BAD HONNEF PHYSICS SCHOOL

ULTRACOLD ATOMS AND MOLECULES

Physikzentrum, Bad Honnef, Germany

August 6 – 12, 2023

Organizers

Carlos Sá de Melo (Atlanta, USA) & Axel Pelster (Kaiserslautern, Gemany)

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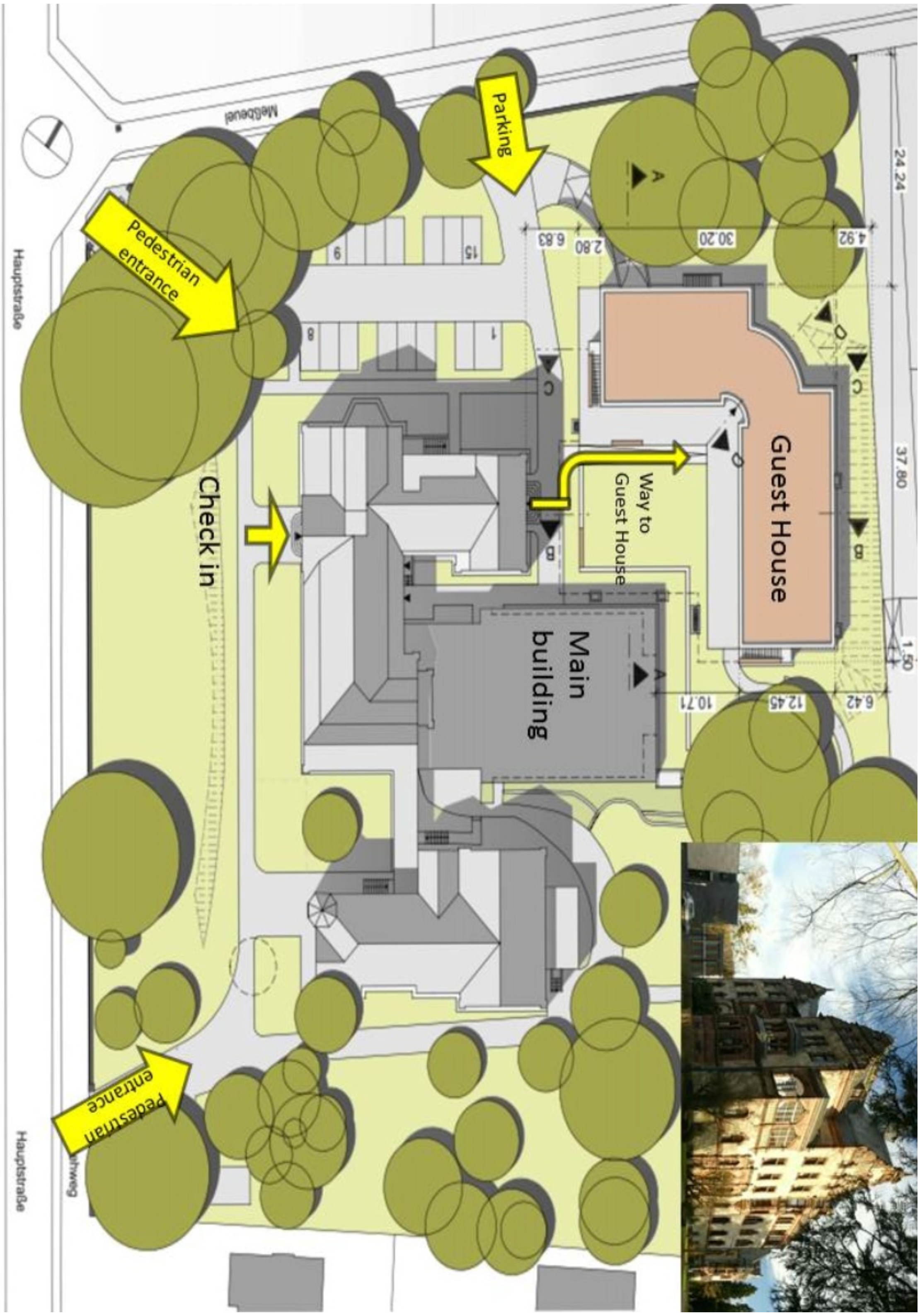
Map of the venue



Venue

Physikzentrum Bad Honnef:

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Physikzentrum Bad Honnef

Preface

Since the first Bose-Einstein condensate of ultracold atomic gases was realized experimentally in 1995, the research field of ultracold quantum gases has been extremely active and has expanded in many different directions. New areas of research are emerging at the borderlines of atomic and molecular physics, quantum optics, and condensed matter physics. However, this rapid evolution in the field of ultracold quantum gases is not adequately reflected in standard curricula. The daily work of a PhD student in both theory and experiment is now so specialized that a broad knowledge about the research field is lacking. To provide a common platform of understanding both theory and experiment in the field of ultracold quantum gases, we organize an international school for physics students. Although the school is mainly intended for PhD students, also interested master students and young postdocs will certainly profit from it. The main goal of the school is to provide a solid introduction to the field of ultracold quantum gases, which will be delivered by internationally recognized experts of the field. Student solutions for the problems, which were mentioned at the lectures, as well as student questions are answered in four plenary sessions. Furthermore, the posters of the participants are presented in four evening sessions.

Together with invited speakers and organizers we expect to have more than 80 participants in presence at the Physics Center in Bad Honnef. Furthermore, participants may also attend the live streamed one-hour presentations at **Zoom** with the link

https://bit.ly/43ryC1G

Note that the times mentioned in the program refer to the current time zone in Germany, i.e. CEST, UTC/GMT +2. Furthermore, all presentations are recorded and are made available shortly afterwards at the platform **Panopto** hosted by RPTU Kaiserslautern-Landau, Germany, with the link

https://bit.ly/3O1AJnd

We wish all participants an interesting school week with many enjoyable discussions.

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Important information for participants and meeting netiquette

Before the meeting:

• Visit **https://zoom.us** and download the software on the computer you will use to join the meeting. It is free of charge for participants!

• Make sure that the computer you use has a good camera and microphone or headset. Test both before the meeting!

• Make sure that you only use ONE computer per room to join the meeting to avoid echoes and interferences!

• The virtual meeting room will be open during the program according to German time. You can visit it before the official start of the sessions to familiarize yourself with its layout and functions.

• Further information on the system and its functionalities is available on the following website **https://support.zoom.us/hc/en-us**

Share details on the meeting with other interested group members. We welcome every participant, also those who were not registered for the original on-site meeting! During the meeting:

• Click on the link given in the preface or open the Zoom software, which is free of charge, on your computer, select the option "join a meeting"/"An Meeting teilnehmen" and enter the **Meeting ID: 968 7321 4778** with **Passcode: 383719**

• Select a username that tells other participants who you are and which institution you are affiliated with. For example: "Axel Pelster (TU Kaiserslautern)".

• Your audio and video will be turned off when you join the meeting initially. You may turn both on and off on your own. During the talks all microphones and cameras will be turned off except for the current speaker.

• The scientific organizers will turn on sound and camera for each presenter when their talk slot commences. Open your presentation on your computer and use the "Share your Screen" option so that the audience may see your slides.

• If you want to ask a question please use the "Raise your hand" icon. The scientific organizers will enable your microphone and camera so that you can ask your question once it is your turn.

• Please remember the time limits for presentations: 50 minutes talk + 10 minutes discussion

Program

Bad Honnef Physics School
Ultracold Atoms and Molecules
Physikzentrum, Bad Honnef
August 6-12, 2023

Sunday, August 6

14:00-18:30	Arrival and registration
18:30-20:00	Dinner
20:00-22:00	*Meet and Greet*

Monday, August 7

07:30-08:45	Breakfast
08:45-09:00	Carlos Sá de Melo (Atlanta, USA): *Opening and welcome*
09:00-10:00	Nathan Lundblad (Lewiston, USA): *Ultracold atomic physics in microgravity: Survey and rf-dressing techniques*
10:00-10:30	Coffee break
10:30-11:30	Tilman Pfau (Stuttgart, Germany): *Ultralong-range Rydberg molecules: The past and future of neutral ultralong-range molecules*
12:00-13:30	Lunch
13:30-14:00	*Questions and Answers/Plenary Discussion 1*
14:00-15:00	*Plenary for Poster Sessions 1 & 2 (Poster Numbers 1-24)*
15:00-15:30	Coffee break
15:30-16:30	Michael Fleischhauer (Kaiserslautern, Germany): *Rydberg-atom physics and technology – Part 1*
16:30-17:00	Coffee break
17:00-18:00	Lauriane Chomaz (Heidelberg, Germany): *Few-body physics with magnetic dipolar atoms in ultracold gases*
18:30-20:00	*Dinner*
20:00-21:00	*Poster Session 1 (Poster Numbers 1-12)*

Bad Honnef Physics School
Ultracold Atoms and Molecules
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Tuesday, August 8

07:30-09:00	Breakfast
09:00-10:00	Nathan Lundblad (Lewiston, USA):
	Ultracold atomic physics in microgravity: Bubble dynamics and outlook
10:00-10:30	Coffee break
10:30-11:30	Tilman Pfau (Stuttgart, Germany):
	Ultralong-range Rydberg molecules:
	Ultralong-range molecular ions under a pulsed ion microscope
12:00-13:30	Lunch
13:30-14:00	*Questions and Answers/Plenary Discussion 2*
14:00-15:00	*Working Groups 1*
15:00-15:30	Coffee break
15:30-16:30	Michael Fleischhauer (Kaiserslautern, Germany):
	Rydberg-atom physics and technology – Part 2
16:30-17:00	Coffee break
17:00-18:00	Lauriane Chomaz (Heidelberg, Germany):
	Many-body physics with magnetic dipolar atoms in ultracold gases
18:30-20:00	*Dinner*
20:00-21:00	*Poster Session 2 (Poster Numbers 13-24)*

Wednesday, August 9

07:30-09:00	Breakfast
09:00-10:00	Tilman Esslinger (Zurich, Switzerland):
	The basics of topological pumping
10:00-10:30	Coffee break
10:30-11:30	Helmut Ritsch (Innsbruck, Austria):
	Quantum gas cavity QED – Fundamentals
12:00-13:30	Lunch

13:30-14:00	*Questions and Answers/Plenary Discussion 3*
14:00-15:00	*Plenary for Poster Sessions 3 & 4 (Poster Numbers 25-47)*
15:00-15:30	Coffee Break
15:30-16:30	Jacques Tempere (Antwerpen, Belgium):
	Ground state properties of Fermi superfluids
	in the BEC-BCS crossover
16:30-17:00	Coffee Break
17:00-18:00	Philipp Preiss (Munich, Germany):
	Pairing and Superfluidity in Ultracold Fermi Gases – Part 1
18:30-20:00	*Dinner*
20:00-	Socializing

Thursday, August 10

07:30-09:00	Breakfast
09:00-10:00	Tilman Esslinger (Zurich, Switzerland):
	The art of topological pumping
10:00-10:30	Coffee break
10:30-11:30	Helmut Ritsch (Innsbruck, Austria):
	Quantum gas cavity QED – Applications
12:00-13:30	Lunch
13:30-18:30	Excursion
18:30-20:00	Dinner
20:00-21:00	*Poster Session 3 (Poster Numbers 25-36)*

Friday, August 11

07:30-09:00	Breakfast
09:00-10:00	André Eckardt (Berlin, Germany):
	Floquet engineering in isolated quantum systems
10:00-10:30	Coffee break

10:30-11:30	Päivi Törmä (Aalto, Finland):
	Bose-Einstein condensation and topological photonics
	with plasmonic lattices – Part 1
12:00-13:30	Lunch
13:30-14:00	*Questions and Answers/Plenary Discussion 4*
14:00-15:00	*Working Groups 2*
15:00-15:30	Coffee break
15:30-16:30	Philipp Preiss (Munich, Germany):
	Pairing and Superfluidity in Ultracold Fermi Gases – Part 2
16:30-17:00	Coffee break
17:00-18:00	Jacques Tempere (Antwerpen, Belgium):
	Collective excitations, vortices and solitons
	in the BEC-BCS crossover
18:30-20:00	Dinner
20:00-21:00	*Poster Session 4 (Poster Numbers 37-47)*

Saturday, August 12

07:30-09:00	Breakfast
09:00-10:00	Päivi Törmä (Aalto, Finland):
	Bose-Einstein condensation and topological photonics
	with plasmonic lattices – Part 2
10:00-10:30	Coffee break
10:30-11:30	André Eckardt (Berlin, Germany):
	Floquet engineering in open quantum systems
11:30-11:45	Axel Pelster (Kaiserslautern, Germany)
	Concluding remarks
12:00-13:30	Lunch
13:30-	Departure

Speaker Abstracts

Few-body and many-body physics with magnetic dipolar atoms in ultracold gases

Lauriane Chomaz

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Ultracold quantum gases provide a pristine platform to study few-body and many-body quantum phenomena with an exquisite degree of control. The achievement of quantum degeneracy in gases of atoms with large magnetic dipole moments in their electronic ground states has opened new avenues of research in which long-range anisotropic dipole-dipole interactions play a crucial role. In this series of two lectures, I will give an overview of experimental progress focusing on few-body and many-body phenomena, respectively.

In the first lecture, I will begin by outlining the peculiar atomic properties of highly magnetic atoms and how this has enabled their cooling. I will then review important aspects of dipolar two-body scattering. I will discuss the intrinsic consequence of the long-range and anisotropic character of the interaction, review important features of both elastic and inelastic dipolar scattering, and present the experimental consequences of these properties. Finally, I will discuss the specificity of short-range scattering and its tunability between magnetic atoms. The complex atomic structure and the large dipolar moments of these atoms lead to a dense spectrum of so-called Feshbach resonances in the s-wave scattering. This reveals chaotic behavior, prevents proper prediction, but enables tunability.

In the second lecture I will focus on many-body effects arising from dipole-dipole interactions in quantum gases of magnetic atoms. I will focus mainly on polarized Bose gases. In this case, the dipolar interactions compete with the conventional short-range contact interactions, the strength of which can be tuned by the Feshbach resonances. I will discuss many-body effects occurring at the mean-field level, including magnetostriction, anisotropy of elementary excitations and superfluid character, and rotonization of the excitation spectrum. I will then discuss the limits of the mean-field regime, i.e. the mean-field instabilities, the potential collapse dynamics, and, specific to the most magnetic atoms, the beyond-mean-field stabilization effect arising from the quantum fluctuations themselves. The latter effect has led to the discovery of novel many-body quantum phases, including liquid-like droplets, droplet crystals, and supersolids, a paradoxical phase of matter that simultaneously exhibits solid and superfluid orders. I will review the experimental observations of such exotic states and their properties. Finally, I will draw a larger picture of other implications of dipolar effects in magnetic quantum systems, including the rich cases of lattice physics, spinfull dipoles, and reduced dimensions.

References:

[1] L. Chomaz, I. Ferrier-Barbut, F. Ferlaino, B. Laburthe-Tolra, B. L. Lev, and T. Pfau, *Dipolar physics: a review of experiments with magnetic quantum gases*, Rep. Prog. Phys. **86**, 026401 (2023).

Floquet engineering in isolated and open quantum systems

André Eckardt

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Driving a quantum system out of equilibrium can provide a challenge for its theoretical description. However, it also offers the opportunity to control its state and properties beyond the strict constraints of thermal equilibrium. Of particular interest are time-periodically driven (aka Floquet) systems. Thanks to their discrete translation symmetry in time, they are described by a theoretical framework, known as Floquet theory, which preserves some of the structures known from the description of undriven quantum systems. For instance, Floquet systems possess quasi-stationary states, called Floquet states, with a periodic time-dependence and their stroboscopic evolution in steps of the driving period is described by an effective time-independent Hamiltonian. These properties can be used to understand their behavior, at least in certain limits, and to design schemes for controlling quantum systems via periodic driving. The latter is known as Floquet engineering.

In the first lecture, I will give an intuitive introduction to Floquet engineering in isolated systems, using the examples of a driven double well and the realization of artificial magnetic fields in a tight-binding lattice. I will, moreover, provide an introduction to basic concepts of quantum Floquet theory and discuss how driving-induced heating challenges Floquet engineering.

In my second lecture, I will then consider open Floquet systems, i.e. periodically driven systems in contact with a thermal bath. Focusing on the limit of ultraweak system-bath coupling, where we find the system to be described by a rate equation, I will argue that these systems generically approach non-equilibrium steady states (NESS). In contrast to equilibrium states, these NESS break detailed balance. This leads to the idea of dissipative Floquet engineering, where both drive and environment are used to engineer NESSs. I will illustrate this concept by discussing generalized non-equilibrium Bose condensation.

References:

[1] A. Eckardt and E. Anisimovas, *High-frequency approximation for periodically driven quantum systems from a Floquet-space perspective*, New J. Phys. **17**, 093039 (2015).

[2] A. Eckardt, Colloquium: *Atomic quantum gases in periodically driven optical lattices*, Rev. Mod. Phys. **89**, 011004 (2017).

[3] D. Vorberg, W. Wustmann, H. Schomerus, R. Ketzmerick, and A. Eckardt, *Non-equilibrium steady states of ideal bosonic and fermionic quantum gases*, Phys. Rev. E **92**, 062119 (2015).

[4] A. Schnell, L.-N. Wu, A. Widera, and A. Eckardt, *Floquet-heating-induced Bose condensation in a scar-like mode of an open driven optical-lattice system*, Phys. Rev. A **107**, L021301 (2023).

The basics of topological pumping

Tilman Esslinger

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Pumps are transport mechanisms in which directed currents result from a cycling evolution of the potential. Thouless pointed out that pumping can have topological origin when considering the motion of quantum particles in spatially and temporally periodic potentials. It is the dynamic counterpart to the quantized Hall effect. In this lecture I will give an introduction to the basic idea of topological pumping and show how this fundamental concept is implemented in cold atoms experiments.

The art of topological pumping

Tilman Esslinger

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The fate of topological transport in the presence of interactions between particles raises fundamental questions on the role of geometry in quantum many-body physics. Advances in topological pumps have now made it possible to address these questions in the highly controlled setting of cold atoms. In this lecture insights from recent experiments will be discussed. By tuning the interactions in a Thouless pump, the breakdown point of pumping was studied. By pumping over long distances in an external potential, topological boundaries – signified by a reversal of the quantised Hall drift – were observed and studied, including an interaction induced boundary.

Rydberg-atom physics and technology

Michael Fleischhauer

Fachbereich Physik und Forschungszentrum OPTIMAS,
Rheinland-Pfälzische Technische Universität Kaiserslautern-Landau, Germany
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Due to their strong and long-range dipole-dipole interactions, Rydberg atoms have become a versatile experimental platform to study equilibrium and non-equilibrium dynamics of interacting spin systems both in unitary and dissipative settings. After discussing different fundamental interactions between Rydberg atoms, including Rydberg blockade and antiblockade, Ising and XY interactions, as well as XY interactions with dynamical gauge fields, I will review suggested and experimentally implemented realizations of various many-body quantum spin Hamiltonians and dissipative models using arrays of trapped Rydberg atoms and in gases. I will discuss some specific and very different applications in detail. This includes the classical facilitation dynamics of Rydberg excitations in the presence of dissipation, resembling epidemic models with an absorbing-state phase transition and self-organized criticality. Furthermore I will discuss the realization of topological lattice models and quantum spin liquids.

Ultracold atomic physics in microgravity: Survey and rf-dressing techniques

Nathan Lundblad

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Moving ultracold atomic physics investigation into microgravity affords a variety of experimental opportunities, including the potential for increased free interaction time, reduced temperature via freefall-enabled cooling schemes, and the elimination of gravitational tilt mgz on atomic ensembles. Here I review physics that has been and is being explored in microgravity, including with the NASA Cold Atom Laboratory (CAL) aboard the International Space Station. I also will lay out basic theoretical framework and modeling approaches for radiofrequency dressing techniques, which are key to using microgravity cold-atom machines to generate novel structures in microgravity that are otherwise inaccessible in the presence of gravity.

Ultracold atomic physics in microgravity: Bubble dynamics and outlook

Nathan Lundblad

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Ultracold atomic physics experiments historically have been driven by the exploration of the parameter space of geometry, topology, interactions, and temperature. Here I survey the motivation and recent data regarding a particular new window of geometry and topology: ultracold bubble dynamics; that is, exploration of the physics of Bose-Einstein condensates (or nearly condensed samples) confined to the surface of an ellipsoid. will review general theoretical understanding (much of which has been achieved in the last few years), review bubble imaging/data from microgravity apparatus, delineate current limitations and challenges, and discuss open questions and next-generation experimental plans.

Ultralong-range Rydberg molecules

Tilman Pfau

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In Part 1 we review the history of atom – electron scattering, which is the basis for the formation of ultralong-range Rydberg molecules which were first proposed in 2000 and observed in 2009. Various regimes for the formation of molecular potential curves due to this quantum scattering will be discussed, including so-called “Trilobite” and “Butterfly” molecules. The formation of trimers, polymers and the smooth transition to density shifts and broadenings of Rydberg lines will close the cycle back to the first historic experiments by Amaldi and Segre in 1934 that lead to the development of quantum scattering theory by Enrico Fermi.

In Part 2 we will discuss the recent discovery of a bound state between an ultracold ion and a Rydberg atom based on a flipping dipole interaction. This molecule was studied using a pulsed ion microscope which allowed the direct measurement of the shape of the molecule, its binding length and the vibration around the equilibrium position. And as an outlook we will close this Part with yet another mechanism that can lead to bound states: namely the interaction between a Rydberg electron and a dipolar molecule.

Pairing and superfluidity in ultracold Fermi gases

Philipp Preiss

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The experimental study of interacting Fermi systems is one of the great success stories of quantum simulation. As a paradigmatic model system, two-component Fermi gases in various regimes of attractive interactions explain the phenomenon of superfluidity and guide our intuitive understanding of collective effects in electronic systems. Yet, clean observations of the underlying physics remain challenging in solid-state systems due to their experimental complexity.

Cold atomic gases offer the opportunity to experimentally study the BCS-BEC crossover from weak to strong attractions in a very clean setting: Ultracold Fermi gases can be realized in a variety of geometries and, most significantly, the interaction strength can be tuned using Feshbach resonances. This versatility has enabled the experimental study of fermionic pairing and superfluidity in many circumstances, ranging from first qualitative observations to highly quantitative measurements of transport and excitation spectra.

In these lectures, I will review the physics of ultracold Fermi gases, introduce the cold atom toolbox for their production and observation, and describe some of the key experiments in the field. I will conclude with an overview over experiments done at Heidelberg University pertaining to the fate of fermion pairing in the small particle number limit.

Quantum gas cavity QED – Fundamentals

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As matter influences the propagation of light waves, light can be used to manipulate matter wave dynamics. In typical experiments as optical traps or cavity QED one of the two effects dominates. However, confining cold atoms in a high finesse optical resonator creates a novel situation, where particles and photons are dynamically coupled by momentum and energy exchange on equal footing. The particles act as a dynamic refractive index for the light waves, which can form structured optical potentials guiding the particles motion, see Fig. 1.

The zero temperature limit of an atomic BEC in an optical lattice trapped in a high Q cavity represents a genuine quantum model system for quantum optics with quantum gases. Due to the dynamical entanglement of atomic motion and light in a weakly coupled system, a measurement of the scattered light detects atomic quantum statistics properties and projects the many-body atomic state to corresponding eigenstates. Similarly measurements on the atoms exhibit nonclassical properties of the light.

For larger interaction strength the light induced long-range coupling of the particles can induce regular crystallization of the particles bound by light and the appearance of new exotic quantum phases with short- and long-range order as found in a supersolid. Recently the analogous appearance of density wave order was also seen in an interacting quasi degenerate Fermi gas.

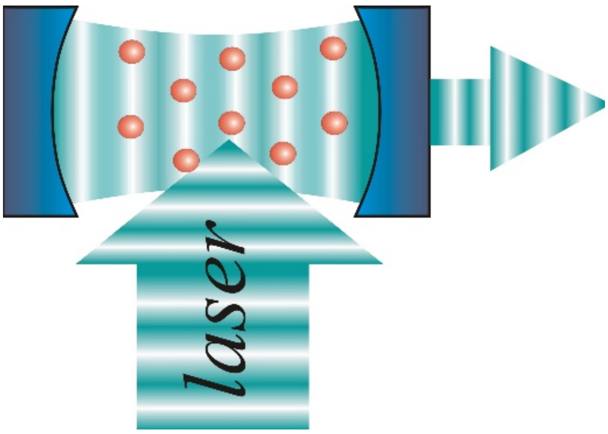

Fig. 1: Generic experimental set up for quantum gas cavity QED.

References:

[1] H. Ritsch, P. Domokos, F. Brenneke, and T. Esslinger, Rev. Mod. Phys. **85**, 553 (2013)

[2] F. Mivehvar, F. Piazza, T. Donner, and H. Ritsch, Adv. Phys. **70**, 1 (2021)

Quantum gas cavity QED – Applications

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We study emerging ordered quantum phases of ultracold quantum gases in multimode optical cavities to synthesize dynamic gauge fields, spin-orbit coupling, or long-range spin interactions. Quantum particles coupled to field modes of optical resonators hybridize with cavity photons, which collectively couple spin and motional dynamics. By help of multiple polarization modes one is able to engineer spin-dependent dynamic optical potentials as well as tailored long-range density and spin-spin interactions towards a versatile analogue quantum simulator. The emerging spin- and density-ordered complex quantum phases can often be characterized in situ via properties of the cavity output spectra. For larger interaction strength the light-induced long-range coupling of the particles can induce regular crystallization of the particles bound by light and the appearance of new exotic quantum phases with short- und long-range order as found in a supersolid or in quasicrystals. Applications range from improved quantum sensing to quantum optimization.

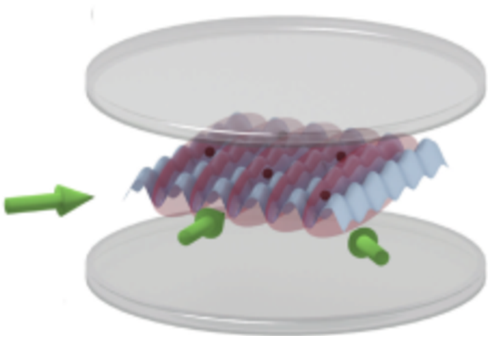

Fig.: Cavity QED with lattice quantum gases.

References:

[1] F. Mivehvar, F. Piazza, T. Donner, and H. Ritsch, Adv. Phys. **70**, 1 (2021)

Ground state properties of Fermi superfluids in the BEC-BCS crossover

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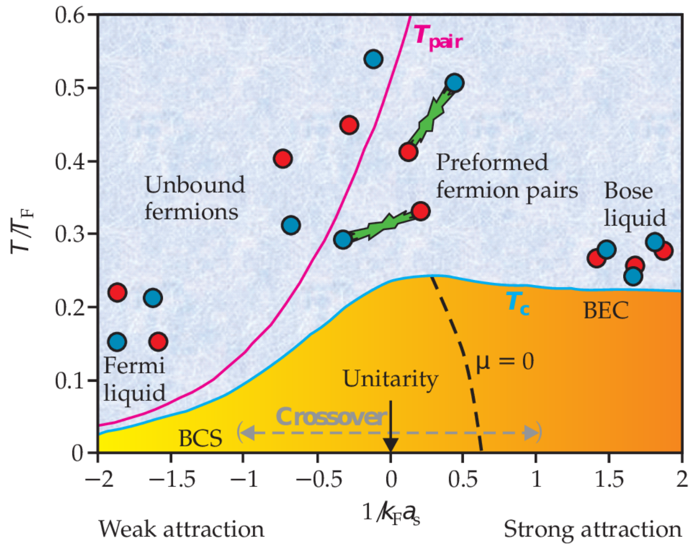
To achieve superfluidity in an ultracold Fermi gas, atoms need to pair up, and a pair condensate has to form. Depending on the interaction strength between the atoms, the pairs can be tightly bound and form a Bose-Einstein condensate (BEC), or weakly bound and form a Bardeen-Cooper-Schrieffer superfluid (BCS). Using Feshbach resonances the interaction strength can be modified, and the entire crossover region between the BEC and BCS regimes can be explored. We start this lecture by reviewing the experimental efforts leading to the creation of a superfluid Fermi gas, and discuss the early observations made regarding its properties. In the experiments, many parameters besides the interaction strength can be tuned, such as dimensionality, temperature, and the population imbalance between the two (hyperfine) spin states that pair up. A theoretical description that is capable of taking into account these adaptable parameters is the path integral or functional integral approach to quantum field theory. This will be the focus of the first lecture. After an explanation of the method in general, it is applied to the ultracold Fermi gases in order to obtain phase diagrams that distinguish the superfluid state from the normal state and reveal the effect of parameters such as the population imbalance (such as the appearance of exotic superfluid phases where pairs condense in a state with non-zero center of mass momentum).



Phase diagram for fermionic superfluids [1].

References:

[1] C. A. R. Sá de Melo, Physics Today, Oct., 45 (2008).

Collective excitations, vortices and solitons in the BEC-BCS crossover

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The superfluid properties of ultracold Fermi gases depend on the excitations of the pair condensate. For Bose-Einstein condensates (BECs), the dominant excitations are sound waves - phase excitations of the order parameter, whereas in the Bardeen-Cooper-Schrieffer (BCS) case, Bogoliubov excitations corresponding to broken Cooper pairs determine the low-temperature properties. For Bose-Einstein condensates, vortices can be detected through the dip in the density at the vortex core, whereas in the BCS case the vortex cores fill up with normal state fermions. In this lecture, we explore the excitations and how they transform throughout the BEC-BCS crossover. We investigate how the collective excitations (Anderson-Bogoliubov 'phase' modes and Higgs-like 'amplitude modes) couple, and what their interplay is with the continuum of broken Cooper pairs. As in the previous lecture, we use the functional integral approach, shown to be equivalent to Anderson's RPA approach for the superfluid. To study long-wavelength, low-energy excitations, an effective field theory can be set up, allowing to study excitations such as vortices and solitons. We'll show that these behave quite differently in the BEC and BCS regimes in what regards their dynamics and interactions.

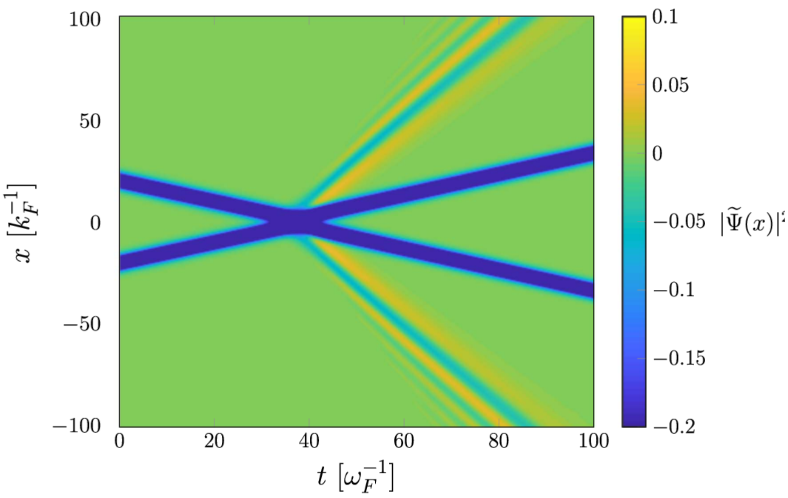

Fig.: The time evolution of the pair density shows two colliding solitons in the BCS regime, generating Anderson-Bogoliubov phonons [1].

References

[1] W. Van Alphen, G. Lombardi, S.N. Klimin, J. Tempere, New J. Phys. **20**, 053052 (2018).

Bose-Einstein condensation and topological photonics with plasmonic lattices

Päivi Törmä

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Arrays of plasmonic nanoparticles, so-called plasmonic lattices, when combined with an emitter material (gain medium), provide a versatile platform for studies on light-matter interaction in the nanoscale, including collective coherent phenomena as well as topological photonics. We have experimentally realized a new type of condensate: a BEC of hybrids of surface plasmons and light in a nanoparticle array, with unique polarization and coherence properties [1-4]. We observe the BEC both in the weak [1] and strong [2-4] light-matter coupling regimes. The spatial and temporal coherence show a change from Gaussian/exponential to power law decay at the transition from polariton lasing to BEC [4]. In the lasing regime, we have observed bound states in continuum (BIC) modes with different topological charges [5,6]. By tuning the size of a hexagonal unit cell, we can realize lasing that shows transitions between states of topological charges zero, one, and two [6]. We found that the transitions are driven by losses, determined by the geometric structure of the modes of different topological charges. Recently, we have experimentally observed non-zero quantum metric and Berry curvature along the diagonals of the Brillouin zone of a square lattice of gold nanoparticles [7]. By a theoretical analysis, we show that the Berry curvature originates solely from non-Hermitian effects [8]. In this talk, an introduction to these topics, and a discussion of the key results will be given.

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Poster Abstracts

Dynamics controlled by Floquet state occupation probabilities in a driven parabolic optical lattice

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Ultracold atoms in a one-dimensional optical lattice and a parabolic trap potential exhibit significantly distinct and rich dynamics when subjected to external periodic driving [1,2]. The dynamics depend upon the initial phase of the driving field. By tracing the Floquet states of the system, which resemble the states of a quantum pendulum, a resonant pendulum, and a chaotic pendulum, we observe that the sudden switch-on of the drive with different phases causes a temporal shift in the Floquet states, resulting in varying occupation probabilities. We find that the distinct nature of the Floquet states populated at each phase governs the dynamical evolution of the initial state. These results are supported by an analytical theory based on the resonance approximation and by comparing the Husimi Q-function of the Floquet states with the stroboscopic Poincaré map.

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Controlling Anderson localization of a Bose-Einstein condensate via spin-orbit coupling and Rabi fields in bichromatic lattices

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We perform theoretical studies of the interplay between disorder, spin-orbit coupling (SOC), and Rabi fields, and show that both SOC and Rabi fields can be used to dramatically control the degree of Anderson localization of a Bose-Einstein condensate in bichromatic lattices. We obtain ground-state phase diagrams in the SOC and Rabi field plane for different values of disorder strength and use realistic experimental parameters compatible with ^{39}K.

We find cases of fixed disorder and SOC (Rabi field), where the Rabi field (SOC) reduces the threshold for localization and controls the localization length. We also show regimes of fixed disorder and Rabi field, where the extent of the ground-state wave function is periodic in the SOC, leading to alternating regions of stronger and weaker localization as SOC changes. Lastly, we describe examples of fixed disorder and SOC, where tuning the Rabi field leads to a strong localization peak.

Relative dynamics of quantum vortices and massive cores in binary BECs

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We study vortices with massive cores [1,2] in binary mixtures of Bose-Einstein condensates. We consider the case of a simple 2D disc geometry. Taking up the work of Richaud et al. [3,4], we introduce a point-vortex model where quantum vortices in the majority species are coupled to the corresponding core masses, i.e. local peaks of the minority species. The point-like dynamics is obtained via a variational Lagrangian approach. In parallel, we validate our analytical results via the numerical resolution of two coupled Gross-Pitaevskii equations. Conversely to the previous works [3,4], where a vortex centre was assumed coincident with the centre of its massive core, we instead introduce a more refined dynamical model: here, the two objects are described by independent sets of dynamical variables and coupled by a harmonic term. Consequently, we study the effect of the new degree of freedom on the vortex-mass relative motion and average dynamics.

As already observed, the first striking effect of the second species is a change of trajectory. Whereas a massless vortex in a 2D disc moves of uniform circular motion, in presence of a second species some radial oscillations may arise. Specifically, our new model brings to a more articulated normal mode analysis, and improves the previous model thanks to the depedency of the small oscillations on the inter-species coupling parameter g_{ab}. This dependency could not be appreciated in the previous model as it did not include the parameter g_{ab} at all. On the other hand, we confirm that, within the physical ranges of the coupling parameters, there is no significant relative motion of the vortex with respect to its core mass.

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Customized polarization-maintaining fiber for a MOT beam in a high-resolution objective

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Ultracold atoms in optical lattices offer a versatile tool to understand the behaviour of particles on a quantum scale. In order to observe these phenomena, high resolution imaging is crucial. The imaging system including a custom-made objective must fulfill two competing requirements: provide high-resolution imaging and create a large MOT beam. We solve this by placing a polarization-maintaining fiber inside the objective which provides circular polarized light. To do so, we use fiber splicing which enables us to create a quarter-waveplate inside the fiber for the polarization and imprint a lens on the fiber tip creating an effective numerical aperture of 0.3. We plan to install this setup in our experimental apparatus for lithium quantum gases, which we currently image via a matter-wave microscope protocol. Combining this with the high-resolution objective, we aim to achieve single-atom resolution with the prospect of probing few to many-body physics.

Probing dynamics and effective interactions in optically trapped photonic condensate

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The bosonic nature of both polaritons and photons allows them to achieve Bose-Einstein condensation (BEC), forming a macroscopically coherent state. Polariton and photon condensates are intensively studied systems, where the nature of equilibrium and non-equilibrium BEC is explored. The distinguishing property of these systems is the presence of intrinsic particle losses resulting from the photon escape from the cavity. Therefore, an external pump is needed to compensate for these effects, which results in a dynamical gain-loss balance in the system.
In high density regime, the strong coupling between excitons and photons is lost, and the system undergoes a crossover into the weak coupling, where one could observe a photonic condensate. Exciton polaritons interact with each other because of the excitonic component, especially when formed into a BEC. However, interactions inside the photonic condensate may originate from nonlinearities of the material itself, e.g. nonlinear refractive index.
In this work, by using a GaAs-based microcavity sample, we experimentally study photon-photon interactions by measuring the dispersion of the photonic condensate in an optical trap using the time-resolved spectral tomography on a streak camera. The sample is excited with the pumping laser shaped into a ring to obtain an effective potential created by the photo-excited excitonic reservoir. In the weak coupling regime, the character of the trap changes and the effective potential results from local changes of the cavity's refractive index induced by excessive carriers, which act at the same time as the photon gain. At strongest pumping powers - which correspond to the highest particle densities in the system - modification of the photon condensate dispersion is clearly visible, which can be interpreted as a result of effective photon-photon interactions. The photonic condensate is driven-dissipative in nature, hence in the experiment we observe a dissipative Bogoliubov spectrum. Our results are important in further understanding of the nature of photonic condensates.

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Investigating induced and spontaneous transitions between discrete time crystal phases

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We demonstrate spontaneous breaking of discrete time-translational symmetry in a driven superfluid quantum gas [1]. The symmetry of the system is spontaneously broken into one of the two Z_2 symmetrical stable solutions, differing by a phase of π. To induce dynamics between the two phases, we can utilize a phase ramping protocol [2] or attempt to engineer a potential landscape that causes a transition in an experimentally observable period. Employing a non-destructive imaging technique, we study the dynamics of our system on a microsecond scale over an extended period [3]. These results can lead to further evaluation of the stability of discrete time crystals against external perturbations and open a new window of opportunity for studying non-equilibrium phases of matter.

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Mattter wave optics for imaging of ultracold atoms in a highly tunable multifrequency optical lattice

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The goals of improving existing and developing new techniques of engineering and probing cold atom systems are naturally always at the frontier of current research in this field. On this poster, I present two important additions to the cold atom toolbox that have recently been realized in our group. The multifrequency lattice, implemented by the interference of several sidebands imprinted on the lattice beams, provides highly dynamic control over the system's geometry.

The second contribution, which was implemented to achieve very high spatial resolution without sacrificing depth of focus due to high numerical aperture, is the newly introduced quantum gas magnifier.

Here, a quarter-period evolution in a harmonic potential, after release from the optical lattice, maps the real space to the momentum distribution, which can subsequently be accessed by ToF imaging.

In the future, the combination of both new methods is anticipated to allow the engineering and probing of such interesting systems as Floquet topological insulators or quasicrystal lattices.

Optimizing optical potentials with physics-inspired learning algorithms

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We present our experimental and theoretical framework, which combines a broadband superluminescent diode with fast learning algorithms to provide speed and accuracy improvements for the optimization of one-dimensional optical dipole potentials, here generated with a digital micromirror device. To characterize the setup and potential speckle patterns arising from coherence, we compare the superluminescent diode to a single-mode laser by investigating interference properties. We employ machine-learning tools to train a physics-inspired model acting as a digital twin of the optical system predicting the behavior of the optical apparatus including all its imperfections. Impleme-nting an iterative algorithm based on iterative learning control we optimize optical potentials an order of magnitude faster than heuristic optimization methods. We compare iterative model-based “offline” optimization and experimental feedback-based “online” optimization. Our methods provide a route to fast optimization of optical potentials, which is relevant for the dynamical manipulation of ultracold gases.

Generation of reconfigurable 2D tweezer array by spatial light modulator for neutral atom quantum computing

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Spatial light modulators (SLM) are a useful tool for beam shaping in cold atom experiments. Phase patterns to diffract into a desired trapping pattern and to correct optical aberration can be superimposed and concurrently displayed at the SLM. We present a SLM-camera system for generating an array of single-atom traps in an atom-cavity experiment. The principal system is an array of ^{87}Rb atoms coupled to a high finesse optical cavity. SLM-generated traps will hold atom qubits in place while the atoms await transport into the cavity. We will use this set-up to perform cavity-enhanced readout of atom qubits for fast error diagnosis. The main optics for trap generation are the SLM, which shapes an incident Gaussian beam, followed by an aspheric lens, which focuses the beam down to tweezer traps. We first image test arrays to correspond angular deflection at the SLM to spatial displacement in the trapping plane. We then specify a trap geometry in realspace coordinates of the trapping plane and use the weighted Gerchberg-Saxton algorithm to calculate a phase pattern to display at the SLM. The algorithm incorporates camera images to reach trap power uniformity of 95%. We also use the SLM and camera to measure wavefront distortion. We program the SLM to deflect two areas of the incident beam to the same point in the trapping plane and measure the interference fringes to detect phase differences along the beam wavefront. We then apply a phase correction at the SLM and observe significant improvement in array uniformity and intensity.

Long-lived squeezed ground states in a quantum spin ensemble

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Spin-nematic squeezing has been generated in a spin-1 Bose-Einstein (BEC) condensate using several methods that exploit collisional interactions using deep magnetic quenches near the second-order continuous quantum phase transition, parametric/Floquet excitation, and adiabatic and short-cut methods to generate squeezed ground states. Here, we explore new methods that exploit the exceptional controllability of the system Hamiltonian. We generate spin squeezed ground states in an atomic spin-1 Bose-Einstein condensate that is tuned near the quantum critical point (QCP) between the polar and ferromagnetic quantum phases of the interacting spin ensemble. In contrast to methods that prepare non-equilibrium atomic squeezed states by quenching through a quantum phase transition (QPT), squeezed ground states are time-stationary and remain squeezed for the lifetime of the condensate.

Towards ultracold fermions in an optical Kagome lattice

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In the electronic band theory of solids, the curvature of a band is related to the density of states and effective mass of charge carriers. Bands with extremely low dispersion – ‘flat bands’ – enhance the effects of interactions and can lead to correlated electronic states that include superconductivity, magnetic order, and charge-density order. In our lab, we use a bichromatic triangular superlattice to generate a Kagome lattice, which experiences geometrical frustration leading to a flat band in its ground state manifold. Here, we report progress towards introducing the fermionic species ^{40}K into the optical Kagome lattice and additional upgrades to our setup. Future research directions include flat-band ferromagnetism and fermionic superfluidity.

Search for the enhanced elastic 3-body interactions at vanishing scattering length in BEC of ^{7}Li

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A Bose-Einstein condensate in the mean field limit is described by a Gross-Pitaevskii equation with a non-linear term due to two-body interactions. Other non-linear interactions may lead to exotic and unexplored quantum phases of matter. Here we present a system of ^{7}Li atoms with potential of having 3-body interactions as the dominant energy scale. This is due to a possible enhancement of the 3-body term caused by numerous reasons that are presented. In order to access this regime, a highly stable magnetic field at about 850 G is required. This would be achieved by an innovative method of using permanent magnets for producing the Feshbach field. We portray the obstacles in successfully building such a system and discuss a window in the experimental parameters space where it is possible to overcome them.

N impenetrable particles bouncing on a mirror: discrete time crystals

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Spontaneous time-translation symmetry breaking had not attracted much attention until Wilczek [1] introduced the concept of time crystals. Despite this particular realization being prohibited by the ,,no-go'' theorem [2], the idea inspired a new version of time crystals, i.e. the discrete time crystals (DTCs) [3]. In general, a DTC is a periodically driven quantum many-body system that spontaneously breaks the discrete time-translational symmetry of the Hamiltonian due to particle interactions and starts evolving with a period s-times longer than the period of the external driving. In our previous works, we developed a theoretical basis for the realization of DTCs in the ultra-cold atom platform, i.e. a Bose-Einstein condensate (BEC) of weakly interacting bosonic atoms bouncing resonantly on a periodically driven atom mirror in a 1D space [3-5]. In our present work we take that idea further, and consider a collection of BECs. Here we will present the first stage of our analysis. It constitutes a classical basis for quantum research of novel time crystal and condensed matter phenomena in the time domain. We consider the dynamics of N impenetrable particles (hard balls) of equal masses stacked above each other in a 1D space. The particles bounce on an oscillating mirror in the presence of gravitational field. We identify the manifolds the particles move on and derive the effective secular Hamiltonian for the resonant motion of the particles. The effective Hamiltonian can be interpreted as describing a fictitious particle in an N-dimensional effective potential (N-dimensional particle) [6].

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EIT-based detection of Rydberg atoms for quantum simulation with cesium atomic ensembles

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A novel method of preparation and detection of Rydberg atoms in atomic ensembles was recently demonstrated on rubidium by Xu et al. [1]. We present the plan to implement the same principles on cesium. The detection is based on electromagnetically induced transparency on a ladder scheme, where the upper level is the Rydberg state. Its energy is shifted when a Rydberg atom is present in the atomic ensemble, causing the transmission of the signal beam to decrease compared to when all atoms are in the ground state. Since the method relies on a phenomenon that does not involve absorption of photons, it is expected to be non-destructive, which was experimentally confirmed in the abovementioned article.

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Dissipative vortex dynamics in homogeneous fermionic superfluids

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In superfluid and superconducting systems, the presence of quantized vortices can lead to dissipation via phase-slippage processes. We study the dissipation process underlying the vortex dynamics by exciting few-vortices configurations in homogeneous fermionic superfluids with tunable interactions, with a high control on single-vortex position. In particular, we study the dynamics of a vortex dipole and of a single vortex moving in a background superflow by tracking the vortex trajectories for different temperatures of the system.

Weighted multi-channel BCS mean-field theory with finite effective range

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The usual Bardeen-Cooper-Schrieffer (BCS) theory for a two-component Fermi gas, either on the Mean-Field (MF) or on the Gaussian level, restricts itself to one interaction channel [1-3]. Generically the pairing field is introduced via a Hubbard-Stratonovich (HS) transformation of the two-particle contact interaction. On a pure MF level, it describes only the formation of Cooper pairs that is responsible for the emergence of fermionic superfluidity. Above the respective critical temperature this yields a free Fermi gas [1,3,4], in contrast to experimental data. The inclusion of an additional interaction channel at the MF level requires a weighted multi-channel HS transformation, that is fixed by an additional saddle point condition of the effective action. This additional channel represents the Hartree-energy, that is experimentally present in the normal phase. To develop this improved MF theory, we require finite-ranged interactions [5] that lead to a UV momentum as already discussed in recent works [6,7]. Using this method, we calculate a few physical properties like the order parameter, the chemical potential, and the ground-state energy.

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Commensurate and incommensurate 1D interacting quantum systems

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Quantum-gas microscopes using ultra-cold atoms in optical lattices offer a powerful platform for quantum simulation with single-atom manipulation and detection capabilities. The key to single-site control is programmable light patterns from a digital micromirror device (DMD) that can create arbitrary potential landscapes. In our most recent study, we apply dynamically varying repulsive DMD potentials to deterministically prepare incommensurate 1D systems of interacting bosonic atoms with controllable particle densities [1].

Starting from a commensurate state with unit filling, the potential barriers are dynamically changed to reduce the available sites while retaining the atom number. We study the spatial distribution of the (in)commensurate gases from the weakly interacting to the strongly interacting regime, as well as the atom number variance to characterise our 1D systems. Finally, we probe particle mobility by applying an external bias field.

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Quasi-localization and quasi-mobility edge for light atoms mixed with heavy ones

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A mixture of light and heavy atoms is considered. We study the kinetics of the light atoms, scattered by the heavy ones, the latter undergoing slow diffusive motion. In three-dimensional space we claim the existence of a crossover region (in energy), which separates the states of the light atoms with fast diffusion and the states with slow diffusion; the latter is determined by the dephasing time. For the two-dimensional case we have a transition between weak localization, observed when the dephasing length is less than the localization length (calculated for static scatterers), and strong localization observed in the opposite case.

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Hydrodynamic description of vortices in photon Bose-Einstein condensates

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Open dissipative systems of quantum fuids, especially in presence of vortices, are well studied numerically in Refs. [1-3]. Motivated by that we strive for finding a corresponding approximate analytical description of photon Bose-Einstein condensates in the presence of vortices. To this end we consider the complex Gross-Pitaevski equation of Ref. [3] and extend the variational approximation to open dissipative systems in such a way that it is not only working for specifc functions like in [4,5]. To this end we develop a variational projection method and combine it with known methods from hydrodynamics. With this we approximately obtain a vortex solution and its corresponding velocity field, which depend on the respective open system parameters and have the same properties as obtained numerically in Ref. [2].

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Out-of-equilibrium dynamical properties of Bose-Einstein condensates in ramped-up weak disorder

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We investigate theoretically how the superfluid and the condensate deformation of a weakly interacting ultracold Bose gas evolve during the ramping up of an external weak disorder potential. Both resulting deformations turn out to consist of two distinct contributions, namely a reversible equilibrium one, already predicted by Huang and Meng in 1992 [1,2], as well as a non-equilibrium dynamical one, whose magnitude depends on the details of the ramping protocol [3]. For the specific case of the exponential ramping-up protocol, we are able to derive analytic time-dependent expressions for the aforementioned quantities. After a sufficiently long time, a steady state emerges that is generically out of equilibrium. We make the first step in examining its properties by studying its relaxation dynamics into it. Also, we investigate the two-time correlation function and elucidate its relation to the equilibrium and the dynamical part of the condensate deformation.

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Quantum simulation of extended electron-phonon coupling models in a hybrid Rydberg atom setup

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State-of-the-art experiments using Rydberg atoms can now operate with large numbers of trapped particles with tunable geometry and long coherence time. We propose a way to utilize this in a hybrid setup involving neutral ground state atoms to efficiently simulate condensed matter models featuring electron-phonon coupling. Such implementation should allow for controlling the coupling strength and range as well as the band structure of both the phonons and atoms, paving the way towards studying both static and dynamic properties of extended Hubbard-Holstein models.

Quantum fluctuations in cavity BEC systems

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When pumping an ultracold atom gas in a cavity strong coupling between the atoms and the light field are induced which facilitates a Dicke phase transition triggered by quantum fluctuations. We show the exotic quantum nature of these fluctuations under such strong coupling and determine their spectral characteristics. In particular, we analytically derive and dissect the exotic sub-Ohmic dissipative Landau and Beliaev-type processes from the microscopic Hamiltonian. In the cavity BEC setup direct nondestructive measurement is available and we quantify the intricate influence on physical observables. Furthermore, we present the tunability of the quantum matter fluctuations by easily accessible parameters of the setup.

Realization of the periodic quantum Rabi model in the deep strong coupling regime with ultracold rubidium atoms

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At moderate coupling strengths, the interaction of light and matter is well described in terms of the Jaynes-Cummings model. When on the other hand the coupling strength approaches the optical resonance frequency, the system enters the deep strong coupling regime, where the full quantum Rabi Hamiltonian becomes relevant, leading to non-intuitive dynamics.

In our experiment we realize the quantum Rabi model using ultracold rubidium atoms in an optical lattice potential, creating an effective two-level system encoded in different Bloch bands. The bosonic mode is represented by the oscillation of atoms in a superimposed optical dipole trapping potential.

We observe atomic dynamics in the deep strong coupling regime with the cold atoms system. At long interaction times we observe collapse and revival of the initial state, as can be described within the so called periodic quantum Rabi model.

Probing the local temperature distribution in electrically pumped broad-area VCSELs

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Ultracold quantum gases confined within optical cavities offer an intriguing platform for the study of many-body open quantum systems. In recent years a multitude of experiments have emerged that couple Bose-Einstein condensates (BEC) to modes of an optical cavity in a way that leads to an effective description in terms of the open Dicke model [1–3]. It is known that in the thermodynamic limit of an infinite particle number *N* the mean-field solution of the Dicke model becomes exact [4]. However, to study the emergence of genuine quantum effects in the dynamics of these systems at finite *N*, a description that goes beyond mean-field theory is required. Here, we present a novel open-system method that allows us to push the boundary for the exact numerical solution of the model up to a mesoscopic number of atoms of about *N=500* and to investigate the deficiencies of a mean-field description. We explore parameter regions where true quantum effects, such as tunneling, become relevant for the dynamics and observable in experiments. Such a regime is required, for instance, to realize a fully quantum associative memory [5].

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Quantum simulation and computation with ytterbium Rydberg atoms in optical tweezer arrays

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Experiments with neutral cold atoms trapped in reconfigurable optical tweezer arrays have recently developed into one of today's leading platforms for quantum simulation and computation. This is due to their intrinsic scalability and single atom control as well as a Rydberg-induced blockade mechanism for generating entanglement. However, achieving fault-tolerant quantum computing with Rydberg atom arrays, still requires improvement of currently achievable fidelities in preparation, gate operation and read-out.

In this poster we present our progress and latest updates towards a ^{171}Yb Rydberg quantum processor. We detail the features and advantages of the alkaline-earth-like atom ^{171}Yb as well as an implementation of the Rydberg-based optical, metastable and ground state qubit architecture.

Recent tweezer experiments utilising ^{171}Yb promise a multitude of advantages to overcome present limitations, such as its highly coherent metastable 'clock' state, a two valence-electron structure and single-photon Rydberg transitions. Novel qubit architectures equipped with mid-circuit measurements exploit these unique properties to encode nuclear qubits in the ground and metastable states. They suggest moderate requirements for experimental parameters, while new error correction schemes specifically tailored towards this isotope convert detected leakage from the qubit subspace into traceable errors.

Measure low intensity terahertz radiation with Rydberg tweezer arrays

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We report a protocol for detecting low-intensity terahertz radiation using Rydberg tweezer arrays. This proposed protocol is divided into two distinct phases: sensing and amplification. During the sensing phase, we harness terahertz-range transitions between highly excited Rydberg states to capture individual terahertz photons. By ensuring that all Rydberg atoms are laser-excited under an anti-blockade condition, we employ the facilitation mechanism [1] to amplify the signal within the Rydberg lattice. Consequently, the protocol efficiently converts a single terahertz photon into a substantial signal of Rydberg excitations. To support our findings, we develop a comprehensive theoretical model that incorporates the motion of atoms within the harmonic tweezer traps, allowing us to simulate the many-body dynamics of the terahertz detector. Utilizing tensor network methods, we simulate the dynamics of large tweezer arrays which can be realized in current experimental setups.

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A new ytterbium experiment for single-atom resolved many-body physics

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Ultracold atomic systems provide a unique playground for exploring quantum many-body phenomena, owing to an exceptional control over Hamiltonians and to their long coherence times. Novel techniques for the manipulation and detection of individual atoms have recently allowed to reach a single-atom level in the degree of control: in particular, optical tweezer arrays allow the realization of programmable quantum systems for exploring quantum simulation and quantum information schemes [1,2]. Here I will report on the ongoing development of a new ultracold atom experimental apparatus, where we will employ optical tweezers to manipulate and detect individual ytterbium atoms at state-of-art level. Such degree of control will allow us to engineer artificial quantum systems for investigating mesoscopic many-body systems with a bottom-up approach. In particular, the peculiar features of ytterbium make it ideal for tackling open questions both in quantum impurity problems and collective light-matter interactions. The long-lived clock state provides a natural choice for the implementation of orbital impurities, displaying either ferromagnetic or antiferromagnetic coupling to ground state atoms as well as optically tunable mobility. We will trigger and monitor the dynamics of many-particle systems with the precise tools of interferometric spectroscopy. We will also exploit the rich internal structure of ytterbium to isolate two- and three-level systems which show great potential to implement new laser cooling schemes and collective atoms-light interactions.

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Probing the local temperature distribution in electrically pumped broad-area VCSELs

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The occurrence of Bose-Einstein condensation of bosons has been theoretically introduced in early 1920's by A. Einstein [1]. Yet only recent experimental study confirmed that a thermalized gas of the most fundamental bosons, i.e. photons, trapped in optical microcavity can display signatures of Bose-Einstein condensation [2]. However, the aspect of nonuniform temperature distribution still needs to be investigated to determine if semiconductor lasers can act as Bose-Einstein condensate of photons.
The most commonly used measurement method to characterize temperature of laser microcavity by monitoring the thermally induced shift in the lasing wavelength provides only information on the average temperature distribution across the entire microcavity surface and more sophisticated techniques for probing local temperature have been developed [3]. However, the inhomogeneity of local temperature distribution and nonuniform current density affects the whole emission spectrum of electrically pumped semiconductor vertical-cavity surface-emitting lasers (VCSELs). This inhomogeneity effect also changes the effective local width of cavity, which is directly connected to the effective inhomogeneous confining potential for the photons, and therefore changes the density of states function and influences extracted values of the Bose-Einstein distribution. The assumption that the density of states has purely 2D-like character and has a fixed value over the whole VCSEL resonator may be an insufficient approximation.
Here, we present a new technique for measuring local spectral temperature distribution in wide aperture oxide-confined VCSELs by locally fitting the Boltzmann distribution to the high-energy tail of the spontaneous emission spectrum. Additionally, through measurement of the local fundamental mode energy by filtering the spontaneous emission in the wavevector space close to the normal incidence, we probed the local resonance of the cavity, which allows us to deduce the local effective potential change of the microresonator. The resulting data can be compared to theoretical simulations of the influence of local temperature and current density on the local potential shape. Studies on the thermalized boson gas of trapped photons in electrically pumped VCSEL microresonators may provide devices that act as Bose-Einstein condensate of photons, allowing for a new direction in Bose-Einstein photon condensation physics research.

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A blue repulsive potential for dysprosium Bose-Einstein condensates

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Repulsive potentials are interesting to study because they allow the trapping of atoms in low intensity regions, thus reducing the probability of an atom absorbing radiation and, consequently, heating up. Such potentials can be realized with lasers working at a frequency that is blue detuned from an absorption line of the atom. Since the resolution of a potential has a lower bound given by diffraction and this bound scales linearly with the laser wavelength, it's also interesting to work with lasers with the shortest possible wavelength to create highly resolved repulsive optical potentials. Such a potential could be used in the future to manipulate our dipolar supersolid in a new trap configuration. With this purpose we have studied the interaction between a dysprosium Bose-Einstein condensate and a repulsive potential realized with a diode laser working around 400 nm. The naked laser's spectrum crosses a strong absorption transition for dysprosium, because of this an experimental scheme to narrow the laser's bandwidth was realized. Using this setup we observed coherent repulsive interaction between the light field and the condensate. The strength of the atom-light interaction was also quantified by a measurement of the atomic dynamical polarizability.

Dissipative dynamics and bistability in the Dicke-Bose-Hubbard model

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We consider a driven dissipative system consisting of Bose-Einstein condensates loaded into a 2D Hubbard lattice and coupled to a single mode of an optical cavity. The dissipative dynamics of the system in the presence of photon loss from the cavity is investigated within the Lindblad master equation formalism. The coherent photon field is treated semi-classically, whereas the dynamics of bosons in the lattice is studied using the cluster mean-field method. We compute a phase diagram which includes a variety of steady-states obtained in the long-time, and bistability regions where different steady-states can coexist. The steady-states include self-organized atomic phases with modulated atomic density such as density waves and supersolids, which appear together with the Dicke superradiant state, as well as the homogeneous atomic phases such as superfluid and Mott insulator, which appear along with the normal radiant state of photons. We discuss tunnelling between different attractors involved in bistability leading to oscillatory dynamics followed by a relaxation due to the dissipation.

A theoretical investigation of topologically robust edge-states in a harmonic synthetic dimension and bridging with experiment

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Since the emergence of topological physics, there has been a fascination with investigating robust phenomena, such as topologically-protected edge states. Within the field of analogue quantum simulation, considerable effort has been devoted to realising such topological effects in various platforms, including ultracold atoms. Unlike solid-state materials, where topological edge states were initially discovered for electrons under the influence of magnetic fields, ultracold atoms are charge neutral and so this physics has been simulated by other means. In this poster, we will discuss theoretical progress at the University of Birmingham towards experimentally investigating an implementation of topological edge states based on a synthetic dimension of harmonic trap states. Building on our recent 1D experiment, we combine the synthetic dimension of harmonic trap states with a second real spatial dimension in order to simulate a 2D topological system. We discuss how effective edges can be created along the synthetic dimension of harmonic trap states and present numerical simulations for realistic experimental parameters.

Unified theory of the nonlinear Schrödinger equation

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The nonlinear Schrödinger equation (NLSE) is a rich and versatile model, which in one spatial dimension has stationary solutions similar to those of the linear Schrödinger equation as well as more exotic solutions such as solitary waves and quantum droplets. We present a unified theory of the NLSE, showing that all stationary solutions of the cubic-quintic NLSE can be classified according to a single number called the cross-ratio. Any two solutions with the same cross-ratio can be converted into one another using a conformal transformation. We also demonstrate a conformal duality between solutions of cubic-quintic NLSEs and lower-order NLSEs. The same analysis can be applied to the Newtonian dynamics of classical particles with polynomial potentials. Our framework provides a deeper understanding of the connections between the physics of the NLSE and the mathematics of algebraic curves and conformal symmetry.

Emergent topological properties of Kronig Penney type models

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Ultracold systems offer a clean testbed for realizing different quantum models, which are challenging to implement with condensed matter systems. Experimental advancement in cold atom physics allows the creation of subwavelength potentials where atoms can strongly interact. This potential allows us to realize the Kronig Penney model and its variations. Introducing a lattice shift in this kind of potential resulted in the emergence of nontrivial topology and topologically protected edge states. Developing control strategies for such systems is of fundamental interest in quantum technologies that rely on robust states for computation.

In this work, we analyze the topological properties of 1d potential, which resembles the Kronig Penney model, by introducing a lattice shift. We have studied the many-body quench between trivial and nontrivial regimes and see the deviations in expected orthogonality catastrophe. The spectral function is calculated which shows the existence of topological protected edge mode.

Catalyzation of supersolidity in binary dipolar condensates

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Breakthrough experiments have newly explored the fascinating physics of dipolar quantum droplets and supersolids. The recent realization of dipolar mixtures opens further intriguing possibilities. We show that under rather general conditions, the presence of a second component catalyzes droplet nucleation and supersolidity in an otherwise unmodulated condensate. For miscible mixtures, droplet catalyzation results from the effective modification of the relative dipolar strength, and may occur even for a surprisingly small impurity doping.
We show that different ground-states may occur, including the possibility of two coexisting interacting supersolids. The immiscible regime provides a second scenario for double supersolidity in an array of immiscible droplets. Further we will discuss how the superfluidity of this mixture can be tested.

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Quantum theory of self-organization in many-body cavity quantum electrodynamics

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Ensembles of atoms strongly coupled with the electric field of an optical cavity offer a formidable laboratory for studying the out-of-equilibrium dynamics of long-range systems in the quantum regime.
In this work, we derive by means of the formalism developed in Ref. [1] a quantum master equation describing the dynamics of atoms which interact with a multimode high-finesse cavity. We then analyse the predictions in several relevant limits, namely semi-classical, mean-field, and beyond mean-field. Our theory reproduces the results of the experiment of Ref. [2] and provides a powerful tool for singling out the individual contributions to the onset of metastability in quantum globally-interacting systems.

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Non-adiabatic physics in long-range Rydberg molecules of different masses

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Although the majority of calculations of the properties of long-range Rydberg molecules are based on the Born-Oppenheimer approximation, the role of non-adiabatic couplings has become a relevant question due to the improvement in theoretical and experimental methods. The strength of these couplings mainly depends on the molecular mass and the narrowness of the avoided crossings in the potential energy surfaces. These rapid changes lead to the existence of adiabatic vibrational states which are bound by quantum reflection off of steep drops in the potential curves. However, non-adiabatic physics has not yet been considered, and could play a complementary or destructive role in this process due to the proximity of these steep drops to sharp avoided crossings. We try to isolate the effect of non-adiabatic physics by systematically examining the behavior of these molecules as their mass decreases, i.e. by comparing Rb_2, Na_2, Li_2, and even a Rydberg molecule containing Rydberg positronium.

Bose gases in a cylindrical trap at canonical ensemble

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The recursive canonical method is a great approach to study the Bose gases in finite systems. Here we apply the idea in a cylindrical confinement in a non-interacting case calculating the condensed fraction and ground-state fluctuations and show analytical as well as numerical results for different trap parameters.

Effects of electric and magnetic dipole-dipole interaction on the shape of the Fermi surface in ultracold trapped Fermi gases

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Ultracold fermionic systems are of great interest both from the fundamental and application-driven point of view. However, unlike in Bose systems, quantum degeneracy in experiments is much more difficult to achieve here. Recently it was done for weakly bound heteronuclear polar molecules of KRb [1] that exhibit electric dipole-dipole interaction (DDI), while previously atomic systems with permanent magnetic dipoles were brought to quantum degeneracy [2]. The presence of the DDI in such systems determines the behavior of their key physical properties, as many-body dipolar effects energetically compete with the large kinetic energy at and below the Fermi surface (FS). It was theoretically predicted [3] and experimentally observed [4] that the FS gets deformed to an ellipsoid due to the presence of the DDI. In order to describe the ground-state properties of such systems, a mean-field variational approach based on the Wigner function was previously developed [5]. Here we study doubly-dipolar systems with both electric and magnetic dipolar moments perpendicular to each other using a Gaussian variational ansatz that makes analytical calculations tractable. Using this approach, we determine the deformation of the FS and system's stability and investigate the interplay of trap geometry and two DDIs present.

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Towards a Bogoliubov theory of 1D anyons in a lattice

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In a one-dimensional lattice anyons can be defined via generalized commutation relations containing a statistical parameter Θ, which interpolates between the boson limit $\Theta=0$ and the pseudo-fermion limit $\Theta=\pi$ [1]. The corresponding anyon-Hubbard model is mapped to a Bose-Hubbard model via a fractional Jordan-Wigner transformation, yielding a complex hopping term with a density-dependent Peierls phase. Here we work towards a Bogoliubov theory by focusing on the underlying mean-field theory. To this end we allow for the condensate to have a finite momentum, which is known from previous works [2-4], and determine it from extremizing the mean-field energy. With this we calculate various physical properties and discuss their dependence on the statistical parameter Θ and the lattice size. Among them are both the condensate and the superfluid density as well as the equation of state and the compressibility. The subsequent analysis of the dispersion of the Bogoliubov quasi-particles is still ongoing and requires further investigations.

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Quantum Fields in the Lab

Clara Tanghe and Karel van Acoleyen

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The quantum group at Ghent University set up a novel experimental cold-atoms lab, of which I am the first PhD student. In the summer of 2022, we realized the first Bose-Einstein condensate in Belgium, employing ^{87}Rb atoms tightly trapped by the magnetic fields of an atom chip.

The broad goal of our system is to study non-equilibrium Quantum Field Theory. For this, in addition to the atom chip, the system includes a blue-detuned laser whose light is sculpted by acousto-optical deflectors (AODs). Through these AODs, the 2D-position and intensity of a projected light spot can be manipulated. By rapid scanning of these spots - about 20 times faster than our typical trapping frequencies - an effective averaged potential can be generated.

In my poster I will present the characteristics of this system, as well as the possible avenues we wish to pursue in the near future.

Namely, we aim to increase our control over the atoms by identifying the effects of the averaging, derived from Floquet theory. Then, we will be in a good position to probe mean-field non-equilibrium effects including the role of perturbative fluctuations and topological effects such as vortices and solitons. Eventually, we will extend our study to effects beyond the mean-field, focusing on dynamical pair creation.

Snake instability in BEC under confinement and rapid rotation

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The instability of soliton solution in Bose-Einstein condensates (BEC) was observed in numerical and experimental studies. One of the dynamical instabilities causing the decay of the soliton is referred to as snake instability in the literature due to the density fluctuation behavior. It is known that soliton decays to an aligned vortex configuration, and the instability of this state was pointed out with the existence of imaginary oscillation energies in the Bogoliubov de-Gennes spectrum of the dark soliton state. We conduct a more detailed analysis of this instability. We assume the dynamical behavior of the condensate can be approximated with the Gross–Pitaevskii equation (GPE) in this decay process and solve this non-linear equation numerically with high-resolution state-of-art solvers. We analyze the stability of the soliton in strongly confined anisotropic harmonic traps by calculating the change in mean energies of soliton and single-vortex solutions as a function of anisotropy and rotation frequency. The stability of each condensate is tested with real-time simulations as well. We also use a variational wave function to analytically investigate the crossover between soliton and aligned vortex solutions. We study the dependence of the imaginary oscillation frequency of the dark soliton state on the physical constants, such as rotation frequency and strength of the anisotropy, to illuminate the role of the Tkachenko modes.

Berezinskii-Kosterlitz-Thouless transitions in an easy-plane ferromagnetic superfluid

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In two-dimensional Bose gases thermal fluctuations preclude the formation of long-range order. Consequently, the superfluid transition is of the Berezinskii-Kosterlitz-Thouless (BKT) type, characterized by the emergence of quasi-long-range order driven by the binding of vortex-antivortex pairs. Spinor Bose gases provide a unique platform to study BKT transitions, on account of their ability to simultaneously exhibit phase and spin ordering. Here we utilize a stochastic Gross-Pitaevskii model to investigate the BKT transitions in an easy-plane ferromagnetic spin-1 Bose gas. We identify the mass/spin superfluid phase diagram as a function of quadratic Zeeman energy. Two BKT transitions occur with decreasing temperature: first mass superfluidity is established, followed at a lower temperature by spin superfluidity. We demonstrate that these transitions are associated with the binding of mass and spin vortex-antivortex pairs, respectively. Above the spin BKT temperature, the component circulations that make up each spin vortex spatially separate, suggesting possible deconfinement analogous to quark deconfinement in high-energy physics. Intercomponent interactions give rise to superfluid drag between the spin components, which we calculate analytically at zero temperature.

Anomalous loss behavior in a single-component Fermi gas close to a p-wave Feshbach resonance & Off-resonant photon interactions in a double-species ultracold atom experiment

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We theoretically investigate three-body losses in a single-component Fermi gas near a p-wave Feshbach resonance in the interacting, non-unitary regime. We extend the cascade model introduced by Waseem et al. [Phys. Rev. A **99**, 052704 (2019)] to describe the elastic and inelastic collision processes. We find that the loss behavior exhibits a n^3 and an anomalous n^2 dependence for a ratio of elastic to inelastic collision rate larger and smaller than one, respectively. The corresponding evolutions of the energy distribution show collisional cooling or evolution toward low-energetic nonthermalized steady states, respectively.

Furthermore, we consider the production of an ultracold double-species mixture of fermionic lithium and bosonic cesium for studying many-body physics and realizing new phases. Trapping two species makes the search for efficient techniques to produce large mass-imbalanced quantum gases necessary. Here, the interaction of the trapping potential of one species with the other species, and the flip of the mixed sample from a non-interacting to a strongly interacting mixture pose challenges to the realization of the experimental platform.

Shell-shaped dual-component BEC mixtures

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Motivated by the recent experimental progress in realizing ultracold quantum gases in shell topologies using radio-frequency dressing in microgravity [1], we study an alternative scheme to create shell-shaped Bose-Einstein condensates (BECs) using 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 [2].
By solving both the Gross-Pitaevskii and the Bogoliubov-de Gennes equations, we investigate the ground state, collective excitations and free expansion of this system. Crucially, we see that the need for microgravity can be circumvented when a magic wavelength is chosen for trapping the mixture. This paves the way to study shell-shaped BECs in Earth-based laboratories.

References:

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Vortex lattices in the confined Bose mixture droplets

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The rotating repulsive Bose condensates under harmonic confinement exhibit vortices and vortex lattices. On the contrary, the metastable attractive BEC rotates with a center-of-mass (COM) motion. The Bose mixture quantum droplets is a self-trapped phase of the condensate, i.e. mechanically stable without any external confinement. In the Thomas-Fermi (TF) regime, the droplets show a flat-top density profile. When the free droplets are rotated, the global ground state is the COM motion. But the flat-top droplets exhibit a splitting instability, i.e. the perturbations on the equilibrium density break the droplet into smaller fragments. External confinement helps to cure this instability. Rotating a confined TF droplet provides a rich phase diagram, including COM motion, singly or multiply quantized vortices, and mixed states. In this paper, we study the strongly confined TF droplet for the rapid rotation frequencies. We find that the TF droplet can form triangular vortex lattices. Interestingly, the density profile of the vortex lattice closely follows the TF profile of the confined droplet and converges to the flat-top profile as the rotation frequency approaches the confinement frequency. Hence, contrary to the diverging size of the rapidly rotating repulsive BECs, the droplet converges to a finite radius. We also study the density dependence of the vortex core sizes and develop an approximate analytical formula, valid for the strongly confined TF regime. Droplets may exhibit a more tractable difference in the core sizes at the center and near the edge. Finally, we calculate the corrections to the uniform vortex density of the TF droplet and find an agreement with the numerical results.

Thermometry for trapped fermionic atoms in the BCS limit

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Measuring the temperature of an interacting fermionic cloud of atoms in the BCS limit represents a delicate task. In the literature temperature measurements have so far been only suggested in an indirect way, where one sweeps isentropically from the BCS to the BEC limit. Instead we suggest here a direct thermometry, which relies on measuring the column density and comparing the obtained data with a Hartree-Fock-Bogoliubov mean-field theory combined with a local density approximation. In case of an attractive interaction between two-components of ^{6}Li atoms trapped in a tri-axial harmonic confinement we show that minimizing the error within such an experiment-theory collaboration turns out to be a reasonable criterion for determining the temperature. The findings are discussed in view of various possible sources of errors.

Quantum phases from competing van der Waals and dipole-dipole interactions with Rydberg atoms

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The interplay of short- and long-range interactions can give rise to novel and rich phases. Interacting Rydberg atoms provide the ideal platform for realizing such phases. We study the ground-state phase diagram of Rydberg atoms in one-dimensional lattice. We find interesting effects in both a uniform and a dimerized chain as a result of the competition between van der Waals and dipole-dipole interactions. In the uniform chain, the Luttinger liquid phase destroys density wave order. The effect of dimerization on the interactions leads to competing bond and density wave orders. Using the Rydberg platform, we show not only the occurrence of bond order and density wave phases independently, but also reveal a bond-order density-wave phase.

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Ultracold Atoms and Molecules
Physikzentrum Bad Honnef, 06.08. - 12.08.2023

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status 07/27/2023

Bad Honnef Physics School *Ultracold Atoms and Molecules*

time	Sunday	time	Monday	time	Tuesday	time	Wednesday	time	Thursday	time	Friday	time	Saturday
		07:30-08:45	Breakfast	07:30-09:00	Breakfast	07:30-09:00	Breakfast	07:30-09:00	Breakfast	07:30-09:00	Breakfast	07:30-09:00	Breakfast
		08:45-09:00	Sá de Melo: Opening										
		09:00-10:00	Lundblad I	09:00-10:00	Lundblad II	09:00-10:00	Esslinger I	09:00-10:00	Esslinger II	09:00-10:00	Eckardt I	09:00-10:00	Törmä II
		10:00-10:30	Coffee Break	10:00-10:30	Coffee Break	10:00-10:30	Coffee Break	10:00-10:30	Coffee Break	10:00-10:30	Coffee Break	10:00-10:30	Coffee Break
		10:30-11:30	Pfau I	10:30-11:30	Pfau II	10:30-11:30	Ritsch I	10:30-11:30	Ritsch II	10:30-11:30	Törmä II	10:30-11:30	Eckardt II
		12:00-13:30	Lunch	12:00-13:30	Lunch	12:00-13:30	Lunch	12:00-13:30	Lunch	12:00-13:30	Lunch	11:30-11:45	Pelster: Conclusion
		13:30-14:00	Questions/ Answers I	13:30-14:00	Questions/ Answers II	13:30-14:00	Questions/ Answers III	13:30-18:30	Excursion	13:30-14:00	Questions/ Answers IV	12:00-13:30	Lunch
14:00-18:30	Arrival & Registration	14:00-15:00	Post. Plen. I No. 1-24	13:30-14:00	Working Group I	13:30-14:00	Post. Plen. II No. 25-47			13:30-14:00	Working Groups II	13:30-	Departure
		15:00-15:30	Coffee Break	15:00-15:30	Coffee Break	15:00-15:30	Coffee Break			15:00-15:30	Coffee Break		
		15:30-16:30	Fleischhauer I	15:30-16:30	Fleischhauer II	15:30-16:30	Tempere I			15:30-16:30	Preiss II		
		16:30-17:00	Coffee Break	16:30-17:00	Coffee Break	16:30-17:00	Coffee Break			16:30-17:00	Coffe Break		
		17:00-18:00	Chomaz I	17:00-18:00	Chomaz II	17:00-18.00	Preiss I			17:00-18:00	Tempere II		
18:30-20:00	Dinner	18:30-20:00	Dinner	18:30-20:00	Dinner	18:30-20:00	Dinner	18:30-20:00	Dinner	18:30-20:00	Dinner		
20:00-22:00	Meet & Greet	20:00-21:00	Post. Sess. I No. 1-12	20:00-21:00	Post. Sess. II No. 13-24	20:00-	Socializing	20:00-21:00	Post. Sess. III No. 25-36	20:00-21:00	Post. Sess. IV No. 37-47		

Zoom: **https://bit.ly/43ryC1G** **Panopto:** **https://bit.ly/3O1AJnd**