Ultracold Quantum Gases:
A Fascinating Playground for Basic Research

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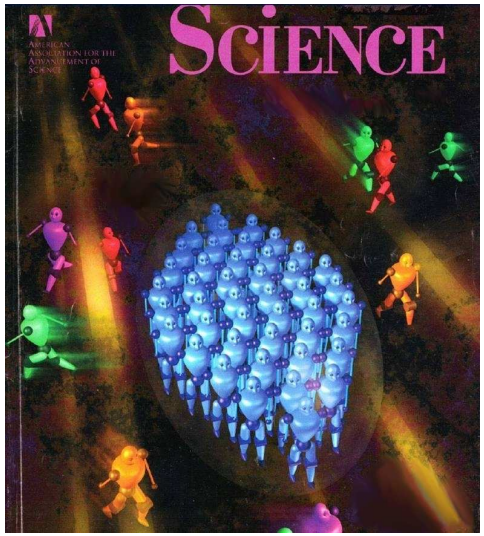
FOR 2247 From few to many-body physics with dipolar quantum gases DFG FWF

1. Introduction
2. Theses Topics
3. Outlook



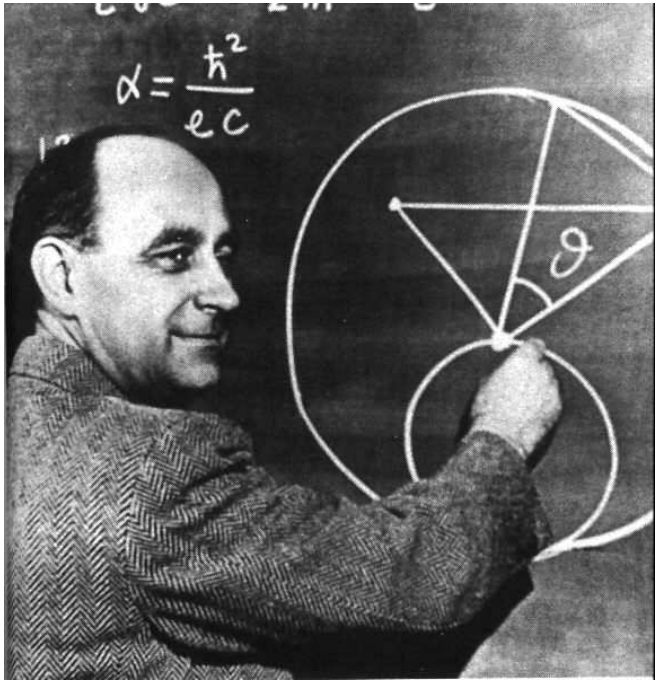
1.1 Identical Quantum Particles

Bosons:

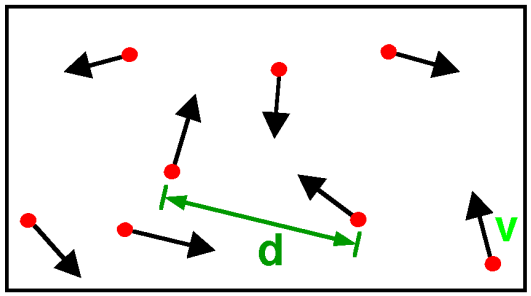
- Symmetric wave function
- Integer spin

Fermions:

- Anti-symmetric wave function
- Half-integer spin



1.2 What is Bose-Einstein Condensation?



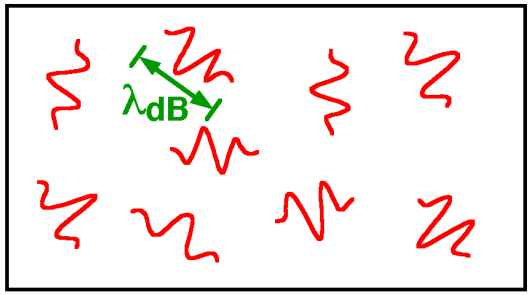
High Temperature T:

thermal velocity v

density d^{-3}

"Billiard balls"

- $n = \frac{1}{d^3}$



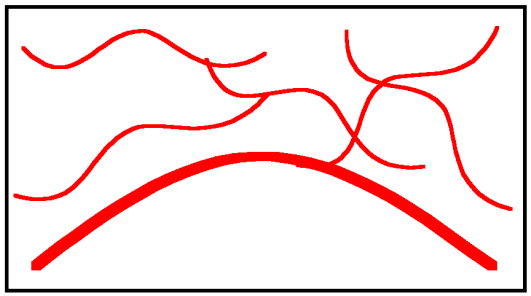
Low Temperature T:

De Broglie wavelength

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

"Wave packets"

- $\lambda_{\mathrm{dB}} = \frac{\hbar}{\sqrt{2Mk_BT}}$

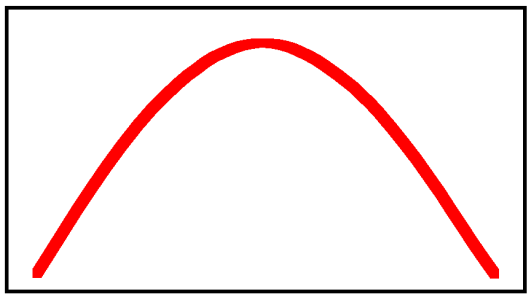


$T=T_{crit}$: Bose-Einstein Condensation

$\lambda_{dB} \approx d$

"Matter wave overlap"

- $\frac{\lambda_{\mathrm{dB}}}{d} \approx 1$



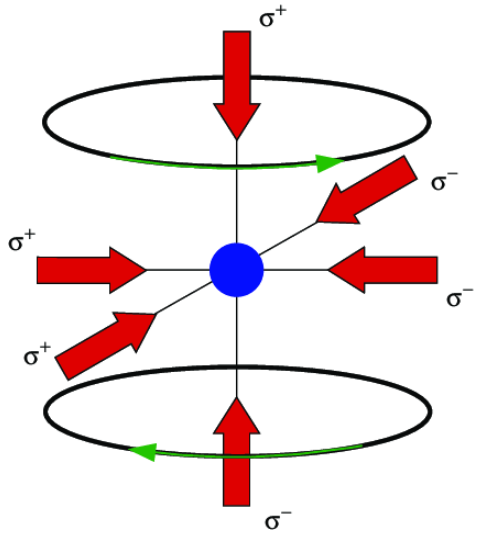
T=0: Pure Bose condensate

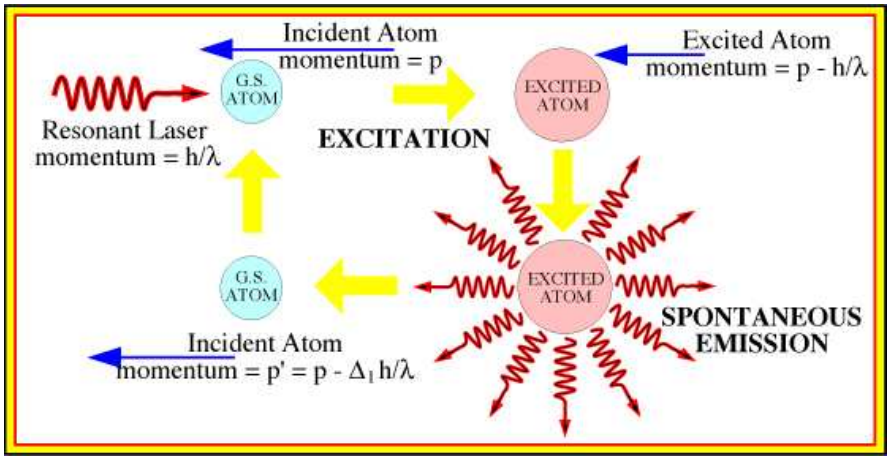
"Giant matter wave"

- $T_c \approx \frac{\hbar^2 n^{3/2}}{2Mk_B}$

1.3 Cooling Techniques

Magneto-optical trap

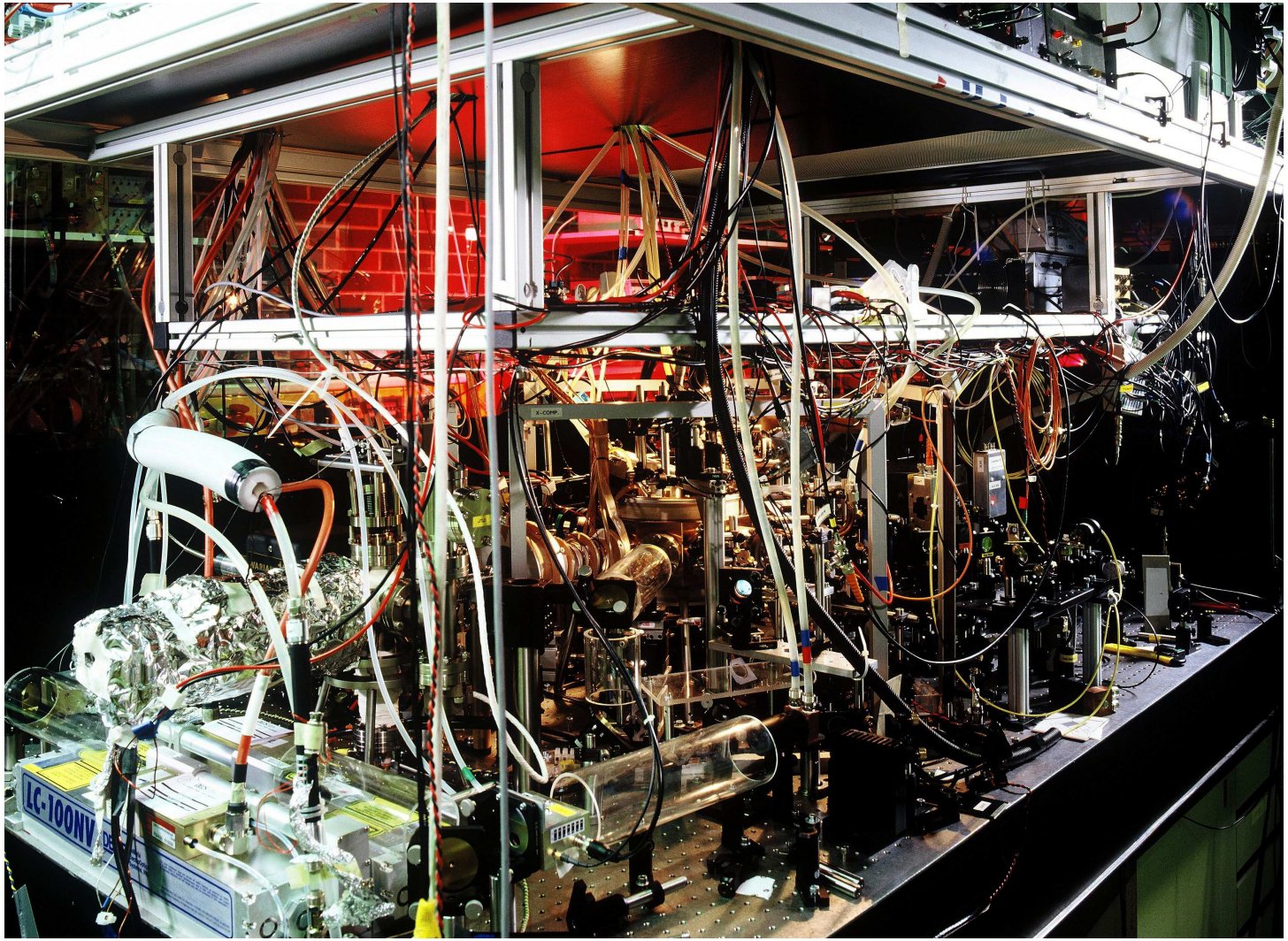




Laser cooling

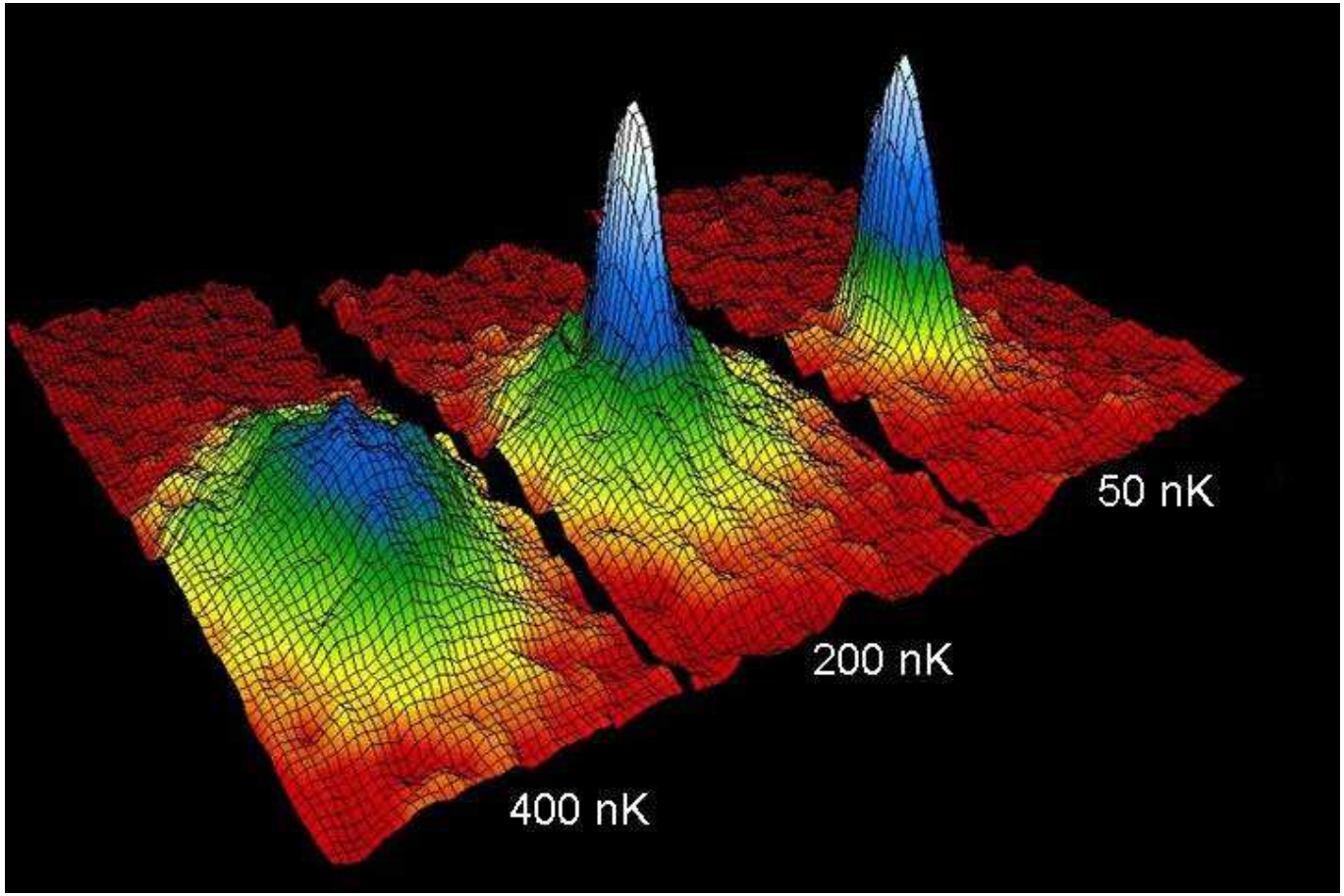
Evaporative cooling

1.4 Experimental Apparatus



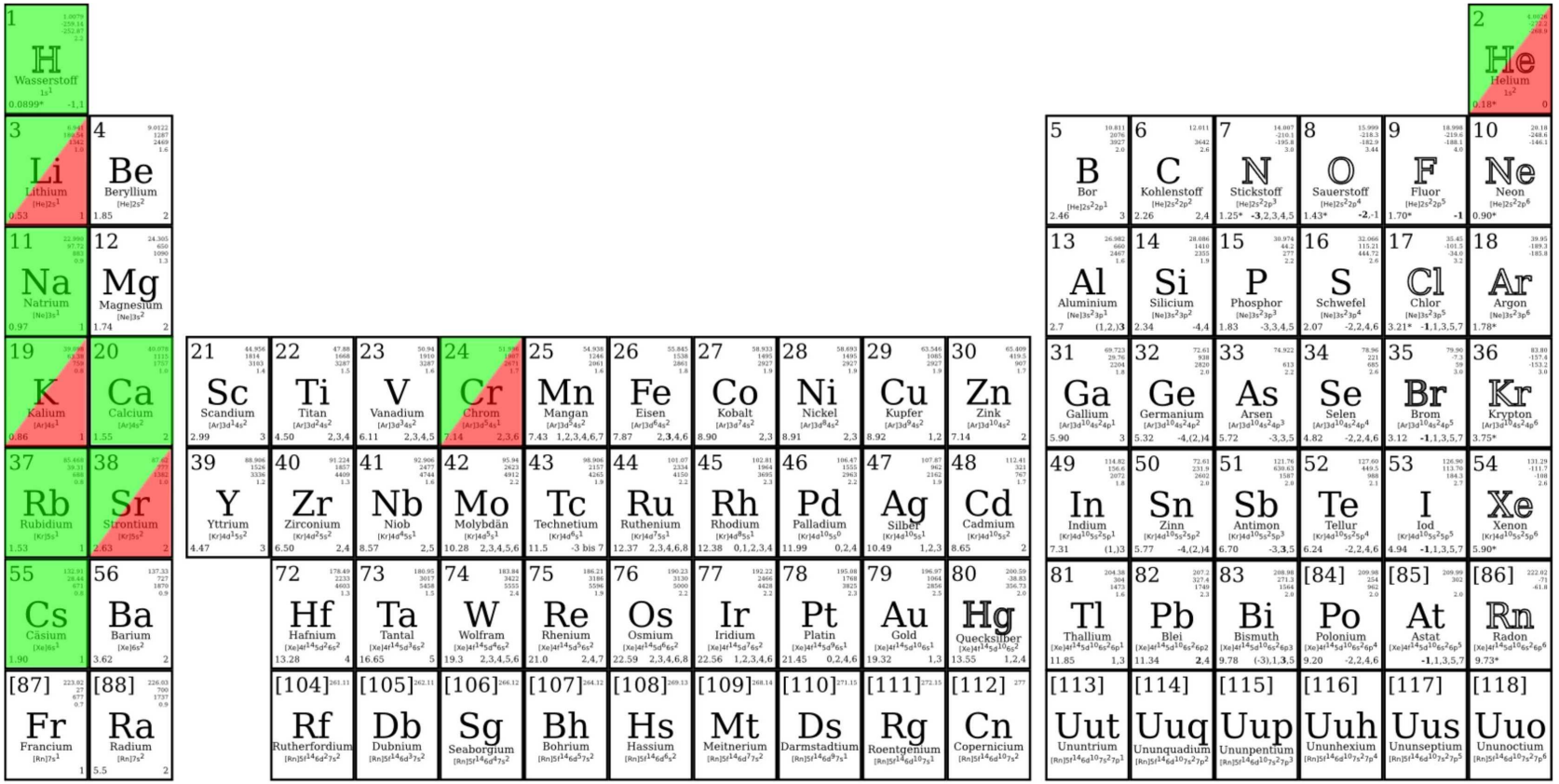
Costs about 1.000.000 EUR

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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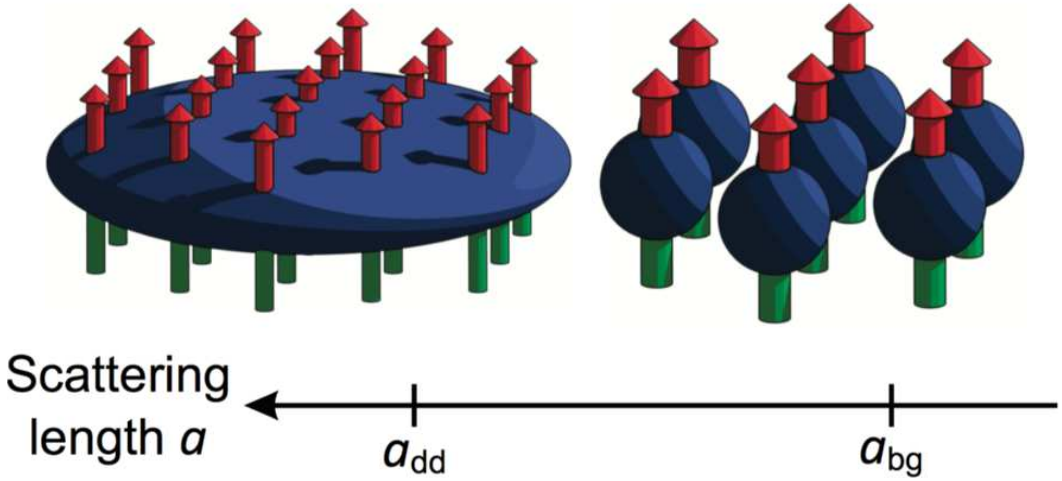
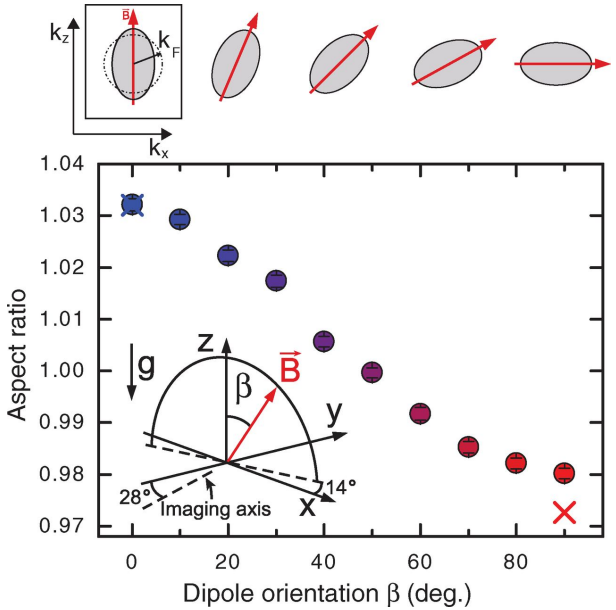
2.1 Strong Dipolar Quantum Gases

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

DFG FWF

Hanover, Innsbruck, Kaiserslautern, Munich, Stuttgart





Dipolar Bose gases:

Quantum droplets

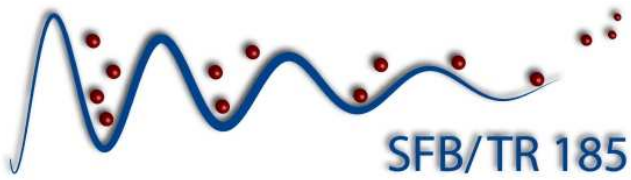
Pfau group (Stuttgart)

Dipolar Fermi gases:

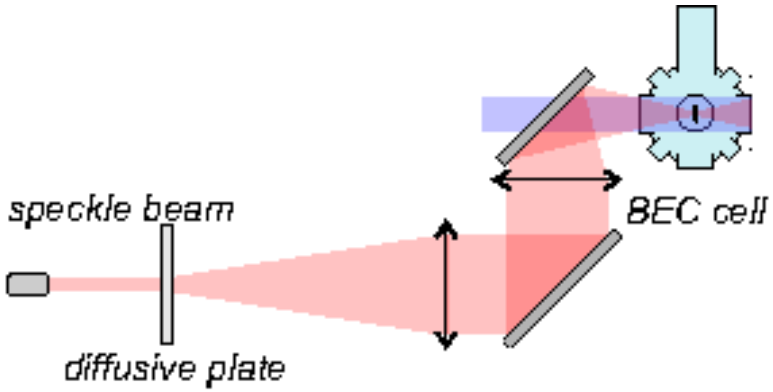
Fermi surface deformed

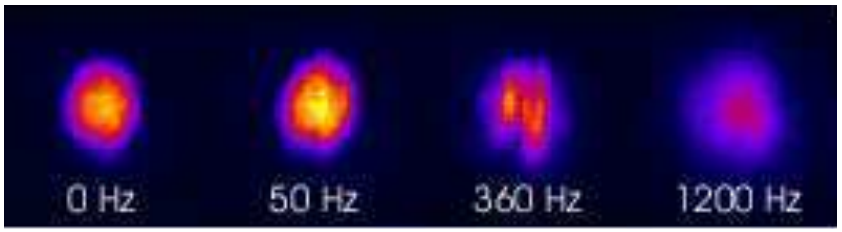
Ferlaino group (Innsbruck)

2.2 Random Potentials



Bonn, Kaiserslautern





Laser speckles **Condensate deformation**

Inguscio group (Florence)

2.3 BCS-BEC-Crossover

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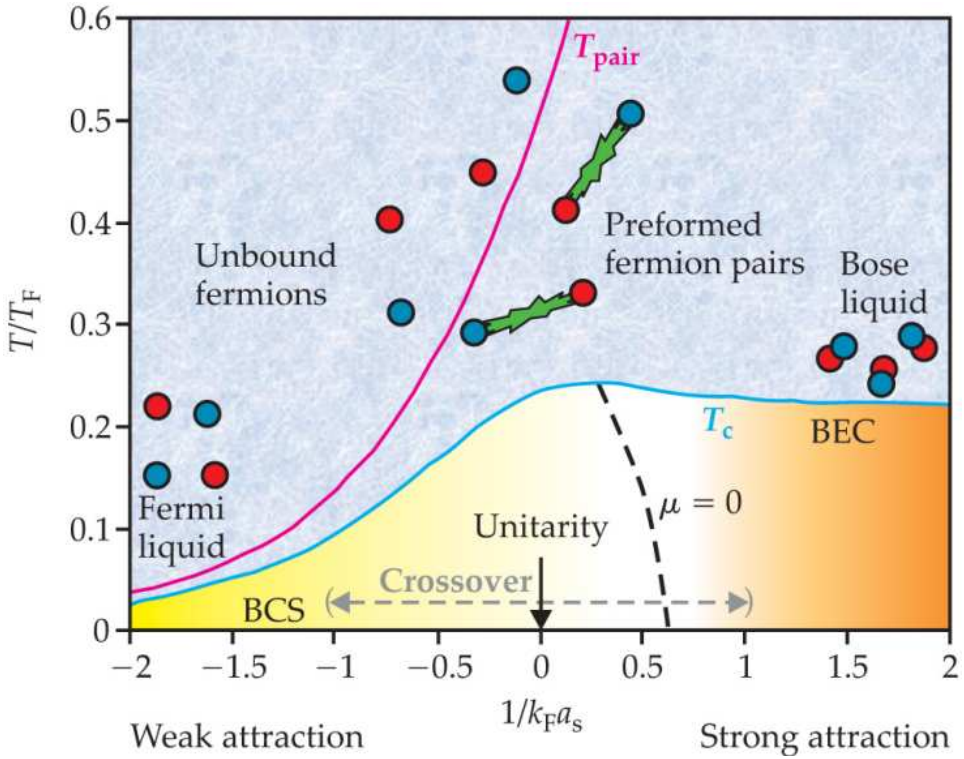
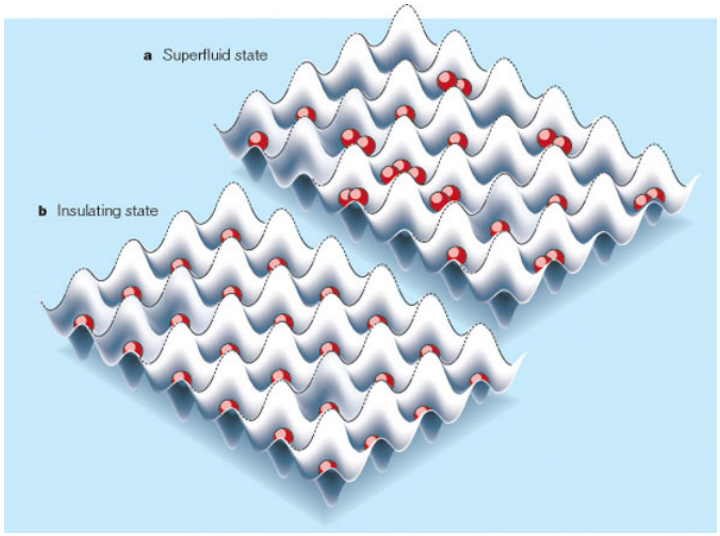
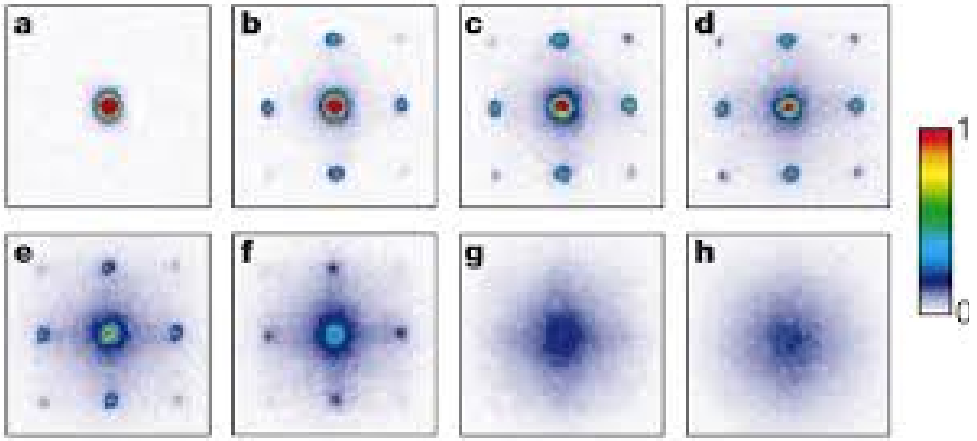
Bonn, Kaiserslautern



Sá de Melo, Physics Today **61**, No. 10, 45 (2008)

2.4 Superfluid-Mott Quantum Phase Transition



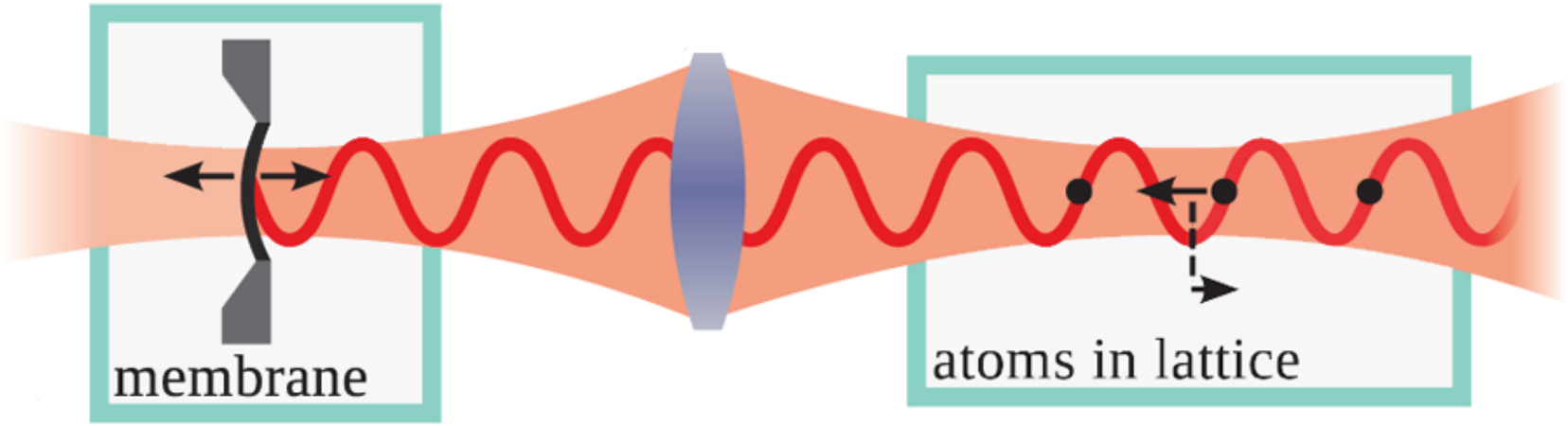


Bloch group (Munich)

2.5 Quantum Gases on Manifolds

Lundblad group (Lewiston)

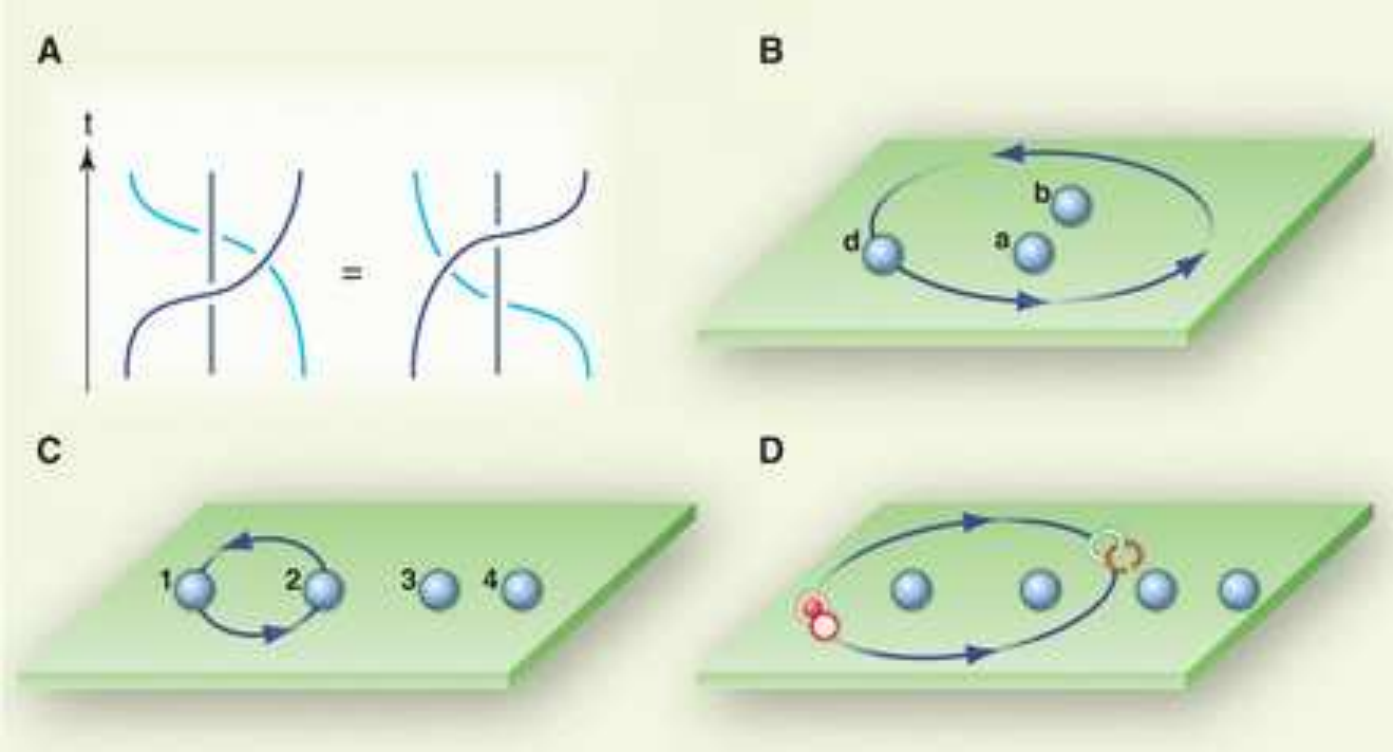
2.6 Hybrid Atom-Optomechanical Systems



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

Treutlein group (Basel)

2.7 Anyonic Statistics



Interpolation between Bose-Einstein and Fermi-Dirac statistics?

Greiner group (Harvard)

2.8 Photon Bose-Einstein Condensates

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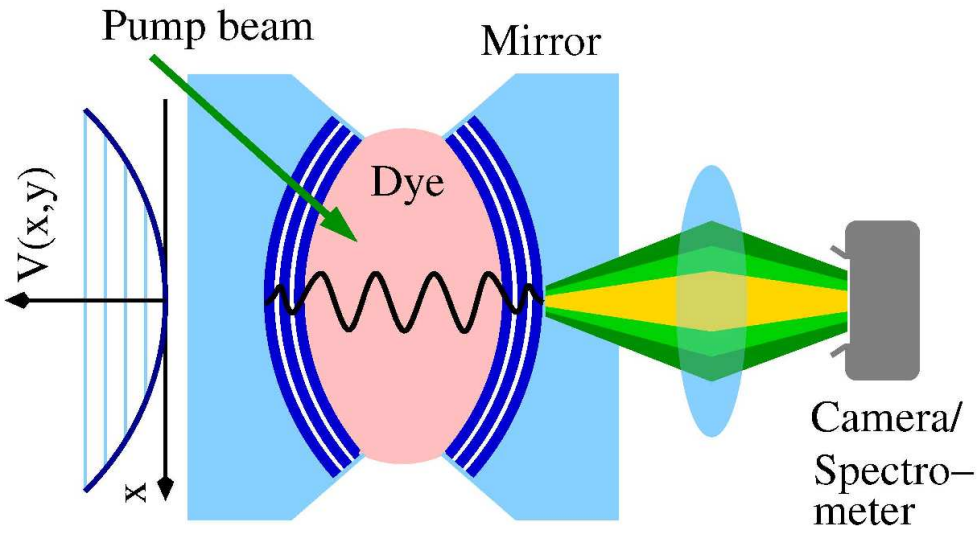
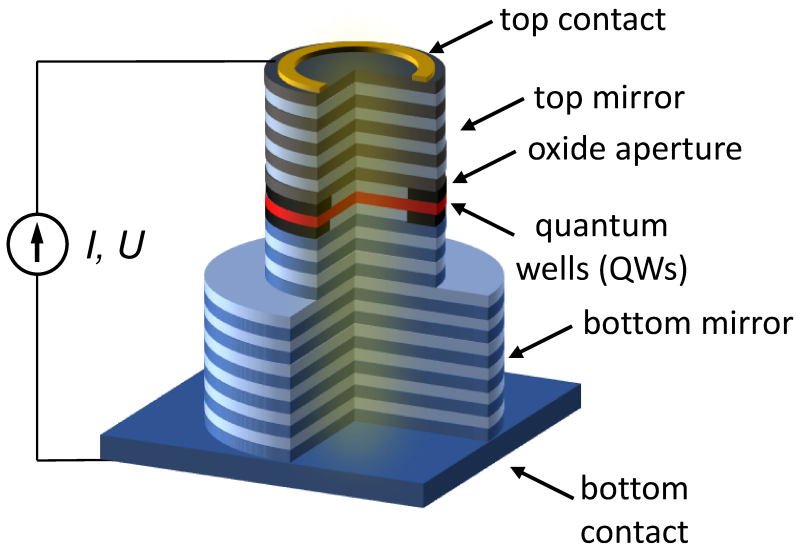
Wrocław University of Science and Technology

Bonn, Kaiserslautern





Dye filled microcavity

Weitz group (Bonn)

Vertical-Cavity Surface-Emitting Laser

Pieczarka group (Wrocław)

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3.1 Homepage

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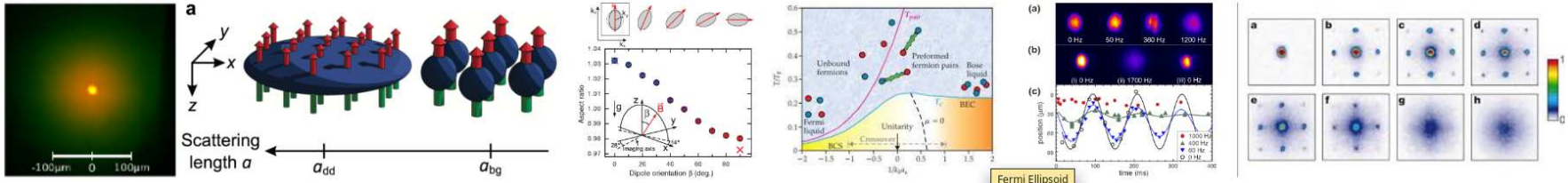
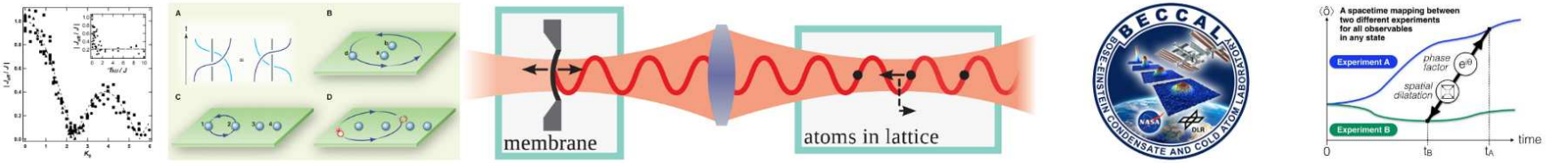
Theory of Ultracold Quantum Gases:



Photon BEC | Dipolar Quantum Droplets | Fermi Surface Deformation | BEC-BCS Crossover | 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 Scientific Events

- **OSCAR School on Open-Dissipative Systems:**
  Tutzing, April 1 – 4, 2025

- **OSCAR Minisymposium**
  Kaiserslautern, June 24 – 25, 2025

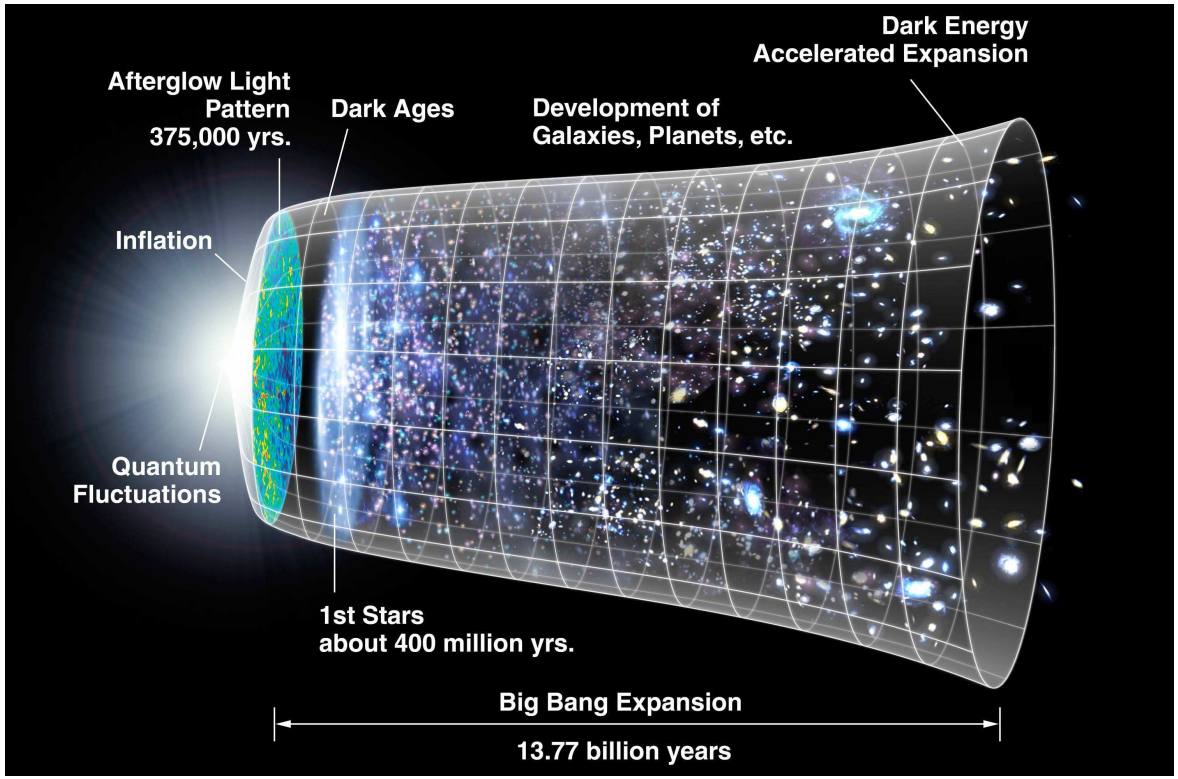
- **Bad Honnef Physics School on Ultracold Quantum Matter**
  Bad Honnef, August 10 – 16, 2025

WILHELM UND ELSE HERAEUS-STIFTUNG

- **Binational Exchange Visits with Belgrade (Serbia) and São Carlos (Brazil)**

DAAD

3.3 Summer Term 2025: Cosmology



- Cosmological principle
- Cosmic distance ladder
- Cosmological standard model
- Cosmic microwave background radiation