Ultracold Quantum Gases:
A Fascinating Playground for Basic Research

Axel Pelster

RPTU

OPTIMAS TU Kaiserslautern

SFB/TR 185

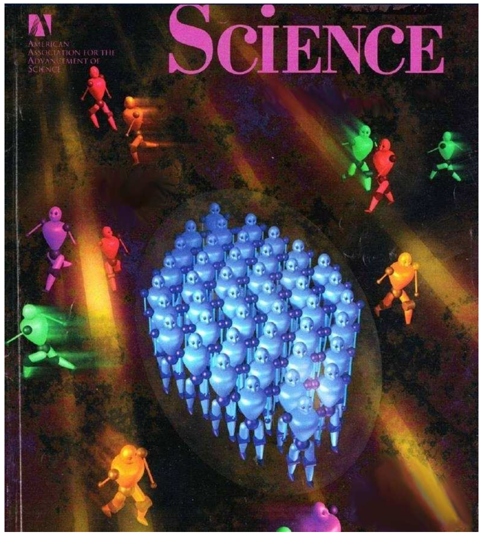
FOR 2247 From few to many-body physics with dipolar quantum gases

DFG FWF

1. Introduction

2. Theses Topics

3. Outlook



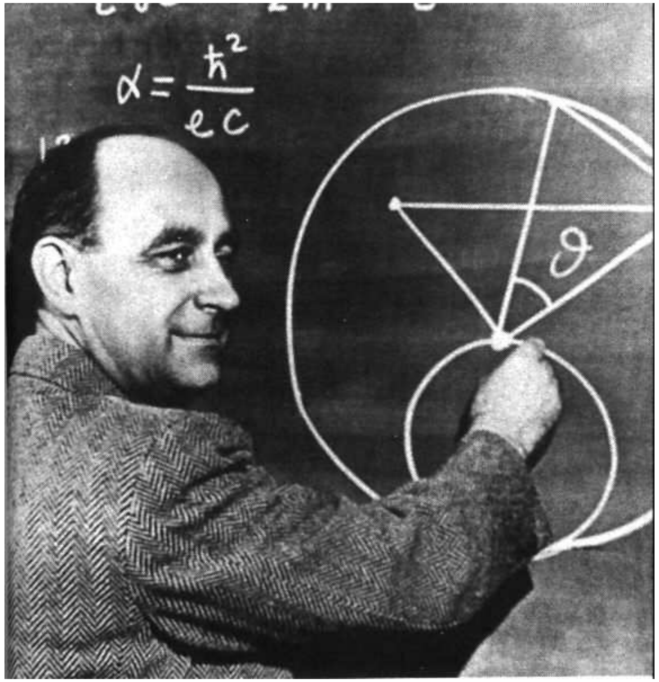
1.1 Identical Quantum Particles

Bosons:

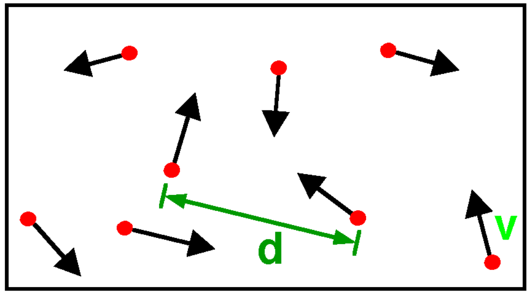
- Symmetric wave function
- Integer spin

Fermions:

- Anti-symmetric wave function
- Half-integer spin



1.2 What is Bose-Einstein Condensation?

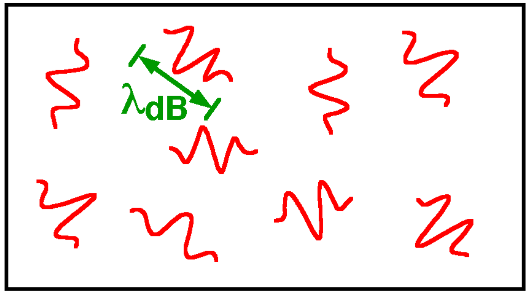


High Temperature T:

thermal velocity v

density d^{-3}

"Billiard balls"

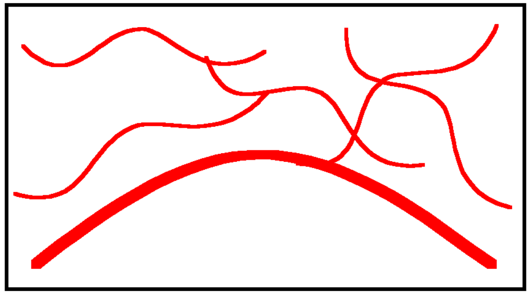


Low Temperature T:

De Broglie wavelength

$\lambda_{dB}=h/mv \propto T^{-1/2}$

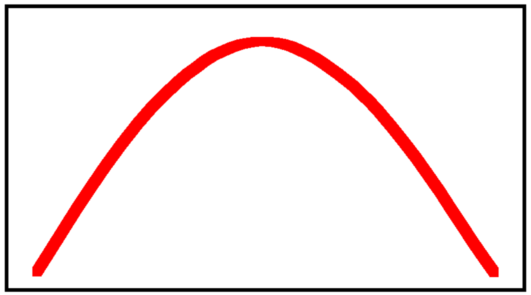
"Wave packets"



$T=T_{crit}$: Bose-Einstein Condensation

$\lambda_{dB} \approx d$

"Matter wave overlap"



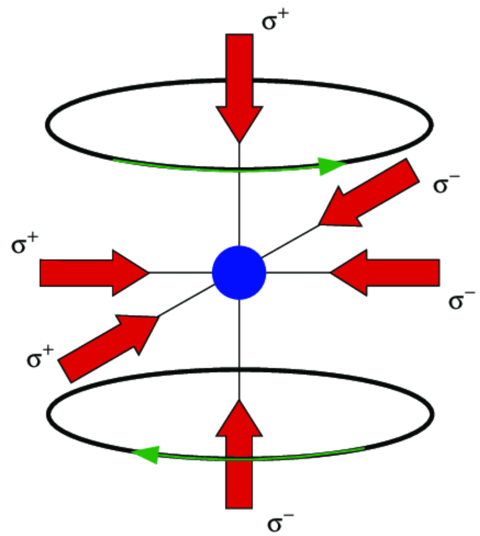
T=0: Pure Bose condensate

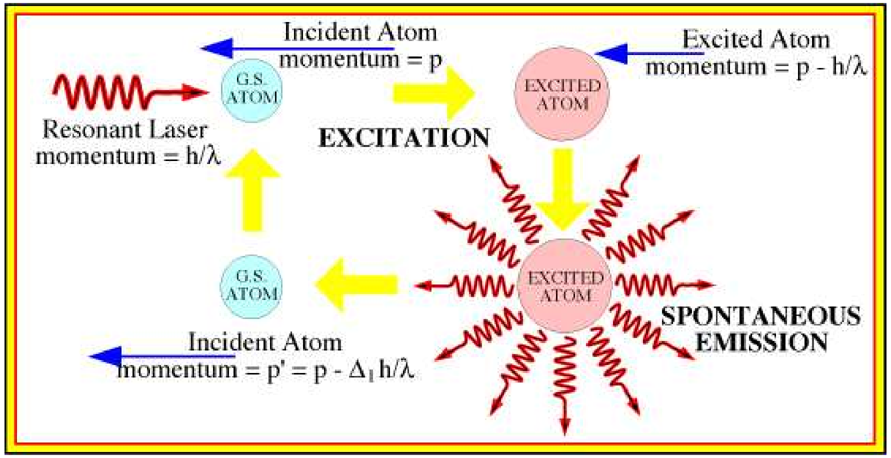
"Giant matter wave"

- $n = \dfrac{1}{d^3}$
- $\lambda_{\mathrm{dB}} = \dfrac{\hbar}{\sqrt{2Mk_BT}}$
- $\dfrac{\lambda_{\mathrm{dB}}}{d} \approx 1$
- $T_c \approx \dfrac{\hbar^2 n^{3/2}}{2Mk_B}$

1.3 Cooling Techniques

Magneto-optical trap

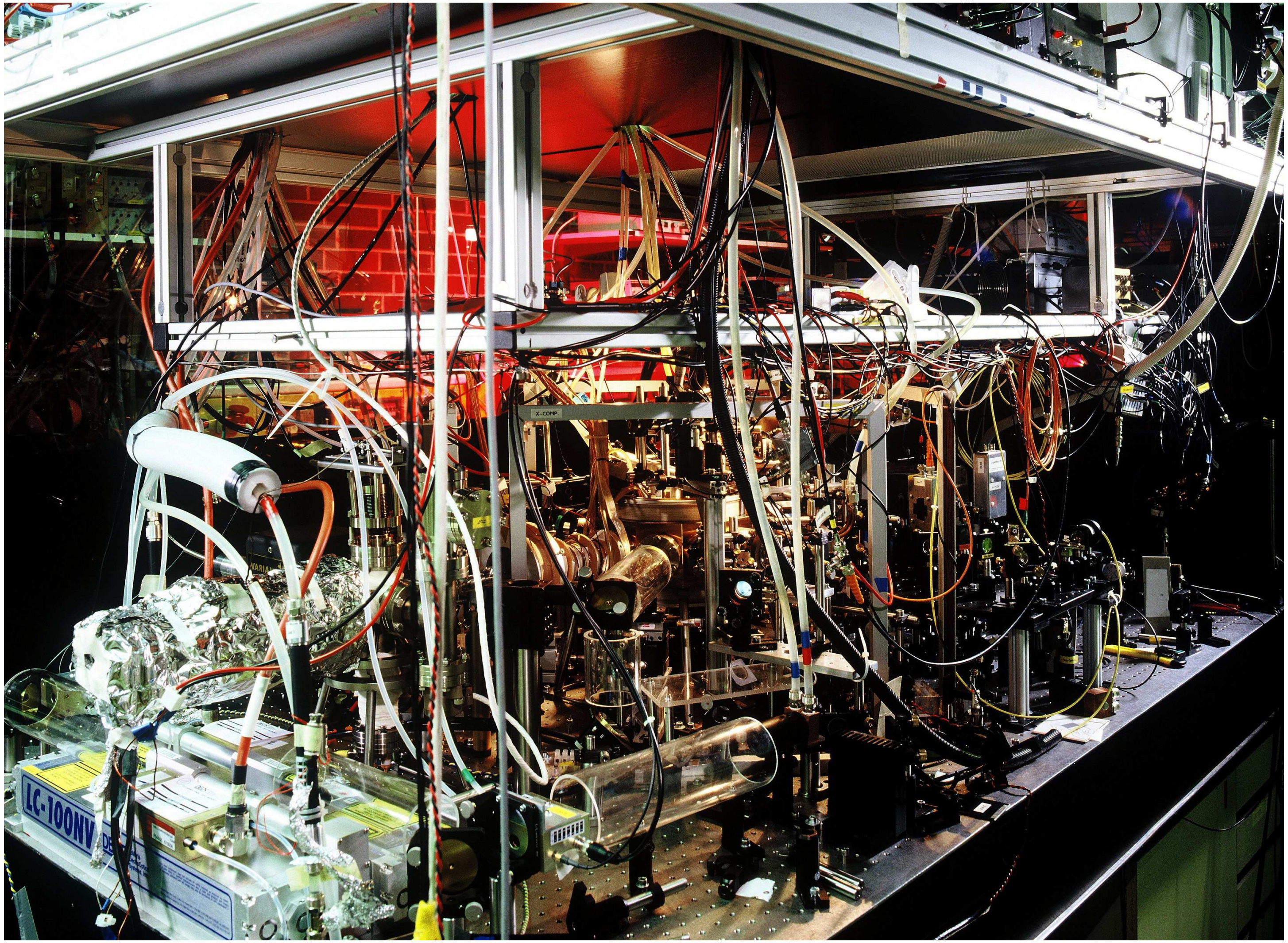




Laser cooling

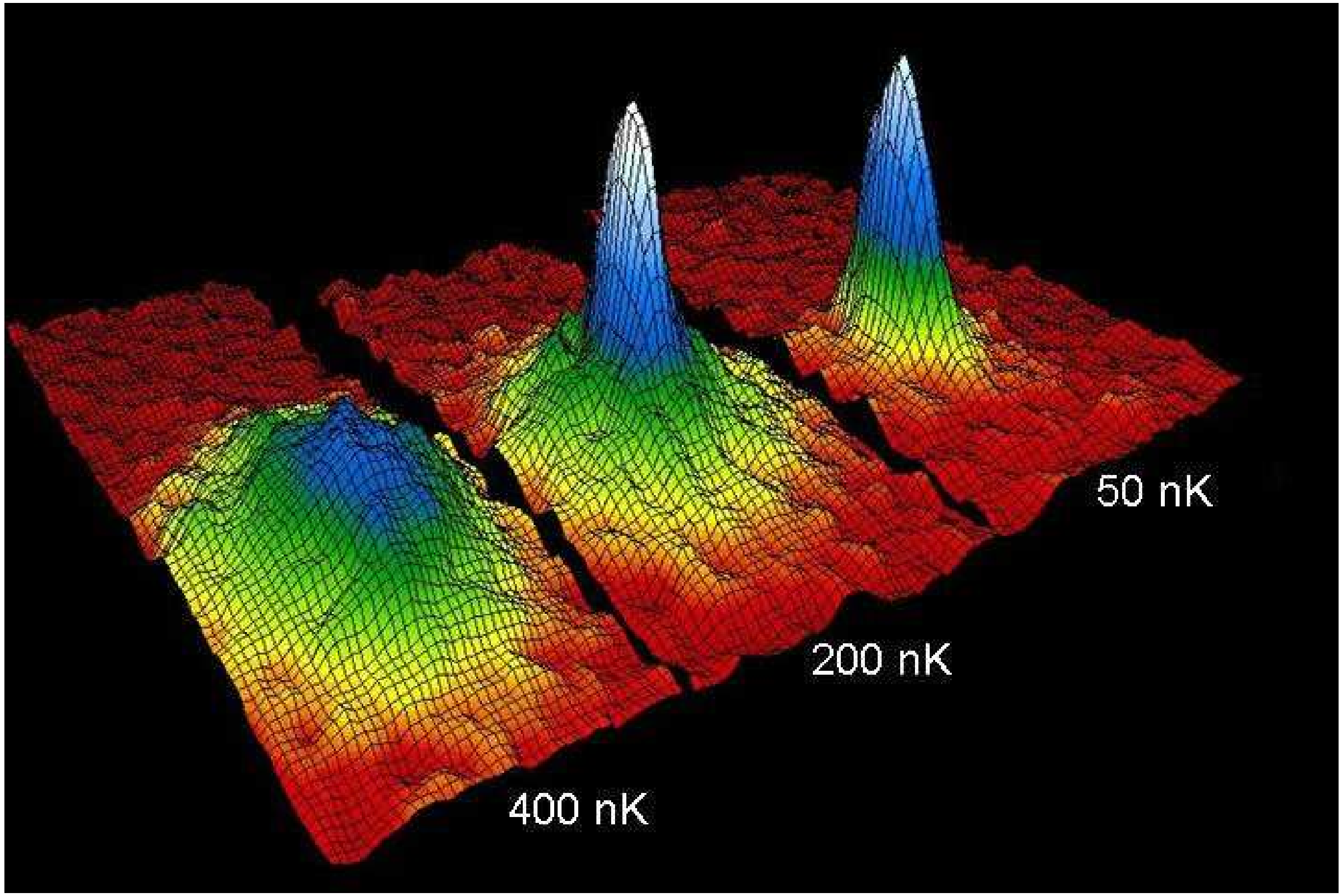
Evaporative cooling

1.4 Experimental Apparatus



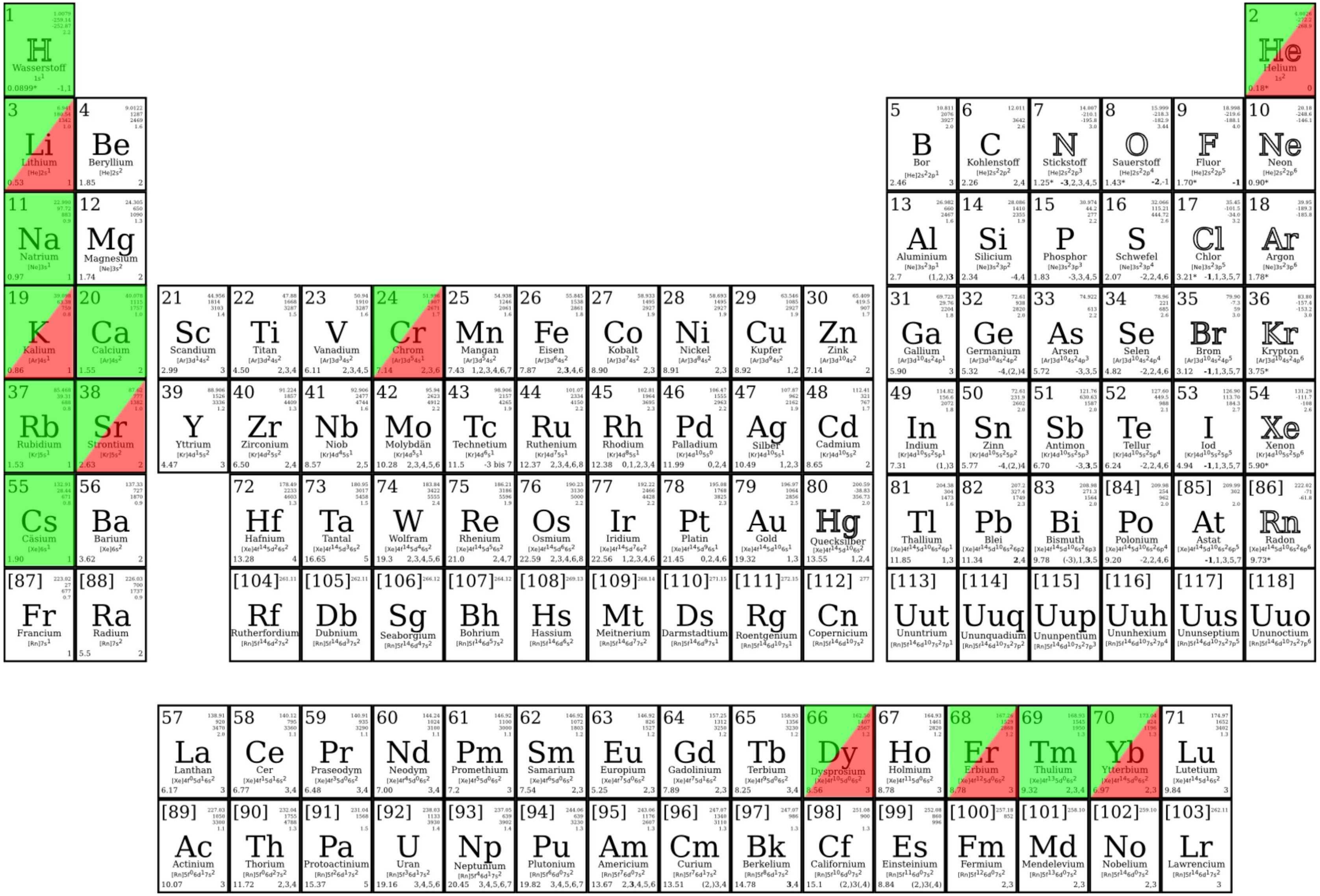
Costs about 1.000.000 EUR

1.5 Time-of-Flight Absorption Pictures



JILA (1995): ${}^{87}_{37}$Rb , N=20 000 , $\omega_1 = \omega_2 = \omega_3/\sqrt{8} = 2\pi\times$ 120 Hz

1.6 Periodic Table of Chemical Elements



Quantum degenerate bosons and fermions

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2.1 Strong Dipolar Quantum Gases

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From few to many-body physics with dipolar quantum gases

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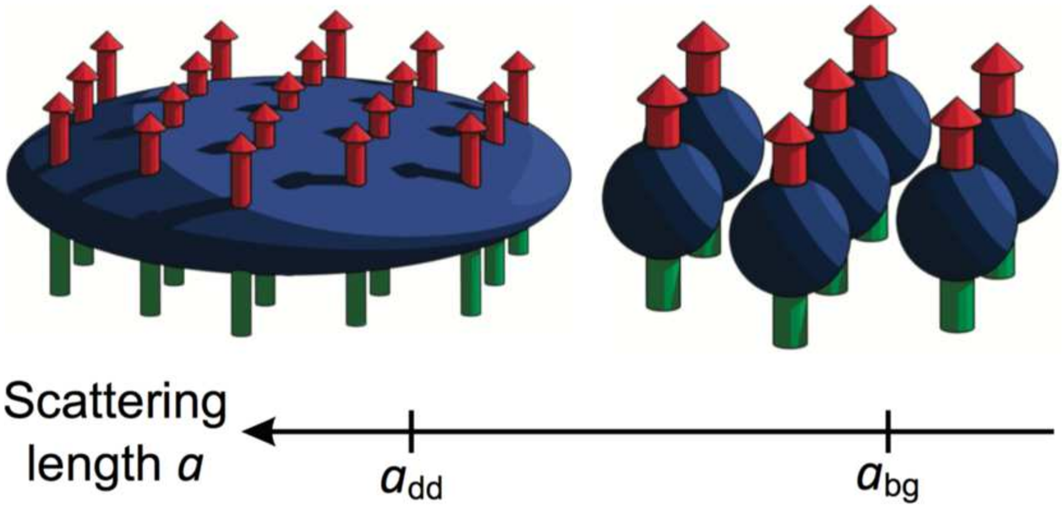
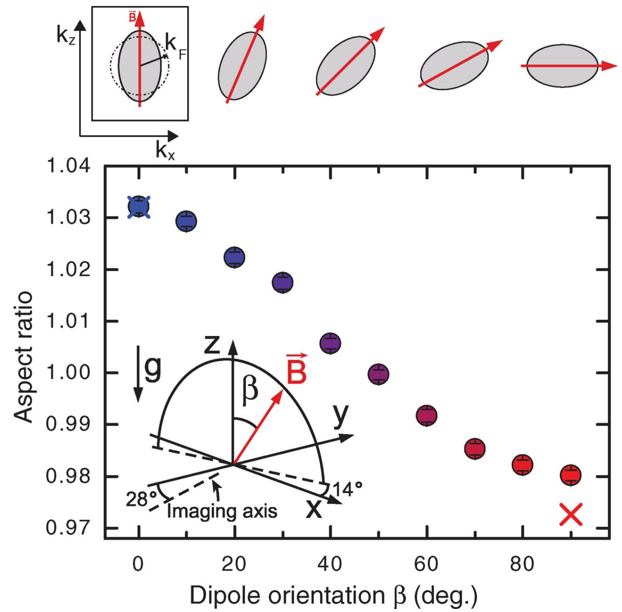
Hanover, Innsbruck, Kaiserslautern, Munich, Stuttgart





Dipolar Bose gases:

Quantum droplets

Dipolar Fermi gases:

Fermi surface deformed

Pelster, Physik-Journal **18**, Nr. 6, 20 (2019)

2.2 Dimensional Crossover in Trapped Photon Gases

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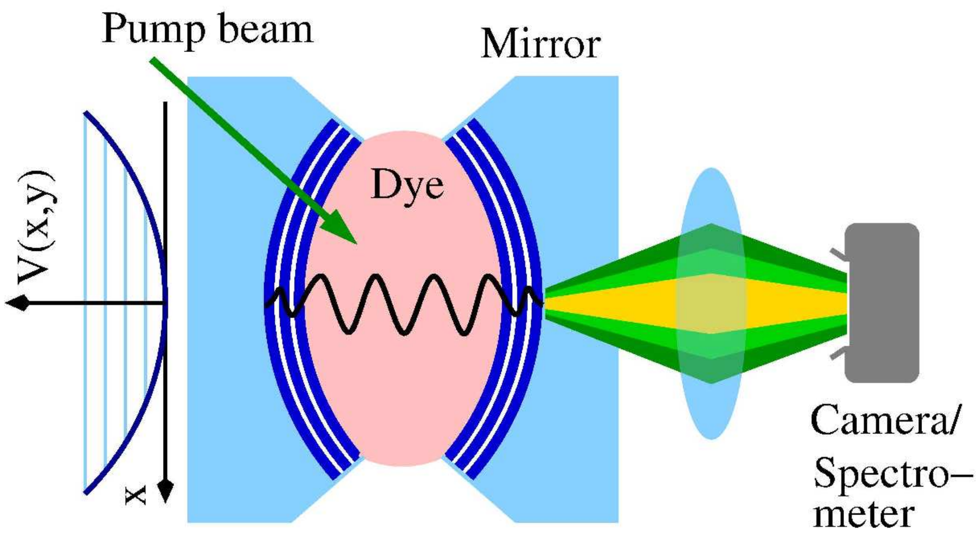
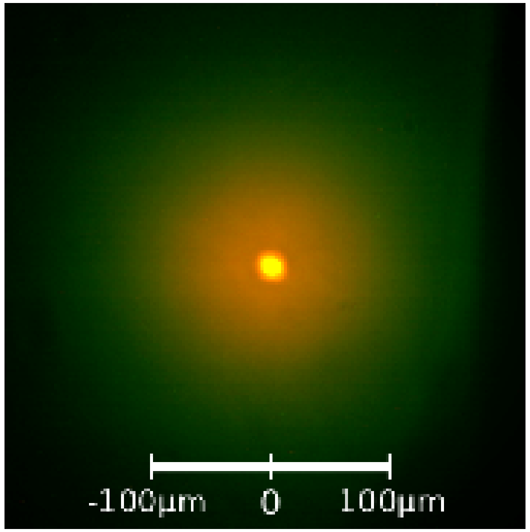
Bonn, Kaiserslautern





Pelster, Physik-Journal **10**, Nr. 1, 20 (2011); Physik-Journal **13**, Nr. 3, 20 (2014)

Theory support for new photon BEC set up
in research group of Georg von Freymann

2.3 Random Potentials

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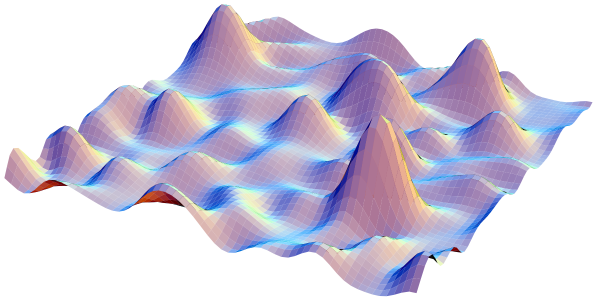
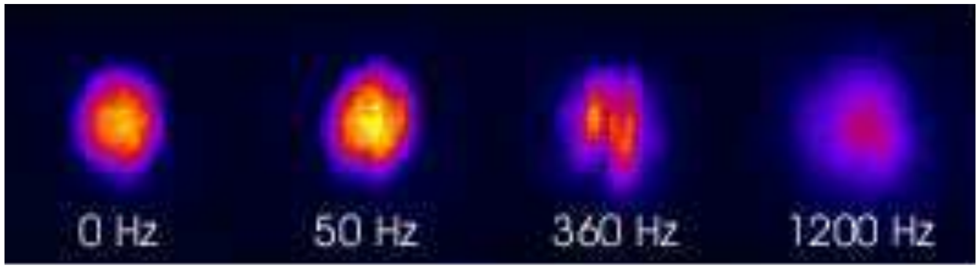
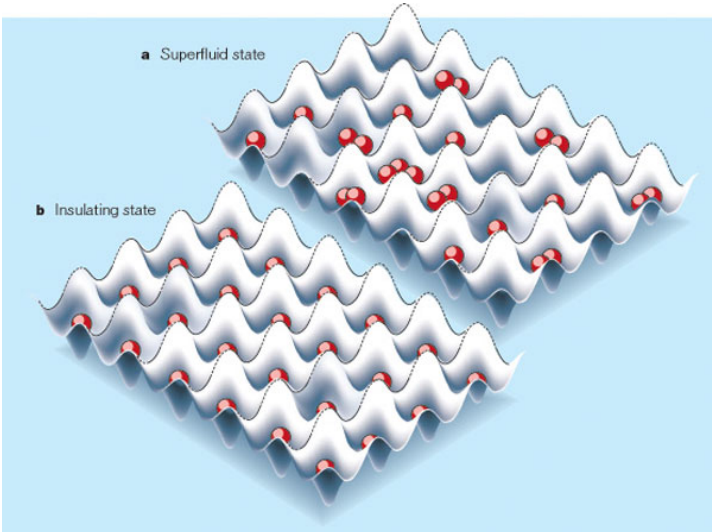
Bonn, Kaiserslautern

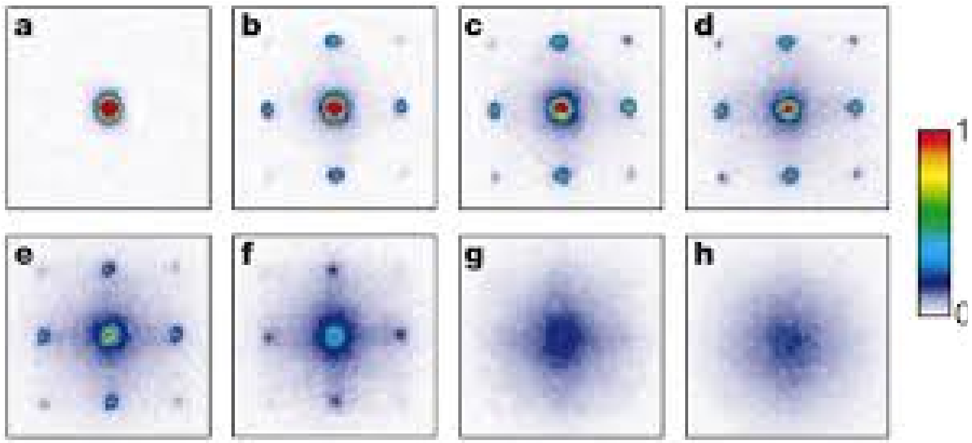




Theory support for ^{6}Li BEC-BCS crossover experiment in research group of Artur Widera

2.4 Bosons in Optical Lattices



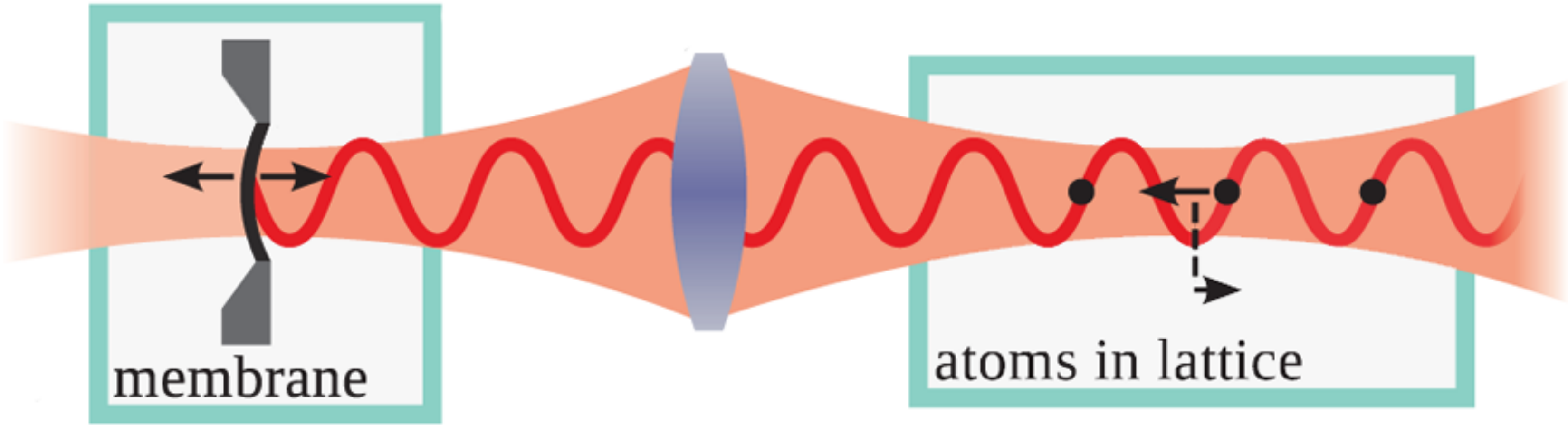


Superfluid-Mott quantum phase transition

2.5 Quantum Gases on Manifolds

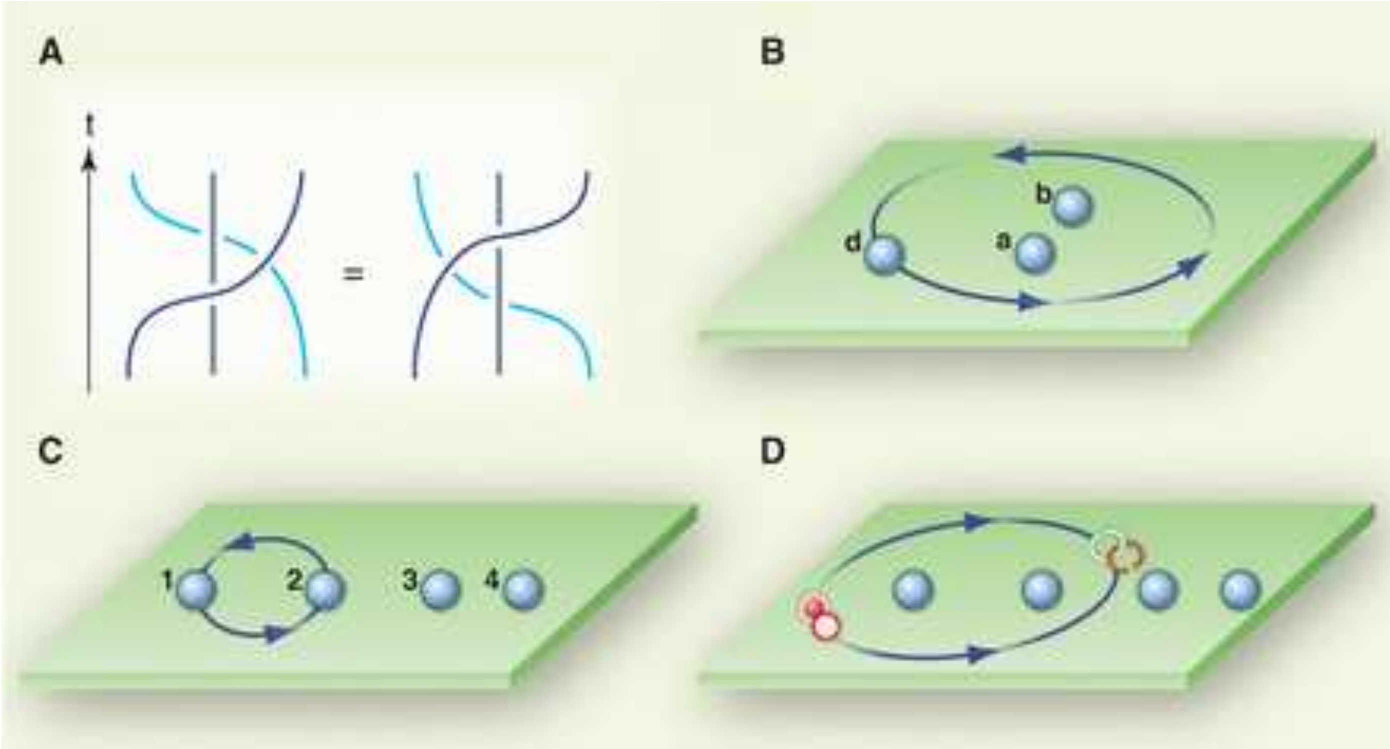
Berezinskii-Kosterlitz-Thouless (BKT) phase transition: unbinding of vortex/antivortex pairs

2.6 Hybrid Atom-Optomechanical Systems



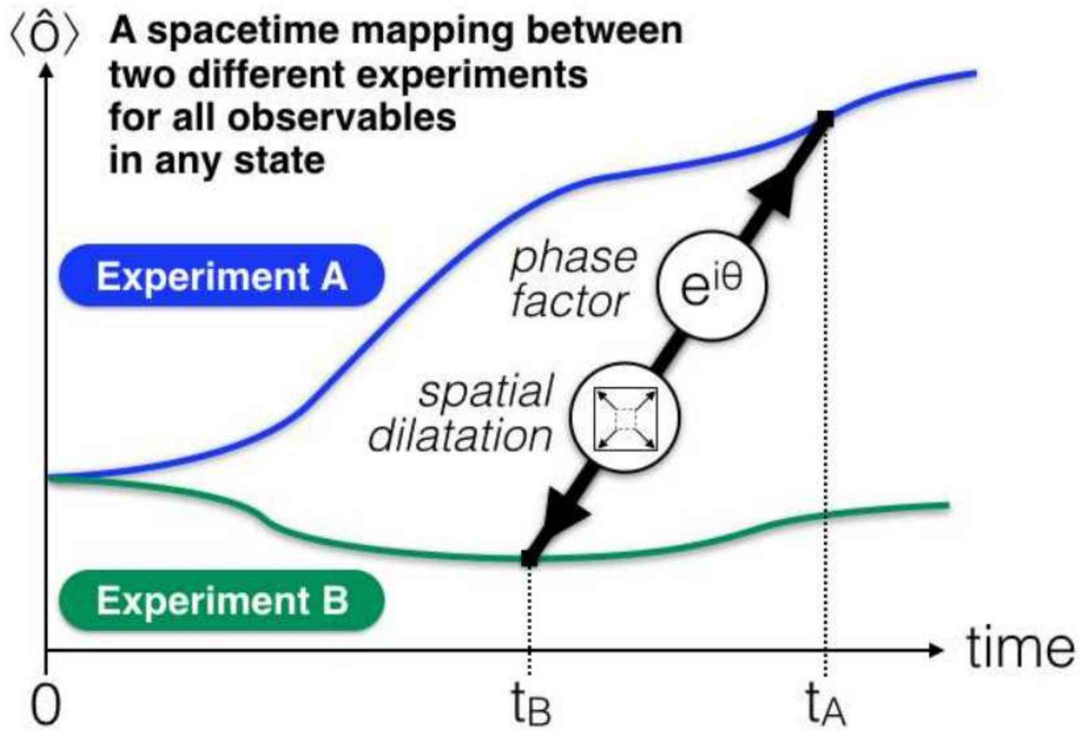
- **Cooling of nanomembrane**
- **Long-range interactions in atom gas mediated by cavity field**
- **Non-equilibrium phase transitions**

2.7 Anyonic Statistics



How to interpolate between Bose-Einstein and Fermi-Dirac statistics?

2.8 Quantum Gas Mappings



New solution strategy:
Map one quantum gas experiment to another

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3.1 Homepage

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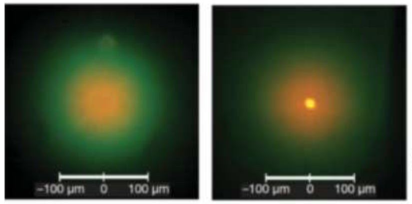
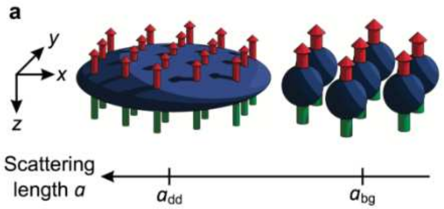
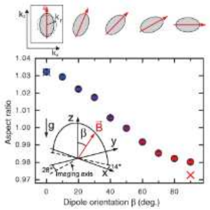
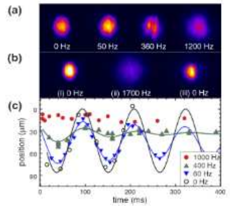
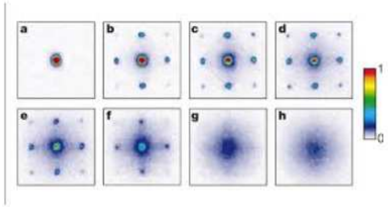
Theory of Ultracold Quantum Gases:



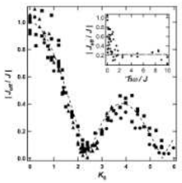


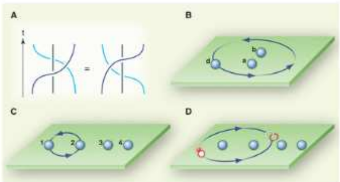


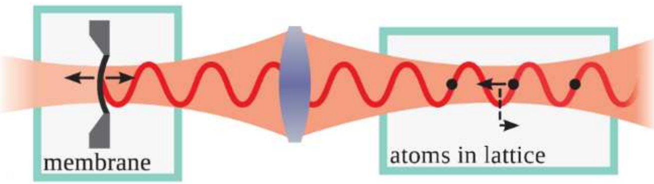


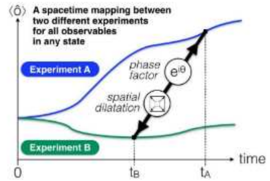


Photon Bose-Einstein Condensate | Dipolar Quantum Droplets | Fermi Surface Deformation | Dirty Boson Problem | Superfluid Mott Quantum Phase Transition









Floquet Physics | Anyonic Quantum Statistics | Hybrid Atom-Optomechanical Systems | Quantum Gases on Curved Manifolds | Quantum Gas Mappings

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3.2 Conferences and Schools

- **813. WEH Seminar**
  Advances in Quantum Simulation and Sensing with Ultracold Gases:
  Bad Honnef, June 24 – 28, 2024

WILHELM UND ELSE HERAEUS-STIFTUNG

- **OSCAR iWeek**
  Phase Transitions:
  Kaiserslautern, August 19 – 23, 2024

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- **Brazilian-German WEH Seminar**
  Superconductivity and Superfluidity – From Condensed Matter to Ultracold Quantum Gases
  Natal, October 14 – 18, 2024

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3.3 Summer Term 2024: General Relativity

- Special Relativity
- Equivalence principle
- Geodesic equation
- Riemann differential geometry
- Einstein field equations
- Schwarzschild metric
- Perihel precession
- Geodesic precession
- Thirring-Lense effect
- Gravitational waves