# Exploring Quantum Many-Body Physics with Ultracold Atoms and Molecules

## 735. WE-Heraeus-Seminar

14 Dec - 18 Dec 2020
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Subject to alterations!

# Introduction

**The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de**

## Aims and scope of the 735. WE-Heraeus-Seminar:

Since the first experimental realization of Bose-Einstein condensation in ultracold atomic gases in 1995, there have been several substantial breakthroughs. Today, systems of bosonic or fermionic quantum gases allow for a very high level of experimental control concerning all ingredients of the underlying many-body Hamiltonian. Therefore, ultracold atomic or molecular quantum gases are considered to be ideal quantum simulators, that is, they are best capable to simulate difficult problems in quantum many-body physics as they occur in condensed matter physics and other fields of physics.

In response to the occurrence of many new research directions in recent years, it is highly desirable to give a coherent overview over the diverse facets which are now appearing, and to reflect upon the future perspectives of the field. Thus, the seminar follows the interdisciplinary concept in bringing together experimental and theoretical scientists, who investigate the properties of ultracold quantum gases from different points of view, to exchange opinions, discuss problems, and disseminate new ideas. On the one hand, invited plenary talks by 23 selected leading international experts will guarantee a high scientific level for the seminar, and will provide its main backbone. On the other hand, all other participants will be given the opportunity to present their current research work within a high-class setting mostly through short talks, but also via a few shorter contributed talks, in part also invited, that will be selected from the applicants, thereby generating a forum for identifying the most promising current trends and future perspectives.

The 735th WEH Seminar is performed in a fully online format, where plenty of time is reserved in the program for discussing the respective research work in plenum via preinstalled zoom sessions. Additionally, individual discussions between the participants are possible at a virtual platform provided by Wonder.

We hope that you enjoy the unusual experience of such a scientific meeting at a distance.

## Scientific Organizers:

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|---|---|
| PD Dr. Axel Pelster | Technische Universität Kaiserslautern, Germany<br>E-mail: axel.pelster@physik.uni-kl.de |
| Prof. Dr. Carlos Sá de Melo | Georgia Institute of Technology, Atlanta, USA<br>E-mail: carlos.sademelo@physics.gatech.edu |

# Program

# Program

## Sunday, 13 December 2020

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|---|---|
| 20:00 | **Wonder Room**<br>Socializing |

## Monday, 14 December 2020

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|---|---|---|
| 08:40 – 09:00 | Axel Pelster | **Opening and Welcome** |

**Session 1: Optical Lattices (Chair: Axel Pelster)**

| | | |
|---|---|---|
| 09:00 – 09:45 | Monika Aidelsburger | **Observing non-ergodicity due to kinetic constraints in tilted Fermi-Hubbard chains** |
| 09:45 – 10:30 | Christof Weitenberg | **Unsupervised machine learning of topological phase transitions from cold-atom data** |
| 10:30 – 11:00 | *COFFEE BREAK* | |
| 11:00 – 12:30 | **Short Talks I** (11 talks, 7 min each)<br>**(Chair: Monika Aidelsburger)** | |
| 12:30 – 14:00 | *LUNCH BREAK* | |
| 14:00 – 15:30 | **Short Talks II** (11 talks, 7 min each)<br>**(Chair: Thomas Gasenzer)**<br>*Short Talk Nr. 17 now Mohammad Tayeb Meftah* | |
| 15:30 – 16:00 | *COFFEE BREAK* | |
| 16:00 – 17:00 | **Short Talks III** (8 talks, 7 min each)<br>**(Chair: Carlos Sá de Melo)** | |

# Program

## Monday, 14 December 2020

### Session 2: Dynamics I (Chair: Carlos Sá de Melo)

| | | |
|---|---|---|
| 17:00 – 17:45 | Waseem Bakr | **Exploring non-equilibrium dynamics in novel Fermi gas systems** |
| 17:45 – 18:30 | Monika Schleier-Smith | **Quantum spin dynamics with optically programmable interactions** |
| 18:30 – 19:30 | **Wonder Room**<br>Individual discussions between speakers and participants, Socializing | |

# Program

## Tuesday, 15 December 2020

### Session 3: Crossover (Chair: Christof Weitenberg)

| | | |
|---|---|---|
| 09:00 – 09:45 | Michael Köhl | **Competing magnetic orders in a bilayer Hubbard model with ultracold atoms** |
| 09:45 – 10:30 | Artur Widera | **Quantum gases in controlled perturbation – from single impurities to time-dependent disorder** |
| 10:30 – 11:00 | *COFFEE BREAK* | |
| 11:00 – 12:30 | **Short Talks IV** (11 talks, 7 min each)<br>**(Chair: Artur Widera)**<br>*Short Talk Nr. 35 cancelled on short notice* | |
| 12:30 – 14:00 | *LUNCH BREAK* | |
| 14:00 – 15:30 | **Short Talks V** (11 talks, 7 min each)<br>**(Chair: Tim Langen)**<br>*Short Talk Nr. 48 cancelled on short notice* | |
| 15:30 – 16:00 | *COFFEE BREAK* | |
| 16:00 – 17:00 | **Short Talks VI** (8 talks, 7 min each)<br>**(Chair: Georg Bruun)** | |

### Sesseion 4: Geometry (Chair: Waseem Bakr)

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|---|---|---|
| 17:00 – 17:45 | Jean Dalibard | **Fresh news from flatland: Testing scale invariance in the lab** |
| 17:45 – 18:30 | Cristiane de Morais Smith | **Quantum fractals** |
| 18:30 – 19:30 | **Wonder Room**<br>Individual discussions between speakers and participants, Socializing | |

# Program

## Wednesday, 16 December 2020

### Session 5: Flat Bands (Chair: Francesca Ferlaino)

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|---|---|---|
| 09:00 – 09:45 | Päivi Törmä | **Interactions and flat bands: superconductivity in Moiré superlattices and non-Fermi liquid normal states** |
| 09:45 – 10:30 | Wei Zhang | **Flat-band Ferromagnetism of SU(N) Hubbard Model on Tasaki Lattices** |
| 10:30 – 11:00 | *COFFEE BREAK* | |

### Session 6: Contributed Talks I (Chair: Wei Zhang)

| | | |
|---|---|---|
| 11:00 – 11:30 | Natalia Chepiga | **Kibble-Zurek exponent and chiral transition of the period-4 phase of Rydberg chains** |
| 11:30 – 12:00 | Tobias Grass | **Fractional quantum hall physics with cold atoms – from state preparation to anyon detection** |
| 12:00 – 12:30 | Hideki Konishi | **Cavity quantum-electrodynamics with atoms and pairs in a strongly interacting Fermi gas** |
| 12:30 – 14:00 | *LUNCH BREAK* | |

### Session 6: Contributed Talks II (Chair: Tobias Grass)

| | | |
|---|---|---|
| 14:00 – 14:30 | Tim Langen | **Observing the supersolid state of matter using ultracold magnetic atoms** |
| 14:30 – 15:00 | Andrea Tononi | **Quantum statistical properties of shell-shaped Bose-Einstein condensates** |
| 15:00 – 15:30 | Zoe Yan | **Resonant dipolar collisions of ultracold molecules induced by microwave dressing** |
| 15:30 – 16:00 | *COFFEE BREAK* | |

# Program

## Wednesday, 16 December 2020

### Session 7: Miscellaneous (Chair: Sandro Stringari)

| | | |
|---|---|---|
| 16:00 – 16:45 | Doerte Blume | **Non-exponential tunneling due to mean-field induced swallowtails** |
| 16:45 – 17:30 | Tin-Lun Ho | **The detection of the intrinsic geometric structure of many-body wave functions** |
| 17:30 – 17:45 | Stefan Jorda | **About the Wilhelm and Else Heraeus Foundation** |
| 17:45 – 19:30 | **Wonder Room**<br>Individual discussions between speakers and participants, Socializing | |

## Thursday, 17 December 2020

### Session 8: Interferences (Chair: Paivi Törmä)

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|---|---|---|
| 09:00 – 09:45 | Alain Aspect | **Hanbury Brown and Twiss bunching of phonons and of the quantum depletion in an interacting Bose gas** |
| 09:45 – 10:30 | Andreas Buchleitner | **Witnessing many-particle interference** |
| 10:30 – 11:00 | *COFFEE BREAK* | |
| 11:00 – 11:45 | Ernst Rasel | **Coherent matter-wave optics on ground and in space** |

## Thursday, 17 December 2020

### Session 9: Quantum Droplets and Supersolids I (Chair: Alain Aspect)

| | | |
|---|---|---|
| 11:45 – 12:30 | Dmitry Petrov | **Mixed bubbles in Bose-Bose mixtures** |
| 12:30 – 14:00 | *LUNCH BREAK* | |
| 14:00 – 14:45 | Giovanni Modugno | **Symmetry breaking and superfluidity in a dipolar supersolid** |
| 14:45 – 15:30 | Sandro Stringari | **Goldstone modes in a harmonically trapped supersolid** |

### Session 9: Quantum Droplets and Supersolids II (Chair: Doerte Blume)

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|---|---|---|
| 15:30 – 16:00 | *COFFEE BREAK* | |
| 16:00 – 16:45 | Francesca Ferlaino | **Birth, life, and death of a dipolar supersolid** |
| 16:45 – 17:30 | Jun Ye | **A degenerate Fermi gas of interacting molecules** |
| 17:30 – 19:30 | **Wonder Room**<br>Individual discussions between speakers and participants, Socializing | |

# Program

## Friday, 18 December 2020

**Session 10: Dynamics II (Chair: Dmitry Petrov)**

| | | |
|---|---|---|
| 09:00 – 09:45 | Peter Schmelcher | **Nonequilibrium quantum dynamics in trapped ultracold bosonic and fermionic mixtures: From quenching across phase boundaries to pump probe spectroscopy** |
| 09:45 – 10:30 | Georg Bruun | **Observing the emergence of a quantum phase transition -- shell by shell** |
| 10:30 – 11:00 | *COFFEE BREAK* | |
| 11:00 – 11:45 | Thomas Gasenzer | **Effective field theories for universal dynamics** |
| 11:45 – 11:55 | Axel Pelster | **Concluding Remarks** |
| 11:55 – 12:30 | **Wonder Room**<br>Individual discussions between speakers and participants, Socializing | |

***End of seminar***

# Short Talks

# Short Talks

## Short Talks I (Monday , 14 Dec. 11:00 – 12:30 h)

| | | |
|---|---|---|
| 1 | Ragheed Alhyder | **An impurity immersed in a double Fermi Sea** |
| 2 | Maria Arazo | **Shell-shaped dipolar BECs** |
| 3 | Antun Balaž | **Faraday and Resonant Waves in Dipolar Cigar-Shaped Bose-Einstein Condensates** |
| 4 | Mikhail Barabanov | **Probing of multiquark structure hadron and heavy ion collisions** |
| 5 | Miguel Angel Bastarrachea Magnani | **Bose and Fermi polaron-polariton mediated interactions** |
| 6 | Luca Bayha | **Observation of Pauli Crystals** |
| 7 | Marvin Holten | **Observation of Pauli Crystals** |
| 8 | André Becker | **Thermometer for interacting harmonically trapped fermions** |
| 9 | Hauke Biss | **Observation of superfluidity in a strongly correlated two-dimensional Fermi gas** |
| 10 | Patrick Boegel | **Self-focusing of BEC in quasi 1D** |
| 11 | Martin Bonkhoff | **Bosonic continuum theory of one-dimensional lattice anyons** |

## Short Talks II (Monday , 14 Dec. 14:00 – 15:30 h)

| | | |
|---|---|---|
| 12 | Sandra Brandstetter | **Few Fermions in tunable potentials** |
| 13 | Mykyta Bulakhov | **Thermodynamics of a weakly interacting Bose gas above the transition temperature** |

# Short Talks

| | | |
|---|---|---|
| 14 | Viktor Cikojevic | **Towards a QMC-based density functional including finite-range effects: excitation modes of a 39 K quantum droplet** |
| 15 | Anna Dawid | **Phase Detection with Neural Networks: Interpreting the Black Box** |
| 16 | Giulia De Rosi | **Thermal evaporation and thermodynamics of one-dimensional liquids in weakly-interacting Bose-Bose mixtures** |
| 17 | Mohammed Tayeb Meftah + Mosbah Difallah | **Bose-Einstein Condensation in Fractional Quantum Statistical Mechanics** |
| 18 | Gabriel Dufour | **Many-body dynamics of partially distinguishable particles** |
| 19 | Hodei Eneriz | **Cavity QED with Bose-Einstein Condensates in a running wave resonator** |
| 20 | Andris Erglis | **Bose–Einstein Condensation in Planar Cavity** |
| 21 | Uwe Fischer | **Going beyond Hartree-Fock: Fully self-consistent determination of the many-body state of ultracold bosonic atoms and benchmarking with the exact two-boson solution** |
| 22 | Tobias Hammel | **A new apparatus for experiments with ultracold Lithium-6 atoms** |

### Short Talks III (Monday , 14 Dec. 16:00 – 17:00 h)

| | | |
|---|---|---|
| 23 | Mehedi Hasan | **Indirect Observation of Zitterbewegung in non-Abelian Gauge Field** |
| 24 | Jonas Benedikt Hauck | **Strong Boundary and Trap Potential Effects on Emergent Physics in Ultra-Cold Gases** |

# Short Talks

| | | |
|---|---|---|
| **25** | Felipe Isaule | **Functional renormalization for Bose-Bose mixtures** |
| **26** | Hans Keßler | **Observation of a dissipative time crystal** |
| **27** | Eugene Kogan | **To have (Kondo effect) and have not renormalization and scaling** |
| **28** | Smail Kouidri | **Finite temperature thermal cloud of dipolar gas in presence of the three-body interactions** |
| **29** | Arthur La Rooij | **Single-atom imaging of fermions in a quantum-gas microscope** |
| **30** | Rui Li | **Induced quantized transport by topology transfer between two coupled 1D lattice systems** |

## Short Talks IV (Tuesday, 15 Dec. 11:00 – 12:30 h)

| | | |
|---|---|---|
| **31** | Axel U. J. Lode | **Optimized Observable Readout from Single-shot Images of Ultracold Atoms via Machine Learning** |
| **32** | Aditi Mandal | **Plasmon modelling in core-level photoemission within multiple scattering approach** |
| **33** | Leonardo Mazza | **Strong correlations in lossy one-dimensional quantum gases: from the quantum Zeno effect to the generalized Gibbs ensemble** |
| **34** | Simeon Mistakidis | **Engineering the many-body quantum dynamics and induced correlations of Bose polarons** |
| ~~**35**~~ | ~~Ivan Morera Navarro~~<br>*Cancelled on short notice!* | ~~**Quantum liquids and pair formation in one-dimensional optical lattices**~~ |

# Short Talks

| | | |
|---|---|---|
| **36** | Ajay Nath | **Generation of solitary matter waves at hottest negative temperature** |
| **37** | Mama Kabir<br>Njoya Mforifoum | **Interference of two composite particles** |
| **38** | Alexey Okulov | **Detection of the reference frame motions with twisted superfluids** |
| **39** | Felix Palm | **Bosonic Pfaffian State in the Hofstadter-Bose-Hubbard Model** |
| **40** | Krzysztof Pawłowski | **Strongly correlated quantum droplets in quasi-1D dipolar Bose gas** |
| **41** | Philipp Preiss | **Many-Body Physics and Quantum Information in Rapidly Assembled Lattice Systems** |

## Short Talks V (Tuesday, 15 Dec. 14:00 – 15:30 h)

| | | |
|---|---|---|
| **42** | Zhiyuan Wei | **Generation of Photonic Matrix Product States with a Rydberg-blockaded atomic array** |
| **43** | Maximilian Prüfer | **The quantum effective action for ultracold gases far from equilibrium** |
| **44** | Milan Radonjic | **Bose-Einstein condensates in weak and strong disorder potentials** |
| **45** | Lukas Rammelmüller | **Investigation of pairing in 1D spin- and mass imbalanced Fermi gases through shot noise correlations** |
| **46** | Sayak Ray | **Prethermalization with negative specific heat** |
| **47** | Alejandro Saenz | **Inelastic confinement-induced resonances in different dimensions** |

# Short Talks

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|---|---|---|
| **48** | ~~Asaad Sakhel~~<br>*Cancelled on short notice* | ~~**Effect of trapping geometry on the parametric resonances in a disordered Bose-Einstein condensate driven by an oscillating potential**~~ |
| **49** | Poornima Shakya | **Snake states of neutral atom from synthetic gauge field** |
| **50** | Marija Šindik | **Quantum droplets in dipolar Bose-Einstein condensates in a ring potential** |
| **51** | Andrii Sotnikov | **Orbital ordering of ultracold alkaline-earth atoms in optical lattices** |
| **52** | Gabriele Spada | **The polarized Fermi-Hubbard superfluid at large order** |

## Short Talks VI (Tuesday, 15 Dec. 16:00 – 17:00 h)

| | | |
|---|---|---|
| **53** | Philipp Stammer | **State distinguishability under weak measurement and post-selection: A system and device perspective** |
| **54** | Enrico Stein | **Trapped Photon Gases at Dimensional Crossover from 2D to 1D** |
| **55** | Kuldeep Suthar | **Many-body localization with synthetic gauge fields in disordered Hubbard chains** |
| **56** | Michal Tomza | **Ultracold ion-atom collisions in the quantum regime** |
| **57** | Vranjes Markic | **QMC study of trapped Bose-Bose mixtures at finite temperature** |
| **58** | Etienne Wamba | **Exact N-point function mapping between pairs of experiments with Markovian open quantum systems** |

# Short Talks

| | | |
|---|---|---|
| **59** | Alexander Wolf | **Ground state and dynamics of shell-shaped BEC mixtures** |
| **60** | Hongzheng Zhao | **Quantum Many-Body Scars in Optical Lattices** |

# Abstracts of Lectures

(in alphabetical order)

# Observing non-ergodicity due to kinetic constraints in tilted Fermi-Hubbard chains

**M. Aidelsburger**

*Fakultät für Physik, Ludwig-Maximilians-Universität München &*
*Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany*

Thermalization of isolated quantum many-body systems is a fundamental problem that has important connections to quantum information theory. While generic models are expected to thermalize according to the eigenstate thermalization hypothesis (ETH), violation of ETH is believed to occur mainly in two types of systems: integrable models and many-body localized systems. In contrast, recent studies have predicted non-ergodic dynamics in disorder-free lattice models, due to a shattering of the Hilbert space into many dynamically disconnected subspaces [1-3]. An experimentally readily accessible model that is expected to exhibit phenomena at the interface of many-body localization [4,5] and Hilbert-space fragmentation is the 1D Fermi-Hubbard model in the presence of a strong linear potential ("tilt").

In this talk, I report on an experimental study of the dynamics of interacting fermions in an optical lattice in the intermediate to low-tilt regime [6]. Starting from a charge-density wave initial state (quarter filling), we investigate potential non-ergodic behavior by tracking the time evolution of the occupation imbalance between even and odd lattice sites. At short times we observe parity-projected real-space Bloch oscillations, which, depending on the strength of the tilt, exhibit interaction-induced damping and additional frequency components. At long times our results reveal a robust steady-state imbalance up to about 700 tunneling times, whose value depends on the interaction strength, however, no clear transition into an ergodic regime has been found. We compare our experimental results to numerical calculations and find excellent agreement throughout.

While in the strong-tilt regime we expect shattering of the Hilbert space to inhibit thermalization due to dipole conservation in certain regimes, this is not expected to hold in the parameter regime studied here. We interpret the robustness of our observations due to the emergence of kinetic constraints, which lead to a significantly slowing down of the dynamics.

[1] S. Moudgalya *et al.*, arXiv:1910.14048 (2019)
[2] P. Sala *et al.*, Phys. Rev. X **10**, 011047 (2020)
[3] V. Khemani and R. Nandkishore, Phys. Rev. B **101**, 174204 (2020)
[4] M. Schulz et al. Phys. Rev. Lett. 122, 040606 (2019)
[5] E. van Nieuwenburg *et al.*, PNAS 116, 9269-9274 (2019)
[6] S. Scherg *et al.*, arXiv: 2010.12965 (2020)

# Hanbury Brown and Twiss bunching of phonons and of the quantum depletion in an interacting Bose gas

Alain Aspect

Université Paris-Saclay, Institut d'Optique Graduate School, CNRS,
Laboratoire Charles Fabry, 91127 Palaiseau, France

We report the realization of a Hanbury Brown and Twiss (HBT)-like experiment with a gas of interacting bosons at low temperatures [1]. The low-temperature regime is reached in a three-dimensional optical lattice and atom-atom correlations are extracted from the detection of individual metastable helium atoms after a long free fall. We observe, in the noncondensed fraction of the gas, a HBT bunching whose properties strongly deviate from the HBT signals expected for noninteracting bosons. In addition, we show that the measured correlations reflect the peculiar quantum statistics of atoms belonging to the quantum depletion and of the Bogoliubov phonons, i.e., of collective excitations of the many-body quantum state. Our results demonstrate that atom-atom correlations provide information about the quantum state of interacting particles, extending the interest of HBT-like experiments beyond the case of noninteracting particles.

## References

[1] H. Cayla, S. Butera, C. Carcy, A. Tenart, G. Hercé, M. Mancini, A. Aspect, I. Carusotto, and D. Clément, Phys. Rev. Lett. **125**, 165301 (2020)

# Exploring non-equilibrium dynamics in novel Fermi gas systems

**E. Guardado-Sanchez[1], B. Spar[1], P. Schauss[1], A. Morningstar[1], P. Brown[1], R. Belyansky[2], J. Young[2], P. Bienias[2], A. Gorshkov[2], T. Iadecola[3], D. Huse[1] and W. Bakr[1]**

*[1]Princeton University, Princeton, NJ, USA*
*[2] University of Maryland/NIST, College Park, MD, USA*
*[3] Iowa State University, Ames, IA, USA*

In recent years, the thermalization of quantum systems has been the subject of intense study. Particularly interesting are systems which exhibit slow or completely arrested thermalization, with many-body localized systems being a prime example of the latter. Recent theoretical work has identified Hilbert space fragmentation in clean, kinetically constrained systems as another mechanism for the breakdown of ergodicity in many-body quantum systems [1][2]. Motivated by engineering such systems with ultracold atoms, I will discuss two recent experiments we have performed. In the first, we studied tilted Fermi-Hubbard systems and discovered a slow thermalization mechanism due to an interplay of charge and heat transport [3]. Modified versions of this system may be used to explore prethermal Hamiltonians with a fragmented Hilbert space in two dimensions. In the second experiment, we studied the short-time quench dynamics of charge-density wave states in a spinless fermionic lattice gas with off-site interactions realized with Rydberg-dressing [4]. We again observed a slowdown of the dynamics for strong, off-site interactions. We discuss connections of this experiment to theoretical work on fragmentation in t-V models.

## References

[1] P. Sala, T. Rakovszky, R. Verresen, M. Knap & F. Pollmann, Phys. Rev. X **10**, 011047 (2020)
[2] V. Khemani, M. Hermele & R. Nandkishore, Phys. Rev. B **101**, 174204 (2020)
[3] E. Guardado-Sanchez, A. Morningstar, B. Spar, P. Brown, D. Huse, & W. Bakr, Phys. Rev. X **10**, 011042 (2020)
[4] E. Guardado-Sanchez, B. Spar, P. Schauss, R. Belyansky, J. Young, P. Bienias, A. Gorshkov, T. Iadecola & W. Bakr, arxiv:2010.05871 (2020)

# Non-Exponential Tunneling due to Mean-Field Induced Swallowtails

**Q. Guan,[1,2] M. K. H. Ome,[3] T. M. Bersano,[3] S. Mossman,[3]**
**P. Engels,[3] and D. Blume[1,2]**

*[1]Homer L. Dodge Department of Physics and Astronomy, The University of Oklahoma, 440 W. Brooks Street, Norman, Oklahoma 73019, USA*
*[2]Center for Quantum Research and Technology, The University of Oklahoma, 440 W. Brooks Street, Norman, Oklahoma 73019, USA*
*[3] Department of Physics and Astronomy, Washington State University, Pullman, Washington 99164-2814, USA*

Typically, energy levels change without bifurcating in response to a change of a control parameter. Bifurcations can lead to loops or swallowtails in the energy spectrum. The simplest quantum Hamiltonian that supports swallowtails is a non-linear 2×2 Hamiltonian with non-zero off-diagonal elements and diagonal elements that depend on the population difference of the two states. This work implements such a Hamiltonian experimentally using ultracold atoms in a moving one-dimensional optical lattice. Self-trapping and non-exponential tunneling probabilities, a hallmark signature of band structures that support swallowtails, are observed. The good agreement between theory and experiment validates the optical lattice system as a powerful platform to study, e.g., Josephson junction physics and superfluidity in ring-shaped geometries.

# Observing the emergence of a quantum phase transition -- shell by shell

**Luca Bayha[1], Marvin Holten[1], Ralf Klemt[1] Keerthan Subramanian[1] , Johannes Bjerlin[2], Stephanie M. Reimann[2], Philipp M. Preiss[1], Selim Jochim[1]**

**and Georg M. Bruun[3]**

*[1] Physikalisches Institut der Universität Heidelberg, 69120 Heidelberg, Germany*
*[2] Mathematical Physics and NanoLund, Lund University, SE-22100 Lund, Sweden*
*[3] Department of Physics and Astronomy, University of Aarhus, Denmark*

Many-body physics describes phenomena which cannot be understood looking at a systems' constituents alone. Striking manifestations are broken symmetry, phase transitions, and collective excitations. Understanding how such collective behaviour emerges when assembling a system from individual particles has been a vision in atomic, nuclear, and solid-state physics for decades. In this talk, I will describe results from a recent collaboration with the experimental group of S. Jochim (Heidelberg), where we observe a few-body precursor of a quantum phase transition from a normal to a superfluid phase. The transition is signalled by the softening of a mode consisting of coherently excited pairs only. Combined with the non-monotonic interaction dependence of its energy, this allows us to identify it as the few-body precursor of the Higgs mode associated with the quantum phase transition in the thermodynamic limit.

## References

[1] G. M. Bruun Phys. Rev. A **90**, 023621 (2014)
[2] J. Bjerlin, S. M. Reimann, G. M. Bruun, Phys. Rev. Lett. **116**, 155302 (2016)
[3] Luca Bayha *et al.*, arXiv:2004.14761 (To appear in Nature)

# Witnessing many-particle interference

**Andreas Buchleitner**

Physikalisches Institut and EUCOR Centre for Quantum Science and Quantum Computing, Albert-Ludwigs-Universität Freiburg, Hermann-Herder-Str. 3,
D-79104 Freiburg

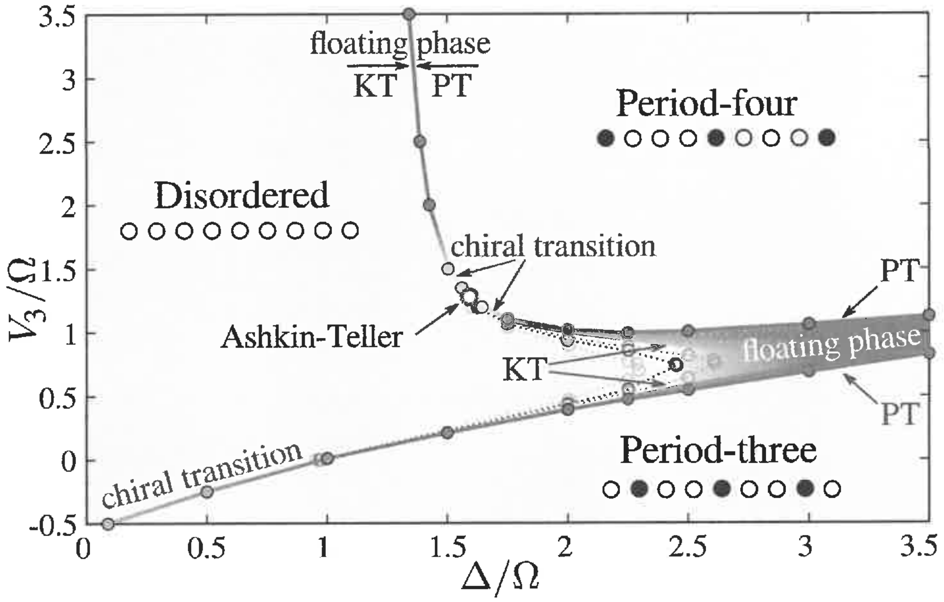
State of the art experiments on controlled ensembles of identical particles exhibit a rapidly increasing complexity as the number of constituents is increased. Distinct sources of this complexity are many-particle interferences and interactions, i.e., indistinguishability and dynamical instability, which, however, are rarely discriminated against each other. This appears surprising, e.g., in the debate on many-particle analogues of (single particle) Anderson localization, since the latter is a pure (single particle) interference effect. We'll discuss the certification of *many-particle interference* in non-interacting as well as in interacting many-particle dynamics (mostly in a Bose-Hubbard like setting), and will briefly touch upon related issues in spectral and open system theory.

# Kibble-Zurek exponent and chiral transition of the period-4 phase of Rydberg chains

**N. Chepiga**[1] **and F. Mila**[2]

[1]*Institute for Theoretical Physics, University of Amsterdam, The Netherlands*
[2]*EPFL, Lausanne, Switzerland*

Chains of Rydberg atoms have emerged as an amazing playground to study quantum physics in 1D. Playing with inter-atomic distances and laser detuning, one can in particular explore the commensurate-incommensurate transition out of density waves through the Kibble-Zurek mechanism, and the possible presence of a chiral transition with dynamical exponent $z > 1$. Here we address this problem theoretically with effective blockade models where the short-distance repulsions are replaced by a constraint of no double occupancy. For the period-4 phase, we show there is an Ashkin-Teller transition point with exponent $\nu=0.78$ surrounded by a direct chiral transition with a dynamical exponent $z=1.14$ and a Kibble-Zurek exponent $\mu=0.4$. For Rydberg atoms with a van der Waals potential, we suggest that the experimental value $\mu=0.25$ is due to a chiral transition with $z\sim1.9$ and $\nu\sim0.47$ surrounding an Ashkin-Teller transition close to the 4-state Potts universality.



## References

[1] N.Chepiga, F.Mila, arXiv:2001.06698 (2020)

# Fresh News from Flatland: Testing Scale Invariance in the Lab

**Jean Dalibard**

*Laboratoire Kastler Brossel, Collège de France, Paris, France*

A fluid is said to be scale-invariant when its interaction and kinetic energies have the same scaling in a dilatation operation. This symmetry, in association with the more general conformal invariance, has profound consequences on the equilibrium properties of the fluid as well as its dynamics.

In this talk, I will present recent experimental investigations of scale invariance using a 2D gas of rubidium atoms, whose dynamics is well described by the Gross-Pitaveskii equation. I will show some expected results for this system, such as the observation of Townes solitons, as well as unexpected ones such as the existence of breathers, i.e. specific initial shapes that undergo a periodic evolution when placed in a harmonic potential. I will conclude with a possible generalization of such phenomena to other scale invariant fluids.

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# Birth, life, and death of a dipolar supersolid

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Over the last years, dipolar quantum gases have become a highly enabling quantum platform as scientists have acquired increasingly fine control over the different sources of inter-particle interactions.

This talk reports on the recent observations of the elusive and paradoxical supersolid state of matter from the Innsbruck perspective. Such paradoxical phase, in which crystal rigidity and superfluid flow coexist, has intrigued scientists across different disciplines for decades.

Using either erbium and dysprosium ultracold gases, we have been able to create supersolidity in the ultracold thanks to the unique interplay between long-range dipolar interactions, contact interactions, and a powerful stabilization mechanism based on quantum fluctuations.

# Effective field theories for universal dynamics

**P. Heinen,$^{1,3}$ A.N. Mikheev,$^{1,3}$ C.-M. Schmied,$^{1,3}$ P. Wittmer,$^{2,3}$**
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Quenched or continuously driven quantum systems can show universal dynamics near non-thermal fixed points, generically in the form of scaling behaviour in space and time [1-3]. Systems where such fixed points can be realized range from post-inflationary evolution of the early universe to low-energy dynamics in cold gases. Effective field theories hold promise to describe the non-perturbative infrared dynamics by allowing to identify the relevant degrees of freedom [1,4,5]. The status of different examples and their relevance to near-linear quasiparticle dynamics as well as to the strongly non-linear dynamics of solitary waves and topological defects will be discussed [4-6].

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Title:

# Fractional Quantum Hall Physics with Cold Atoms – from state preparation to anyon detection

Authors: Tobias Graß[1], Bárbara Andrade[2], Valentin Kasper[1], Bruno Juliá-Díaz, Niccolò Baldelli[1], Utso Bhattacharya[1], Christof Weitenberg[3], Maciej Lewenstein[1]

Abstract:

Atomic quantum simulators are promising systems to explore the physics of topological quantum matter. For instance, cold atoms in a rotating trap form ground states described by the Laughlin wave function. One striking feature of such system are its particle-like excitations which behave neither like fermions nor like bosons, so-called anyons. Here, we first discuss an adiabatic scheme to prepare a Laughlin state of atoms, and then we show how anyonic excitations can be generated and traced via impurity particles. It is shown that the anyon statistics is reflected by the angular momentum of the impurities.

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# The Detection of the Intrinsic Geometric Structure of Many-Body Wavefunctions

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The Detection of the Intrinsic Geometric Structure of Many-Body Wavefunctions

Abstract: We shall present an algorithm to uncover the intrinsic geometric structure of the many-body wavefunctions of quantum gas clusters from their images. Our algorithm is motivated by the recent experiments on “Pauli crystals”. However, it is a scheme that solely based on the experimental images without any theoretical input. From these geometric structures, one can also identify the phase transitions and the spin structures of the clusters.

# Competing magnetic orders in a bilayer Hubbard model with ultracold atoms

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Fermionic atoms in optical lattices have served as a compelling model system to study and emulate the physics of strongly-correlated matter. Driven by the advances of high-resolution microscopy, the recent focus of research has been on two-dimensional systems in which several quantum phases, such as anti-ferromagnetic Mott insulators for repulsive interactions and charge-density waves for attractive interactions have been observed. However, the aspired emulations of real materials, such as bilayer graphene, have to take into account that their lattice structure composes of coupled layers and therefore is not strictly two-dimensional. In this work, we realize a bilayer Fermi-Hubbard model using ultracold atoms in an optical lattice and demonstrate that the interlayer coupling controls a crossover between a planar anti-ferromagnetically ordered Mott insulator and a band insulator of spin-singlets along the bonds between the layers. Our work will enable the exploration of further fascinating properties of coupled-layer Hubbard models, such as theoretically predicted superconducting pairing mechanisms.

# Cavity quantum-electrodynamics with atoms and pairs in a strongly interacting Fermi gas

**H. Konishi**[1], K. Roux[1], V. Helson[1] and J.P. Brantut[1]

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The last decade has seen a convergence of concepts and methods between many-body physics, in particular condensed matter, and quantum optics, exemplified by the use of quantum gases as simulators for many-body phenomena. The use of quantized light fields with ultracold atoms permitted in the settings of cavity QED, however, has been restricted to thermal or bosonic atoms, without the ability to control independently the atom-atom and light-matter interactions.

I will present the experimental realization of a quantum-degenerate, strongly interacting Fermi gas coupled to a high-finesse cavity. The optical spectrum of the coupled system will be presented and compared with theory, confirming that the strong light-atom coupling regime is reached simultaneously with unitary atom-atom interactions, when light is resonant with the optical transitions for either spin component of the gas [1].

I will also present a study of resonant photon-pair interactions in the Fermi gas, using photo-association to ultra-long-range molecules. The cavity transmission spectrum close to these transitions exhibits the anti-crossing characteristic of strong light-matter coupling, signaling the onset of coherent 'pair-polaritons'. I will describe the dependence of the optical spectrum on interaction strength, and connect the optical spectrum of the cavity with Tan's contact, a universal property of the many-body physics of the Fermi gas. This provides a new connection between quantum optics and strongly correlated matter.

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# Observing the supersolid state of matter using ultracold magnetic atoms

**M. Guo, F. Böttcher, J. Hertkorn, J.-N. Schmidt, K. Ng, M. Schmidt, S. Graham, H. P. Büchler, T. Langen and T. Pfau**

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We study theoretically and experimentally the emergence of supersolid properties in a dipolar Bose-Einstein condensate. The theory reveals a ground state phase diagram with three distinct regimes - a regular Bose-Einstein condensate and incoherent and coherent crystals of quantum droplets. The coherent droplet crystals are connected by a background condensate, which leads - in addition to the periodic density modulation - to a robust phase coherence throughout the whole system [1,2]. We further theoretically demonstrate that we are able to dynamically approach the ground state in our experiment and that its lifetime is limited only by three-body losses. Experimentally we probe and confirm the signatures of the phase diagram by observing the *in-situ* density modulation as well as the phase coherence using matter wave interference in situ [2]. We further prove the supersolid nature of the coherent droplet arrays by directly observing their low-energy Goldstone mode [3]. The dynamics of this mode is reminiscent of the effect of second sound in other superfluid systems and features an out-of-phase oscillation of the crystal and superfluid densities. This mode exists only due to the phase rigidity of the experimentally realized state, and therefore confirms the genuine superfluidity of the supersolid. Finally, we report on the first direct *in-situ* measurement of density fluctuations across the superfluid-supersolid phase transition [4]. This allows us to introduce a general and straightforward way to extract the static structure factor, estimate the spectrum of elementary excitations and directly image the dominant fluctuation patterns, including the roton modes.

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# Symmetry breaking and superfluidity in a dipolar supersolid

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The supersolid is a fundamental quantum phase of matter that is predicted to combine the properties of solids with those of superfluids. It was theorized about 50 year ago, and since then it has been studied theoretically and searched experimentally in various physical systems, until very recently without success. I will discuss how a Bose-Einstein condensate of strongly magnetic atoms realizes the supersolid, exploiting a combination of attractive and repulsive long-range interactions to create a spontaneous, periodic density modulation without loss of coherence [1]. With experiments based on the study of the collective oscillations, it is possible to study its counterintuitive mixed properties. For example, compressional oscillations allow testing the simultaneous breaking of gauge and translational symmetries, which prove the coexistence of fluid and solid natures [2]. Rotational oscillations allow instead revealing a reduced moment of inertia for the supersolid, which is a direct evidence of superfluidity [3]. In the future, the high degree of control of the magnetic condensates may allow to investigate in depth the properties of the supersolid phase of matter.

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# Quantum Fractals

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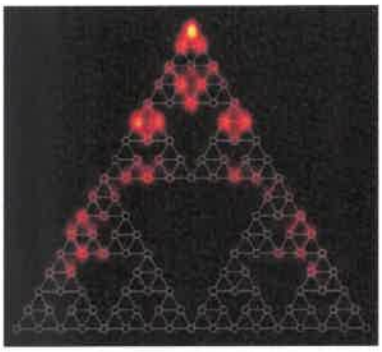
The human fascination for fractals dates back several centuries, when structures known nowadays as a Sierpinski gasket were used in decorative art in churches. Nonetheless, it was only in the last century that mathematicians faced the difficult task of classifying these structures. In the 80's, the focus was on understanding how a particle diffuses in a fractal structure. However, those were **classical fractals.** This century, the task is to understand **quantum fractals**. Last year, we experimentally realized a Sierpinski gasket using a scanning tunneling microscope to pattern adsorbates on top of Cu(111) and showed that the wavefunction describing electrons in a Sierpinski gasket fractal has the Hausdorff dimension d=1.58 [1,2]. However, STM techniques can only describe **equilibrium** properties.



Now, we went a step beyond and using state-of-the-art photonics experiments, we unveiled their **quantum dynamics**. By injecting photons in waveguide arrays arranged in a fractal shape, we were able to follow their motion and understand their quantum dynamics with unprecedented detail. We built and investigated three types of fractals to reveal not only the influence of different Hausdorff dimension, but also of geometry [3].

Finally, I will tell you about the dynamics of systems governed by a fractional Langevin equation. It turns out that this kind of approach may describe the Gardner phase in glasses, which is a phase exhibiting a fractal structure in the free energy landscape. We find an anomalous diffusion and reveal the existence of a novel regime, characterizing a Time Glass [4].

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# Mixed bubbles in Bose-Bose mixtures

**P. Naidon[1] and D. S. Petrov[2]**

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Repulsive Bose-Bose mixtures are known to either mix or phase-separate into pure components. Here [1] we predict a mixed-bubble regime in which bubbles of the mixed phase coexist with a pure phase of one of the components. This is a beyond-mean-field effect which occurs for unequal masses or unequal intraspecies coupling constants and is due to a competition between the mean-field term, quadratic in densities, and a nonquadratic beyond-mean-field correction. We find parameters of the mixed-bubble regime in all dimensions and discuss implications for current experiments.

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# Coherent matter-wave optics on ground and in space

Ernst M. Rasel for the QUANTUS and MAIUS cooperation

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In 2017, the MAIUS-1 sounding-rocket flight established coherent matter wave optics and quantum gas experiments in the space. Since its launch, the Cold Atom Laboratory (CAL) offers such experiments nearly routinely to its users in orbit on the International Space Station (ISS). In parallel ground development continues in the drop tower in Bremen for preparation of the next sounding flights as well as for BECCAL, succeeding CAL at the ISS. Moreover, new microgravity facilities such as the Einstein Elevator in Hannover started operation. The talk will give a brief overview of the latest status of our activities on developing coherent matter-wave optics for space-borne quantum-gas experiments and precision interferometry.

# Quantum Spin Dynamics with Optically Programmable Interactions

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The dream of the quantum engineer is to have an "arbitrary waveform generator" for designing quantum states and Hamiltonians. Motivated by this vision, I will report on advances in optical control of long-range interactions among cold atoms. By coupling atoms to light in an optical resonator, we generate tunable non-local Heisenberg interactions, characterizing the resulting phases and dynamics by real-space imaging. Notable observations include interaction-induced protection of spin coherence [1] and photon-mediated spin-mixing [2]—a mechanism for generating correlated atom pairs. I will present recent results on optically programming the distance-dependence of the spin-spin couplings and the resulting correlations in an array of atomic ensembles. I will also touch on a complementary approach of Rydberg dressing for optical control of local interactions [3], and discuss prospects in quantum simulation [4], quantum optimization [5], and quantum metrology.

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# Nonequilibrium quantum dynamics in trapped ultracold bosonic and fermionic mixtures: From quenching across phase boundaries to pump probe spectroscopy

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Our focus is the correlated non-equilibrium quantum dynamics for a binary mixture of ultracold trapped atoms. Three different scenarios will be addressed. First [1] we explore the quench dynamics of a binary Bose–Einstein condensate crossing the miscibility–immiscibility threshold. Increasing the interspecies repulsion leads to the filamentation of the density of each species, involving shorter wavenumbers and longer spatial scales in the many-body approach compared to mean-field theory. These filaments appear to be strongly correlated and exhibit domain-wall structures. We simulate single-shot images to connect our findings to possible experimental realizations. In the second part [2] of the presentation we monitor the correlated quench induced dynamical dressing of a spinor impurity repulsively interacting with a Bose-Einstein condensate. Inspecting the evolution of the structure factor, three distinct dynamical regions arise upon increasing the interspecies interaction. These regions are found to be related to the segregated nature of the impurity and to the Ohmic character of the bath. In particular, for miscible components polaron formation is imprinted on the spectral response of the system. We further illustrate that for increasing interaction an orthogonality catastrophe occurs and the polaron picture breaks down. Next [3] we propose and investigate a pump-probe spectroscopy scheme to unveil the time-resolved dynamics of fermionicor bosonic impurities immersed in a harmonically trapped Bose-Einstein condensate. In this scheme a pump pulse initially transfers the impurities from a noninteracting to a resonantly interacting spin state and, after a finite time in which the system evolves freely, the probe pulse reverses this transition. This directly allows us to monitor the nonequilibrium dynamics of the impurities as the dynamical formation of coherent attractive or repulsive Bose polarons and signatures of their induced interactions are imprinted in the probe spectra. The short and long time behaviour will be discussed including enhanced energy redistribution processes and the formation of a steady state characterized by substantial losses of coherence of the impurities.

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# Goldstone modes in a harmonically trapped supersolid

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*The spontaneous and simultaneous breaking of gauge and translational symmetry, typical of a supersolid, is at the origin of a novel class of gapless excitations. I will present recent theoretical implications holding in harmonically trapped Bose-Einstein condensed gases. The case of both dipolar [1] and spin-orbit [2] configurations will be discussed.*

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# Quantum statistical properties of shell-shaped Bose-Einstein condensates

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The recent development of NASA's Cold Atom Laboratory, a space-based facility for ultracold atoms experiments, allows the routine production of Bose-Einstein condensates in microgravity [1]. The ongoing investigations are focusing on shell-like geometries [2], in which the atoms are confined on a thin ellipsoidal surface with radio frequency-induced adiabatic potentials [3]. We analyze [4,5] the quantum statistical properties of spherical and ellipsoidal shells, focusing on the phenomena of Bose-Einstein condensation and superfluidity. Our results constitute a reliable benchmark for the current experimental investigations.

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# Interactions and flat bands: superconductivity in moire superlattices and non-Fermi liquid normal states

**A. Julku[1], K.-E. Huhtinen[1], P. Kumar[1], S. Peotta[1], L. Liang[1], T.J. Peltonen[2], T.T. Heikkilä[2], Y. Takasu[3], Y. Takahashi[3], and P. Törmä[2]**

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Flat bands enhance interaction and correlation effects due to their vanishing kinetic energy and high density of states. In particular, exponentially enhanced critical temperatures of superconductivity have been predicted for small interactions. We have shown that supercurrents and superfluidity is guaranteed in this promising scenario by the quantum geometry of the band [1]. The quantum geometric contribution of superconductivity has now become relevant in the context of recently observed superconductivity in twisted bilayer graphene, as shown by us and other groups [2]. Ultracold gases offer exciting opportunities for fundamental studies of flat band interaction effects, since versatile flat band geometries can be experimentally created and the interaction precisely controlled. We have shown by dynamical mean-field studies that the interacting normal state of a Lieb lattice hosts two different non-Fermi liquid phases: a pseudogap, and a new type of insulator [3]. Moreover, we show that non-Fermi liquid features manifest in experimentally accessible observables such as double occupancy and entropy [4]. Both of these predictions concern properties present at temperatures of present-day setups.

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# Unsupervised machine learning of topological phase transitions from cold-atom data

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Identifying phase transitions is one of the key challenges in quantum many-body physics. Recently, machine learning methods have been introduced as an alternative way of localizing phase boundaries also from noisy and imperfect data and as a tool to gain new insight into complex many body phases. In this talk, I will present our efforts to identify topological phases from momentum-space images of cold-atom Floquet systems and discuss various methods of unsupervised machine learning including clustering, anomaly detection and influence functions. We employ machine learning to post process the data to a constant micromotion phase and subsequently identify the full topological phase diagram providing a benchmark for unsupervised detection of phases.

# Quantum gases in controlled perturbation – from single impurities to time-dependent disorder

**D. Adam[1], S. Barbosa[1], Q. Bouton[2], S. Burgardt[1], S. Hiebel[1], J. Koch[1], B. Nagler[1], and A. Widera[1]**

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Perturbations can strongly modify the properties of a quantum system and give rise to exciting quantum states. I will discuss recent experimental progress to understand the properties of quantum gases with controlled perturbations in two complementary scenarios.

First, I will present recent results, expanding our approach to interface single neutral impurities with an ultracold gas [1]. I will show how dephasing dynamics of the impurity's internal state coherence in a Ramsey-type sequence close to a Feshbach resonance allow extracting information on the surrounding bath's temperature or density. Moreover, comparing dephasing dynamics in a thermal gas and a Bose-Einstein condensate, we find an increased coherence time in the condensate. We attribute this observation to the zero-temperature response of the BEC when interacting with the impurity.

Second, I will discuss our experiments investigating an ultracold Fermi gas along the BEC-BCS crossover in time-dependent disorder. We use disorder quenches to study the relaxation dynamics of an interacting quantum gas and unravel the contributions of density and phase [2]. Moreover, we study the dissipative dynamics of an interacting gas in disorder with tunable correlation time to probe excitations and dynamics [3].

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# Resonant Dipolar Collisions of Ultracold Molecules Induced by Microwave Dressing

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We demonstrate microwave dressing on ultracold, fermionic $^{23}$Na$^{40}$K ground-state molecules and observe resonant dipolar collisions with cross sections exceeding three times the s-wave unitarity limit. The origin of these interactions is the resonant alignment of the approaching molecules' dipoles along the intermolecular axis, which leads to strong attraction. We explain our observations with a conceptually simple two-state picture based on the Condon approximation. Furthermore, we perform coupled-channel calculations that agree well with the experimentally observed collision rates. The resonant microwave-induced collisions found here enable controlled, strong interactions between molecules, of immediate use for experiments in optical lattices.

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# A degenerate Fermi gas of interacting molecules

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The preparation of a degenerate Fermi gas of polar molecules sets the stage to explore novel many-body physics [1]. We apply precisely controlled electric fields to turn on elastic dipolar interactions by orders of magnitude while suppressing reactive losses. Efficient dipolar evaporation leads to the onset of quantum degeneracy in an array of two-dimensional optical traps [2]. When the electric field is used to tune excited molecular states into degeneracy with the scattering threshold, we observe sharp collision resonances that give rise to three orders-of-magnitude modulation of the chemical reaction rate [3]. Using this resonant shielding, we realize a long lifetime of polar molecular gas at very high electric fields.

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# Flat-band Ferromagnetism of SU(N) Hubbard Model on Tasaki Lattices

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We investigate the para-ferro magnetic transition of the repulsive SU(N) Hubbard model on a type of one- and two-dimensional decorated cubic lattices, referred as Tasaki lattices, which feature massive single-particle ground state degeneracy. Under certain restrictions for constructing localized many-particle ground states of flat-band ferromagnetism, the quantum model of strongly correlated electrons is mapped to a classical statistical geometric site-percolation problem, where the nontrivial weights of different configurations must be considered. We prove rigorously the existence of para-ferro transition for the SU(N) Hubbard model on one-dimensional Tasaki lattice and determine the critical density by the transfer-matrix method. In two dimensions, we numerically investigate the phase transition of SU(3), SU(4) and SU(10) Hubbard models by Metropolis Monte Carlo simulation. We find that the critical density exceeds that of standard percolation, and increases with spin degrees of freedom, implying that the effective repulsive interaction becomes stronger for larger N. We further rigorously prove the existence of flat-band ferromagnetism of the SU(N) Hubbard model when the number of particles equals to the degeneracy of the lowest band in the single-particle energy spectrum.

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# Abstracts of Short Talks

(in alphabetical order)

# An impurity immersed in a double Fermi Sea

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We present a variational calculation of the energy of an impurity immersed in a double Fermi sea of noninteracting fermions. We show that in the strong-coupling regime, the system undergoes a first-order transition between polaronic and trimer states. Our result suggests that the smooth crossover predicted in previous literature for a superfluid background is the consequence of Cooper pairing and is absent in a normal system.

# Shell-shaped dipolar BECs

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We study the effect of gravity on shell-shaped Bose-Einstein condensates of dipolar atoms. While contact interaction is short-range and isotropic, dipolar interaction presents an anisotropic and long-range character [1]. As a result, the system becomes sensitive to orientation. Our aim is to investigate this nature of dipole-dipole interactions in shell-shaped condensates under gravity.

Shell-like potentials, as well as other geometries beyond the harmonic confinement, have been considered experimentally [2] and theoretically [3,4,5] in the last years for trapping ultracold atoms. However, spherical shell-shaped condensates with dipolar interactions have been only examined in the thin shell limit [6] and under rotation [7].

Due to Earth's gravity, the atoms sag to the bottom of the trap. The proposal of an experimental framework for realising a shell-shaped condensate at NASA's Cold Atom Laboratory [8] has brought to interest the behaviour of such condensates under microgravity conditions [9,10,11]. We show that the addition of the gravitational sag to the anisotropic nature of the dipole-dipole interaction gives rise to new phenomenology, and we aim to present shell-shaped dipolar condensates as a viable candidate for sensing small changes either in the strength and orientation of gravity.

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# Faraday and Resonant Waves in Dipolar Cigar-Shaped Bose-Einstein Condensates

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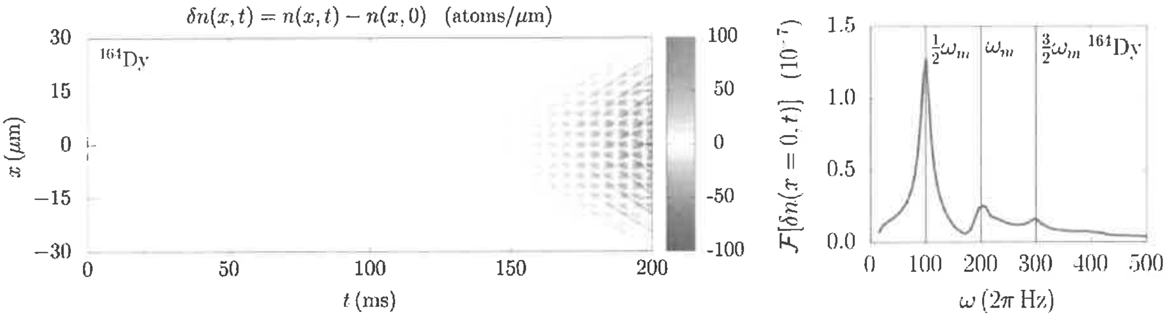
Faraday and resonant density waves emerge in Bose-Einstein condensates as a result of harmonic driving of the system [1-3]. They represent nonlinear excitations and are generated due to the interaction-induced coupling of collective oscillation modes and the existence of parametric resonances. Using a mean-field variational and a full numerical approach, we study density waves in dipolar condensates at zero temperature [1], where breaking of the symmetry due to anisotropy of the dipole-dipole interaction (DDI) plays an important role. We derive variational equations of motion for the dynamics of a driven dipolar system and identify the most unstable modes that correspond to the Faraday and resonant waves. Based on this, we also derive the analytical expressions for spatial periods of both types of density waves as functions of the contact and the DDI strength. Finally, we compare the obtained variational results with the results of extensive numerical simulations that solve the dipolar Gross-Pitaevskii equation in 3D.



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# Probing of multiquark structure hadron and heavy ion collisions

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The spectroscopy of charmonium-like mesons with masses above the $2m_D$ open charm threshold has been full of surprises and remains poorly understood [1]. The currently most compelling theoretical descriptions of the mysterious *XYZ* mesons attribute them to hybrid structure with a tightly bound $c\bar{c}$ diquark [2] or $cq\bar{c}\bar{q}'$ tetraquark core [3 - 5] that strongly couples to S-wave $D^{(*)}\overline{D}^{(*)}$ molecular like structures. In this picture, the production of a *XYZ* states in high energy hadron collisions and its decays into light hadron plus charmonum final states proceed via the core component of the meson, while decays to pairs of open-charmed mesons proceed via the $D^{(*)}\overline{D}^{(*)}$ component. These ideas have been applied with some success to the *XYZ* states [2], where a detailed calculation finds a $c\bar{c}$ core component that is only above 5% of the time with the $D\overline{D}^{(*)}$ component (mostly $D^{(0)}\overline{D}^{(*0)}$) accounting for the rest. In this picture these states are compose of three rather disparate components: a small charmonium-like $c\bar{c}$ core with $r_{rms} < 1$ fm, a larger $D^{(+)}D^{(*-)}$ component with $r_{rms} = \hbar/(2\mu_+B_+)^{1/2} \approx 1.5$ fm and a dominant component $D^{(0)}\overline{D}^{(*0)}$ with a huge, $r_{rms} = \hbar/(2\mu_0 B_0)^{1/2} > 9$ fm spatial extent. Here $\mu_+(\mu_0)$ and $B_+(B_0)$ denote the reduced mass for the $D^{(+)}D^{(*-)}$ $(D^{(0)}\overline{D}^{(*0)})$ system and the relevant binding energy $|m_D + m_{D^*} - M_{X(3872)}|$ ($B_+ = 8.2$ MeV, $B_0 < 0.3$ *MeV*). The different amplitudes and spatial distributions of the $D^{(+)}D^{(*-)}$ and $D^{(0)}\overline{D}^{(*0)}$ components ensure that the *X(3872)* is not an isospin eigenstate. Instead it is mostly $I = 0$, but has a significant (~ 25 %) $I = 1$ component. In the hybrid scheme, *XYZ* mesons are produced in high energy proton-nuclei collisions via its compact ($r_{rms} < 1$ fm) charmonium-like structure and this rapidity mixes in a time ($t \sim \hbar/\delta M$) into a huge and fragile, mostly $D^{(0)}\overline{D}^{(*0)}$, molecular-like structure. $\delta M$ is the difference between the *XYZ* mass and that of the nearest $c\bar{c}$ mass pole core state, which we take to be that of the $\chi_{c1}(2P)$ pure charmonium state which is expected to lie about 20 ~ 30 MeV above $M_{X(3872)}$ [6]. In this case, the mixing time, $c\tau_{mix}$ 5 ~ 10 fm, is much shorter than the lifetime of *X(3872)* which is $c\tau_{X(3872)} > 150$ fm. The experiments with proton-proton and proton-nuclei collisions with $\sqrt{S_{pN}}$ up to 26 Gev and luminosity up to $10^{32}$ cm$^{-2}$s$^{-1}$ planned at NICA may be well suited to test this picture for the *X(3872)* and, possibly, other *XYZ* mesons. In near threshold production experiments in the $\sqrt{S_{pN}} \approx 8$ GeV energy range, *XYZ* mesons can be produced with typical kinetic energies of a few hundred MeV (i.e. with $\gamma\beta \approx 0.3$). In the case of *X(3872)*, its decay length will be greater than 50 fm while the distance scale for the $c\bar{c} \rightarrow D^{(0)}\overline{D}^{(*0)}$ transition would be 2 ~ 3 fm. Since the survival probability of an $r_{rms} \sim 9$ fm "molecular" inside nuclear matter should be very small, *XYZ* meson production on a nuclear target with $r_{rms} \sim 5$ fm or more (A ~ 60 or larger) should be strongly quenched. Thus, if the hybrid picture is correct, the atomic number dependence of *XYZ* production at fixed $\sqrt{S_{pN}}$ should have a dramatically different behavior than that of the $\psi'$, which is long lived compact charmonium state. The current experimental status of *XYZ* mesons together with hidden charm tetraquark candidates and present simulations what we might expect from *A*-dependence of *XYZ* mesons in proton-proton and proton-nuclei collisions are summarized.

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# Bose and Fermi polaron-polariton mediated interactions

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We present a theoretical study of the many-body properties of exciton-polariton impurities created in a microcavity semiconductor [1], when coupled to a medium, either a Bose-Einstein condensate of polaritons with opposing spin, or a two-dimensional electron gas. The resulting quasiparticles, the so-called Bose and Fermi polaron-polaritons [2,3], mix the properties of light and matter, giving rise to a plethora of effects with dressed photons interactions such that Feshbach physics [4], mediated interactions [5], and polariton bound-states [6]. We review those effects by means of a strong coupling theory under the T-matrix approximation.

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# Observation of Pauli Crystals

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Understanding the emergence of many-body physics when assembling a system from individual particles is an ongoing challenge. The finite size of mesoscopic systems results in single particle gaps and shell structures, well known from nuclear and atomic physics. Here I will present our progress on realizing a mesoscopic system with ultracold fermions. We can deterministically prepare closed shells of up to 12 fermions in the ground state of a two dimensional trap. We tune the interactions from non-interacting to being the largest scale of the system. With this unique capability we investigate the interplay of single particle gaps and pairing. For filled shells there is a minimal required attraction for pairing to overcome the single particle gap. In the thermodynamic limit, the onset of pairing with increasing interaction gives rise to a quantum phase transition to a superfluid state. This is accompanied by an undamped Higgs mode.

Remarkably, we observe a precursor of this mode already in a mesoscopic system consisting of six fermions [1]. The lowest monopole excitation shows mode softening as function of the interaction strength. The non-monotonicity is the few-body analogue of the gap closing at the phase transition. By measuring the atom number distribution of the excitation, we can show that it is a pair excitation as expected for the Higgs mode precursor. In the future, we plan to investigate this few-body precursor of a phase transition in more detail, by investigating the emergence of a paired state directly in momentum space.

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# Thermometer for interacting harmonically trapped fermions

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Cooling $^{6}$Li atoms within a harmonic potential and tuning the s-wave scattering length via Feshbach resonance, the BCS-BEC crossover can be realised experimentally [1,2]. Here we work out the BCS mean-field theory and include the harmonic trapping potential via the local density approximation [3,4]. Based on this mean-field approach, we derive analytically and solve numerically the two algebraic self-consistency equations for the order parameter and the particle-number density. As a result we obtain the density profiles as a function of the temperature and the s-wave scattering length. Comparing them with measured density profiles [5,6] allows to determine the temperature of the fermionic cloud.

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# Observation of superfluidity in a strongly correlated two-dimensional Fermi gas

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Ultracold 2D Fermi are clean and controllable model systems that are ideally suited to study the interplay of strong correlations and reduced dimensionality. Recent experiments have observed pair condensation [1], algebraically decaying correlations [2] and phase coherence [3] at low temperatures.
In this contribution, we present a direct experimental observation of superfluidity in an ultracold 2D Fermi gas. We achieve this by moving a periodic potential through the system and observing no dissipation below a critical velocity, in excellent agreement with the Landau criterion [4-7]. We measure the critical velocity as a function of interaction strength and find a maximum in the crossover regime between bosonic and fermionic superfluidity. We also study the temperature dependence of the critical velocity and observe a phase transition from the superfluid to the normal state.
These results make it possible to study the evolution of the low-energy excitation spectrum at the crossover from bosonic to fermionic superfluidity and to gain valuable insights into the dynamic properties of strongly correlated 2D many-body systems.

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# Self-focusing of BEC in quasi 1D

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The standard way to control the position and the strength of maximal focusing of a matter-wave is to use a lens which imprints a position-dependent phase on the initial wave. However, quantum mechanics allows focusing even without a lens [1,2], based on diffractive focusing, where the initial wave function is a real-valued one with a non-Gaussian shape. Hence, the problem of optimal focusing translates into finding an appropriate initial wave function [3]. We explore the phenomenon of diffractive focusing of an atomic Bose-Einstein

condensate (BEC) in the regime, where the resonant atom-atom interaction plays a key role, and describe this effect in phase space within the Wigner function approach.

This project is supported by the German Space Agency (DLR) with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under the grant numbers 50WP1705 and 50WM1862.

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# Bosonic continuum theory of one-dimensional lattice anyons

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Anyons with arbitrary exchange phases exist on 1D lattices in ultracold gases [1]. Yet, known continuum theories in 1D do not match. We derive the continuum limit of 1D lattice anyons via interacting bosons. The theory maintains the exchange phase periodicity fully analogous to 2D anyons. This provides a mapping between experiments, lattice anyons, and continuum theories, including Kundu anyons [2] with a natural regularization as a special case. We numerically estimate the Luttinger parameter as a function of the exchange angle to characterize long-range signatures of the theory.

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# Few Fermions in tunable potentials

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Fermionic quantum systems with a tuneable atom number have proven to be viable for exploring the emergence of many-body phenomena [1]. In our experimental setup we can prepare both many-and few-body fermionic quantum systems in a two-dimensional harmonic potential. As a next step, we plan to implement a new trapping potential, created by a blue detuned laser beam, which is shaped using a digital micro mirror device (DMD). This should allow us to create nearly arbitrary uniform potentials. We plan to investigate homogeneous Fermi gases, which enable us to overcome some of the limitations imposed by a harmonic confinement. It should, for example, be possible to perform momentum resolved RF-spectroscopy in the 2D BEC-BCS crossover. We thereby hope to gain additional insight into the previously observed many-body pairing above the critical temperature [2]. In addition to this, the high flexibility of the DMD allows us to create double box potentials, which can be used for the exploration of transport physics in both the few- and the many-body regime.

Furthermore, the digital micro mirror device can also be used to dynamically alter the trapping potential. This could potentially be used to create rotational excitations in a few-body system or to probe the dispersion relation of systems with different atom numbers.

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# Thermodynamics of a weakly interacting Bose gas above the transition temperature

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We study thermodynamic properties of weakly interacting Bose gases above the transition temperature of Bose-Einstein condensation in the framework of a thermodynamic perturbation theory. Cases of local and non-local interactions between particles are analyzed both analytically and numerically. We obtain and compare the temperature dependencies for the chemical potential, entropy, pressure, and specific heat to those of noninteracting gases. The results set reliable benchmarks for thermodynamic characteristics and their asymptotic behavior in dilute atomic and molecular Bose gases above the transition temperature.

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# Towards a QMC-based density functional including finite-range effects: excitation modes of a 39 K quantum droplet

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Some discrepancies between experimental results on quantum droplets made of a mixture of 39 K atoms in different hyperfine states and their analysis within extended Gross-Pitaevskii theory (which incorporates beyond mean-field corrections) have been recently solved by introducing finite-range effects into the theory [1]. We will present a study [2] of the influence of these effects on the monopole and quadrupole excitation spectrum of extremely dilute quantum droplets using a density functional built from first-principles quantum Monte Carlo calculations, which can be easily introduced in the existing Gross-Pitaevskii numerical solvers. Our results show differences of up to 20% with those obtained within the extended Gross-Pitaevskii theory, likely providing another way to observe finite-range effects in mixed quantum droplets by measuring their lowest excitation frequencies.

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# Phase Detection with Neural Networks: Interpreting the Black Box

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Neural networks (NNs) usually hinder any insight into the reasoning behind their predictions. We demonstrate [1-2] how influence functions [3] can unravel the black box of NN when trained to predict the phases of the one-dimensional extended spinless Fermi-Hubbard model at half-filling. Results provide strong evidence that the NN correctly learns an order parameter describing the quantum transition in this model. We demonstrate that influence functions allow to check that the network, trained to recognize known quantum phases, can predict new unknown ones within the data set. Moreover, we show they can guide physicists in understanding patterns responsible for the phase transition. This method requires no a priori knowledge on the order parameter, has no dependence on the NN's architecture or the underlying physical model, and is therefore applicable to a broad class of physical models or experimental data.

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# Thermal evaporation and thermodynamics of one-dimensional liquids in weakly-interacting Bose-Bose mixtures

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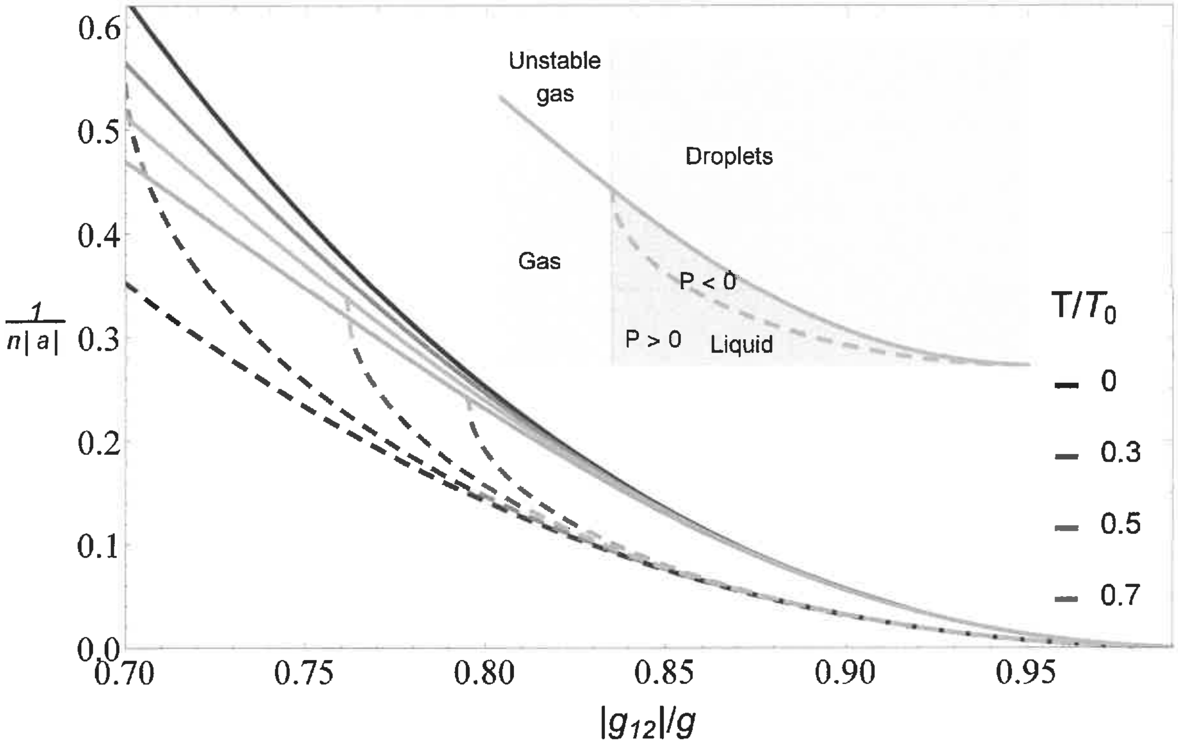
We study the low-temperature thermodynamics of weakly-interacting liquids in one-dimensional attractive Bose-Bose mixtures. The Bogoliubov approach is used to simultaneously describe both quantum and thermal fluctuations. We investigate in detail the thermal liquid-gas transition and draw the phase diagram. We methodically analyze the main thermodynamic quantities of the liquid: the chemical potential, Tan's contact, the adiabatic sound velocity and the specific heat at constant volume. The strong dependence of the thermodynamic quantities on the temperature may be used as a precise temperature probe for experiments with quantum liquids.



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# Bose-Einstein Condensation in Fractional Quantum Statistical Mechanics

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## *Abstract*

We apply the Caputo-Fabrizio derivative of order $\alpha$ to derive the eigenvalues of non-local Schrödinger equation for a free particle in a 3D box. Afterwards, we consider 3D Bose-Einstein condensation of an ideal gas with the obtained energy spectrum. Interestingly, in this approach the critical temperatures $T_c$ of condensation for $1<\alpha< 2$ are greater than the standard ones. Furthermore, the condensation in 2D is shown to be possible. In the limiting case, for $\alpha= 2$, our results are in complete agreement with those presented in standard quantum statistical mechanics.

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# Many-body dynamics of partially distinguishable particles

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A complete description of bosonic and fermionic many-body systems should also include unobserved degrees of freedom which could allow to distinguish the particles. Indeed, the existence of such "labels" leads to the suppression of many-particle interference, as demonstrated by the Hong-Ou-Mandel experiment in the case of two non-interacting bosons. We extend this line of thought to the realm of many interacting particles evolving continuously in a multimode setting, for example cold atoms in an optical lattice. In particular, we consider changes in the dynamics of the Bose-Hubbard model when the bosons are split into mutually distinguishable species. We look for signatures of this distinguishability in the time-dependent expectation values of observables. While two-particle correlations are needed to detect indistinguishability in the non-interacting case, we show that single-particle observables are already sensitive to many-particle interference in the presence of interactions.

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# Cavity QED with Bose-Einstein Condensates in a running wave resonator

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## 1. Scientific context

Recently self-emergence phenomena, like glassiness and crystallization, have been extensively studied using pumped condensed atomic sampled, coupled to a high finesse optical resonator [1]. So far these experiments have been realized in standing wave cavities, which impose the resonator geometry to the lattice being formed by the atoms and the light scattered into the cavity modes. Adopting degenerate multimode cavities opens new horizons to study order emergence effects, where compliant lattices between atoms and light can show a dynamical evolution [2]; crystal defects and frustration could be studied with such a system.

## 2. Results and perspectives

The results are so far related to the charging of the dipole trap formed in the intracavity radiation field at 1560 nm. The improvement on the frequency and power locking of this radiation to the cavity has permitted us to make a new series of experiments that rely on the ability of turning the magnetic field off rapidly without disturbing the cavity. Thanks to this, we have implemented a true molasses and demonstrated a seven-fold increase in the in-trap number of atoms by using a gray molasses technique utilizing hyperfine dark and bright states arising through two-photon Raman transitions [3]. Atoms at deeper potentials need to be addressed by a further red-detuned cooler from the F = 2 to F' = 3 transition of 87Rb D2 line, since the dipole trap creates a large differential Stark shift between ground and exited states. We have observed that the gray molasses technique still works at this far detuned condition and that more atoms can be loaded into the trap by modifying the frequency of the Raman beams appropriately. On the other hand, the waist of the trapped center in the cloud of atoms gets reduced, indicating lower temperatures than the ones achieved by ordinary techniques. This is a great advantage for creating large samples of ultracold atoms fast and efficiently, as shown for the process of creating all-optical BECs in microgravity [4].

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# Bose–Einstein Condensation in Planar Cavity

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The photonic Bose-Einstein condensate is a recently observed collective ground state of a coupled light-matter system. We describe of this novel quantum state on the basis of macroscopic quantum electrodynamics in dispersing and absorbing environments. To this end, we identify the effective modes of the electromagnetic field in an absorbing cavity which are thermalized via their coupling to an ensemble of dye molecules with rovibrationally dressed electronic transitions. We derive a master equation for the coupled photon–dye dynamics and solve it to find the photon condensate.

We apply our formalism to a planar cavity and theoretically demonstrate that the condensation can occur in a two-dimensional untrapped gas. Each photon mode is determined by the transversal wavevector of the photon, while the longitudinal wavevector stays fixed. We demonstrate as the spacing between modes decreases, the threshold of condensation smears out and Bose–Einstein condensation eventually disappears.

# Going beyond Hartree-Fock: Fully self-consistent determination of the many-body state of ultracold bosonic atoms and benchmarking with the exact two-boson solution

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We study zero-temperature quantum fluctuations in harmonically trapped one-dimensional interacting Bose gases, using the self-consistent multiconfigurational time-dependent Hartree (MCTDH) method. We define phase fluctuations from the full single-particle density matrix by the spatial decay exponent of off-diagonal long-range order. In a regime of mesoscopic particle numbers and moderate contact couplings, we derive the spatial dependence of the amplitude of phase fluctuations, determined from the self-consistently derived shape of the field operator orbitals and Fock space orbital occupation amplitudes. It is shown that the phase fluctuations display a peak, which in turn corresponds to a dip of the first-order correlations in position space, akin to what has previously been obtained in the Tonks–Girardeau limit of very large interactions and low densities. Finally we benchmark our results with two bosons in a one-dimensional harmonic trap, by comparing its exact solution to the self-consistent numerical solution by using MCTDH method.

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# A new apparatus for experiments with ultracold Lithium-6 atoms

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Efficient quantum simulation using ultracold atoms is usually limited by a variety of technical factors such as the available laser power, the numerical aperture of the objective, the possible magnetic field strength and switching speed of the coils or the geometry of the vacuum set-up. These strongly influence cycle times of the experiment and the control one has over the system. To challenge such limitations encountered in previous experiments using Lithium-6 atoms precooled by a Zeeman slower and captured in an octagonal steel chamber we are currently designing and building up a new experimental set-up within the "Heidelberg Quantum Architecture" program. Such improvements can be vital in correlation measurements when high statistics are required or in the preparation of lattices with control at each lattice point.

In this poster I will present the current state of the experimental design as well as an outlook on what will be implemented in the near future. The design evolves around a small octagonal glass cell with a diameter of only 5 cm and large optical access as it allows for the use of a 0.8NA objective vertically and 0.25NA horizontally. The increased NA will enhance our ability to deterministically prepare and image single atoms, substantially increasing the fraction of captured photons. It also enables the use of much smaller and therefore faster tuneable magnetic field coils. Replacing the Zeeman slower with a 2D-MOT as the precooling stage, we aim for a significant reduction of cycle times to below one second.

As this project is in its early stages we are in a prime position to implement fundamental ideas into the set-up, one of which is the effort to make the whole ensemble as modular and interchangeable as possible. This does not only present a powerful tool for controlling the system, but also keeps the set-up easily adjustable to explore different physical phenomena. It also lets us incorporate the knowledge collected in previous experiments such like the deterministic preparation of few atoms in low entropy states, the 2D preparation of large systems as well as the cross-over between them.

# Indirect Observation of *Zitterbewegung* in non-Abelian Gauge Field

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We experimentally realize SU(2)-symmetric artificial gauge field with the tripod laser scheme. First, the non-Abelian nature of the artificial gauge field is revealed by performing loop operations, at different orders, in the parameter space [1]. It was found that the dynamics of internal states leads to a new thermometric scheme that exploits the interferometric-displacement of atoms [1]. Afterwards, the coupling dynamics of internal (i.e., spin)- and external (i.e., momentum)-degrees of freedoms, in a two-dimensional non-Abelian gauge field, leads to an indirect way of observing *Zitterbewegung* in an artificial non-Abelian gauge field [2]. Despite the fact that the oscillation of the center-of-mass is small (~nm) in real-space, we go to momentum space to observe the oscillation of the internal degrees of freedom that is attributed to the spin-orbit-interaction in a two-dimensional degenerate Fermi gas.

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# Strong Boundary and Trap Potential Effects on Emergent Physics in Ultra-Cold Gases

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The field of quantum simulations in ultra-cold atomic gases has been remarkably successful. In principle it allows for an exact treatment of a variety of highly relevant lattice models. But so far there is a lack in the theoretical literature concerning the systematic study of the effects of the trap potential as well as the finite size of the systems, as numerical studies of such non periodic lattices are numerically demanding. We use the recently introduced real-space truncated unity functional renormalization group [1] to study the before-mentioned 'boundary effects' with a focus on the impact they have on the superconducting phase of the 2D Hubbard model. We find that not only lower temperatures need to be reached compared to current capabilities, but also system sizes need to increase to achieve the unconventional superconducting state.

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# Observation of Pauli Crystals

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Strong correlations between Fermions lie at the heart of many open questions concerning quantum matter that remain unresolved to this day. Effective descriptions of such systems in terms of weakly interacting constituents are unknown and the strong fermionic correlations must be considered.

In our experiment, we take a novel approach to study a strongly interacting two-dimensional Fermi superfluid by starting from very small systems, prepared deterministically in the ground state. We find evidence for the presence of a few body precursor of the superfluid phase transition and study its dependence on particle number [1]. On this poster, I present first results obtained by applying of a time-of-flight imaging technique, both spin and single particle resolved, to this system. This enables us to extract arbitrary N-body correlations of our many-body state. First measurements reveal strong high-order momentum correlations even between identical, non-interacting, Fermions. These manifest due to Pauli's principle, leading to particular geometric arrangements of trapped Fermions also referred to as Pauli Crystals [2].

We plan to extend these measurements to both interacting systems and larger particle numbers in the future to tackle the issue of the pairing mechanism in strongly interacting Fermi gases.

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# Functional renormalization for Bose-Bose mixtures

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We study balanced and repulsive Bose-Bose mixtures at zero temperature using the Functional Renormalization Group (FRG) [1]. This is a non-perturbative framework that successfully describes several properties of cold quantum gases [2,3]. We analyze the RG flows at different momentum scales. We study the role of density and spin fluctuations and examine the condition for phase separation. We also show results for thermodynamics properties, and find that our results compare favorably with perturbative approaches. Finally, we discuss extensions of our work. In particular, we discuss the study of attractive mixtures, where the FRG could provide an accurate picture of the strongly-interacting regime.

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# Observation of a dissipative time crystal

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A phase of matter may emerge when an underlying symmetry in the system is spontaneously broken. For example, crystal formation, like in a liquid-solid phase transition, is accompanied by the breaking of spatial translation symmetry as atoms localize in space. Recently, an analogous phenomenon of symmetry breaking in time, which leads to the emergence of a "time crystal", has received significant attention. While most of the experiments focused on time crystals in driven isolated systems the quintessential dissipative time crystal (DTC) remains elusive. Here, we present the first experimental realization of such a DTC in an atom-cavity system. This dynamical phase is characterized by a period doubled switching between checkerboard density wave patterns. We demonstrate the robustness of this phase against temporal perturbations from a noisy drive. Persistent subharmonic response over multiple driving cycles suggests a rich interplay between short-range collisional and long-range cavity-mediated interactions. Our work provides a framework for exploring phases of matter with spatio-temporal order in systems coupled to an environment, which is ever-present in real-world applications.

# TO HAVE (KONDO EFFECT) AND HAVE NOT: RENORMALIZATION AND SCALING

**Eugene Kogan**

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We discuss Kondo effect in the framework of a general model, describing a quantum impurity with degenerate energy levels interacting with a gas of itinerant electrons and derive scaling equation for the interaction parameters to the second order for such a model. The approach is applied to the spin-anisotropic Kondo model generalized for the case of the power law DOS for itinerant electrons. The scaling equation is specified and solved analytically in terms of elliptic functions. We also introduce spin-anisotropic Coqblin--Schrieffer model, apply the general method to derive scaling equation for that model and integrate the derived equation analytically.

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# Finite temperature thermal cloud of dipolar Bose gas in presence of the three-body interactions

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(Dated: November 18, 2020)

We present our numerical calculation of the dipolar Bose gas in presence of the three-body contact interactions by using the Generalized Hartree-Fock-Bogoliubov approximation (GHFB). We study the effect of the dipolar interaction on the evolution of the condensate density and the thermal cloud. We determine the condensate fraction, the non-condensate fraction and the anomalous fraction.

**Keywords**:Generalized Hartree-Fock-Bogoliubov approximation (GHFB); Hartree-Fock-Bogoliubov Popov approximation (HFB-P); Bose-Einstein-condensation (BEC); Contact interaction (CI); Dipolar interaction (DI); Coupling strength of the three-body interactions (CSTBI).

PACS numbers: 21.10.Pc,21.60.-n,21.60.Jz

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# Single-atom imaging of fermions in a quantum-gas microscope

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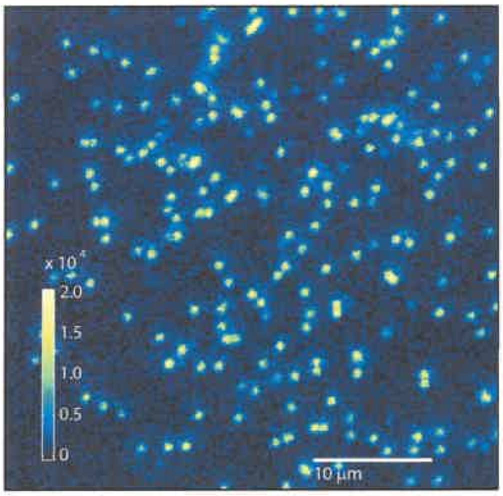
Ultracold atoms in optical lattices have become a key tool to simulate and test fundamental concepts of condensed-matter physics, in particular to study out-of-equilibrium dynamics in quantum many-body systems. In our experiment, we image fermionic 40K atoms in an optical lattice with single-site and single-atom resolution. Previously we used electromagnetically-induced-transparency (EIT) cooling[1,2] to generate fluorescent photons, see figure. We observed a collectively enhanced fluorescence rate which limited our resolution in dense samples. To overcome this we have implemented Raman-sideband-cooling (RSBC), with this cooling and imaging process we are better equipped to study strongly correlated systems in dense clouds. On our poster I will present the both these techniques and discuss the observed differences. Secondly, we will discuss some recent findings from simulations of our microscope data. Several techniques to reconstruct the lattice occupations from noisy EMCCD images were compared. The most successful method, based on deconvolution, is also applied to the experiment's data. The results from these simulations and the enhanced microscope data will be shown on the poster.



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# Induced quantized transport by topology transfer between two coupled 1D lattice systems

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We show that a topological pump in a one-dimensional (1D) insulator can induce a strictly quantized transport in an auxiliary chain of non-interacting fermions weakly coupled to the first. The transported charge is determined by an integer topological invariant of the fictitious Hamiltonian of the insulator, given by the covariance matrix of single-particle correlations. If the original system consists of non-interacting fermions, this number is identical to the TKNN (Thouless, Kohmoto, Nightinghale, den Nijs) invariant of the original system and thus the coupling induces a transfer of topology to the auxiliary chain. When extended to particles with interactions, for which the TKNN number does not exist, the transported charge in the auxiliary chain defines a topological invariant for the interacting system. In certain cases this invariant agrees with the many-body generalization of the TKNN number introduced by Niu, Thouless, and Wu (NTW). We illustrate the topology transfer to the auxiliary system for the Rice-Mele model of non-interacting fermions at half filling and the extended superlattice Bose-Hubbard model at quarter filling. In the latter case, the induced transport of charge is fractionally quantized.

# Optimized Observable Readout from Single-shot Images of Ultracold Atoms via Machine Learning

**Axel U. J. Lode[1], Rui Lin[2], Miriam Büttner[1], Luca Papariello[3], Camille Lévêque[4], R. Chitra[2], Marios C. Tsatsos[5], Dieter Jaksch[6], and Paolo Molignini[6]**

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Single-shot images are the standard readout of experiments with ultracold atoms -- the tarnished looking glass into their many-body physics. The efficient extraction of observables from single-shot images is thus crucial. Here, we demonstrate how artificial neural networks can optimize this extraction. In contrast to standard averaging approaches, machine learning allows both one- and two-particle densities to be accurately obtained from a drastically reduced number of single-shot images. Quantum fluctuations and correlations are directly harnessed to obtain physical observables for bosons in a tilted double-well potential at an unprecedented accuracy. Strikingly, machine learning also enables a reliable extraction of momentum-space observables from real-space single-shot images and vice versa. This obviates the need for a reconfiguration of the experimental setup between in-situ and time-of-flight imaging, thus potentially granting an outstanding reduction in resources.

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# Plasmon modelling in core-level photoemission within multiple scattering approach

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Photoemission is a many electron process involving transition from a N- electron initial state to a (N-1)-electron final state due to perturbation by photons (x-ray and uv radiation). Photoemission energy loss spectroscopy (PEELS) aims at providing information on the dielectric function near the surface. Basically, it consists the monitoring of a plasmon satellite in a photoemission spectrum as a function of the direction of the outgoing electron that has suffered a plasmon loss. In order to be able to derive quantitative information on the (surface) dielectric function, a comparison with suitable theoretical model is necessary upon which we are working presently. We are developing such theoretical model and incorporating it into a computer code MsSpec [1]. We use an electron-boson Hamiltonian where the photoelectron and the core hole are coupled to bosonic-type excitations in the solid via fluctuations potentials [2-3], to take into account both types of plasmon losses (intrinsic and extrinsic) and their interference. A fully quantum description of plasmons involves an accurate calculation of the dielectric function which contains the many-body response of the system, including plasmons and their interactions with other (quasi-)particles, which control their lifetime and their decay channels. So, we use the quantum many-body method of Fermi liquids to model the dielectric function and its behaviour under external fields. Thus further, to calculate the dielectric function accurately, we approximate the exact fluctuation potentials by model analytical fluctuation potentials. We will present our results with different such model fluctuation potentials that have been proposed in the literature alongwith the calculated ones which incorporates plasmon dispersion from hydrodynamic to random phase approximation (RPA) and beyond improving with static and dynamic local field corrections and we will explore the importance of taking into account multiple scattering (MS) when the outgoing electron has lost energy through the excitation of a plasmon [4].

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# Strong correlations in lossy one-dimensional quantum gases: from the quantum Zeno effect to the generalized Gibbs ensemble

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We consider strong two-body losses in bosonic gases trapped in one-dimensional optical lattices. We exploit the separation of time scales typical of a system in the many-body quantum Zeno regime to establish a connection with the theory of the time-dependent generalized Gibbs ensemble. Our main result is a simple set of rate equations that capture the simultaneous action of coherent evolution and two-body losses. This treatment gives an accurate description of the dynamics of a gas prepared in a Mott insulating state and shows that its long-time behaviour deviates significantly from mean-field analyses. The possibility of observing our predictions in an experiment with $^{174}$Yb in a metastable state is also discussed.

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# Engineering the many-body quantum dynamics and induced correlations of Bose polarons

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We unravel the stationary properties and the correlated nonequilibrium quantum dynamics of few spinor bosonic and fermionic impurities immersed in a BEC via simulating Ramsey and pump-probe spectroscopy [1,2,3]. For the ground state of the impurities we reveal and quantify their attractive induced interactions for arbitrary impurity-BEC interactions as well as identify bipolaron states at strong attractions. Monitoring the time-evolution of the contrast we unveil the existence, dynamical deformation and the temporal orthogonality catastrophe of Bose polarons [1]. Remarkably, multipolaron and excited states of the impurities are captured in the spectrum of the contrast and found to exhibit characteristic correlation patterns [2]. Further experimental evidences of the time-resolved formation of polaronic structures are offered by utilizing pump-probe spectroscopy [3]. Remarkably, the dynamical generation of coherent attractive or repulsive Bose polarons and signatures of their induced-interactions are imprinted in the probe spectra. For strong repulsions, enhanced energy redistribution processes occur, which for long timescales lead to a steady state of the fully incoherent impurities acquiring an effectively large temperature. The impact of adiabatic and diabatic pump pulses on the polaron formation is also appreciated. The origin of induced impurity-impurity correlations is quantified within an effective two-body Hamiltonian [4].

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# Quantum liquids and pair formation in one-dimensional optical lattices

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Since the theoretical proposal [1] for creating dilute quantum droplets in ultracold atomic systems many experimental groups have been able to produce them using bosonic mixtures [2, 3, 4]. We have proposed an extension to one-dimensional optical lattices for bosonic mixtures and we have demonstrated that quantum droplets exist in this system [5, 6]. I will present the ground-state phase diagram where the different phases are characterized by examining the density profile and off-diagonal one- and two-body correlation functions. An scan from the weakly interacting situation to the strongly interacting one is performed and a rich variety of phases is found, including atomic superfluid gases, atomic superfluid droplets, pair superfluid droplets, pair superfluid gases, and a Mott-insulator phase. Then, I will move to discuss the formation of a bound state at the few-body level using an effective dimer Hamiltonian and its connection with the quantum droplet in the many-body problem. Finally I will present some relevant examples for an experimental implementation and the possible connection with dipolar systems.

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# Generation of solitary matter waves at hottest negative temperature

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In this work, we present an analytical model to realize the hottest negative temperature in the context of one-dimensional ultracold atoms. Based on mean-field approximation, we construct a large family of solutions for 1D Gross-Pitäevskii equation (GPE) in presence of combination of expulsive and bi-chromatic optical lattice (BOL) traps. The choice of expulsive-BOL trap combination results in the formation of upper bound in system's energy which is a pre-requisite for realization of negative temperature [1-3]. From our model, we reveal a non-trivial correlation between the power of laser intensity used for forming BOL trap and the resultant temperature of the considered system. The tuning of laser power intensity results in the increase of the frustrated lattice depth of BOL trap which concurrently increases the hottest negative temperature. To emphasize the result, we present the variation of occupation density of ultracold with changing frustrated depth. This increase in the temperature of the system is also reaffirmed by the calculation of entropy and plotting of curve in between entropy versus energy.

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# Interference of two composite particles

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The dynamics of systems of identical particles is characterized by many-body interference. However, the interfering particles (bosons or fermions) can be composite objects, raising the question of the conditions under which bound states of several particles behave as ideal elementary bosons or fermions. Here we consider the dynamics of two bound pairs on a 1D lattice and observe their Hong-Ou-Mandel interference on an impurity. We investigate to which extent the composite nature of the bound pairs affects their interference.

# Detection of the reference frame motions with twisted superfluids

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Degenerate quantum gases are expected to become the future acceleration sensors and gravitometers [1]. Their essentially many-body behaviour is accurately described in many experimental situations by macroscopic wavefunction in the framework of Gross-Pitaevskii equation [2]. In particular the response to rotations of reference frame of a quantum gas trapped in a toroidal container may be a macroscopic persistent flow of condensate [3]. The more interesting dynamics is expected to be observable experimentally for helical confinement of quantum gas [4]. Helical trapping potential appears as interference pattern of the two counter-propagating optical vortices [5] with oppositely directed orbital angular momenta [6]. The oppositely directed angular momenta of photons might be arranged by optical phase-conjugation [7]. The perfect phase-conjugator based on Sagnac loop for optical vortices with ultimate reflectivity and beam fidelity had been proposed in [8]. For degenerate quantum gas in spiral trapping geometry it had been shown already that rotations of the reference frame may cause the linear displacement of condensate along rotation axis with a constant speed defined by angular velocity of frame and helix handedness [9]. In current report we extend this analysis to show by exact solutions of GPE with helical potential [4] that reverse effect takes place: the linear displacement of condensate with constant velocity initiates the rotation of condensate. The linear accelerations of reference frame are detectable as well because of phase-modulation of condensate wavefunction caused by this linear acceleration.

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# Bosonic Pfaffian State in the Hofstadter-Bose-Hubbard Model

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Topological states of matter, such as fractional quantum Hall states, are an active field of research due to their exotic excitations. One of the most prominent examples for such a state is the so-called Pfaffian [1]. It was seen in extensive numerical studies that its bosonic analog provides a good description of bosons at filling factor $\nu=1$. A particularly striking feature of the Pfaffian are its anyonic excitations exhibiting non-Abelian braiding statistics. Ultracold atoms in optical lattices provide a highly controllable and adaptable platform to study exotic states of matter. However, the presence of the lattice can strongly affect the ground state of a system.

Here, using DMRG, we show that the ground state of the Hofstadter-Bose-Hubbard model on a square at filling factor $\nu=1$ and $\alpha=1/6$ magnetic flux quanta per plaquette is a lattice analog of the continuum Pfaffian [2]. To establish this fact we studied the on-site correlations of the ground state, which indicate its paired nature, and found a charge gap signaling its incompressibility. We argue that the emergence of a charge density wave on thin cylinders and the behavior of the two- and three- particle correlation functions at short distances provide evidence for the ground state being closely related to the continuum Pfaffian state.

The signatures discussed here are accessible in cold atom experiments. Given recent experimental progress the Pfaffian state seems readily realizable using adiabatic preparation schemes.

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# Strongly correlated quantum droplets in quasi-1D dipolar Bose gas

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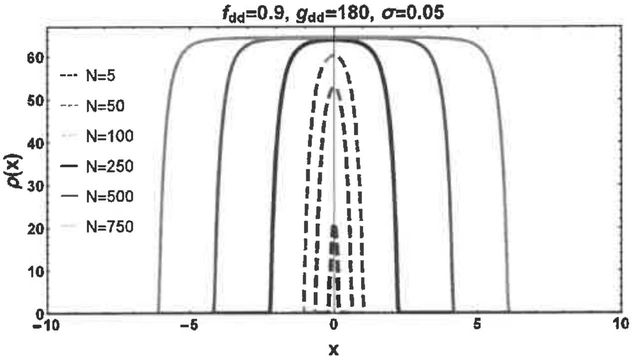
We exploit a few- to many-body approach to study strongly interacting dipolar bosons in the quasi-one-dimensional system. The dipoles attract each other while the short range interactions are repulsive. Solving numerically the multiatom Schrödinger equation, we discover that such systems can exhibit not only the well-known bright soliton solutions but also novel quantum droplets for a strongly coupled case. For larger systems, basing on microscopic properties of the found few-body solution, we propose a new equation for a density amplitude of atoms. It accounts for fermionization for strongly repelling bosons by incorporating the Lieb-Liniger energy in a local density approximation and approaches the standard Gross-Pitaevskii equation (GPE) in the weakly interacting limit. Not only does such a framework provide an alternative mechanism of the droplet stability, but it also introduces means to further analyze this previously unexplored quantum phase. In the limiting strong repulsion case, yet another simple multiatom model is proposed. We stress that the celebrated Lee-Huang-Yang term in the GPE is not applicable in this case.



*Density of a quasi1D Bose gas, for strongly repulsive short-range interaction, and weak attractive dipolar forces.*

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# Many-Body Physics and Quantum Information in Rapidly Assembled Lattice Systems

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Cold atoms in optical lattices are extremely interesting systems at the interface of condensed matter physics and quantum optics: They naturally realize Hamiltonians known from the solid state but are amenable to single-particle control usually found in few-mode systems. This combination opens the door for experimental schemes that combine ideas from quantum information and many-body physics.

Our newly established group will focus on novel approaches to measuring global properties of the density matrix of many-body systems. This approach may serve, for example, to characterize out-of-equilibrium systems through their entanglement dynamics. A major bottleneck in measuring such quantities has been the requirement for extremely large statistics. We will tackle this problem through new techniques for the rapid assembly of optical lattice systems from individually laser-cooled atoms. This poster will introduce the agenda of our group.

# The quantum effective action for ultracold gases far from equilibrium

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In many-body quantum systems, novel phenomena can emerge on the macroscopic level. Motivated by quantum field theoretical descriptions, we introduce the equal-time quantum effective action giving access to effective theories for dynamically emerging macroscopic phenomena. For our experimental study, we employ a quasi one-dimensional spinor Bose gas in a far from equilibrium regime where universal dynamics has been observed [1]. The spatially resolved read-out of the complex valued transversal spin field [2] allows the extraction of one-particle irreducible correlation functions, which are the building blocks of the quantum effective action. We discuss the experimental challenges for extracting higher order correlation functions and present our experimental findings which reveal a strong suppression of the four-vertex at low momenta emerging in the highly occupied [3].

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# Bose-Einstein condensates in weak and strong disorder potentials

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We show a time-dependent extension of a perturbative mean-field approach to the dirty boson problem by considering how switching on and off a weak disorder potential affects the stationary state of an initially equilibrated Bose-Einstein condensate by the emergence of a disorder-induced condensate deformation [1]. We find that in the switch on scenario the stationary condensate deformation turns out to be a sum of an equilibrium part first obtained by Huang and Meng [2], that actually corresponds to adiabatic switching on, and a dynamically-induced part, where the latter depends on the particular driving protocol. If the disorder is switched off afterwards, the resulting condensate deformation acquires an additional dynamically-induced part in the long-time limit, while the equilibrium part vanishes. Our results demonstrate that the condensate deformation represents an indicator of the generically non-equilibrium nature of steady states of a Bose gas in a temporally controlled weak disorder.

Moreover, we present a study of the static column density profiles and the corresponding transverse cloud widths of a harmonically trapped molecular BEC in laser speckle potentials [3]. A theoretical model, that is non-perturbative with respect to the disorder and includes quantum fluctuations, is compared with the actual experiment. For weak disorder we find quantitative agreement with the perturbative approach of Huang and Meng [2], while for strong disorder our theory perfectly reproduces the geometric mean of the measured transverse widths. However, we also observe a systematic deviation of the individual measured widths from the theoretically calculated ones and suggest a potential future improvement.

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# Investigation of pairing in 1D spin- and mass-imbalanced Fermi gases through shot noise correlations

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

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

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# Prethermalization with negative specific heat

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We study non-canonical relaxation in a composite cold atoms system, consisting of subsystems that possess negative microcanonical specific heat. The system exhibits prethermalization far away from integrability due to the appearance of a single adiabatic invariant. The Thirring instability drives the constituent subsystems towards the edges of their allowed energy spectrum, thus greatly enhancing the contrast between the prethermal state and the long time thermal outcome.

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# Inelastic Confinement-Induced Resonances in Different Spatial Dimensions

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Inelastic confinement-induced resonances [1] can occur, if an anharmonic trap potential couples the degrees of freedom of center-of-mass motion and relative motion. Transferring energy between these two degrees of freedom allows for coherent molecule-formation [2] or bond breaking. Originally, these resonances were observed (but mistakenly attributed to elastic confinement-induced resonances) in a quasi one-dimensional quantum gas, i.e. for a very tight confinement in two spatial dimensions [3]. Later, they were also predicted to occur in quantum dots or dipolar gases [4]. In the latter case, a variation of the dipole strength allows for additional tunability.

In the present study the influence of the dimensionality of the confinement potential on inelastic confinement-induced resonances is considered. Furthermore, the previously introduced simplified model for predicting the position of these resonances is extended to higher dimensional traps, improved, and compared to results of full ab initio calculations.

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# Effect of trapping geometry on the parametric resonances in a disordered Bose–Einstein condensate driven by an oscillating potential

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We report parametric resonances (PRs) in a numerical investigation of a driven one-dimensional, interacting, and disordered Bose–Einstein condensate (BEC) confined in different traps [1]. The BEC is excited by an oscillating Gaussian obstacle along a broad range of driving frequencies $\Omega$. The PRs are detected via a quantity that is closely related to the time-average of the kinetic energy. The significant result of this work is that the trapping geometry plays a major role in defining the values of $\Omega$ at which PRs arise and controls their response to disorder. As such, it reveals the interplay of trapping geometry and disorder in these resonances. The dynamics of the modal coefficient $C_0(t)$ as well as that of the phase-mismatch $\delta(t)$ between the $C_0(t)$ and $C_1(t)$ are examined at and away from PR. At PR, $|C_0(t)|$ is generally found to be lower in magnitude than away from it, demonstrating that the atoms leave the $n = 0$ ground state towards higher states. In the harmonic oscillator trap, the dynamic pattern of $\delta(t)$ is found to be quite robust against changes in the disorder strength contrary to the box potential. This is because in the box the ratio of the random-potential and kinetic energies is higher than in the harmonic trap signaling that the influence of disorder is weaker in the latter.

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# Snake states of neutral atom from synthetic gauge field in a ring-cavity

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We propose the creation of an atomic analogue of electronic snake states in which electrons move along one-dimensional snake-like trajectory in the presence of a suitable magnetic field gradient. To this purpose, we propose the creation of laser induced synthetic gauge field inside a three-mirror ring cavity and show that under appropriate conditions, the atomic trajectory in such configuration mimics snake-state like motion. We analyse this motion using semi-classical and full quantum mechanical techniques for a single atom. We provide a detailed comparison of the original electronic phenomena and its atomic analogue in terms of relevant energy and length scales and conclude by briefly pointing out the possibility of consequent study of ultra-cold condensate in similar ring-cavity configuration.

# Quantum droplets in dipolar Bose-Einstein condensates in a ring potential

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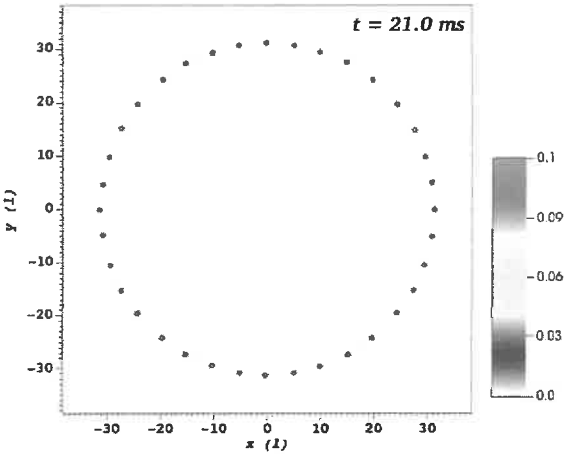
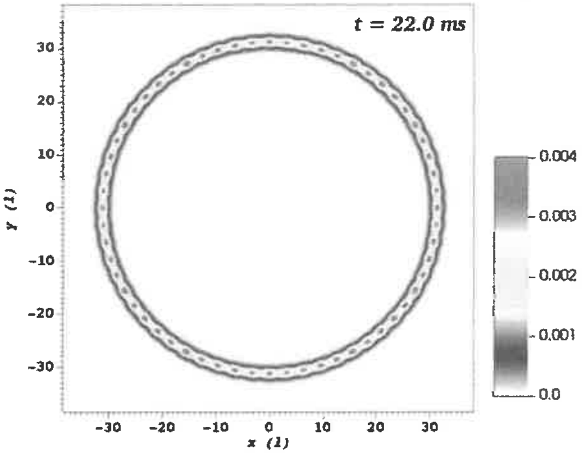
We study formation of quantum droplets in dipolar Bose-Einstein condensates in a ring-shaped geometry using numerical techniques. A condensate is initially prepared in a stable ground state of the system, and droplet formation is triggered by a sudden quench of the contact interaction. We investigate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





# Orbital ordering of ultracold alkaline-earth atoms in optical lattices

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We report on a dynamical mean-field theoretical analysis of emerging low-temperature phases in multicomponent gases of fermionic alkaline-earth(-like) atoms in state-dependent optical lattices. Using the example of Yb-173 atoms, we show that a two-orbital mixture with two nuclear spin components is a promising candidate for studies of not only magnetic but also staggered orbital ordering peculiar to certain solid-state materials. We calculate and study the phase diagram of the full Hamiltonian with parameters similar to existing experiments and reveal an antiferroorbital phase. This long-range-ordered phase is inherently stable, and we analyze the change of local and global observables across the corresponding transition lines, paving the way for experimental observations. Furthermore, we suggest a realistic extension of the system to include and probe a Jahn-Teller source field playing one of the key roles in real crystals.

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# *The polarized Fermi-Hubbard superfluid at large order*

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Using the connected determinant Monte Carlo algorithm [1], we have obtained first results in the superfluid phase of the attractive Fermi-Hubbard model — a simple model describing optical lattice experiments. Expanding around the BCS Hamiltonian, we sum up all diagrams up to large order and we observe that the series is convergent even in the strongly correlated regime. We discuss the relation between the large-order behavior and singularities as a function of the expansion parameter. We benchmark our results against determinant diagrammatic Monte Carlo [2] in the unpolarized regime and we explore the previously inaccessible polarized regime, where we observe the first order phase transition which was observed experimentally in the continuum.

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# State distinguishability under weak measurement and post-selection: A system and device perspective

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We quantify the disturbance of a quantum state undergoing a sequence of observations, and particularly focus on a weak measurement followed by post-selection and compare these results to the projective counterpart.

Taking into account the distinguishability of both, the system and the device, we obtain the exact trade-off between the system state disturbance and the change of the device pointer state.

We show that for particular post-selection procedures the coupling strength between the system and the device can be significantly reduced without loosing measurement sensitivity, which is directly transferred to a reduced state disturbance of the system.

We observe that a weak measurement alone does not provide this advantage but only in combination with post-selection a significant improvement in terms of increased measurement sensitivity and reduced state disturbance is found.

We further show that under realistic experimental conditions this state disturbance is small, whereas the exact post-selection probability is considerably larger than the approximate value given by the overlap of the initial and final state when neglecting the system state disturbance.

# Trapped Photon Gases
# at Dimensional Crossover from 2D to 1D

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Photon Bose-Einstein condensates are characterised by a quite weak interaction, so they behave nearly as an ideal Bose gas [1,2]. Moreover, since the current experiments are conducted in a microcavity, the longitudinal motion is frozen out and the photon gas represents effectively a two-dimensional trapped gas of massive bosons. In this contribution we therefore focus on a harmonically confined ideal Bose gas in two dimensions, where the anisotropy of the confinement allows for a dimensional crossover. If the anisotropy is even large enough so that the squeezed direction is frozen out, then only one degree of freedom survives and the system can be considered to be quasi-one dimensional. We work out the thermodynamic properties for such a system analytically and examine, in particular, the dimensional information which is contained in the respective thermodynamic quantities. With this our results are useful for future experiments of photon gases at the dimensional crossover from 2D to 1D in view of determining their effective dimensionality from thermodynamic quantities.

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# Many-body localization with synthetic gauge fields in disordered Hubbard chains

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The phenomenon of many-body localization (MBL) is attracting significant theoretical and experimental interest over the past few years. The signatures of MBL have been observed in recent cold-atom experiments in optical lattices [1,2,3,4]. The recent experimental advances of synthetic gauge fields [5] allow us to explore the MBL with magnetic flux. We discuss the role of synthetic magnetic fields on the localization properties of disordered fermions. The spectral statistics exhibit a transition from ergodic to MBL phase, and the transition shifts to larger disorder strengths with increasing magnetic flux. The dynamical properties indicate the charge excitation remains localized whereas spin degree of freedom delocalized in the presence of synthetic flux. The full localization of spin excitation can be recovered when spin-dependent disorder potential is realized [6]. Furthermore, we show the effect of quantum statistics on the local correlations and show that the long-time spin oscillations of a hard-core boson system are destroyed in contrast to the fermionic case.

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# Ultracold ion-atom collisions in the quantum regime

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Hybrid systems of laser-cooled trapped ions and ultracold atoms combined in a single experimental setup have recently emerged as a new platform for fundamental research in quantum physics and chemistry [1]. Reaching the ultracold s-wave quantum regime has been one of the most critical challenges in this field for a long time. Unfortunately, the lowest attainable temperatures in experiments using the Paul ion trap are limited by the possible rf-field-induced heating related to the micromotion [2]. Recently, buffer gas cooling of a single ion in a Paul trap to the quantum regime of ion-atom collisions was realized, and a deviation from classical Langevin theory was observed by studying the spin-exchange dynamics, indicating quantum effects in the ion-atom collisions [3]. I will present how quantum-chemical calculations of electronic structure and multichannel scattering dynamics can guide and explain quantum physics and chemistry experiments. In particular, I will describe how, in collaboration with experimental groups from Amsterdam [3], Stuttgart [4], and Freiburg, we have overcome the micromotion limitation. I will also discuss incoming applications, including observation and application of magnetic Feshbach resonances, to control ultracold ion-atom collisions.

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# QMC study of trapped Bose-Bose mixtures at finite temperature

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We present our recent study [1] of thermal properties of a trapped Bose-Bose mixture in a dilute regime using quantum Monte Carlo methods. We have investigated the dependence of the superfluid density and the condensate fraction on temperature, for the mixed and separated phases. To this end, we have used the path-integral Monte Carlo method for finite temperatures and the diffusion Monte Carlo method, in the zero-temperature limit, comparing the obtained results with solutions of the coupled Gross-Pitaevskii equations. We notice anisotropy of superfluid density in some phase-separated mixtures. Our results also show that the superfluid density and condensate fraction have slightly different temperature evolution, showing noteworthy situations where the superfluid fraction is smaller than the condensate fraction.

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# Exact space-time N-point-function mapping between pairs of experiments with open quantum gases within the Markovian regime

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We present an exact space-time mapping between the N-point correlation functions of two different quantum gas experiments to extend a quantum-field mapping result for closed systems [Phys. Rev. A94, 043628 (2016)] to the general case of open quantum systems with the Markovian property. For this, we consider an open many-body system consisting of a D-dimensional quantum gas of bosons or fermions that interacts with a bath under Born-Markov approximation and evolves according to a Lindblad master equation in a regime of loss or gain. We derive the Heisenberg evolution of any arbitrary N-point function of the system in such a regime. Our quantum field mapping for closed quantum systems is rewritten in the Schrödinger picture and then extended to open quantum systems by relating onto each other two different evolutions of the N-point functions of the open quantum system. As a concrete example of the mapping, we consider the mean-field dynamics of a one-dimensional Bose-Einstein condensate being locally bombarded by a dissipating beam of electrons in both cases when the beam amplitude or the waist is steady and modulated.

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# Generation of Photonic Matrix Product States with a Rydberg-blockaded atomic array

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In this work, we show how one can deterministically generate photonic matrix product states with high bond and physical dimensions with an atomic array if one has access to a Rydberg-blockade mechanism. We develop both a quantum gate and an optimal control approach to universally control the system and analyze the photon retrieval efficiency of atomic arrays. Comprehensive modeling of the system shows that our scheme is capable of generating a large number of entangled photons. We further develop a multi-port photon emission approach that can efficiently distribute entangled photons into free space in several directions, which can become a useful tool in future quantum networks.

Reference: Z.-Y. Wei et al., arXiv:2011.03919

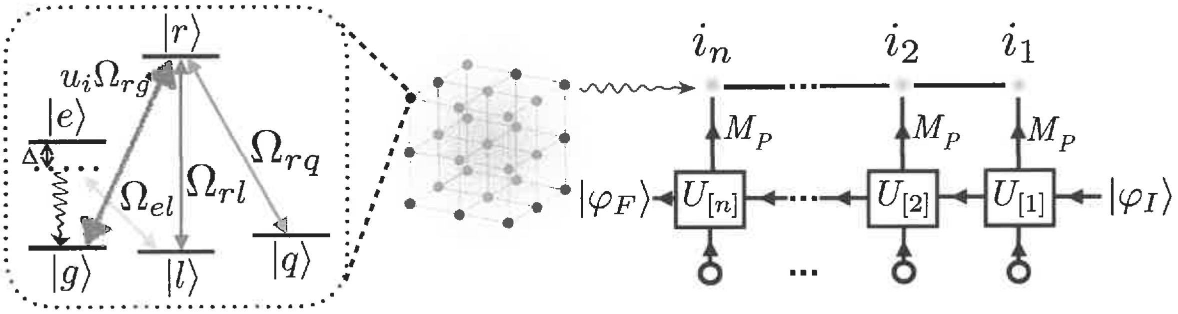

Fig.1 The system and the MPS generation protocol

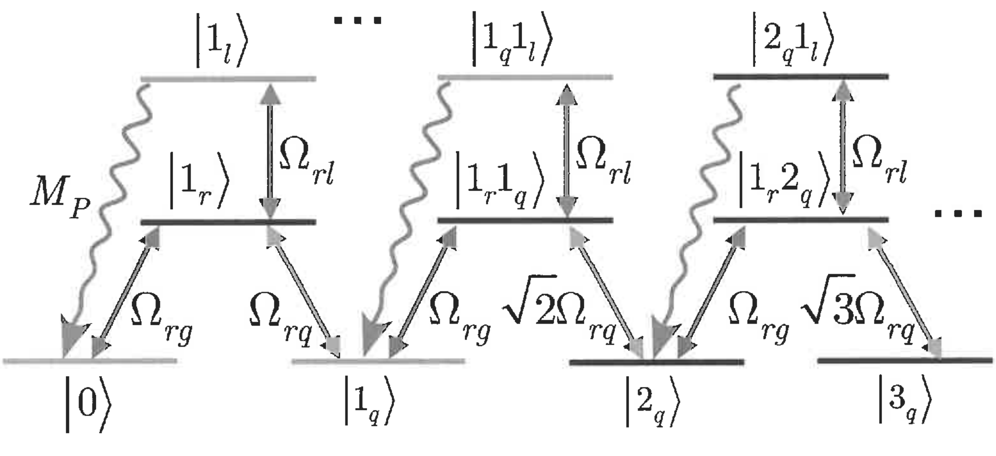

Fig.2 The collective Hilbert space

# Ground state and dynamics of shell-shaped BEC mixtures

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Recently, there has been great interest in the properties of hollow Bose-Einstein condensates (BECs) which can be generated with radio-frequency (rf) dressing [1]. As an alternative method, we propose to realize hollow BECs by utilizing a dual-species mixture. A proper choice of the parameters allows us to create a ground state where one species is in the center and generates a repulsive effective potential for the second species, giving rise to a shell-shaped BEC [2]. In order to explore the main properties of our setup we perform numerical simulations of both the Gross-Pitaevskii and the Bogoliubov-de Gennes equations. In particular, we investigate the spectrum of collective excitations along the transition from a filled to a hollow geometry. In the latter case, a new inner boundary appears and leads to a change of the collective mode spectrum. Since an experimental realization of this system requires perfect collocation of the two species, the experimental parameters are chosen similar to those of the upcoming BECCAL apparatus which will provide a dual-species mixture in microgravity.

This project is supported by the German Space Agency DLR with funds provided by the Federal Ministry for Economic Affairs and Energy (BMWi) under grant number 50WP1705.

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# Quantum Many-Body Scars in Optical Lattices

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The concept of quantum many-body scars has recently been put forward as a route to describe weak ergodicity breaking and violation of the eigenstate thermalization hypothesis. We propose a simple setup to generate quantum many-body scars in a doubly modulated Bose-Hubbard system which can be readily implemented in cold atomic gases. The dynamics are shown to be governed by kinetic constraints which appear via density-assisted tunneling in a high-frequency expansion. We find the optimal driving parameters for the kinetically constrained hopping which leads to small isolated subspaces of scared eigenstates. The experimental signatures and the transition to fully thermalizing behavior as a function of driving frequency are analyzed.

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