.

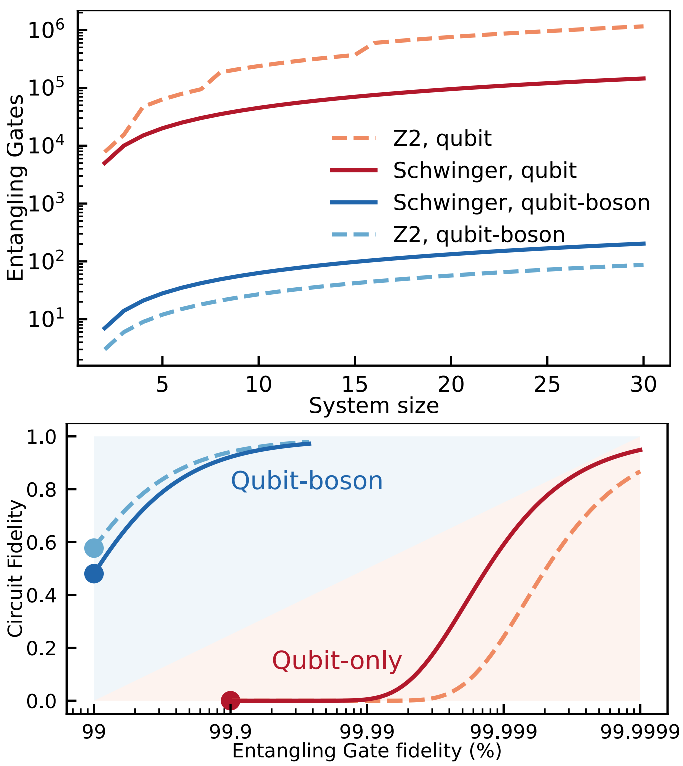

FIG. 3. Entangling gate count compared between digital qubit-boson and all-qubit hardware for one trotter step of the bosonic Z2 and Schwinger models, considering the Fock-binary encoding. Ensuing Trotter step circuit fidelity for ten sites for various near and long term entangling gate fidelities.

A comparative study of Neural quantum state architectures for quantum spin models

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There have been a lot of recent advances in using artificial neural networks, as variational ansatze (Neural quantum states), to approximate the ground states of quantum systems. Various neural network architectures including Restricted Boltzmann Machines (RBMs) [1], Recurrent Neural Networks (RNNs) [2], and Transformers [3] have been successfully used to approximate the ground states of many quantum spin models with a significant accuracy compared to state-of-the-art methods including exact diagonalization (ED) and Density matrix renormalization group (DMRG). However, it can become increasingly difficult for a neural quantum state (NQS) architecture to represent the ground state of a quantum system, as the complexity of the Hamiltonian increases [4]. Additionally, the optimal NQS architecture for representing the groundstate of a system could vary depending on the model that one wants to study. In this work, we systematically study the accuracy of two neural network ansatze, RBMs and RNNs, for the 1D Heisenberg model for spin-$\frac{1}{2}$ and spin-1 systems. We perform a comparative study of how the accuracy in the ground state energies varies with the hyperparameters of the respective neural network ansatze, for both spin-$\frac{1}{2}$ and spin-1 systems.

[1] G. Carleo and M. Troyer (2017) , *Solving the quantum many-body problem with artificial neural networks*, Science **355.6325**, 602-606 (2017).

[2] M. Hibat-Allah, et al. *Recurrent neural network wave functions*, Physical Review Research **2.2**, 023358 (2020).

[3] L. L. Viteritti, R. Rende, F. Becca, *Transformer variational wave functions for frustrated quantum spin systems* arXiv **2211** 05504 (2022).

[4] M. Y. Pei, S. R. Clark, *Neural-network Quantum States for Spin-1 systems: spin-basis and parameterization effects on compactness of representations*, Entropy **23.7**, 879 (2021).

A Fermionic Quantum Gas Microscope for the Continuous Regime

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The quantum gas microscope is a powerful tool that allows to probe dilute quantum matter with single atom resolution, and has proven extremely useful for analog quantum simulation of lattice and spin-chain Hamiltonians. Here we report on the realization of a Lithium 6 quantum gas microscope devoted instead to the study of Fermi gases in continuous space and explore the projection dynamics from an initial many-body wavefunction onto individual lattice sites. This new "continuous space quantum gas microscope" offers the perspective to probe strongly interacting Fermi gases and topological quantum matter at an unprecedented length scale.

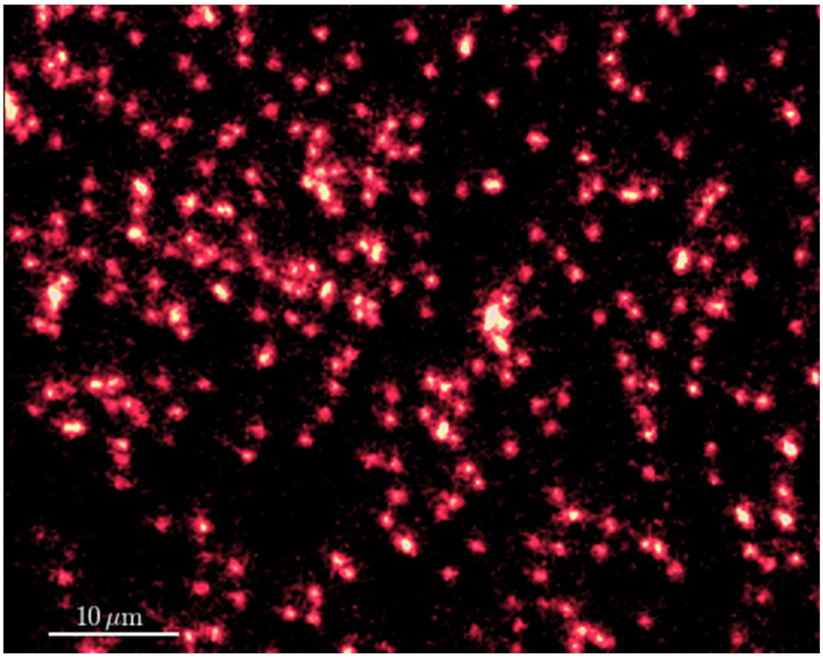

Figure 1: Image of a lithium 6 cloud taken with our quantum gas microscope.

Thermal fading of the $1/k^4$-tail of the momentum distribution induced by the hole anomaly

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We provide the ab-initio Path Integral Monte Carlo calculation of the momentum distribution in a one-dimensional repulsive Bose gas at finite temperatures. We explore all interaction and thermal regimes. An important reference temperature is that of the hole anomaly, observed as a peak in the specific heat and a maximum in the chemical potential [1]. We find that at large momentum k and temperature above the anomaly threshold, the universal tail $\mathscr{C}/k^4$ of the distribution (proportional to the Tan's contact $\mathscr{C}$) is screened by the $1/|k|^3$-term due to a dramatic thermal increase of the internal energy. The same fading is consistently revealed in the short-distance behavior of the one-body density matrix (OBDM) where the $|x|^3$-dependence disappears for temperatures above the anomaly. At very high temperatures, the OBDM and the momentum distribution approach the Gaussian of classical gases. We obtain a new and general analytic tail for the momentum distribution and a minimum k fixing its range of validity, both calculated with Bethe-Ansatz and valid for any interaction strength and temperature [2].

[1] G. De Rosi, R. Rota, G. E. Astrakharchik, and J. Boronat, *Hole-induced anomaly in the thermodynamic behavior of a one-dimensional Bose gas*, SciPost Phys. **13**, 035 (2022)
[2] G. De Rosi, G. E. Astrakharchik, M. Olshanii, and J. Boronat, *Thermal fading of the $1/k^4$-tail of the momentum distribution induced by the hole anomaly, arXiv:2302.03509* (2023)

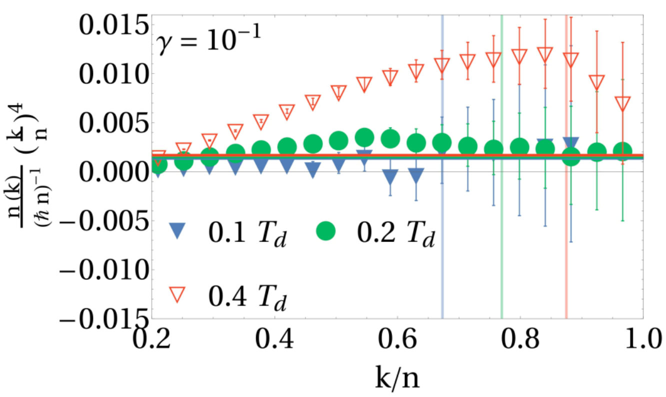

Figure 1 : $n(k)k^4$ vs momentum k for the weakly-interacting regime $\gamma = 10^{-1}$. Solid (empty) symbols correspond to temperatures below (above) the anomaly T_A and represent PIMC results. The minimum value $k_{\min}/n$ is denoted by vertical lines with increasing temperature from low (left) to high (right) values. Horizontal lines report the tail $\mathscr{C}/(2\pi\hbar N)$ calculated with thermal Bethe-Ansatz method and they overlap at different temperatures.

Quantum simulation of the central spin model with a Rydberg atom and polar molecules in optical tweezers

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Central spin models, where a single spinful particle interacts with a spin environment, find wide application in quantum information technology and can be used to describe, *e.g.*, the decoherence of a qubit over time. We propose a method of realizing an ultracold quantum simulator of a central spin model with XX (spin-exchanging) interactions. The proposed system consists of a single Rydberg atom ("central spin") and surrounding polar molecules ("bath spins"), coupled to each other via dipole-dipole interactions (Fig. 1(a)). By mapping internal particle states to spin states, the system effectively realizes a central spin model (Fig. 1(b)), with simulated spin-exchanging interactions.

As an example system geometry, we consider a ring-shaped arrangement of bath spins, and show how it allows to exact precise control over the interaction strengths. We demonstrate that this setup allows to realize a central spin model with highly tunable parameters and geometry, for applications in quantum science and technology [1].

[1] J. Dobrzyniecki and M. Tomza, *Quantum simulation of the central spin model with a Rydberg atom and polar molecules in optical tweezers*, arXiv:2302.14774 (2023).

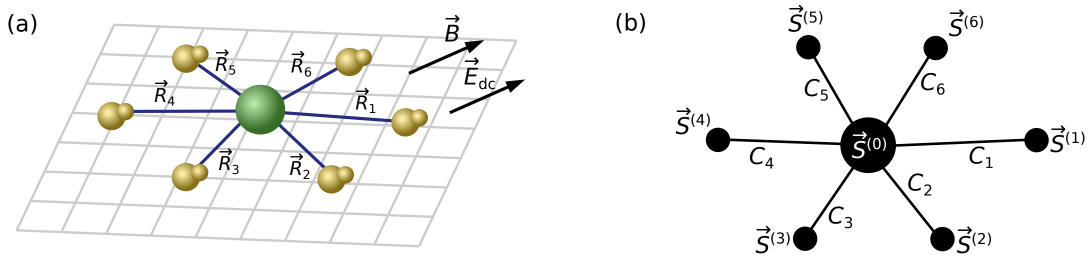

Figure 1: (a) An example atom-molecule system trapped, *e.g.*, in optical tweezers. Each molecule $k = 1, ..., N_{\text{bath}}$ ($N_{\text{bath}} = 6$) is placed at a position $\vec{R}_k$ from the atom at the center. An external electric (magnetic) field $\vec{E}_{\text{dc}}$ ($\vec{B}$) is used to tune the particle transition frequencies as needed, to properly implement spin-exchange processes. (b) A schematic depiction of the central spin model realized by the above setup. The atom acts as the central spin $\vec{S}^{(0)}$ and each molecule k acts as a bath spin $\vec{S}^{(k)}$, which interacts with the central spin with strength C_k.

Quantum transport of strongly correlated fermions

Tilman Enss

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Fermionic transport at strong interaction often cannot be understood by fermionic quasi-particles alone. We present a theoretical framework for quantum transport that takes into account strong local correlations of fermion pairs. In attractively interacting ultra-cold Fermi gases, these contact correlations make substantial contributions to viscous, thermal and sound transport. We calculate the transport coefficients both numerically in the Luttinger-Ward framework and analytically in the virial expansion. By analyzing the real-frequency spectral properties of the particles and pairs, we derive an effective kinetic theory for the bulk viscosity based on pinch singularities. We compare our results with recent sound diffusion measurements in the quantum critical regime and discuss the role of the quantum scale anomaly in the dynamics of two-dimensional Fermi gases.

[1] T. Enss, *Bulk viscosity and contact correlations in attractive Fermi gases,* Phys. Rev. Lett. **123**, 205301 (2019).

[2] K. Fujii and T. Enss, *Bulk viscosity of resonantly interacting fermions in the quantum virial expansion,* arXiv:2208.03353.

[3] B. Frank, W. Zwerger, and T. Enss, *Quantum critical thermal transport in the unitary Fermi gas,* Phys. Rev. Research **2**, 023301 (2020).

[4] P. A. Murthy, N. Defenu, L. Bayha, M. Holten, P. M. Preiss, T. Enss, and S. Jochim, *Quantum scale anomaly and spatial coherence in a 2D Fermi superfluid,* Science **365**, 268-272 (2019).

Intensity correlations in the Driven Dicke Model

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Superradiance originates from the cooperative coupling between an ensemble of emitters and a single radiation mode [1]. In the presence of an external driving laser, the dynamics of the system is described by the so called Driven Dicke model (DDM) [2]. Recently, we have implemented this iconic model laser driving a dense and elongated cloud of cold Rb atoms along its main axis [3]. To go deeper in the exploration of this model, we report recent measurements aimed to investigate the intensity correlations in the steady state($g_2(t)$) of the light emitted by the system into the superradiant mode. We observe the establishment of collective effects in it, manifested as an increasing of the oscillation frequency of g2(t) with respect to the single atom case. This behaviour was predicted by means of DDM and never observed before [4]. Beside its fundamental interest, a pristine investigation of the collective behaviour in $g_2(t)$ might shed a light on the time crystalline nature of this driven-disspative system.

[1] Dicke, *Coherence in spontaneous radiation processes*, Physical Review **93**, 99 (1954)

[2] Agarwal et al., *Collective atomic effects in resonance fluorescence*, PRA **15**, 1613 (1977)

[3] Ferioli et al., *Observation of a superradiant phase transition in free space*, arXiv **2207**, 1036 (2022)

[4] Agarwal et al., *Intensity correlations of a cooperative system*, PRL **42**, 1260 (1977)

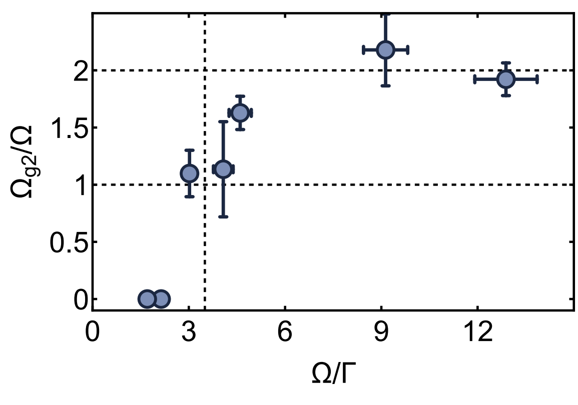

Figure 1: Measurement of the oscillation frequency of $g_2(t)$: in the superradiant phase it is double with respect to the Rabi frequency of the driving laser.

Observation of Universal Hall Response in Strongly Interacting Fermions

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The Hall effect, which originates from the motion of charged particles in a magnetic field, has deep consequences for the description and characterization of materials, extending far beyond the original context of condensed matter physics. Although the Hall effect for non-interacting particles is well explained, understanding it in interacting systems still represents a fundamental challenge even in the small-field case. Here [1] we directly observe the build-up of the Hall response in an interacting quantum system by exploiting controllable quench dynamics in an atomic quantum simulator, see Figure 1. By tracking the motion of ultracold fermions in a two-leg ribbon threaded by an artificial magnetic field, we measure the Hall response as a function of synthetic tunnelling and atomic interactions. We unveil an interaction-independent universal behaviour above an interaction threshold, in clear agreement with theoretical analyses [2-3]. Our approach and findings open new directions for the quantum simulation of strongly correlated topological states of matter.

[1] T. -W. Zhou, G. Cappellini, D. Tusi, L. Franchi, J. Parravicini, C. Repellin, S. Greschner, M. Inguscio, T. Giamarchi, M. Filippone, J. Catani and L. Fallani *arXiv:2205.13567*, to appear in *Science*.

[2] S. Greschner, M. Filippone and T. Giamarchi, *Universal Hall Response in Interacting Quantum Systems*, Phys. Rev. Lett. **122**, 083402 (2019).

[3] M. Filippone, C.-E. Bardyn. S. Greschner and T. Giamarchi, *Vanishing Hall Response of Charged Fermions in a Transverse Magnetic Field*, Phys. Rev. Lett. **123**, 086803 (2019).

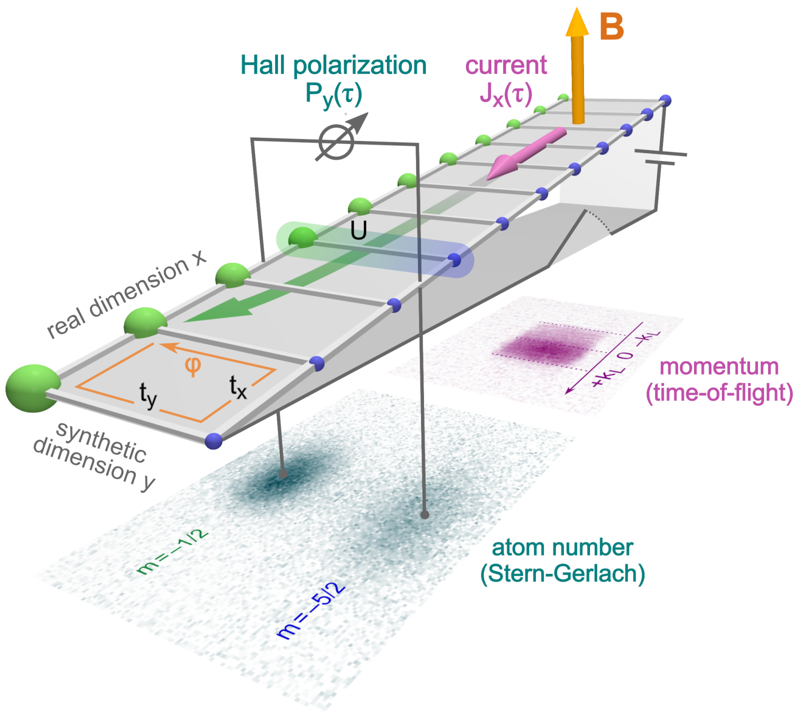

Figure 1: **Experimental scheme.** A synthetic ladder is realized by trapping fermionic ^{173}Yb atoms in a 1D optical lattice and coupling their nuclear spins $m_{\mathrm{F}} = -1/2$ and $m_{\mathrm{F}} = -5/2$ via two-photon Raman transitions. The position-dependent phase of the Raman coupling simulates a magnetic field B with Aharonov-Bohm phase φ per unit cell. An atomic current is activated by tilting the ladder with an optical gradient, equivalent to a constant electric field E_x. The radius difference of the green and blue spheres illustrates the leg population imbalance (Hall polarization) induced by the Hall drift. The time-dependent longitudinal current $J_x(\tau)$ and the Hall polarization $P_y(\tau)$ are measured with time-of-flight imaging and optical Stern-Gerlach detection, respectively (typical acquisitions are shown below the ladder).

Universal van der Waals force between heavy polarons in superfluids

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We investigate the long-range behavior of the induced Casimir interaction between two spinless heavy impurities, or polarons, in superfluid cold atomic gases [1]. With the help of effective field theory (EFT) of a Galilean invariant superfluid, we show that the induced impurity-impurity potential at long distance universally shows a relativistic van der Waals-like attraction ($\sim 1/r^7$) resulting from the exchange of two superfluid phonons. We also clarify finite temperature effects from the same two-phonon exchange process. The temperature T introduces the additional length scale c_s/T with the speed of sound c_s. Leading corrections at finite temperature scale as T^6/r for distances $r \ll c_s/T$ smaller than the thermal length. For larger distances the potential shows a nonrelativistic van der Waals behavior ($\sim T/r^6$) instead of the relativistic one (see Fig. 1). Our EFT formulation applies not only to weakly coupled Bose or Fermi superfluids but also to those composed of strongly correlated unitary fermions with a weakly coupled impurity. The sound velocity controls the magnitude of the van der Waals potential, which we evaluate for the fermionic superfluid in the BCS-BEC crossover.

[1] K. Fujii, M. Hongo, and T. Enss, "Universal van der Waals Force Between Heavy Polarons in Superfluids," Phys. Rev. Lett. **129**, 233401 (2022).

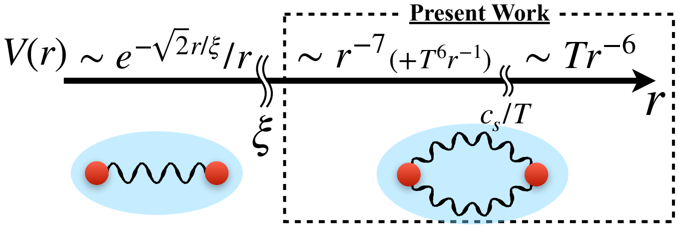

Figure 1: Schematic picture of the scaling regimes of the induced attractive Casimir interaction $V(r)$

Self-binding in low-dimensional mass-imbalanced fermionic mixtures

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In the last 10 years, the few-body bound states made of 1 light fermion interacting attractively with N heavy fermions were analyzed in all spatial dimensions [1,2,3], and we discussed the 1D case up to N=5 [4]. To address the large N limit and to investigate the formation of N+1 clusters in one-dimensional fermionic mixtures with weak attraction, we developed [4] a mean-field approach based on the Thomas-Fermi approximation for the heavy atoms kinetic energy. If extended to the thermodynamic limit [5], our method predicts the binding of such N+1 clusters into a self-bound charge-density wave, a counterintuitive phenomenon which was not expected to occur due to the large Pauli pressure of the system.

Recently, we have extended our method to describe the two-dimensional case, in which the formation of bound states is complicated by the same scaling with length of the kinetic energy and of the interaction energy of the system. Nonetheless, similarly to the 1D case, we find that the 2D one can be described with a single parameter that combines the mass-ratio and N, and we are also able to analyze the N+1 clusters and discuss the bulk properties in the thermodynamic limit.

[1] N. P. Mehta, *Born-Oppenheimer study of two-component few-particle systems under one-dimensional confinement*, Phys. Rev. A **89**, 052706 (2014).

[2] R. Liu, C. Peng, and X. Cui, *Universal tetramer and pentamer in two-dimensional fermionic mixtures*, Phys. Rev. Lett. **129**, 073401 (2022).

[3] D. Blume, *Universal Four-Body States in Heavy-Light Mixtures with a Positive Scattering Length*, Phys. Rev. Lett. **109**, 230404 (2012).

[4] A. Tononi, J. Givois, and D. S. Petrov, *Binding of heavy fermions by a single light atom in one dimension,* Phys. Rev. A **106**, L011302 (2022).

[5] J. Givois, A. Tononi, and D. S. Petrov, *Self-binding of one-dimensional fermionic mixtures with zero-range interspecies attraction*, SciPost Phys. **14**, 091 (2023).

Dynamical mean field theory of the bilayer Hubbard model with Inchworm Monte Carlo

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Dynamical mean-field theory allows access to the physics of strongly correlated materials with nontrivial orbital structure, but relies on the ability to solve auxiliary multiorbital impurity problems. The most successful approaches to date for solving these impurity problems are the various continuous time quantum Monte Carlo algorithms. Here, we consider perhaps the simplest realization of multiorbital physics: the bilayer Hubbard model on an infinite-coordination Bethe lattice. Despite its simplicity, it turns out that the vast majority of this model's phase diagram cannot be predicted by using traditional Monte Carlo methods. We show that these limitations can be largely circumvented by recently introduced Inchworm Monte Carlo techniques. We then explore the model's phase diagram at a variety of interaction strengths, temperatures and filling ratios.

Negative Absolute Temperatures in a Triangular Optical Lattice

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Negative absolute temperatures describe a situation where the entropy of a closed system reduces as the internal energy increases, and this leads to the peculiar situation that atoms in a band dominantly occupy the highest energy states in the band [1]. Here, we report the observation of negative absolute temperatures in a triangular optical lattice — a non-bipartite lattice where geometric frustration leads to two inequivalent maxima in the lowest band. This leads to strikingly different critical interaction strengths for the bosonic superfluid to Mott insulator transition at positive and negative absolute temperatures. We furthermore show for both cases how coherence emerges dynamically from a Mott insulator to a superfluid state, reminiscent of the Kibble-Zurek mechanism.

Reference:

[1] Braun S, Ronzheimer JP, Schreiber M, Hodgman SS, Rom T, Bloch I, Schneider U. "Negative absolute temperature for motional degrees of freedom". Science. **339**(6115) pp. 52-55 (2013).

Boundaries Changes Squeezing in a 1D Heisenberg Spin Chain

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Spin squeezing protocols successfully generate entangled many-body quantum states, key pillars of the second quantum revolution. We show analytically the simulation of one-axis twisting models from the Heisenberg spin-1/2 chain with periodic boundary conditions when accompanied by a position-dependent spin-flip coupling induced by a single laser field [1]. On the other hand, a far richer twisting model appears when we apply open boundary conditions to the same system [2]. In both cases we are able to obtain two-axis counter twisting dymanics under specific conditions, providing Heisenberg level of squeezing and acceleration of dynamics. However, open boundary conditions show promising advantages due to a simpler and more forgiving possible experimental set up. Full numerical simulations confirm our analytical findings.

[1] T. Hernández Yanes, M. Płodzień, M. Mackoit Sinkevičienė, G. Žlabys, G. Juzeliūnas, E. Witkowska, *One- and two-axis squeezing via laser coupling in an atomic Fermi-Hubbard model*, Phys. Rev. Lett. **129**, 090403 (2022)

[2] T. Hernández Yanes, G. Žlabys, M. Płodzień, D. Burba, M. Mackoit Sinkevičienė, E. Witkowska, G. Juzeliūnas, *Spin squeezing in open Heisenberg spin chains*, arXiv:**2302.09829** [quant-ph] (2023)

Diffusion of underdamped single ultracold atoms in engineered environments

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Diffusion is a transport phenomenon that appears as a fundamental process in almost all physical systems. It can occur in very different regimes, ranging from subdiffusion to hyperballistic diffusion, depending on the external parameters. In addition to the properties of a bath or the diffusing particle, the diffusion in systems subjected to external forces is critical for understanding transport phenomena in complex systems.
Here we present a system, where we can observe the diffusion dynamics of single atoms in a tilted periodic potential. An one-dimensional optical lattice allows transporting individual caesium atoms with variable and controllable lattice depth, velocity or acceleration, and thus force. For example, the force exerted on individual atoms can be huge, exceeding standard gravitation by orders of magnitude. Thereby, very different regimes of diffusion can be experimentally accessed. We find that we can tune the system's macroscopic diffusion coefficient by varying the lattice depth and acceleration while applying optical molasses onto the atoms as a "bath of light" for the diffusion. Additionally, the atoms can be transported through a bath of ultracold rubidium atoms. We observe the interplay of the large thermal bath and the single transported atoms trapped in the accelerated lattice and report its effective friction.

Nuclear reactions and structure at the precision frontier

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The combination of *ab initio* methods (AIMs) and Effective Field Theory (EFT) have ushered in a new era of precision in nuclear physics, guided by theoretical uncertainties derived from many-body techniques and the interaction between neutrons and protons constructed from EFT based on the underlying fundamental theory of QCD. Recent efforts have focused on extending the reach of nuclear structure wave-function based methods [1] enabling us to compute bound and low-lying spectroscopy, as well as developing many-body method to compute reactions (multichannel, capture and induced by weak interaction) observables in a consistent framework. These advances have enabled us to compute reactions involved in primordial nucleosynthesis from first principles [2]. We will present a brief overview of the formalism, along with selected applications aimed at computing nuclear reactions relevant to astrophysics. The challenge is now to design highly-accurate methods that scale smoothly with A to extend the range of application to heavier-mass systems in the future.

[1] C. Robin, N. Pillet, D. P. Arteaga, and J.-F. Berger, Physical Review C **93**, 024302 (2016).

[2] G. Hupin, S. Quaglioni, and P. Navrátil, Nature Communications **10**, 351 (2019).

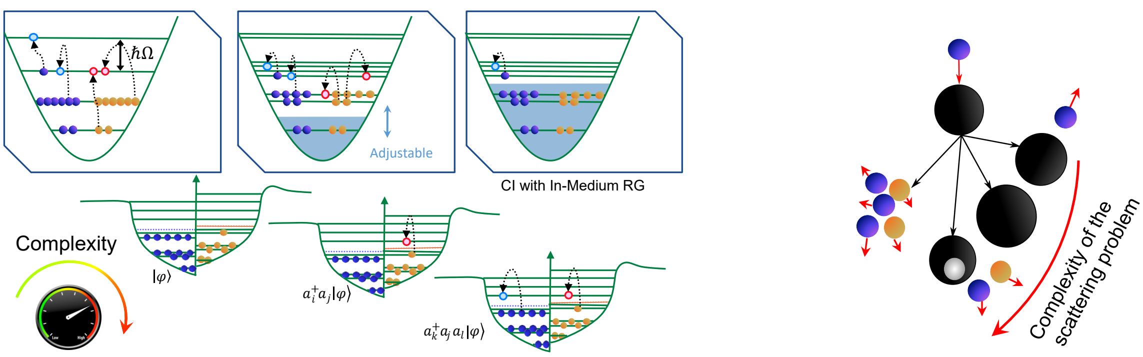

Figure 1: Direction for *ab initio* nuclear structure wave-function based methods (left) and nuclear reaction theory (right) for expending the reach of accurate prediction and interpretation of nuclear observables.

Fermi Gas Microscopy in a Lattice with Tunable Geometry

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We report on an optical lattice for quantum gas microscopy of ultracold fermionic lithium in which the lattice geometry can be tuned to realize triangular, honeycomb, and non-bipartite square connectivities. We use this tunability to study the magnetic properties of the anisotropic triangular Hubbard model, a minimal model for the interplay of geometric frustration and strong correlations [1]. At half-filling and $U/t \sim 9$, as the lattice is tuned from square to triangular, we observe a transition from a collinear Néel antiferromagnet to a short-range 120° spiral phase, accompanied by a reduction of spin correlations due to frustration. Upon doping, near triangular geometries, spin correlations show a pronounced particle-hole asymmetry and suggest a ferromagnetic region at heavy particle doping. This work extends the reach of quantum gas microscopy to a wide range of Hubbard models beyond the nearest-neighbor square lattice. Such lattices are relevant to numerous phases in correlated materials, notably including the particle-hole asymmetric phases of cuprate superconductors. Simultaneously, we improve on the state of the art in reducing technical noise in an optical lattice. This improves the prospects of adiabatic preparation schemes, which may be crucial in reaching lower temperatures.

[1] Muqing Xu, Lev Haldar Kendrick, Anant Kale, Youqi Gang, Geoffrey Ji, Richard T. Scalettar, Martin Lebrat, and Markus Greiner, *Doping a Frustrated Fermi-Hubbard Magnet*, arXiv:2212.13983 (2022).

Attractive Fermi-Hubbard Model in a Magnetic Field

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We use the numerical linked-cluster expansion method to study finite-temperature densities and two-body correlation functions of the attractive square lattice Fermi-Hubbard model in the presence of a magnetic field. We quantify the amount of pairing of the majority species with the minority species as we sweep the chemical potential and the magnetic field and focus on the behavior of excess fermions. We find evidence that in two dimensions, the excess fermions behave like a free Fermi gas in a sea of pairs. Our results are consistent with recent experimental findings using ultracold atoms in an optical lattice.

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Benchmarks of Generalized Hydrodynamics for the Lieb-Liniger Gas

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Generalized hydrodynamics (GHD) is a recent theoretical approach that is becoming a go-to approach for describing and understanding out-of-equilibrium behaviour of integrable and near-integrable quantum many-body systems on large scale. Here, we benchmark the performance of GHD against an array of alternative theoretical approaches, for an interacting one-dimensional (1D) Bose gas described by the Lieb-Liniger model. In particular, we study quantum shock waves and trains of grey solitons arising through the evolution of a localized density bump or dip, along with collisional oscillations in a quantum Newton's cradle setup, for various interaction strengths and initial equilibrium temperatures of the 1D Bose gas. By performing detailed quantitative comparisons with these alternative, microscopic approaches, we find that GHD generally performs very well at sufficiently high temperatures or strong interactions, when phase coherence and interference phenomena on short wavelengths are suppressed. For low temperatures and weak interactions, we highlight situations where GHD, while not capturing such interference phenomena, can nevertheless describe a coarse-grained behaviour modelled by convolution averaging that mimics finite imaging resolution in ultracold atom experiments. This implies that agreement of GHD with these experiments is not necessarily due to the intrinsic accuracy of GHD on microscopic scale, but is because of the fact that both the theory and experiment rely on large-scale coarse graining. The worst performance of GHD is observed for very weak interactions and at very low temperatures—in the regimes where the local density approximation, intrinsic to GHD, breaks down. We have also benchmarked Navier-Stokes GHD within a quantum Newton's cradle setup for a double- to single-well trap quench of a weakly interacting quasicondensate at sufficiently high initial temperatures, and observed excellent agreement with classical field simulations (based on stochastic projected Gross-Pitaevskii equation) in both transient dynamics and final relaxed state, as well as in the characteristic thermalisation timescale.

[1] O. A. Castro-Alvaredo, B. Doyon, and T. Yoshimura, *Emergent Hydrodynamics in Integrable Quantum Systems Out of Equilibrium*, Phys. Rev. X **6**, 041065 (2016).

[2] B. Bertini, M. Collura, J. De Nardis, and M. Fagotti, *Transport in Out-of-Equilibrium XXZ Chains: Exact Profiles of Charges and Currents*, Phys. Rev. Lett. **117**, 207201 (2016).

[3] R. S. Watson, S. A. Simmons, and K. V. Kheruntsyan, *Benchmarks of Generalized Hydrodynamics for 1D Bose Gases.*, arXiv:2208.0661.

Multifractality and transport in cavity-QED materials

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SESSION 2

A mathematical analysis of Density Matrix Embedding Theory

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In this poster, I will present joint work on the mathematical aspects ([4,5]) of Density Matrix Embedding Theory (DMET) ([1,2,3]), an embedding theory designed with the reduced density matrix (1-RDM). After specifying a precise mathematical framework, we prove in [6] that the 1-RDM of the ground state is a fixed point when interactions are neglected. We then prove the existence and analyticity of a fixed point of this algorithm in the weak interaction limit, and study the convergence of the DMET iterative scheme. Finally, we expose numerical simulations in agreement with our results.

[1] G. Knizia and G. Chan, *Density Matrix Embedding: A Simple Alternative to Dynamical Mean-Field Theory*, PRL **109**, 18 (2012)

[2] G. Knizia and G. Chan,*Density Matrix Embedding: A Strong-Coupling Quantum Embedding Theory*,J. Chem. Theory Comput. **9**, 3, (2013)

[3] S. Wouters, C. Jiménez-Hoyos, Q. Sun, G. Chan *A Practical Guide to Density Matrix Embedding Theory in Quantum Chemistry*, J. Chem. Theory Comput. **12**, 6 (2016)

[4] X. Wu, M. Lindsey, T. Zhou, Y. Tong and L. Lin, *Enhancing robustness and efficiency of density matrix embedding theory via semidefinite programming and local correlation potential fitting*, Phys. Rev. B **102**, 085123, (2020)

[5] F. Faulstich, R. Kim, Z. Cui, Z. Wen, G. Chan and L. Lin, *Pure State v-Representability of Density Matrix Embedding Theory*, J. Chem. Theory Comput. , **18**, 2, (2022)

[6] É. Cancès, F. Faulstich, A. Kirsch, E. Letournel, A. Levitt, *Some mathematical insights on DMET*, to be published (2023)

Collective excitations of superconductors and Fermi superfluids in the BCS-BEC crossover

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We present a review of our recent theoretical investigations of collective excitations in the superfluid/superconducting phase of neutral [1-3] and charged [4,5] fermionic systems. We calculate the dispersion and damping of collective excitations at nonzero temperatures, being focused on new features which appear in strongly coupled superconductors and superfluids with respect to the thoroughly studied far BCS regime. The coexistence and interaction of different branches of collective excitations: plasma oscillations, pair-breaking Higgs modes, and Carlson-Goldman phonon-like excitations are examined. The path integral methods for superfluid Fermi gases and for Coulomb gas are combined into a unified Gaussian pair-density fluctuation method which extends the Gaussian fluctuation approximation to account for plasmonic modes. This approximation can describe all branches of collective excitations existing in a charged superfluid or superconductor.

The spectra of collective excitations are determined using two complementary methods: from the spectral weight functions of the pair-field response and density response, and from the complex poles of the fluctuation propagator. In the case when the plasma frequency is sufficiently low to be in resonance with the pair-breaking threshold, a resonant avoided crossing of different modes is shown. It is accompanied by resonant enhancement of the response provided by the pair-breaking modes due to their interaction with plasma oscillations. This may facilitate the experimental observation of the pair-breaking modes. In the other case when the plasma frequency substantially exceeds the gap, the Coulomb interaction can affect low-lying collective excitations. At a sufficiently strong coupling, new branches of gapless and gapped low-lying collective excitations appear with respect to the known modes of the BCS regime, which manifest different behavior as functions of the momentum and the temperature.

[1] H. Kurkjian, S. N. Klimin, J. Tempere, and Y. Castin, *Pair-Breaking Collective Branch in BCS Superconductors and Superfluid Fermi Gases*, Phys. Rev. Lett. **122**, 093403 (2019)
[2] S. N. Klimin, J. Tempere, and H. Kurkjian, *Phononic collective excitations in superfluid Fermi gases at nonzero temperatures*, Phys. Rev. A **100**, 063634 (2019)
[3] S. N. Klimin, J. Tempere and H. Kurkjian, Collective excitations of superfluid Fermi gases near the transition temperature, Phys. Rev. A **103**, 043336 (2021)
[4] T. Repplinger, S. Klimin, M. Gélédan, J. Tempere, and H. Kurkjian, *Plasmons in three-dimensional superconductors*, Phys. Rev. B **107**, 014504 (2023)
[5] S. N. Klimin, J. Tempere, T. Repplinger, and H. Kurkjian, *Collective excitations of a charged Fermi superfluid in the BCS-BEC crossover*, arXiv:2208.09757 (2023)

Hall conductivity in multiband systems and strained Sr_2RuO_4

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The Hall conductivity is an interesting probe of correlated multiband systems. Theoretically, it is rather challenging to analyze. While predictions of the longitudinal conductivity routinely employ the appropriate Kubo formula, they have long remained on a more basic, semiclassical level for the Hall conductivity. We first present a real-frequency Kubo formula for the Hall conductivity of multiband systems and discuss its relevance on a variety of models. Then, we turn to recent experiments on uniaxially strained Sr_2RuO_4. In Ref. 1, measurements of the Hall number for variable strain were related to the scattering rate via a simple tight-binding model. We compare these predictions to a full-fledged many-body calculation utilizing density functional theory, dynamical mean-field theory, and the numerical renormalization group, similarly as in Ref. 2.

[1] P.-Y. Yang, H. M. L. Noad, M. E. Barber, N. Kikugawa, D. Sokolov, A. P. Mackenzie, C. W. Hicks, *Probing momentum-dependent scattering in uniaxially stressed* Sr_2RuO_4 *through the Hall effect*, arXiv:2302.07763 (2023)

[2] F. B. Kugler, M. Zingl, H. U. R. Strand, S.-S. B. Lee, J. von Delft, A. Georges *Strongly correlated materials from a numerical renormalization group perspective: How the Fermi-liquid state of* Sr_2RuO_4 *emerges*, Phys. Rev. Lett. 124, 016401 (2020)

Diagrammatic Strong Coupling Lattice QMC: a Cuprate Case

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We introduce a strong coupling perturbation scheme starting from an arbitrary reference system optimised for a given many-body problem [1]. The dual-fermion scheme [2] is used to formulate general diagrammatic QMC series for effective self-energy correction. Using a lattice version of the DQMC or CT-INT methods [3] we calculate lowest order corrections in the shift of chemical potential and the next-nearest hopping for periodic 8×8 systems in external electronic bath. Results for standard cuprates model with $U = 8t = W$ for the temperature of the order of $T = 0.1t$ show formation of the pseudo-gap and Fermi-arcs. We discuss the magnetic and superconducting instability in DF-QMC scheme [4].

[1] S. Iskakov, M. I. Katsnelson, and A. I. Lichtenstein, arXiv (2023).
[2] G. Rohringer, H. Hafermann, A. Toschi, A. A. Katanin, A. E. Antipov, M. I. Katsnelson, A. I. Lichtenstein, A. N. Rubtsov, and K. Held, Rev. Mod. Phys. **90**, 025003 (2018).
[3] E. Gull, A. J. Millis, A. I. Lichtenstein, A. N. Rubtsov, M.Troyer, and Ph. Werner, Rev. Mod. Phys. **83**, 349 (2011).
[4] E. Z. Stepanov, S. Iskakov, M. I. Katsnelson, and A. I. Lichtenstein, (unpublished).

Multi-channel fluctuating field approach to competing instabilities in interacting electronic systems

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Correlated fermion systems often display complex phase diagrams with different competing orderings. A theoretical description of competing instabilities remains one of the major challenges of modern condensed matter physics. We introduce a multi-channel extension of the recently developed fluctuating field approach [1,2] to tackle this problem, based on a variational optimization of a trial action that explicitly contains the leading fluctuation channels [3]. Application of the approach to extended Hubbard models captures the interplay of competing charge density wave, antiferromagnetic, *s*-wave superconductivity, and phase separation fluctuations [3,4]. For the case of the attractive model, our approach has allowed us to identify a novel phase that is characterised by the coexistence of *s*-wave superconductivity and phase separation [4]. Our findings resonate with previous observations of interplaying phase separation and superconducting phases in electronic systems, most importantly in high-temperature superconductors.

[1] A. N. Rubtsov, *Fluctuating local field method probed for a description of small classical correlated lattices*, Phys. Rev. E **97**, 052120 (2018)

[2] A. N. Rubtsov, E. A. Stepanov, and A. I. Lichtenstein, *Collective magnetic fluctuations in Hubbard plaquettes captured by fluctuating local field method*, Phys. Rev. B **102**, 224423 (2020)

[3] E. Linnér, A. I. Lichtenstein, S. Biermann, E. A. Stepanov, *Multi-channel fluctuating field approach to competing instabilities in interacting electronic systems*, arXiv:2210.05540 (2022)

[4] E. Linnér, C. Dutreix, S. Biermann, E. A. Stepanov, *Coexistence of s-wave superconductivity and phase separation in the half-filled extended Hubbard model with attractive interactions*, arXiv:2301.10755 (2023)

Collective excitations in mesoscopic Fermi gases

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Understanding the elementary excitations of strongly interacting many-body systems in terms of the independent motion of individual particles and their collective behaviour has been a central theme in many fields ranging from nuclear physics to cold atoms [1,2]. In order to study elementary excitations precise control of the optical potential is required. We present a generic protocol based on phase-shifting interferometry [3] to determine the complete phase front aberrations from the source to the atoms. Building on this, we study the quadrupole mode of a mesoscopic Fermi system across the BEC-BCS crossover by means of spectroscopic probes. Therefore, we use an established spilling technique [4] to prepare a balanced system of few fermionic atoms in a tightly confined tweezer. Tuning of the interparticle interactions via a Feshbach resonance and the atom number of the system allows us to observe the transition from single-particle to collective excitations.

[1] B. Mottelson Science 193 (4250), 287-294 (1976)
[2] S. Giorgini et al. Rev.Mod.Phys. 80, 125 (2008)
[3] P. Zupancic et al. Optics express 24.13, 13881-13893 (2016)
[4] F. Serwane et al. Science 332 (6027), 336-338 (2011)

Non-local correlations and criticality in the triangular lattice Hubbard model

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We investigate the role of non-local electronic correlations at finite temperatures in the half-filled triangular lattice Hubbard model using the dynamical vertex approximation ($D\Gamma A$), a diagrammatic extension [1] of the dynamical mean-field theory (DMFT). We analyze the impact of (quantum) phase transitions on finite temperature properties at the one- and two-particle level. We discuss the absence of magnetic ordering at finite temperatures due to the fulfilment of the Mermin-Wagner theorem and the (Mott) metal-insulator crossover. In addition we compare the results of this method to the ones obtained by other cutting-edge techniques like DMFT, its real-space cluster extension cellular dynamical mean- field theory (CDMFT) and diagrammatic Monte Carlo (DiagMC) [2].

[1] G. Rohringer, H. Hafermann, A. Toschi, A.A. Katanin, A.E. Antipov, M.I. Katsnelson, A.I. Lichtenstein, A. N. Rubtsov, and K. Held, Rev. Mod. Phys. 90, 025003 (2018).

[2] Alexander Wietek, Riccardo Rossi, Fedor Simkovic IV, Marcel Klett, Philipp Hansmann, Michel Ferrero, E. Miles Stoudenmire, Thomas Schäfer, Antoine Georges, Phys. Rev. X 11, 041013 (2021).

Dynamics of massive superfluid vortices

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Quantum vortices are generally thought of as funnel-like holes around which a quantum fluid exhibits a swirling flow. In this picture, vortex cores are empty regions where the superfluid density goes to zero.

Here we generalize this framework, by allowing the vortices to have a non-zero mass. The latter may arise for example due to atoms which are distinguishable from the ones composing the superfluid, or are excited out of it as a result of thermal or quantum fluctuations and remain trapped in the vortex cores.

Providing vortices with a mass alters dramatically their dynamics, since the particles trapped in the vortex core experience an effective synthetic gauge field provided by the surrounding superfluid component, which leads to a density-dependent synthetic magnetic field.

In a hard-walled cylindrical container [1] and on an annulus [2] the additional mass leads to a modification of the precession frequency, and the usual precession turns into a cyclotron motion, which for large mass eventually becomes unstable.

In a generic trapping potential $V \propto r^k$, the dynamics acquires an additional intriguing feature which may be easily observed: the direction of precession changes sign for sufficiently large mass [3].

[1] A. Richaud, V. Penna, and A. L. Fetter, *Dynamics of massive point vortices in a binary mixture of Bose-Einstein condensates*, Phys. Rev. A **103**, 023311 (2021)

[2] M. Caldara, A. Richaud, M. Capone, and P. Massignan, *Massive superfluid vortices and vortex necklaces on a planar annulus*, arXiv:2301.08493

[3] A. Richaud, P. Massignan, V. Penna, and A. L. Fetter, *Dynamics of a massive superfluid vortex in r^k confining potentials*, Phys. Rev. A **106**, 063307 (2022)

The Mott metal-insulator transition in the two-dimensional Hubbard model - a cellular dynamical mean-field study on large clusters

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We study the half-filled two-dimensional Hubbard model on a square lattice in cellular dynamical mean-field theory (CDMFT), a real-space cluster extension [1] of the dynamical mean-field theory. By increasing the number of cluster sites up to 6x6 we observe a progressive reduction of the onset interaction U* of a metal-insulator crossover. In particular, in the case of 4x4 sites, we observe a site- dependent U*, which is lower at the center sites than at the corner sites. In addition to this real-space analysis we investigate different periodization schemes for the one-particle spectral function in the half-filled and doped case.

[1] M. Klett, N. Wentzell, T.Schäfer, F. ŠimkovicIV, O. Parcollet, S. Andergassen, and P. Hansmann, Phys. Rev. Research 2, 033476 (2020).

Triangular ad-atom surface lattices as a platform for correlated Hund's physics

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In the triangular lattice Hubbard model, the interplay of strong correlations and geometrical frustration gives rise to a variety of emergent phenomena. At intermediate coupling a metal-insulator transition is observed and spin liquid physics have been proposed, whereas at strong coupling a magnetic insulator is found. Triangular lattice structures can be realized in a variety of materials, such as layered transition metal dichalcogenides, organic salts of the κ-ET family, or X:Si(111) ad-atom systems ($X =$ Pb, Sn, C), where various kinds of correlated phenomena have been observed. In this work we propose X:SiC(0001) ad-atom systems ($X =$ Cr, V, Ti) as a new platform to control and probe two-band physics in the triangular lattice Hubbard model. In particular we expect Hund's coupling to play a major role in the physics of V:SiC(0001). We use first-principles density functional theory calculations in conjunction with the constrained random phase approximation to derive a material-realistic model for the electronic structure. Using dynamical mean-field theory we explore the phase diagram as a function of ad-atom species and temperature.

Real space electronic structure quantum Monte Carlo for periodic systems: reaching the thermodynamic limit

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Electronic structure quantum Monte Carlo (QMC) in real space is now routinely used to calculate energy differences (eg, cohesions/bindings, band gaps, energy orderings, reaction barriers, etc) and other expectations (eg, magnetic moments) of interacting systems of electrons and ions with typical accuracy of 1-2% when compared to experiments on real materials. However, one of the standing challenges that hampers calculations of larger supercells for periodic systems is the presence of finite size biases. So far the methods to filter out these biases have been based on approximate extrapolations, help of approximate mean-field/ effective Hamiltonians as well as sampling of boundary twists (ie, sampling of the Brillouin zone) and, recently, using the grand canonical instead of canonical ensemble. Unfortunately, these errors are unavoidably mixed with inherent - even if small - biases of QMC such as the ones from the fixed-node/phase approximation and therefore difficult to discern, regardless of the fact that the fixed-node/phase errors by themselves are remarkably small (ie, a few % of the correlation energy). We propose essentially two ideas to eliminate the finite size errors. The first one is based on probing the extrapolations of all calculated states/excitations to a common limit with resulting check for the thermodynamic limit consistency [1,2]. This mainly enables us to get under the control biases that originate in the potential energy. However, the sampling of the Brillouin zone even with twists remains problematic since for systems with complicated Fermi surfaces the cost could be prohibitive, in addition to a very slow convergence especially for many metals of interest. In order to address this problem we suggest a particular form of the trial wave function that enables us to eliminate this difficult component of the finite size bias with an almost arbitrary accuracy [3]. Calculations that illustrate the ideas and corresponding results will be presented.

[1] C. A Melton and L. Mitas, *Many-body electronic structure of LaScO3 by real-space quantum Monte Carlo*, Phys. Rev. B **102**, 045103 (2020)
[2] A. Annaberdiyev, C. A. Melton, G. Wang and L. Mitas, *Electronic structure of alpha-RuCl3 by fixed-node and fixed-phase diffusion Monte Carlo*, Phys. Rev. B **106**, 075127 (2022)
[3] L. Mitas, in progress.

Irreversible entropy transport between superfluids

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Since the discovery of superfluidity, the nature of the flow between two superfluids has been the subject of intense and ongoing research, revealing many intriguing phenomena such as the Josephson and fountain effects that can be understood in terms of hydrodynamic, reversible flow of an entropy-free superfluid. Here, we observe that a large, nonlinear particle current flows through a channel connecting two fermionic superfluids at unitarity in response to temperature and chemical potential biases and demonstrate by directly measuring the concurrent nonlinear entropy current that the flow itself is not superfluid, revealing the breakdown of hydrodynamics. We find that the nonlinear dynamics can be described by a phenomenological model based on Onsager's theory of irreversible processes that can constrain microscopic theories of this system. While some phenomenological parameters vary significantly with the geometry of the channel, the advectively transported entropy per particle is extremely robust.

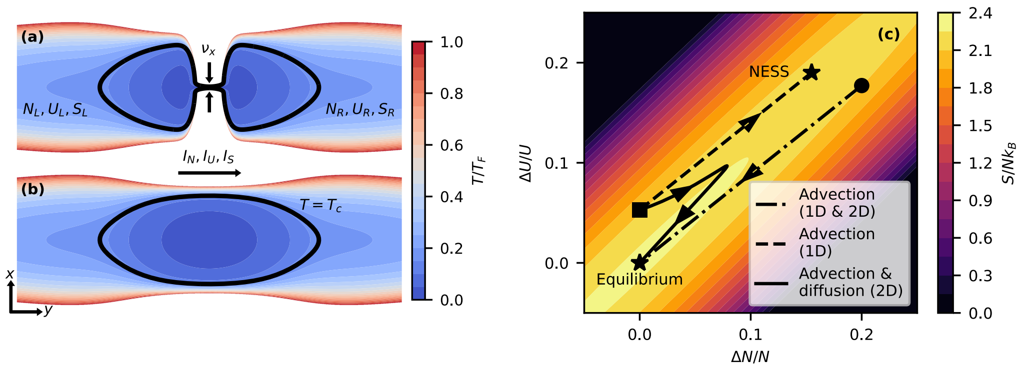

Figure 1: Particles, energy, and entropy can flow through a 1D or 2D channel between two unitarity fermionic superfluids, tracing out a path through phase space depending on the microscopically allowed processes until they reach equilibrium, where entropy is maximized, or a non-equilibrium steady state.

Experiment to Pinpoint the 3D Anderson Transition in Real Space with Matter Waves

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Abstract

The ability to load ultra-cold atoms at a well-defined energy in a disordered potential is crucial to study quantum transport, and in particular Anderson localization. In this talk, In recent years we developed a new method (RF transfer of BEC atoms from a disorder-insensitive state to a to a disorder-sensitive one) for achieving that goal. We have refined this method to enable us realize our long lasting goal if measuring the "mobility-edge" of the 3D Anderson transition. We present the initial, but seemingly reproducible, results of this quest. We shall discuss our present understanding of the challenges that persist, and some ideas to address them.

Finite-size analysis in neural network classification of critical phenomena

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We analyze the supervised learning problem of ferromagnetic phase transitions from the statistical physics perspective. We consider two systems in two universality classes, the two-dimensional Ising model and two-dimensional Baxter-Wu model, and perform careful finite-size analysis of the results of the supervised learning of the phases of each model. We find that the variance of the neural network (NN) output function (VOF) as a function of temperature has a peak in the critical region. Qualitatively, the VOF is related to the classification rate of the NN. We find that the width of the VOF peak displays the finite-size scaling governed by the correlation length exponent, ν, of the universality class of the model. We check this conclusion for several NN architectures---a fully connected NN, a convolutional NN and several members of the ResNet family---and discuss the accuracy of the extracted critical exponent ν .

Dimensional crossover on multileg attractive-U Hubbard ladders

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We study the ground state properties of a polarized two-component Fermi gas on multileg attractive-U Hubbard ladders. Using exact diagonalization and density matrix renormalization group method simulations, we construct grand canonical phase diagrams for ladder widths of up to W = 5 and varying perpendicular geometries, characterizing the quasi-one-dimensional regime of the dimensional crossover. We unveil a multicritical point marking the onset of partial polarization in those phase diagrams, a candidate regime of finite-momentum pairing. We compare our findings with recent experimental and theoretical studies of quasi-one-dimensional polarized Fermi gases.

Observation of phase transitions in cavity QED

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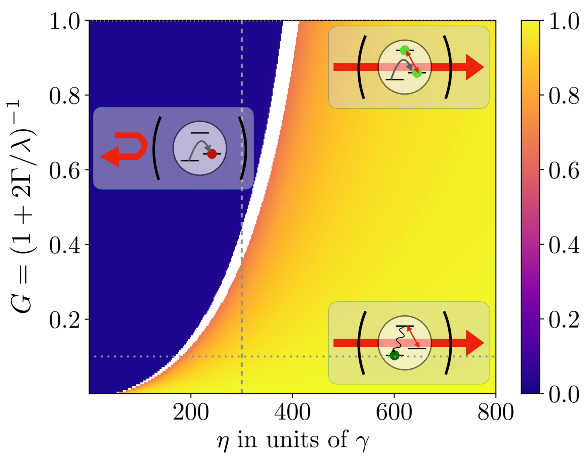
A cloud of laser-cooled rubidium atoms is routinely transported into a high-finesse optical resonator. Due to the strong collective light-matter coupling, the atomic ensemble significantly alters the resonator's transmission, which can then be used to monitor the dynamics of this many body quantum system. On the other hand, light inside the cavity pumps the multilevel atoms into an uncoupled state via a critical runaway process. With time-resolved measurements of the cavity output, we can track this genuine dynamical transition and measure finite-size scaling relations of the enhanced photon number fluctuations [1].

By shining an additional repumper laser on the atoms, the two phases of the coupled atom-cavity system can be stabilized. They correspond to different hyperfine ground states of the atoms, and only one of them is coupled to the cavity mode. Atoms being in this latter state block cavity transmission, while the uncoupled state leads to high transmission. We demonstrate experimentally that there is a bistability region where the two phases coexist. We find a hysteresis in the order parameter when either of the two control parameters is swept across the bistability region. We interpret the phenomenon in terms of the recent paradigm of first-order, driven-dissipative phase transitions [2].

[1] T. W. Clark, A. Dombi, F. I. B. Williams, Á. Kurkó, J. Fortágh, D. Nagy, A. Vukics, and P. Domokos, *Time-resolved observation of a dynamical phase transition with atoms in a cavity*, Phys. Rev. A **105**, 063712 (2022)
[2] B. Gábor, D. Nagy, A. Dombi, T. W. Clark, F. I. B. Williams, K. V. Adwaith, A. Vukics, and P. Domokos, *Ground-state bistability of cold atoms in a cavity*, Phys. Rev. A **107**, 023713 (2023)

Figure 1 : Phase diagram describing the transmission blockade breakdown transition in the steady state.



Thermal-induced Local Imbalance in Repulsive Binary Bose Mixtures

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We study repulsive two-component Bose mixtures with equal populations and confined in a finite-size box through path-integral Monte Carlo simulations. For different values of the s-wave scattering length of the interspecies potential, we calculate the local population imbalance in a region of fixed volume inside the box at different temperatures. We find two different behaviors: for phase-separated states at $T = 0$, thermal effects induce a diffusion process which reduces the local imbalance whereas, for miscible states at $T = 0$, a maximum in the local population imbalance appears at a certain temperature, below the critical one. We show that this intriguing behavior is strongly related to the bunching effect associated with the Bose-Einstein statistics of the particles in the mixture and to an unexpected behavior of the cross pair distribution function not reported before.

FFLO correlations in polarized ultracold Fermi gases

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Quite generally, an imbalance between the densities of spin-up and spin-down fermions hinders pairing and superfluidity in two-component attractive Fermi gases. The Fulde-Ferrell-Larkin-Ovchinnikov (FFLO) phase, in which pairs condense at a finite value of center-of-mass momentum to compensate for the mismatch of the two Fermi surfaces, was proposed many years ago as a possible superfluid phase compatible with a finite polarization. Here, we show how significant precursor FFLO fluctuation effects appear already in the normal phase of polarized Fermi gases at finite temperature [1], and how they could be observed experimentally. At zero temperature [2], we discuss how the quasi-particle parameters of the normal Fermi gas are changed when approaching an FFLO quantum critical point. Within a fully self-consistent t-matrix approach we find that the quasi-particle residues vanish, and the effective masses diverge at the FFLO quantum critical point, with a complete breakdown of the quasi-particle picture that is similar to what is found in heavy-fermion materials at an antiferromagnetic quantum critical point.

[1] M. Pini, P. Pieri, and G. Calvanese Strinati, Phys. Rev. Res. **3**, 043068 (2021).
[2] M. Pini, P. Pieri, and G. Calvanese Strinati, Phys. Rev. B **107**, 054505 (2023).

Real-frequency quantum field theory applied to the Anderson impurity model

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A major challenge in the field of correlated electrons is the computation of dynamical correlation functions. For comparing with experiment, one is interested in their real-frequency dependence, which is difficult to get as imaginary-frequency data from the Matsubara formalism require analytic continuation, a numerically ill-posed problem. Here, we employ quantum field theory in the Keldysh instead of the Matsubara formalism, giving direct access to the self-energy and dynamical susceptibilities on the real-frequency axis. We present results from the functional renormalization group (fRG) and from solving the self-consistent parquet equations for the Anderson impurity model, and compare our results to benchmark data obtained with the numerical renormalization group as well as second-order perturbation theory. We find that capturing the full frequency-dependence of the four-point vertex significantly improves the fRG results compared to previous implementations, and that solving the parquet equations reproduces the NRG benchmark data best but is only feasible up to moderate couplings. Our methodical advances pave the way for treating more complicated models, e.g. adding a bias voltage or momentum degrees of freedom.

Separation of quadrupole, spin, and charge across the magnetic phases of a one-dimensional interacting spin-1 gas

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We study the low-energy collective properties of a one-dimensional spin-1 Bose gas using bosonization. After giving an overview of the technique, emphasizing the physical aspects, we apply it to the S = 1 Bose-Hubbard Hamiltonian and find a separation of the quadrupole-spin-charge sectors, confirmed by time–matrix-product states (time-MPS) numerical simulations. Additionally, through the single-particle spectrum, we show the existence of the superfluid–Mott-insulator transition and the point at which the physics are described by a Heisenberg-like Hamiltonian. The magnetic phase diagrams are found for both the superfluid and insulating regimes; the latter is determined by decomposing the complete Heisenberg bilinear-biquadratic Hamiltonian, which describes the Mott insulator, into simpler, effective Hamiltonians. This allows us to keep our methods flexible and transferable to other interesting interacting condensed matter systems.

[1] FRO and KRR, *Separation of quadrupole, spin, and charge across the magnetic phases of a one-dimensional interacting spin-1 gas*, Phys. Rev. B **107**, 085424 (2023).

[2] T. Giamarchi, *Quantum physics in one dimension* (OUP, 2003).

[3] D. M. Stamper-Kurn and M. Ueda, *Spinor Bose gases: Symmetries, magnetism, and quantum dynamics*, Rev. Mod. Phys. **85**, 1191 (2013).

[4] T. Ulbricht, et al, *Color-charge separation in trapped SU(3) fermionic atoms*, Phys. Rev. A **82**, 011603 (2010).

[5] K. Rodríguez, A. Argüelles, A. K. Kolezhuk, L. Santos, and T. Vekua, *Field-Induced Phase Transitions of Repulsive Spin-1 Bosons in Optical Lattices*, Phys. Rev. Lett. **106**, 105302 (2011).

[6] M. S. Bulakhov, et al, *Magnetic phases and phase diagram of spin-1 condensate with quadrupole degrees of freedomMagnetic phases and phase diagram of spin-1 condensate with quadrupole degrees of freedom*, J. Phys. A Math. Theor. **54**, 165001 (2021).

Antiferromagnetic fluctuations in copper oxide superconductors

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As proposed by Ph. W. Anderson [1] we confirm by an electronic Raman scattering (ERS) study that cuprate physics is mainly controlled by antiferromagnetic (AFM) fluctuations in the under-doped cuprate regime. We came to this conclusion which is in line with many earlier and recent experiments (NMR, INS, RIXS, Raman, STM) [2] and theoretical calculations [3]. We followed gradually the transition from an AFM Mott insulator to a superconducting (SC) metal in bismuth cuprate (Bi-2212). This was achieved by tracking the doping *(p)* dependence of the spin singlet excitation (SSE) originating from the AFM order, the quasiparticle excitation related to the metallic phase and the Bogoliubov quasiparticles associated with the SC pairing. We show that all our Raman data indicate that the pseudogap (PG) is mainly of AFM origin [5] . We identify the PG energy scale $\Delta_{pg}(p)$ with doping as the one of the spin singlet excitation $\Delta_{sse}(p)$. We show that as the pseudogap collapses, the quasiparticle lifetime exponentially increases. We reveal that the SC gap Δ_{sc} and the critical temperature T_c are linked in an extended range of doping, such as: $\Delta_{sc}(p) \propto \Delta_{sse}(p)\, T_c(p)$ in agreement with earlier ARPES and optical studies [4-5] . This empirical relation is universal whether the SC gap is probed in the nodal or anti-nodal regions of the Brillouin zone. This suggests that AFM fluctuations play a significant role in controlling $T_c(p)$ in the pseudogap regime.

References:

[1] Ph. W. Anderson, Science **235**, 1196 (1987).
[2] B. Keimer, S. A. Kivelson, M. R. Norman, S. Uchida, and J. Zaanen, Nature **518**, 179 (2015); I. Vinograd et al. Phys. Rev. B **106** 054522 (2022); G. Blumberg et al. Science **278**, 1427 (1997); S. O'Mahony et al. PNAS **119**, e2207449119 (2022).
[3] N. Lin, E. Gull, and A. J. Millis, Phys. Rev. Lett. **109**, 106401 (2012); W. Wu et al. Phys. Rev. X **8**, 021048 (2018), B. Kyung et al. Phys. Rev. B **73**, 165114 (2006), A. Abanov, A. V. Chubukov, and J. Schmalian, Adv. Phys. **52**, 119 (2003).
[4] H. Ding et al. Phys. Rev. Lett. **87**, 227001 (2001); C. C. Homes, S. V. Dordevic, T. Valla, and M. Strongin, Phys. Rev. B **72**, 134517 (2005).
[5] M. Mezidi et al. Phys. Rev. B **106**, 174513 (2022) ; DOI: 10.1103/PhysRevB.106.174513,

The strongly driven Fermi polaron

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Quasiparticles are emergent collective excitations of matter. Selectively manipulating them by external fields thus allows for tuning material properties. However, despite remarkable progress, it remains challenging to observe the dominant effect of the drive in solids, due to the complex interplay of various collective excitations, including electrons, phonons, or plasmons. Taking advantage of the precise and fast control of ultracold atoms, we report on the creation of strongly driven Fermi polarons; quasiparticles formed by impurities interacting with an atomic Fermi sea. By using a high-intensity radio-frequency (rf) source, we achieve Rabi couplings of about ten times the Fermi energy. This ultrastrong drive enables us to manipulate the quasiparticle properties of the Fermi polaron. We develop the tool of steady state spectroscopy as a probe of the energy of the drive dressed polaron, which tends to zero as the drive strength increases. At a field coupling on the order of the Fermi energy, the polaron decays an order of magnitude faster than in the absence of the drive. At the strongest fields, the impurity starts to decouple from the Fermi sea, resulting in a destruction of the polaron. Our results demonstrate the potential for ultracold atoms to provide key insights into the properties of matter driven with strong light fields.

Correlated insulator and supersolid phases in a one-dimensional Z_2 lattice gauge theory

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We study hard core bosons on a one dimensional lattice coupled to a dynamical Z_2 gauge field on the lattice links. Our model Hamiltonian commutes with a local Z_2 operator defined on each site. Each choice of the eigenvalue (± 1) of these local operators corresponds to a different sector of the Hilbert space. This model has been extensively studied when all eigenvalues are fixed at $+1$ and it was found that in the ground state, the bosons get confined into dimers that form a luttinger liquid at all fractional fillings without ever forming a mott insulator state. In contrast, we consider different ordered patterns of the eigenvalues of these local operators. We find that in these sectors, the ground state can stabilize correlated mott insulator and supersolid phases at different filling fractions. We use numerical and analytical calculations to characterize the single particle spectrum and the expected many-body phases as we change the pattern of eigenvalues of the local symmetry operators. We are motivated by the recent progress in ultracold atomic experiments that can potentially realize these lattice gauge theory models and observe these phases of matter.

Renyi entropy of quantum anharmonic chain at non-zero temperature

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Interplay of quantum and classical fluctuations in the vicinity of the quantum critical point (QCP) gives rise to various regimes and phases with distinctly quantum character, such as superconductivity. Due to the lack of understanding of physical mechanisms associated with quantum criticality phase diagrams of many critical systems are still not explainable. In this work, we show that the Rényi entropy is a precious tool to characterise the phase diagram not only around the QCP but also away from it, thanks to its capability to detect the emergence of a local order and the corresponding local moment formation at finite temperature. We introduce a new algorithm based on path integral equations, sampled by Langevin dynamics, for the evaluation of the Rényi entropy. We study the entropy, its temperature dependence and its scaling and compare it to the study of correlations. Rényi entropy peak at finite temperature coincides with the para-disorder transition at zero temperature. With subsystem-size scaling we conclude that the transition belongs to the Ising universality class. Furthermore, we show that discretisation in the imaginary-time considerably moves the critical point. At finite temperature we discover three regimes - para, disordered and quasi long-range ordered. The divergence of Rényi entropy coincides with the spin freezing crossover between para and disordered regime that shows no temperature dependence. The breaking of quasi long-range order, on the other hand, shows temperature dependence. The results demonstrate that the new method can be used in the study of water ice phase transition. By the analogy it also demonstrates that such crossover is expected to happen in all ϕ^4-like systems.

Orbital-selective metal-insulator transition: effect of non-local collective electronic fluctuations

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Orbital-selective phenomena attract enormous interest nowadays. A prominent example is the orbital-selective Mott phase, where itinerant and localised electrons live in different orbitals of the same material. Since its theoretical prediction, the orbital-selective Mott transition has been intensively studied by the *state-of-the-art* theoretical methods that are based on local approximations to electronic correlations, namely the dynamical mean-field theory and the slave-spin approach. Nevertheless, the microscopic mechanism of the formation of this phase in realistic materials remains unclear.

I will show that consistently taking into account non-local collective electronic fluctuations using the novel dual triply irreducible local expansion (D-TRILEX) method [1-3] completely changes the *state-of-the-art* picture of the metal-insulator transition in the two-orbital Hubbard model [4-6]. In particular, I will demonstrate that strong magnetic fluctuations suppress the orbital-selective Mott transition in favour of the non-orbital-selective Néel transition to the ordered antiferromagnetic phase [4]. I will also discuss the possibility to realise the orbital-selective metal-insulator transition in the presence of strong magnetic fluctuations [6].

[1] E. A. Stepanov, V. Harkov, A. I. Lichtenstein, "Consistent partial bosonization of the extended Hubbard model", *Phys. Rev. B* **100**, 205115 (2019);
[2] V Harkov, M Vandelli, S Brener, AI Lichtenstein, EA Stepanov, "Impact of partially bosonized collective fluctuations on electronic degrees of freedom", *Phys. Rev. B* **103**, 245123 (2021);
[3] M. Vandelli, J. Kaufmann, M. El-Nabulsi, V. Harkov, A. I. Lichtenstein, E. A. Stepanov, "Multi-band D-TRILEX approach to materials with strong electronic correlations", *SciPost Phys.* 13, 036 (2022);
[4] Evgeny A. Stepanov, "Eliminating Orbital Selectivity from the Metal-Insulator Transition by Strong Magnetic Fluctuations", *Phys. Rev. Lett.* **129**, 096404 (2022);
[5] M. Vandelli, J. Kaufmann, V. Harkov, A. I. Lichtenstein, K. Held, E. A. Stepanov, "Extended regime of coexisting metallic and insulating phases in a two-orbital electronic system", *arXiv: 2204.02116* (2022);
[6] E. A. Stepanov and S. Biermann, *to be published*;

Finite density properties and crystalline phases in a quantum link ladder

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Condensed matter physics of gauge theories coupled to fermions can exhibit a rich phase structure, but are nevertheless very difficult to study in Monte Carlo simulations when they are afflicted by a sign problem. As an alternate approach, we use tensor network methods to explore the finite density physics of Abelian gauge theories without dynamical matter. Our focus is on exploring the finite density physics of Abelian gauge theories without dynamical matter. As a case study, we investigate the U(1) gauge invariant quantum link ladder with spin-1/2 gauge fields in an external electric field, which leads to condensation of winding electric fluxes in the ground state. This poster is based on the work [1].

[1] P. Stornati et. Al *Crystalline phases at finite winding densities in a quantum link ladder*, PhysRevD 107 (2023)

Acceleration of the Auxiliary-Field Quantum Monte Carlo Procedure

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Auxiliary-field quantum Monte Carlo (AFQMC) is a computational technique used in quantum many-body physics to study the properties of interacting systems. By using the Hubbard-Stratanovich transformation, it maps the interacting many-body system onto a non-interacting system coupled to fluctuating random fields. Due to its high accuracy and low polynomial scaling, between cubic and quartic, it is widely used in quantum simulations.

In this work, we discuss various optimization techniques for accelerating the AFQMC procedure. These include:

- optimization of the time step for orbital propagation;
- choice of the propagator that minimizes the number of $\hat{H}\left|\Psi\right\rangle$ operations;
- Acceleration of the exchange energy evaluation, which is usually the most computationally expensive operation in the AFQMC procedure.

By implementing these techniques, we can significantly speed up the AFQMC procedure by up to two orders of magnitude without any loss of accuracy.

Probing non-equilibrium dynamics across the BKT critical point by dynamical control of bilayer 2D Bose gases

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We report on the observation of non-equilibrium dynamics across the Berezinskii-Kosterlitz-Thouless (BKT) critical point by dynamical control of bilayer 2D Bose gases. We quench the system by coherently splitting a single 2D Bose gas into two, resulting in a sudden crossing from the superfluid to the normal phase, and we monitor the relaxation dynamics using matter-wave interferometry technique [1]. From the interference patterns, we obtain the time evolution of the phase correlation function and vortex density and compare with the real-time renormalization group theory [2]. We further report on the observation of the BKT transition in a bilayer 2D Bose gas with controllable coherent coupling between the two layers, which shows coupling-dependent critical point [3]. Our multiple-RF dressing technique for trapping ultracold atoms [4] allows precise and dynamical control of the coupling strengths between the two layers, which can be used to probe further non-equilibrium phenomena in 2D systems across the BKT critical point.

[1] S. Sunami, V. Singh, D. Garrick, A. Beregi, A.J. Barker, K. Luksch, E. Bentine, L. Mathey and C.J. Foot. Observation of the BKT transition in a 2D bose gas via matter-wave interferometry. Phys. Rev. Lett. **128**, 250402 (2022)
[2] S. Sunami, V. Singh, D. Garrick, A. Beregi, A.J. Barker, K. Luksch, E. Bentine, L. Mathey and C.J. Foot. Universal scaling of the dynamic BKT transition in quenched 2D Bose gases. arXiv:2209.13587 (2022).
[3] S. Sunami, V. Singh, A. Beregi, D. Garrick, E. Chang, L. Mathey and C.J. Foot. Probing BKT universality in coupled bilayer 2D Bose gases. *in preparation*.
[4] T. L. Harte, E. Bentine, K. Luksch, A. J. Barker, D. Trypogeorgos, B. Yuen, and C. J. Foot. Ultracold atoms in multiple radio-frequency dressed adiabatic potentials. Phys. Rev. A **97**, 013616 (2018)

Modern Quantum Field Theory of the Electron Liquid

Kun Chen

We present a new perspective on fundamental problems in electronic structure and superconductivity through the lens of modern quantum field theory (QFT). We propose a renormalized QFT approach to describe valence electrons in metals, uncovering hidden emergent localities in the electron self-energy and electron-electron interaction, which lays the foundation for the development of next-generation ab-initio methods. Additionally, we use finite-temperature QFT to analyze the fine structure of Cooper-pair correlations in (semi)metals at high temperatures, revealing that this correlation provides a robust probe for predicting pairing instability in low-density superconductors with ultra-low transition temperatures. Our approach provides new insights and potential solutions to the many-electron problem through the innovative application of QFT.

Magnetism and metallicity in moiré transition metal dichalcogenides

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Recent experiments on moiré transition metal dichalcogenides have established this class of compounds as a highly tunable platform for the study of correlated electronic phenomena such as the correlation-driven Mott metal-insulator transition, quantum criticality and superconductivity [1,2]. At the same time these materials can be approximately described in terms of the single-band moiré Hubbard model on a triangular lattice [3]. We investigate the properties of this model at half-filling, where it hosts a variety of metallic, insulating and magnetic phases and we study in detail their interplay with an externally applied Zeemann field. At finite temperatures we employ the dynamical mean-field theory (DMFT) and its cluster extensions CDMFT and DCA in order to capture both local and non-local correlations, while at $T = 0$ the recently developed Variational Discrete Action Theory (VDAT) [4] is used to elucidate the polarization transition.

[1] Li, T., Jiang, S., Li, L. et al. *Continuous Mott transition in semiconductor moiré superlattices*, Nature **597**, 350–354 (2021)

[2] Ghiotto, A., Shih, EM., Pereira, G.S.S.G. et al. *Quantum criticality in twisted transition metal dichalcogenides*, Nature **597**, 345–349 (2021)

[3] Fengcheng Wu, Timothy Lovorn, Emanuel Tutuc, and A. H. MacDonald, *Hubbard model physics in transition metal dichalcogenide moiré bands*, Phys. Rev. Lett. **121**, 026402 (2018)

[4] Zhengqian Cheng and Chris A. Marianetti, *Foundations of variational discrete action theory*, Phys. Rev. B **103**, 195138 (2021)

Equation of state of superfluid neutron matter with low-momentum interactions

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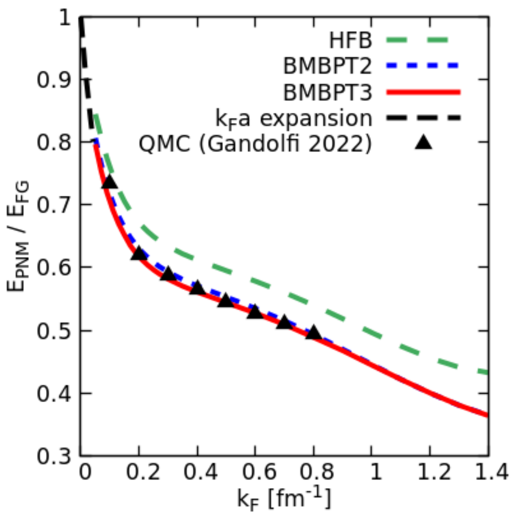
The behavior of the unbound neutrons in the inner crust of neutron stars is linked to various neutron-star characteristics such as glitches in the repetition rate of pulsars. We present a calculation of low-density superfluid neutron matter [1] using a method that we had previously developed to describe two-component Fermi gases with attractive interactions [2]. The starting point is a two-body interaction softened using renormalization-group techniques. The resulting interaction is used in Bogoliubov many-body perturbation theory, which is a perturbative expansion around the Hartree-Fock-Bogoliubov (HFB) ground state. As in the case of ultracold atoms, it turns out that also in neutron matter the cutoff should be scaled with the Fermi momentum. Then, including perturbative corrections to the HFB energy up to third order, we observe that at densities corresponding to the inner crust of neutron stars, the cutoff dependence of the ground state energy is strongly reduced and the results are in excellent agreement with quantum Monte-Carlo calculations.

[1] V. Palaniappan, S. Ramanan, and M. Urban, Phys. Rev. C 107, 025804 (2023).
[2] M. Urban and S. Ramanan, Phys. Rev. A 103, 063306 (2021).



Real-Time Diagrammatic Monte Carlo For Dissipative Impurity Model

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We propose a novel approach to nonequilibrium real-time dynamics of quantum dissipative impurities models coupled to a non-interacting bath [1], which within the limit of strong dissipations can bypass the sign problem. The method is based on a Diagrammatic Monte Carlo sampling of the real-time perturbation theory.

[1] M.Schirò and O. Scarlatella, *Quantum impurity models coupled to Markovian and non-Markovian baths.*, The Journal of chemical physics **151 4**, 2222 (2019)

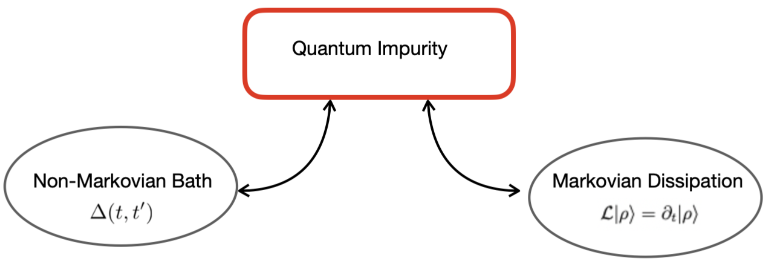

Figure 1: A quantum impurity system is coupled to a quantum bath with non-trivial correlations, and non-linearly coupled to a Markovian bath by a Lindblad master equation.

Superfluid signatures in a dissipative quantum point contact

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We study theoretically and experimentally the charge transport through a dissipative quantum point contact between two fermionic superfluids. Superconducting junctions are known to exhibit multiple Andreev reflections - a high-order cotunneling of a quasi-particle together with multiple Cooper pairs - which gives rise to a current at chemical potential biases below the energy gap. An interesting question is the fate of such a high-order coherent process in the presence of dissipation. To study this theoretically, we develop a model with a local particle loss as a dissipation mechanism and compute the DC particle current and loss rate using the Keldysh formalism. We find that the current generated by the seemingly delicate high-order tunneling is surprisingly robust to particle losses. This result agrees with experimental data measured in a cold-atom transport setup with a lossy quantum point contact between two fermionic superfluid reservoirs. We apply a pair-breaking, spin-dependent dissipation at the contact and observe that the excess current characteristic of superfluidity survives even at dissipation strength larger than the superfluid gap [1].

[1] M.-Z. Huang et al., *Superfluid current through a dissipative quantum point contact*, arXiv:2210.03371 [cond-mat.quant-gas]

Strongly-Coupled Fermions from the Lattice

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We present thermodynamic and linear-response functions for two and three dimensional fermi gases computed from lattice field theory. Along with results of phenomenological interest in both supernova and cold-atomic physics, we present a novel "Symanzik improvement" scheme for parametrically improving convergence to the continuum limit [1].

[1] A. Alexandru, P. Bedaque, E. Berkowitz, N. Warrington *Structure Factors of Neutron Matter at Finite Temperature*, Phys. Rev. Lett. **126**, 132701 (2021)

High-order diagrammatic expansion around BCS Hamiltonians: Polarized superfluid phase of the attractive Hubbard model

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In contrast to conventional QMC methods, expansions of intensive quantities in series of connected Feynman diagrams can be formulated directly in the thermodynamic limit. Over the last decade, diagrammatic Monte Carlo algorithms made it possible to reach large expansion orders and to obtain state-of-the-art results for various models of interacting fermions in 2 and 3 dimensions, mostly in the normal phase.

We obtained first results inside a superconducting phase, for the 3D attractive Hubbard model [1]. Spontaneous symmetry breaking is implemented by expanding around a BCS Hamiltonian. All diagrams up to 12 loops are summed thanks to the connected determinant algorithm [2] with anomalous propagators. Working on the BCS side of the strongly correlated regime, we observe convergence of the expansion, and benchmark the results against determinant diagrammatic Monte Carlo [3]. In presence of a polarizing Zeeman field (where unbiased benchmarks are unavailable due to the fermion sign problem) we observe a first-order superconducting-to-normal phase transition (see Figure), and a thermally activated polarization of the superconducting phase well captured by a quasiparticle description. We also discuss the large-order behavior of the expansion and its relation to Goldstone and instanton singularities.

[1] G. Spada, R. Rossi, F. Simkovic, R. Garioud, M. Ferrero, K. Van Houcke, F. Werner, arXiv:2103.12038

[2] R. Rossi, PRL **119**, 045701 (2017)

[3] E. Burovski, N. Prokof'ev, B. Svistunov, M. Troyer, PRL **96**, 160402 (2006)

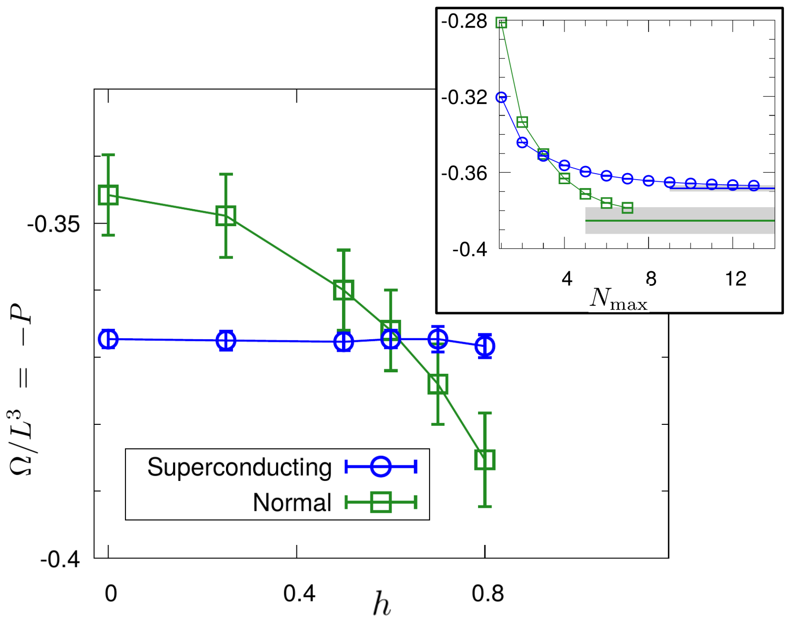

Figure 1: Grand-potential density *vs.* Zeeman field $h = (\mu_\uparrow - \mu_\downarrow)/2$, at $T = 1/16 \approx T_c/4$. Circles: superconducting phase, obtained by expanding around BCS mean-field theory. Squares: normal phase, obtained by expanding around the normal mean-field solution. The crossing between the curves signals the first-order phase transition. Inset: same quantity *vs.* truncation order $N_{\max}$, at $h = 0.8$; horizontal lines with error bands are the $N_{\max} \to \infty$ extrapolated results also shown in the main panel.

Squeezing oscillations in a multimode bosonic Josephson junction

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Quantum simulators built from ultracold atoms promise to study quantum phenomena in interacting many-body systems. However, it remains a challenge to experimentally prepare strongly correlated continuous systems such that the properties are dominated by quantum fluctuations. Here, we show how to enhance the quantum correlations in a multimode bosonic Josephson junction; our approach is based on the ability to track the dynamics of quantum properties. After creating a bosonic Josephson junction at the stable fixed point of the classical phase space, we observe squeezing oscillations in the two conjugate variables. We show that the squeezing oscillation frequency can be tuned by more than one order of magnitude and we are able to achieve a spin squeezing close to 10 dB by utilizing this oscillatory dynamics. The impact of improved spin squeezing is directly revealed by detecting enhanced spatial phase correlations between decoupled condensates. Our work provides new ways for engineering correlations and entanglement in the external degree-of-freedom of interacting many-body systems[1].

[1] Zhang, Tiantian, et al. "Squeezing oscillations in a multimode bosonic Josephson junction." *arXiv preprint arXiv:2304.02790* (2023).

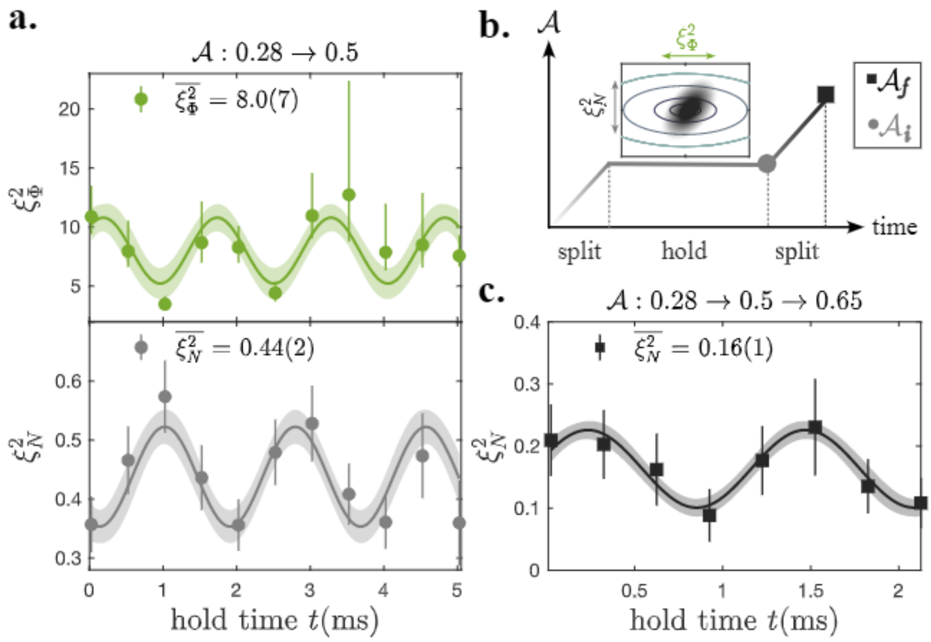

Figure 1: Squeezing oscillations and two-step sequence. a. Measured number (gray circle) and phase (green circle) squeezing factors as a function of hold time in strongly coupled double well after a linear ramp from a single well We observe squeezing oscillations in both quadratures with comparable frequencies and a phase shift of π. **b.** Schematic of the two-step splitting procedure. The inset shows quantum state distribution in the classical phase space from Bose-Hubbard model. **c.** Measured number squeezing oscillations, stemming from the hold time in the coupled double well, after two-step splitting to a decoupled double well. All solid lines are fits with a sine function and bands indicate 68% prediction confidence interval. Error bars represent one s.e.m.

Quantum Advantage in Simulating Floquet Thermalized Systems on a Cold-Atom Processor

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Nonequilibrium dynamics of quantum many-body systems is challenging for classical computing [1,2], providing opportunities for demonstrating practical quantum computational advantage with analogue quantum simulators [3]. Due to the intimate connection with a random matrix ensemble, it is proposed to be classically intractable to sample the driven thermalized many-body states of a Bose-Hubbard system [4], and further extract multi-point correlations from the output-strings for characterizing quantum systems [5]. Here, leveraging dedicated precise manipulations and atom-number-resolved detection through a quantum gas microscope with bichromatic superlattices, we implement and sample the driven Hubbard chains in the thermalized phase involving up to 32 sites with 20 atoms. In this regime, the estimated effective computational power of sampling in our quantum simulator is comparable to that of the fastest supercomputer with currently known best algorithms. We employ the Bayesian tests to verify that our prepared systems operate in the driven thermalized phase. Multi-point correlations of up to 14th-order extracted from the experimental samples offer clear distinctions between the thermalized and many-body-localized phases. Our work [6] paves the way towards practical quantum computational advantage applied in simulating Floquet dynamics of many-body systems.

[1] R. P. Feynman, *Simulating physics with computers*, Int. J. Theor. Phys. **21**, 467 (1982)
[2] J. Preskill, *Quantum computing and the entanglement frontier*, arXiv:1203.5813 (2012)
[3] A. J. Daley, *et al.*, *Practical quantum advantage in quantum simulation*, Nature **607**, 667 (2022)
[4] S. Thanasilp, *et al.*, *Quantum supremacy and quantum phase transitions*, Phys. Rev. B **103**, 165132 (2021)
[5] T. Schweigler, *et al.*, *Experimental characterization of a quantum many-body system via higher-order correlations.*, Nature **545**, 323 (2017)
[6] Y.-G. Zheng, *et al.*, *Efficiently extracting multi-point correlations of a Floquet thermalized system*, arXiv:2210.08556 (2022)

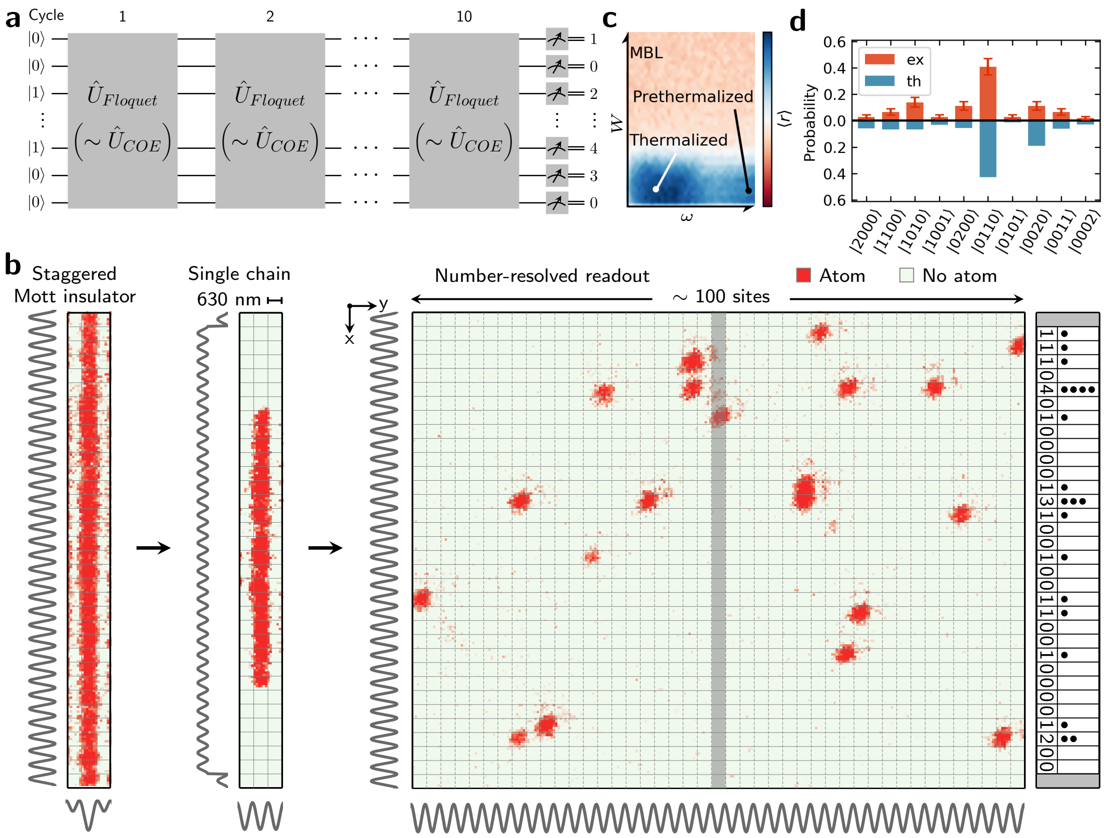

Figure 1: **Sampling on a Floquet many-body system.** **a**, Quantum circuit illustration of the experiment. After ten cycles of the Floquet unitary evolution, we sample the output of the final states on the Fock basis. **b**, We implement the protocol in our analogue quantum simulator based on the quantum gas microscope set-up. First, a defect-free Mott insulator is prepared via staggered cooling. Utilizing the site-resolved addressing, we cut a single chain with N_b particles in the centre. Then the system evolves under a driven Bose-Hubbard model to the final states. The edges of the system are fixed by a box trap imposed by a DMD, forming a one-dimensional chain with L sites in the x direction. Before detection, we expand the atoms in the y direction over 100 sites, which circumvents the pair-wise loss of multiple atoms trapped in a single site during fluorescence imaging. **c**, The phase diagram of a driven Bose-Hubbard chain. For low driving frequency and weak disorders, the system will thermalize after several cycles of driving. If the intensity of the disorder increases, the thermalization breaks down and the system arrives at a MBL phase. **d**, The probability distribution estimated from the collected samples of the $L = 4$, $N_b = 2$ system. The error bars come from the Poisson statistics.