SFB/TRANSREGIO 49

FRANKFURT-KAISERSLAUTERN-MAINZ

CONDENSED MATTER SYSTEMS WITH VARIABLE MANY-BODY INTERACTIONS

INTERNATIONAL SCHOOL 2016

THERMAL, QUANTUM, AND TOPOLOGICAL PHASE TRANSITIONS

JOHANN WOLFGANG GOETHE UNIVERSITÄT FRANKFURT AM MAIN

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

MATERIALS SCIENCE IN MAINZ

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COLLEGE FOR THE ADVANCEMENT OF POSTGRADUATE EDUCATION

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Introduction

International School on Thermal, Quantum, and Topological Phase Transitions

sponsored by

Collaborative Research Center SFB/TR49

The International School will provide a concise overview on phase transitions, which occur in various systems of condensed matter physics and often reveal universal properties. In particular, similarities and differences of thermal, quantum, and topological phase transitions are worked out. The pedagogical talks are provided by both experimental and theoretical physicists of international reputation.

Within the framework of the Collaborative Research Center SFB/TR49 **Condensed Matter Systems with Variable Many-Body Interactions**, which is funded since 2007 by the German Research Foundation (DFG), the collective behavior of interacting many-body systems is investigated on a broad phenomenological context. The topics embrace cooperative phenomena such as the Mott metal-insulator transition, superconducting/superfluid phases with strong interactions or Bose-Einstein condensation under various and sometimes extreme conditions. Besides the properties of the ground state, excitations and exchange processes, also containing dynamical aspects of correlations and coherence, are investigated in the SFB/TR49.

Further information about the Collaborative Research Center SFB/TR49 is available at its homepage

http://www.tr49.de

College for the Advancement of Postgraduate Education in the SFB/TR49

The researchers of the SFB/TR49 strive for two principle goals: The production of international first-class research results and the education of qualified experts and scientists of many-body interactions in condensed matter physics, both of which are equally important responsibilities towards society. It is an universally accepted truth that these two areas, research and postgraduate education, go hand in hand. Success in one area also requires excellence in the other and vice versa.

The College for the Advancement of Postgraduate Education is an integrated graduate school with the primary intention of improving and furthering the education of young researchers affiliated with the research projects of the Transregio. The College keeps high academic standards and strives for an optimal graduation time of three years for PhD candidates. To this end, the College will provide training opportunities, guidance, and a pleasant networking environment in order to assist the research progress of doctoral students towards graduation without delays. The College assists members in acquiring a variety of other skills that are expected from doctoral candidates on their way to become a self-reliant researcher, who not only excels in science, but is also ready to fill the position of a leading, responsible and independent scientist as demanded in all parts of society. The College offers many customized and transregional training opportunities, such as workshops, seminars, soft skill courses, lecture series, exchanges, books, excursions, information services, and - last but not least - personal career development and guidance.

Further information about the College for the Advancement of Postgraduate Education is available at its homepage

http://lucky.physik.uni-kl.de/~tr49/mgk

International School on Thermal, Quantum, and Topological Phase Transitions

Building on the success of various educational activities within the College for the Advancement of Postgraduate Studies, we organize for the third time an international school which is geared towards specific topics in methods and research for students. The summer school is open for international registration and the lectures will be given by invited experts. It covers many research fields of the SFB/TR49 and is, therefore, of central importance.

The international school in Bad Endorf (Bavaria) covers phase transitions, which are driven and characterized by thermal, quantum or topological properties. In particular, concrete examples of phase transitions within the realm of ultracold quantum gases in traps or optical lattices as well as of condensed matter physics are treated in detail. Although all these systems are physically quite different, their respective phase transitions reveal certain similarities which will be worked out. Furthermore, the school aims at providing an overview over both the theoretical and the experimental probing of the respective phase transitions.

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WLAN

consult hotel reception

Program

Monday, March 21

Until 14:30	Arrival at venue
14:30-15:15	*Welcome Coffee and Registration*
15:15-15:30	Opening
15:30-16:45	Jean Zinn-Justin (Paris):
	From Infinites in QED to the General Renormalization Group
16:45-17:00	Discussion
17:00-18:15	Fabrice Gerbier (Paris):
	Ultracold Quantum Gases in Optical Lattices – Part I
18:15-18:30	Discussion
18:30-20:00	*Dinner*
20:00	Poster Session I and Socializing

Tuesday, March 22

07:30-08:30	*Breakfast*
08:30-09:45	Jean Zinn-Justin (Paris):
	Phase Transitions and Renormalization Group:
	From Theory to Numbers
09:45-10:00	Discussion
10:00-10:30	*Coffee Break*
10:30-11:45	Fabrice Gerbier (Paris):
	Ultracold Quantum Gases in Optical Lattices – Part II
11:45-12:00	Discussion
12:00-13:30	*Lunch*

13:30-14:45	Markus Garst (Cologne):
	Introduction to Quantum Phase Transitions – Part I
14:45-15:00	Discussion
15:00-15:30	*Coffee Break*
15:30-16:45	Alexander Altland (Cologne):
	Topological Phases of Condensed Matter Physics:
	Three Case Studies – Part I
16:45-17:00	Discussion
17:00-18:15	Tobias Donner (Zurich):
	Critical Behavior of a Bose Gas
18:15-18:30	Discussion
18:30-20:00	*Dinner*
20:00	Poster Session II and Socializing

Wednesday, March 23

07:30-08:30	*Breakfast*
08:30-09:45	Alexander Altland (Cologne):
	Topological Phases of Condensed Matter Physics:
	Three Case Studies – Part II
09:45-10:00	Discussion
10:00-10:30	*Coffee Break*
10:30-11:45	Tobias Donner (Zurich):
	Quantum Phase Transition in a Long-Range Interacting System
11:45-12:00	Discussion
12:00-12:30	*Lunch package*
12:30-21:00	**Excursion and Dinner**

Thursday, March 24

07:30-08:30	*Breakfast*
08:30-09:45	Ulrich Schneider (Cambridge): *Creating and Probing Topological Band Structures with Ultracold Atoms – Part I*
09:45-10:00	Discussion
10:00-10:30	*Coffee Break*
10:30-11:45	Markus Garst (Cologne): *Introduction to Quantum Phase Transitions – Part II*
11:45-12:00	Discussion
12:00-13:30	*Lunch*
13:30-14:45	Ulrich Schneider (Cambridge): *Creating and Probing Topological Band Structures with Ultracold Atoms – Part II*
14:45-15:00	Discussion
15:00-15:30	*Coffee Break*
15:30	Departure from venue

Abstracts of Lectures

Topological Phases in Condensed Matter Physics: Three Case Studies

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In these talks we will develop key ideas of topological phases and transitions between them within the framework of three concrete case studies. The first is a simple model of a topological insulator, the so-called Su-Schrieffer-Heeger chain. The second is the Kosterlitz-Thouless transition, a topological phase transition in two dimensions which defines the universality class of a large number of two-dimensional phase transitions. And the third is the so-called Z2 lattice gauge theory, an effective theory relevant to a large number of condensed matter contexts, and to applications at the interface to quantum information science. We will aim to emphasize common concepts relevant to these examples and to a wider class of transitions between phases discriminated by different types of topology.

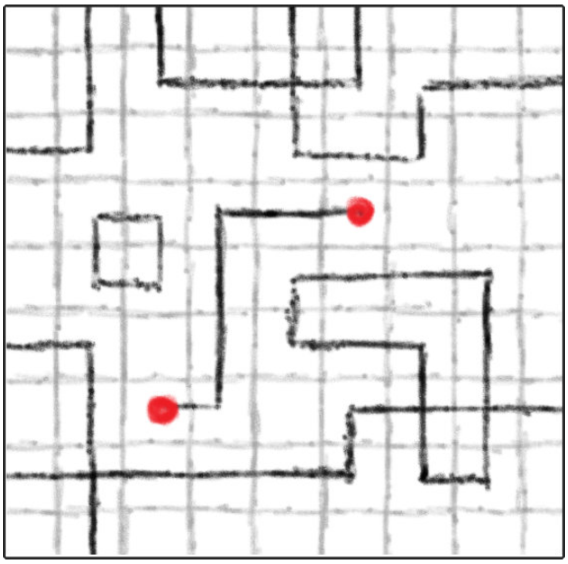

Figure 1: Cartoon of a two-fold excited Z2 spin liquid.

Critical Behavior of a Bose Gas

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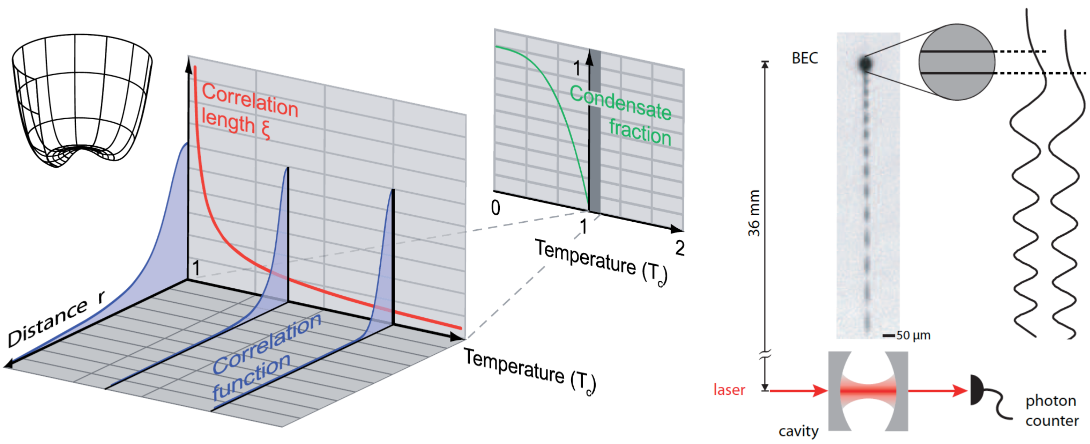
`http://www.quantumoptics.ethz.ch/index.php?id=166`

Starting from basic features of second-order phase transitions, I will concentrate in this lecture on the normal to superfluid phase transition of a Bose-Einstein condensate. I will use this example to discuss the concepts of criticality and universality. Finally, I will present experimental approaches to study the critical behavior of Bose gases and to measure critical exponents of this phase transition [1].

[1] T. Donner, S. Ritter, T. Bourdel, A. Öttl, M. Köhl, and T. Esslinger: *Critical Behavior of a Trapped Interacting Bose Gas*, Science **315**, 1556 (2007).



Quantum Phase Transitions in a Long-Range Interacting System

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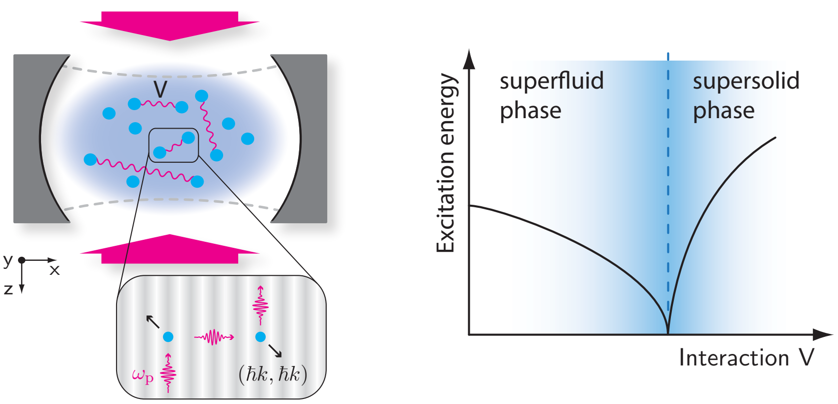
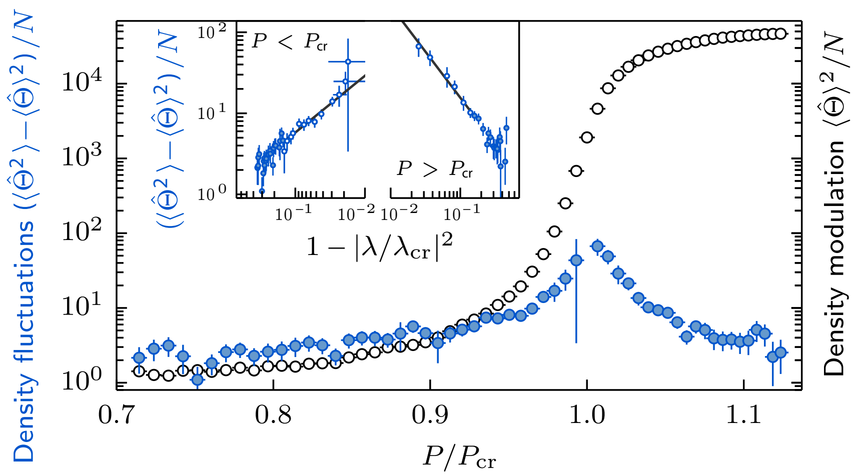
The presence of long-range interactions in a many-body system can lead to the formation of intriguing new quantum phases such as supersolids or charge density waves [1]. A well known effect of long-range interactions is the roton-minimum in superfluid Helium, which is expected to be a precursor of a phase transition to a supersolid. In this lecture, I will discuss ways to experimentally create such long-range interactions in quantum gases, and to study the emerging phases. In close connection to the first lecture, I will present measurements of a critical exponent at the quantum phase transition from a superfluid to a supersolid phase [2].

[1] R. Mottl, F. Brennecke, K. Baumann, R. Landig, T. Donner, and T. Esslinger: *Roton-type mode softening in a quantum gas with cavity-mediated long-range interactions*, Science **336**, 1570 (2012).

[2] R. Landig, F. Brennecke, R. Mottl, T. Donner, and T. Esslinger: *Measuring the dynamic structure factor of a quantum gas undergoing a structural phase transition*, Nature Communications **6**, 7046 (2015).





Introduction to Quantum Phase Transitions

Markus Garst
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An introduction to the basic concepts of quantum phase transitions will be presented [1,2]. We start with a general discussion of the scaling hypothesis, the phase diagram, its crossovers and the quantum critical thermodynamics. Afterwards we introduce various specific examples of quantum critical systems. First, we introduce the superfluid-insulator transition and the dilute Bose gas. Second, quantum phase transitions in magnetic insulators will be discussed with a particular focus on low-dimensional spin systems like chains and ladders. Third, we review quantum phase transition in metals. We introduce the Hertz-Millis model and discuss its successes and shortcomings.

[1] S. Sachdev, *Quantum phase transitions*, 2nd Edition (Cambridge University Press, 2011)

[2] M. Vojta, *Thermal and Quantum Phase transitions*, Lectures given at the Les Houches Doctoral Training School in Statistical Physics 2015, `http://statphys15.inln.cnrs.fr`

[3] Ch. Rüegg et al., Phys. Rev. Lett. **101**, 247202 (2008)

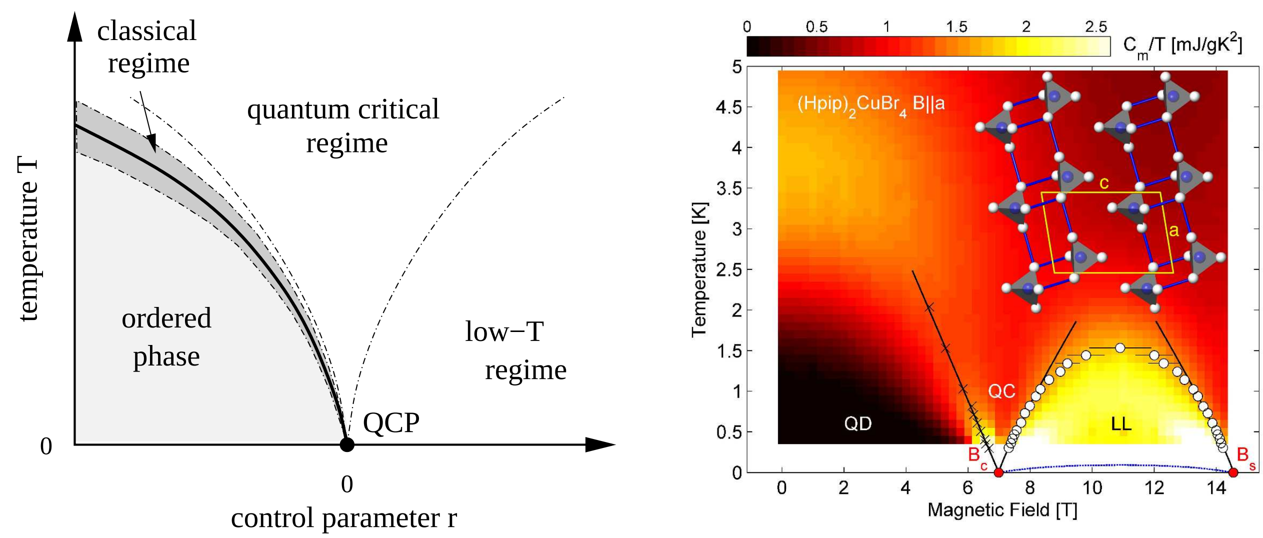

Figure 1: Left: Generic phase diagram with a quantum critical point (QCP) at temperature $T = 0$ between a disordered and an ordered phase as a function of a control parameter r. Here, the ordered phase extends to finite temperatures giving rise to a line of classical transitions emanating from the QCP. Right: Phase diagram of the spin-ladder material $(Hpip)_2CuBr_4$ which shows two quantum phase transitions as a function of magnetic field [3]. In the regime between the two critical fields the spin excitations are described by the Luttinger liquid (LL) theory.

Ultracold quantum gases in optical lattices

Fabrice Gerbier
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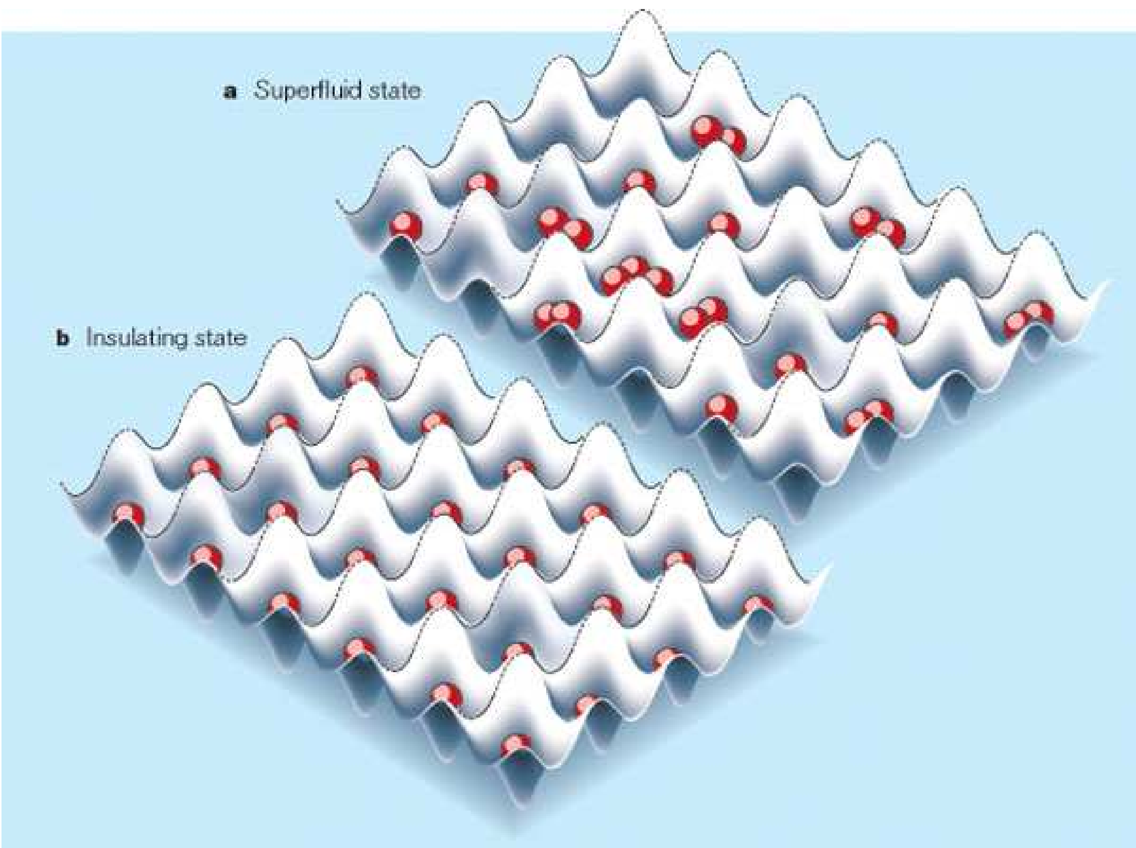
http://www.lkb.ens.fr/-Condensats-de-Bose-Einstein-?lang=en

I will present the physics of ultracold quantum gases in optical lattices, emphasizing the regime of very low temperatures and strong interactions. For bosons, a quantum phase transition takes place from a superfluid phase to a Mott insulator phase with drastically different coherence and transport properties. I will review experimental studies of these phases, where many-body properties are revealed by novel techniques often borrowed from quantum optics. These experiments provide a new perspective on many-body systems, complementary to condensed matter experiments, where the emphasis is traditionnally on transport and scattering of probe particles. I will discuss prospects to realize more complex quantum many-body phases. Current experiments are limited by finite temperatures and heating, and novel cooling methods applicable for ultralow (nK or below) temperature gases are sorely needed. I will review proposals and initial experiments in this direction.



Creating and Probing Topological Band Structures with Ultracold Atoms

Ulrich Schneider
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In these lectures we will look at the practical task of realizing topological band-structures for ultracold atoms. As these atoms are electrical neutral, they don't feel the Lorentz force that is typically responsible for the Hall effect. We will therefore review several techniques to simulate these effects, including rotating quantum gases, Raman dressing, laser-induced hopping in deep lattices and lattice modulation. In addition we will discuss different ways to probe the resulting structures, including transport and interferometric probes. Finally, we will look at some of the challenges associated with realizing strongly correlated topological phases.

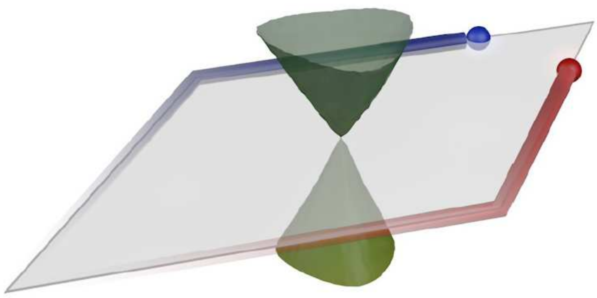

Figure 1: Ultracold bosons allow for direct interferometric measurements of the Berry flux by employing a momentum-space analogue of Aharonov-Bohm interferometry.

From Infinities in QED to the General Renormalization Group

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At its birth, Quantum Field Theory (QFT) has been confronted with a somewhat unexpected problem, the appearance of infinities. The calculation of physical processes was yielding infinite results. An empirical recipe, called renormalization, was eventually discovered, which allowed deriving finite predictions from divergent expressions. The procedure would hardly have been convincing if the corresponding predictions would not have been confirmed with increasing precision by experiments. A new concept, Renormalization Group, first abstracted from formal properties of QFT, but whose full meaning, in a more general form, was only completely appreciated in the general framework of continuous, macroscopic phase transitions, has led, later, to a satisfactory interpretation of renormalizable QFT and to the application of QFT methods to the calculation of universal quantities in critical phenomena [1].

[1] J. Zinn-Justin, *Quantum Field Theory and Critical Phenomena*, Fourth Edition, Oxford University Press (2002)

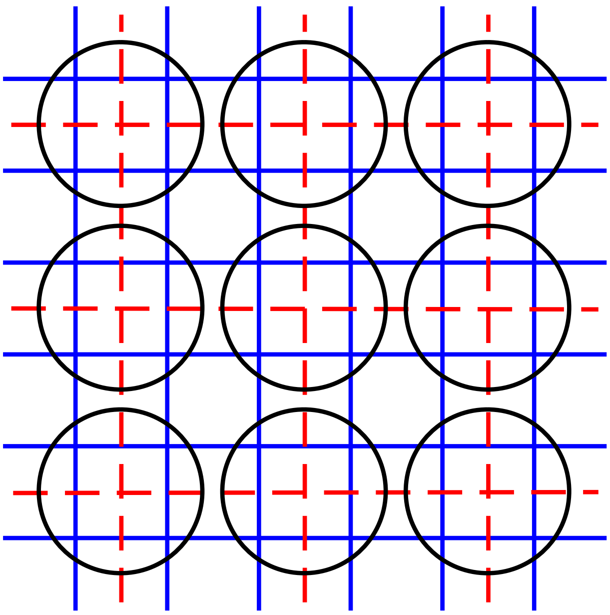

Figure 1: Illustration of the Kadanoff decimation scheme which represents an important step of the renormalization group approach.

Phase Transitions and Renormalization Group: From Theory to Numbers

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The large distance behaviour, near the critical temperature, of continuous phase transitions with short range interactions can be reproduced by an effective local field theory. Within this framework, the universal properties of the large distance can be determined by finding fixed points of general, functional renormalization group (RG) equations (Wilson, Wegner). For dimension $D > 4$, the large scale behavior is governed by the Gaussian fixed point (related to mean field theory), while for $D < 4$ the Gaussian fixed point is unstable. Near $D = 4$, the RG equations can be solved in the form of an $\epsilon = 4 - D$ expansion, a new stable fixed point is found and this leads to the famous Wilson-Fisher expansion for critical exponents and other universal quantities. Moreover, one realizes that, in this framework, the effective field theory can be reduced to a renormalizable field theory and, at leading order in the critical domain, the much simpler quantum field theory renormalization group can be used. A number of physicists, including the Saclay group (Brézin, Le Guillou, Zinn-Justin) have developed sophisticated field theory techniques, to prove general scaling laws and to calculate exponents to higher orders [1].

After the discovery that perturbative series and, thus, epsilon expansions are divergent, it has been understood that mathematical summation techniques have to devised to calculate precise and reliable numbers. Moreover, with an additional assumption, as an alternative to the epsilon expansion, one can use perturbation series directly in fixed dimension $D = 3$ (Parisi). The summation of $D = 3$ series obtained by Nickel have led to the most precise estimates (Le Guillou and Zinn-justin, Guida Zinn-Justin) for exponents and the equation of state of the Ising universality class.

[1] J. Zinn-Justin, *Phase Transitions and Renormalization Group*, Oxford University Press (2007)

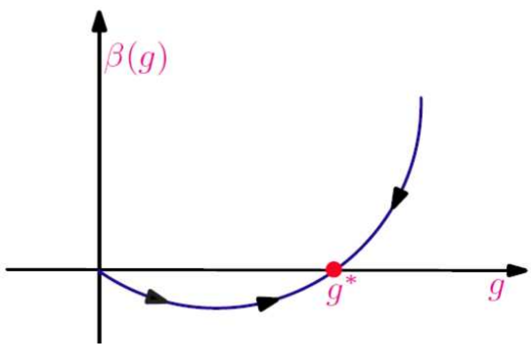

Figure 1: The renormalization group β-function for $D < 4$.

List of Posters

Javed Akram (Berlin):
Sculpting quasi one-dimensional Bose-Einstein condensate to generate calibrated matter-waves

Michaela Altmeyer (Frankfurt):
Magnetism, spin texture and in-gap states: Atomic specialization at the surface of oxygen deficient $SrTiO_3$

Christian Baals and Jian Jiang (Kaiserslautern):
Non-equilibrium dynamics of interacting bosons in an optical lattice

Steffen Backes (Frankfurt):
Interplay of electronic correlations and oxygen vacancies in $SrVO_3$

Christoph Berke (Dresden):
Stability of Weyl semi-metals under the formation of charge density waves

Mario Bijelic (Frankfurt):
Variational Monte Carlo simulations in solid state physics

Vladislav Borisov (Frankfurt):
Multiferroic charge transfer salt: TTF-CA

Elena Gati (Frankfurt):
Transport and thermodynamic studies of the unusual metal-insulator transition in κ*-*$(BEDT\text{-}TTF)_2Hg(SCN)_2Cl$

Steffi Hartmann (Frankfurt):
Charge-spin-lattice correlations in the half-metallic CMR material $HgCr_2Se_4$

Ana Hudomal (Belgrade):
Gravitational waves from periodic three-body systems

Bernhard Irsigler (Berlin):
Dimensional phase transitions of bosons in optical lattices with tunable hopping

Philipp Jäger (Kaiserslautern):
Investigation of Anderson insulating phases in interacting systems using DMRG

Kevin Jägering (Kaiserslautern):
Introduction and application of time-dependent Density Matrix Renormalization Group (tDMRG)

Ryui Kaneko (Frankfurt):
Emergent triangular structure in doped extended honeycomb Hubbard model

Aaram Kim (Frankfurt):
Interplay between spin-orbit coupling and Coulomb interaction in the multi-orbital Hubbard model

Chris Koschenz (Dresden):
The five-orbital Hubbard model for iron pnictides and iron chalcogenides - magnetic ordering and superconductivity

Jan Krieg (Frankfurt):
Thermodynamics and renormalized quasiparticles in the vicinity of the dilute Bose gas quantum critical point in two dimensions

Martin Kübler (Kaiserslautern):
Improved Ginzburg-Landau theory for bosons in optical lattices via degenerate perturbation theory

Philipp Lange (Frankfurt):
Physical dipoles and second-order perturbation theory for dipolar fermions in two dimensions

Fabian Letscher (Kaiserslautern):
Strong correlations in driven dissipative Rydberg gases

Ying Li (Frankfurt):
Magnetic interactions with strong spin-orbit couplings: challenges in design and modelling of Kitaev materials

Dominik Linzner (Kaiserslautern):
Reservoir induced topological order and quantized pumps in open lattice models with interactions

Laura Mihalceanu (Kaiserslautern):
Collective effects and instabilities of a magnon gas

Denis Morath (Kaiserslautern):
Coupled chains: The 1D-3D crossover

Axel Pelster (Kaiserslautern):
Multi-mode Tavis-Cummings model with time-delayed feedback control

Lars Postulka (Frankfurt):
Field-induced ordered phases in the tetragonal quasi-2d dimer system $Ba_{0.9}Sr_{0.1}CuSi_2O_6$

Pascal Puphal (Frankfurt):
Single crystal growth of tunable quantum spin systems

Kira Riedl (Frankfurt):
Frustrated spin systems

Andreas Rückriegel (Frankfurt):
Rayleigh-Jeans condensation of pumped magnons in thin YIG films

Dominik Straßel (Kaiserslautern):
Spin trimers coupled in 2D and 1D

Satya Krishna Thallapaka (Frankfurt):
Thermal expansion measurements of the mixed systems $Cs_2CuCl_{4-x}Br_x$ $(0 < x < 4)$

Etienne Wamba (Kaiserslautern):
Mapping different experiments in Bose-Einstein condensates

Karim Zantout (Frankfurt):
The two-particle self-consistent theory and comparisons to RPA

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Notes

time	Monday	time	Tuesday	time	Wednesday	time	Thursday
		until 08:30	Breakfast	until 08:30	Breakfast	until 08:30	Breakfast
		08:30-10:00	**Jean Zinn-Justin** *Phase Transitions and Renormalization Group: From Theory to Numbers*	08:30-10:00	**Alexander Altland** *Topological Phases in Condensed Matter Physics: Three Case Studies – Part II*	08:30-10:00	**Ulrich Schneider** *Creating and Probing Topological Band Structures with Ultracold Atoms – Part I*
		10:00-10:30	Coffee Break	10:00-10:30	Coffee Break	10:00-10:30	Coffee Break
		10:30-12:00	**Fabrice Gerbier** *Ultracold Quantum Gases in Optical Lattices – Part II*	10:30-12:00	**Tobias Donner** *Quantum Phase Transition in a Long-Range Interacting System*	10:30-12:00	**Markus Garst** *Introduction to Quantum Phase Transitions – Part II*
until 14:30	Arrival	12:00-13:30	Lunch	12:00-12:30	Lunch package	12:00-13:30	Lunch
14:30-15:15	Welcome Coffee	13:30-15:00	**Markus Garst** *Introduction to Quantum Phase Transitions – Part I*	12:30-18:00	Excursion to Herrenchiemsee	13:30-15:00	**Ulrich Schneider** *Creating and Probing Topological Band Structures with Ultracold Atoms – Part II*
15:15-15:30	Opening	15:00-15:30	Coffee Break			15:00-15:30	Coffee Break
15:30-17:00	**Jean Zinn-Justin** *From Infinities in QED to the General Renormalization Group*	15:30-17:00	**Alexander Altland** *Topological Phases in Condensed Matter Physics: Three Case Studies – Part I*			15:30	Departure
17:00-18:30	**Fabrice Gerbier** *Ultracold Quantum Gases in Optical Lattices – Part I*	17:00-18:30	**Tobias Donner** *Critical Behavior of a Bose Gas*				
18:30-20:00	Dinner	18:30-20:00	Dinner	18:00-21:00	Dinner in Prien		
20:00-	Poster Session I	20:00-	Poster Session II				