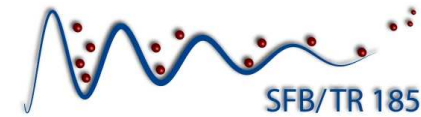


Ultracold Quantum Gases: A Fascinating Playground for Basic Research

Axel Pelster

RPTU



FOR 2247



From few to many-body physics
with dipolar quantum gases

DFG FLWF

1. Introduction

2. Theses Topics

3. Outlook



1.1 Identical Quantum Particles

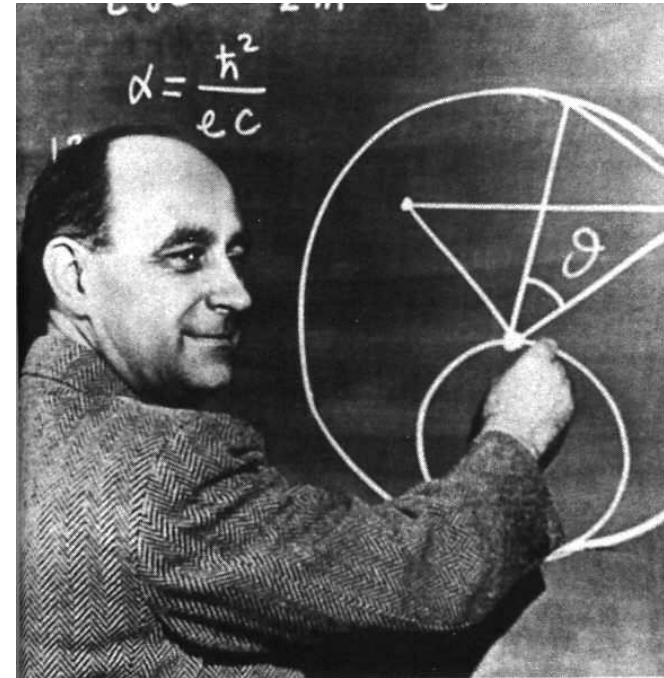
Bosons:

- Symmetric wave function
- Integer spin

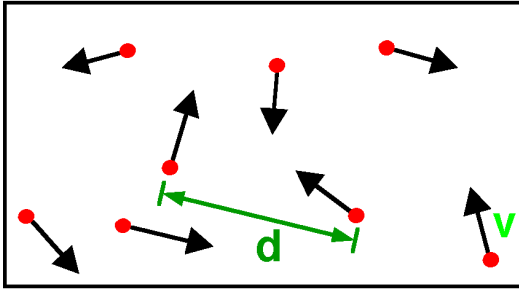


Fermions:

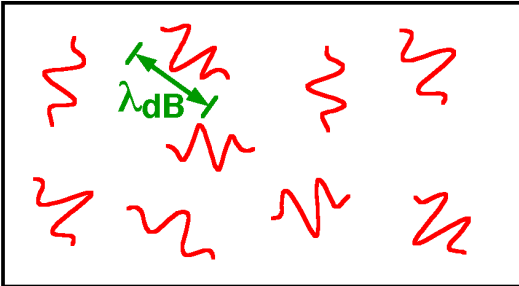
- Anti-symmetric wave function
- Half-integer spin



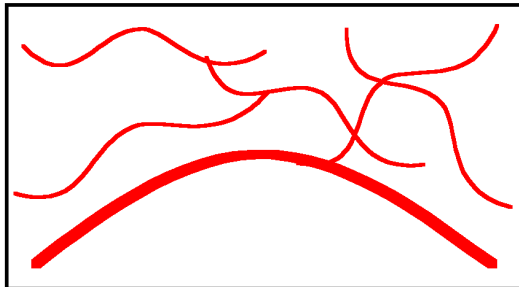
1.2 What is Bose-Einstein Condensation?



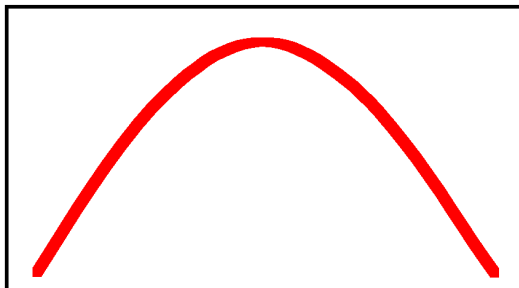
High Temperature T:
 thermal velocity v
 density d^{-3}
 "Billiard balls"



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"

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

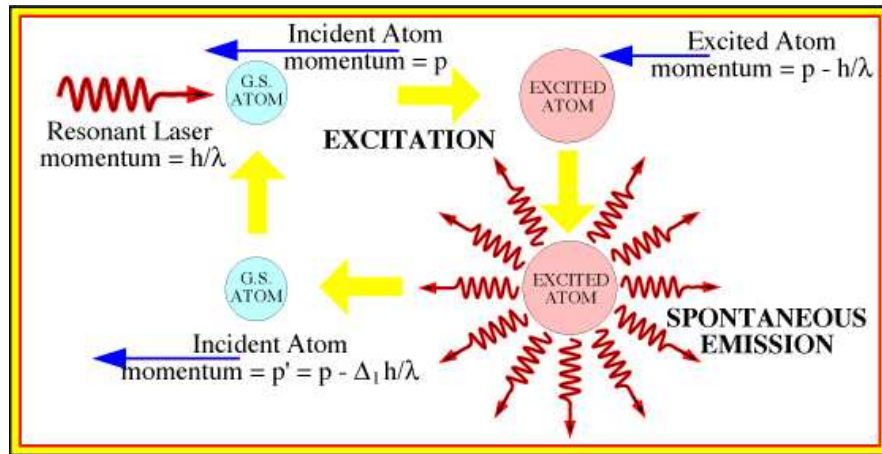
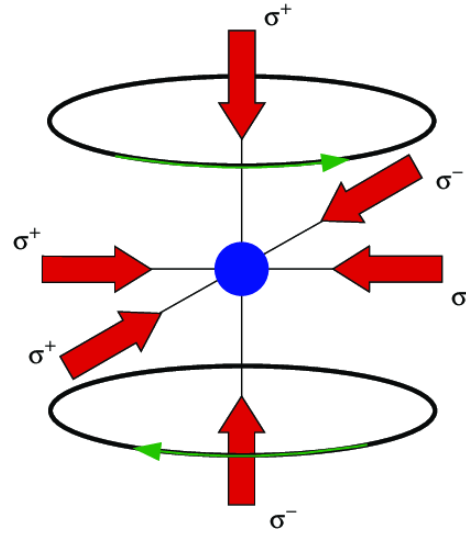
- $\lambda_{dB} = \frac{\hbar}{\sqrt{2Mk_B T}}$

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

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

1.3 Cooling Techniques

Magneto-optical trap

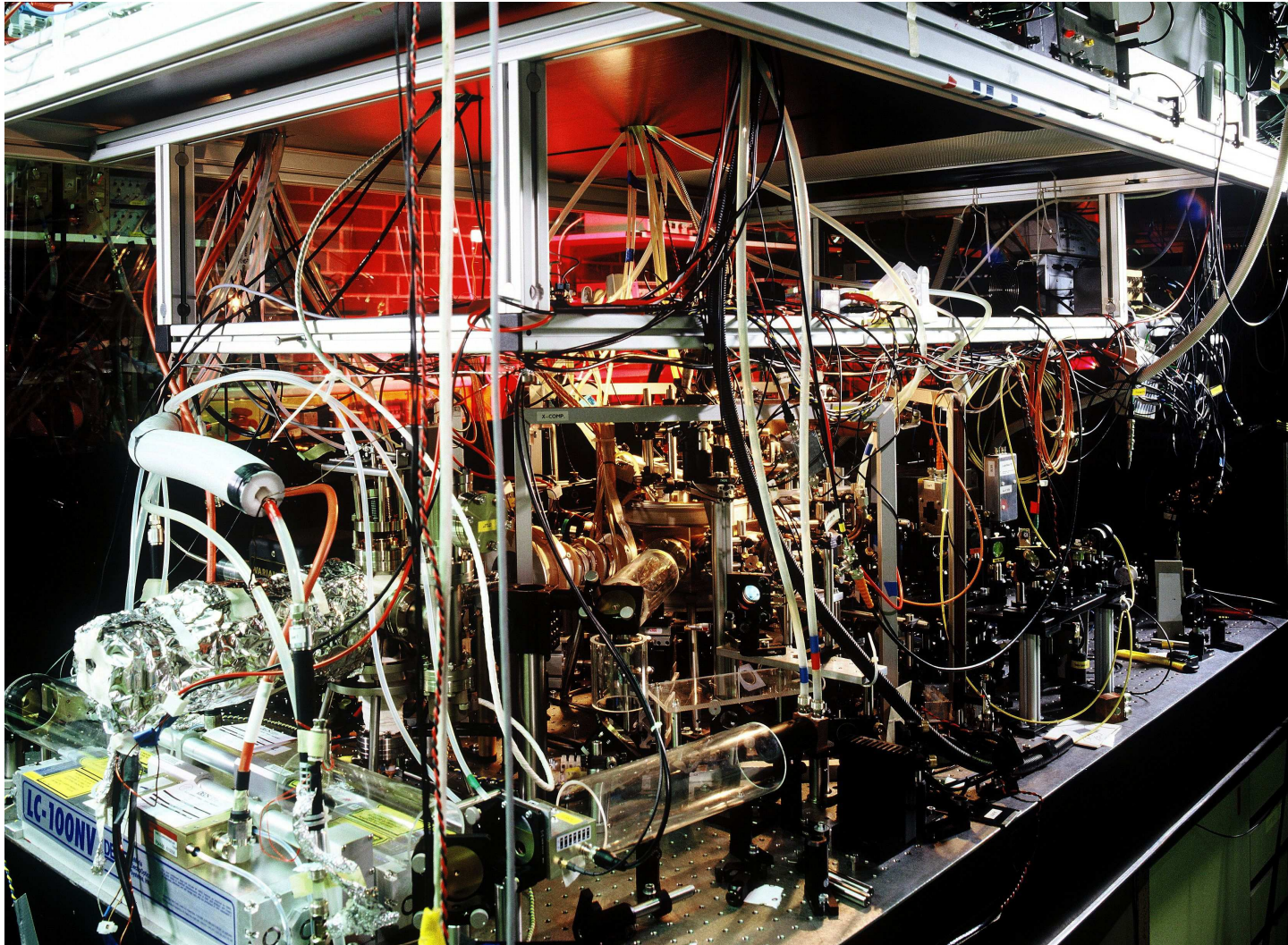


Laser cooling



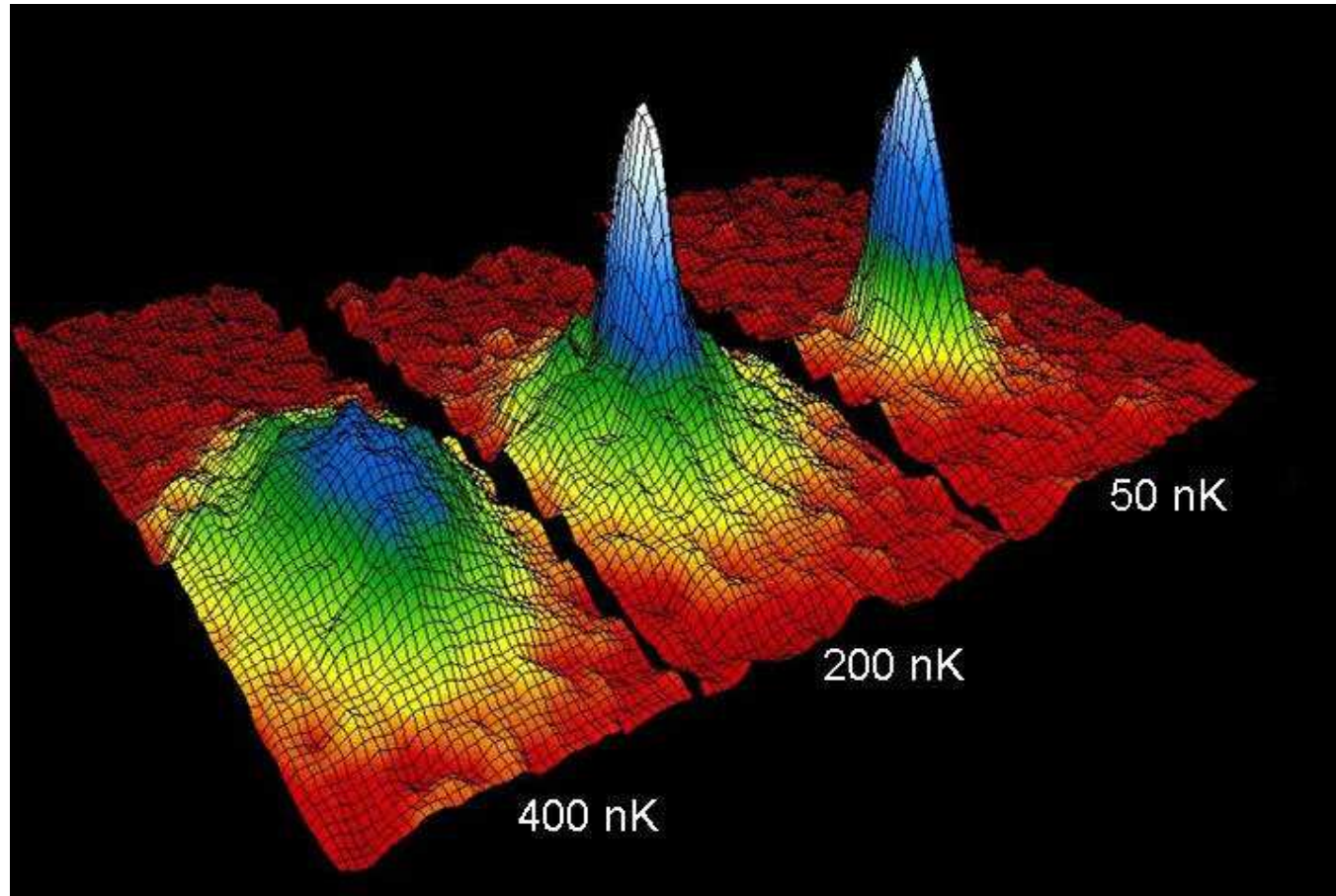
Evaporative cooling

1.4 Experimental Apparatus



Costs about 1.000.000 EUR

1.5 Time-of-Flight Absorption Pictures



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

1.6 Periodic Table of Chemical Elements

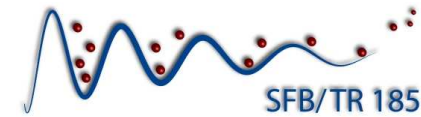
1 H Wasserstoff (He)1s ¹ 0.0899* -1.1																	2 He Helium (He)1s ² 0.18* 0
3 Li Lithium (He)2s ¹ 0.53 1	4 Be Beryllium (He)2s ² 1.85 2																
11 Na Natrium (Ne)3s ¹ 0.97 1	12 Mg Magnesium (Ne)3s ² 1.74 2																
19 K Kalium (Ar)4s ¹ 0.86 1	20 Ca Calcium (Ar)4s ² 1.05 2	21 Sc Scandium (Ar)3d ¹ 4s ² 2.99 3	22 Ti Titan (Ar)3d ² 4s ² 3.45 2,3,4	23 V Vanadium (Ar)3d ³ 4s ² 6.11 2,3,4,5	24 Cr Chrom (Ar)3d ⁵ 4s ¹ 7.14 2,3,6	25 Mn Mangan (Ar)3d ⁵ 4s ² 7.43 1,2,3,4,6,7	26 Fe Eisen (Ar)3d ⁶ 4s ² 7.87 2,3,4,6	27 Co Kobalt (Ar)3d ⁷ 4s ² 8.90 2,3	28 Ni Nickel (Ar)3d ⁸ 4s ² 8.91 2,3	29 Cu Kupfer (Ar)3d ¹⁰ 4s ¹ 8.92 1,2	30 Zn Zink (Ar)3d ¹⁰ 4s ² 7.14 2	31 Ga Gallium (Ar)3d ¹⁰ 4s ¹ 4p ¹ 5.90 3	32 Ge Germanium (Ar)3d ¹⁰ 4s ² 4p ² 5.32 -4,4	33 As Arsen (Ar)3d ¹⁰ 4s ² 4p ³ 5.72 -3,3,4,5	34 Se Selen (Ar)3d ¹⁰ 4s ² 4p ⁴ 4.82 -2,4,6	35 Br Brom (Ar)3d ¹⁰ 4s ² 4p ⁵ 3.12 -1,1,3,5,7	36 Kr Krypton (Ar)3d ¹⁰ 4s ² 4p ⁶ 3.75* 0
37 Rb Rubidium (Kr)5s ¹ 1.53 1	38 Sr Strontium (Kr)5s ² 1.263 2	39 Y Yttrium (Kr)4d ¹ 5s ² 4.47 3	40 Zr Zirkonium (Kr)4d ² 5s ² 6.50 2,4	41 Nb Niob (Kr)4d ⁴ 5s ¹ 8.57 2,5	42 Mo Molybdän (Kr)4d ⁵ 5s ¹ 10.28 2,3,4,5,6	43 Tc Technetium (Kr)4d ⁵ 5s ² 11.5 -3 bis 7	44 Ru Ruthenium (Kr)4d ⁷ 5s ¹ 12.37 2,3,4,6,8	45 Rh Rhodium (Kr)4d ⁸ 5s ¹ 12.38 0,1,2,3,4	46 Pd Palladium (Kr)4d ¹⁰ 5s ⁰ 11.99 0,2,4	47 Ag Silber (Kr)4d ¹⁰ 5s ¹ 10.49 1,2,3	48 Cd Cadmium (Kr)4d ¹⁰ 5s ² 8.65 2	49 In Indium (Kr)4d ¹⁰ 5s ² 5p ¹ 7.31 1,3	50 Sn Zinn (Kr)4d ¹⁰ 5s ² 5p ² 5.77 -4,(2),4	51 Sb Antimon (Kr)4d ¹⁰ 5s ² 5p ³ 6.70 -3,3,5	52 Te Tellur (Kr)4d ¹⁰ 5s ² 5p ⁴ 6.24 -2,2,4,6	53 I Iod (Kr)4d ¹⁰ 5s ² 5p ⁵ 4.94 -1,1,3,5,7	54 Xe Xenon (Kr)4d ¹⁰ 5s ² 5p ⁶ 5.90* 0
55 Cs Cäsium (Xe)6s ¹ 1.90 1	56 Ba Barium (Xe)6s ² 3.62 2	72 Hf Hafnium (Xe)4f ¹⁴ 5d ² 6s ² 13.28 4	73 Ta Tantal (Xe)4f ¹⁴ 5d ³ 6s ² 16.65 5	74 W Wolfram (Xe)4f ¹⁴ 5d ⁴ 6s ² 19.3 2,3,4,5,6	75 Re Rhenium (Xe)4f ¹⁴ 5d ⁵ 6s ² 21.0 2,4,7	76 Os Osmium (Xe)4f ¹⁴ 5d ⁶ 6s ² 22.59 2,3,4,6,8	77 Ir Iridium (Xe)4f ¹⁴ 5d ⁷ 6s ² 22.56 1,2,3,4,6	78 Pt Platin (Xe)4f ¹⁴ 5d ⁹ 6s ¹ 21.45 0,2,4,6	79 Au Gold (Xe)4f ¹⁴ 5d ¹⁰ 6s ¹ 19.32 1,3	80 Hg Quecksilber (Xe)4f ¹⁴ 5d ¹⁰ 6s ² 13.55 1,2,4	81 Tl Thallium (Xe)4f ¹⁴ 5d ¹⁰ 6s ¹ 6p ¹ 11.85 1,3	82 Pb Blei (Xe)4f ¹⁴ 5d ¹⁰ 6s ² 6p ² 11.34 2,4	83 Bi Bismuth (Xe)4f ¹⁴ 5d ¹⁰ 6s ² 6p ³ 9.78 (-3),1,3,5	[84] Po Polonium (Xe)4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁴ 9.20 -2,2,4,6	[85] At Astat (Xe)4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁵ -1,1,3,5,7	[86] Rn Radon (Xe)4f ¹⁴ 5d ¹⁰ 6s ² 6p ⁶ 9.73* 0	
[87] Fr Francium (Rn)7s ¹ 1	[88] Ra Radium (Rn)7s ² 5.5 2	[104] Rf Rutherfordium (Rn)5f ¹⁴ 6d ² 7s ² 1	[105] Db Dubnium (Rn)5f ¹⁴ 6d ³ 7s ² 1	[106] Sg Seaborgium (Rn)5f ¹⁴ 6d ⁴ 7s ² 1	[107] Bh Bohrium (Rn)5f ¹⁴ 6d ⁵ 7s ² 1	[108] Hs Hassium (Rn)5f ¹⁴ 6d ⁶ 7s ² 1	[109] Mt Meitnerium (Rn)5f ¹⁴ 6d ⁷ 7s ² 1	[110] Ds Darmstadtium (Rn)5f ¹⁴ 6d ⁸ 7s ² 1	[111] Rg Roentgenium (Rn)5f ¹⁴ 6d ⁹ 7s ² 1	[112] Cn Copernicium (Rn)5f ¹⁴ 6d ¹⁰ 7s ² 1	[113] Uut Ununtrium (Rn)5f ¹⁴ 6d ¹⁰ 7s ² 7p ¹ 1	[114] Uuq Ununquadium (Rn)5f ¹⁴ 6d ¹⁰ 7s ² 7p ² 1	[115] Uup Ununpentium (Rn)5f ¹⁴ 6d ¹⁰ 7s ² 7p ³ 1	[116] Uuh Ununhexium (Rn)5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁴ 1	[117] Uus Ununseptium (Rn)5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁵ 1	[118] Uuo Ununoctium (Rn)5f ¹⁴ 6d ¹⁰ 7s ² 7p ⁶ 1	
57 La Lanthan (Xe)4f ¹ 5d ⁰ 6s ² 6.17 3	58 Ce Cer (Xe)4f ¹ 5d ¹ 6s ² 6.77 3,4	59 Pr Praseodym (Xe)4f ² 5d ⁰ 6s ² 6.48 3,4	60 Nd Neodym (Xe)4f ² 5d ⁰ 6s ² 7.00 3,4	61 Pm Promethium (Xe)4f ² 5d ¹ 6s ² 7.2 3	62 Sm Samarium (Xe)4f ³ 5d ⁰ 6s ² 7.54 2,3	63 Eu Europium (Xe)4f ³ 5d ¹ 6s ² 5.25 2,3	64 Gd Gadolinium (Xe)4f ³ 5d ¹ 6s ² 7.99 2,3	65 Tb Terbium (Xe)4f ⁴ 5d ⁰ 6s ² 8.25 3,4	66 Dy Dysprosium (Xe)4f ⁴ 5d ¹ 6s ² 8.56 3	67 Ho Holmium (Xe)4f ⁴ 5d ¹ 6s ² 8.78 3	68 Er Erbium (Xe)4f ⁴ 5d ¹ 6s ² 8.78 3	69 Tm Thulium (Xe)4f ⁴ 5d ¹ 6s ² 8.92 -2,3,4	70 Yb Ytterbium (Xe)4f ⁴ 5d ¹ 6s ² 8.97 -2,3	71 Lu Lutetium (Xe)4f ⁴ 5d ¹ 6s ² 9.84 3			
[89] Ac Actinium (Rn)5f ¹ 6d ¹ 7s ² 10.07 3	[90] Th Thorium (Rn)5f ⁰ 6d ² 7s ² 11.72 2,3,4	[91] Pa Protoactinium (Rn)5f ⁰ 6d ¹ 7s ² 15.37 5	[92] U Uran (Rn)5f ³ 6d ¹ 7s ² 9.16 3,4,5,6	[93] Np Neptunium (Rn)5f ⁴ 6d ¹ 7s ² 20.45 3,4,5,6,7	[94] Pu Plutonium (Rn)5f ⁶ 6d ⁰ 7s ² 19.82 3,4,5,6,7	[95] Am Americium (Rn)5f ⁷ 6d ⁰ 7s ² 13.67 2,3,4,5,6	[96] Cm Curium (Rn)5f ⁷ 6d ¹ 7s ² 13.51 (2),3,4	[97] Bk Berkelium (Rn)5f ⁷ 6d ¹ 7s ² 14.78 3,4	[98] Cf Californium (Rn)5f ⁷ 6d ² 7s ² 15.1 (2),3,(4)	[99] Es Einsteinium (Rn)5f ⁷ 6d ² 7s ² 8.84 (2),3,(4)	[100] Fm Fermium (Rn)5f ¹² 6d ⁰ 7s ² 2.3	[101] Md Mendelevium (Rn)5f ¹³ 6d ⁰ 7s ² 2.3	[102] No Nobelium (Rn)5f ¹⁴ 6d ⁰ 7s ² 2.3	[103] Lr Lawrencium (Rn)5f ¹⁴ 6d ¹ 7s ² 3			

Quantum degenerate **bosons** and **fermions**

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From few to many-body physics
with dipolar quantum gases

DFG FLWF

1. Introduction

2. Theses Topics

3. Outlook



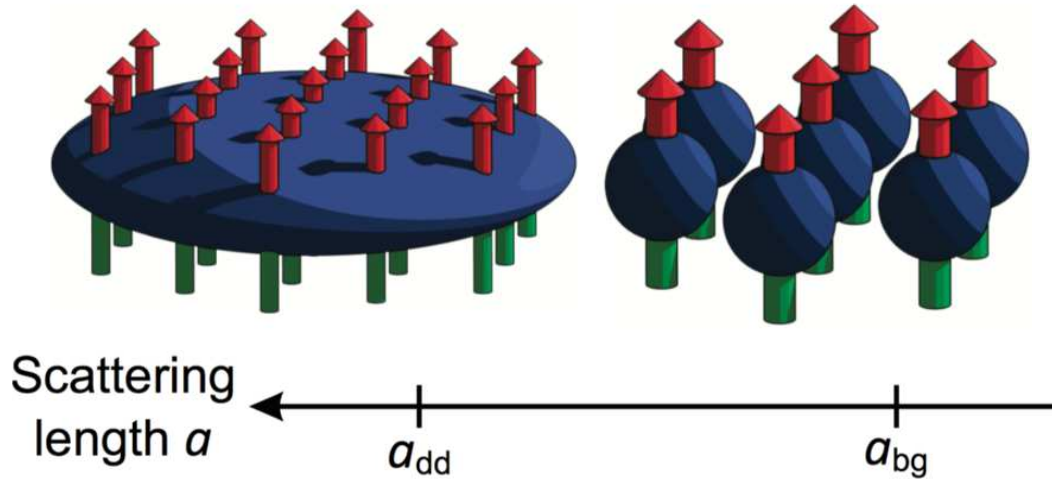
2.1 Strong Dipolar Quantum Gases



From few to many-body physics
with dipolar quantum gases



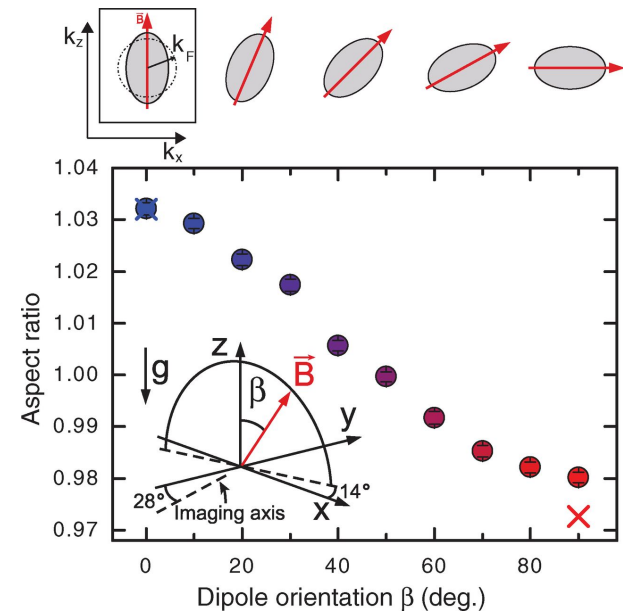
Hanover, Innsbruck, Kaiserslautern, Munich, Stuttgart



Dipolar Bose gases:

Quantum droplets

Pfau group (Stuttgart)

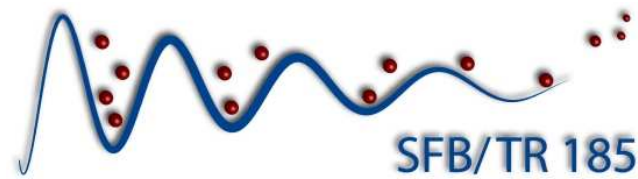


Dipolar Fermi gases:

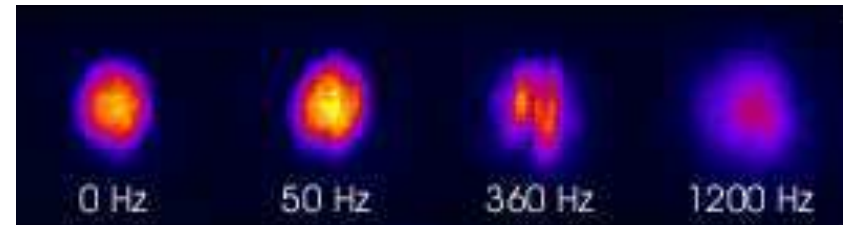
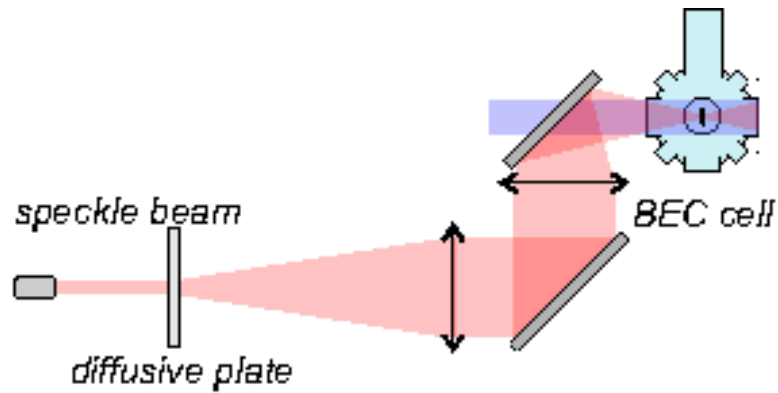
Fermi surface deformed

Ferlaino group (Innsbruck)

2.2 Random Potentials



Bonn, Kaiserslautern

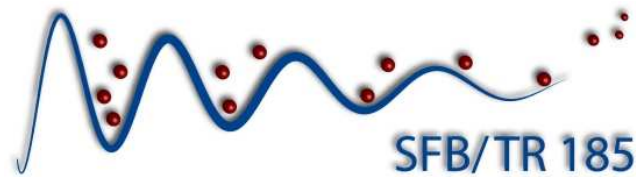


Laser speckles

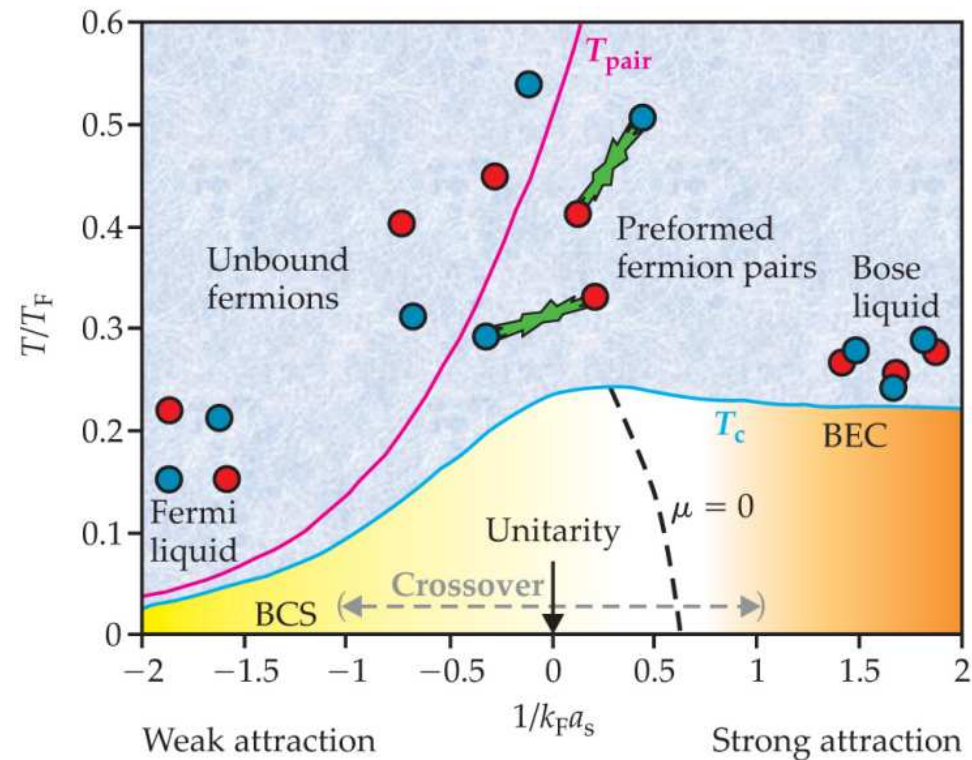
Condensate deformation

Inguscio group (Florence)

2.3 BCS-BEC-Crossover

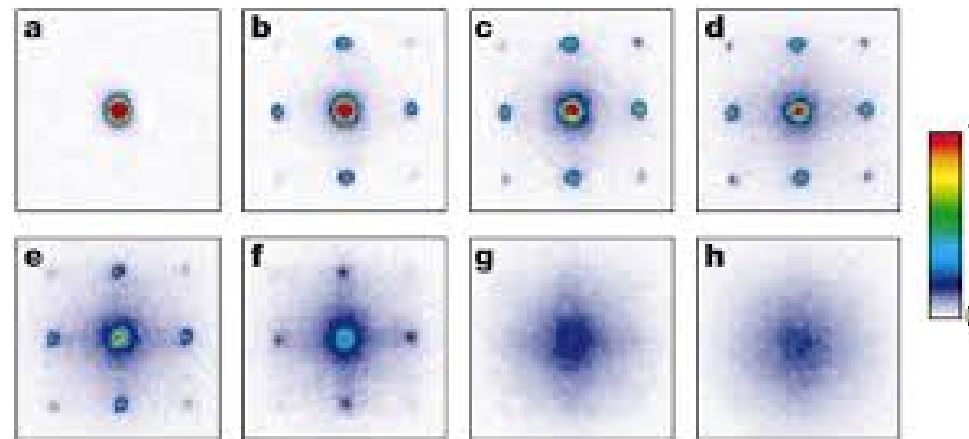
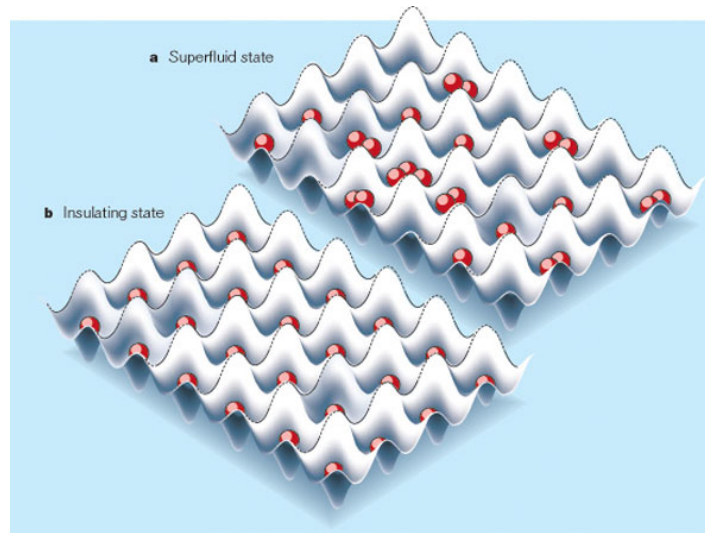


Bonn, Kaiserslautern



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

2.4 Superfluid-Mott Quantum Phase Transition



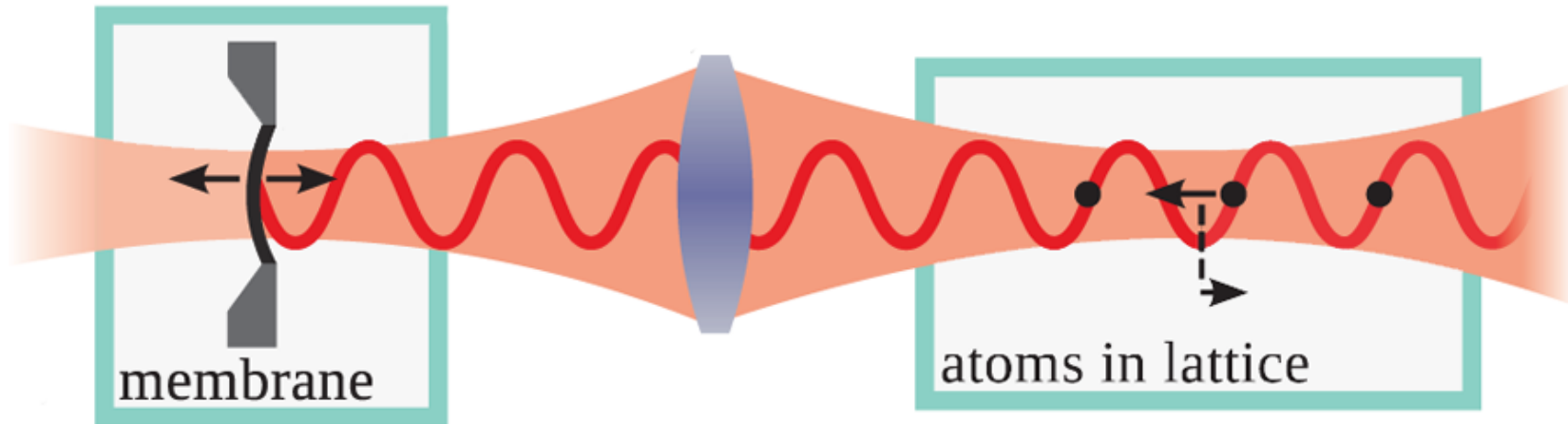
Bloch group (Munich)

2.5 Quantum Gases on Manifolds



Lundblad group (Lewiston)

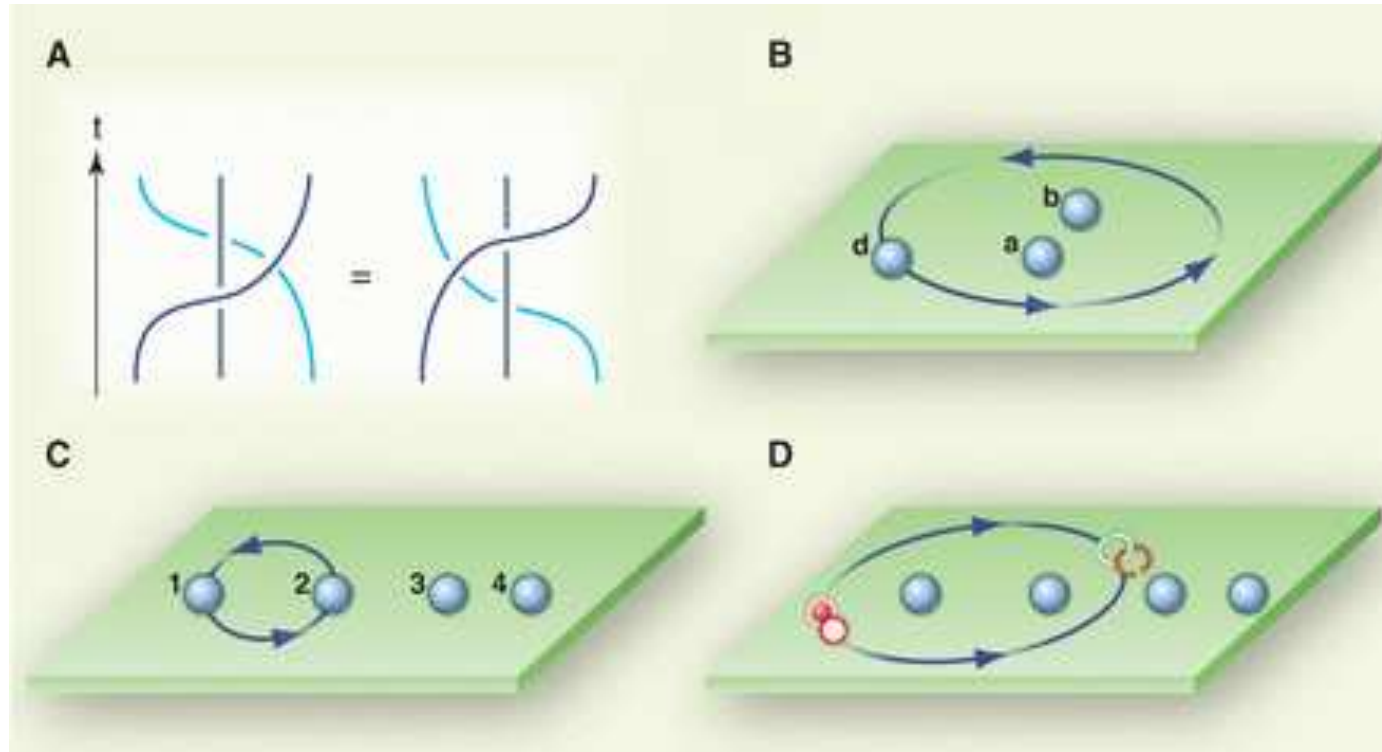
2.6 Hybrid Atom-Optomechanical Systems



- **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?

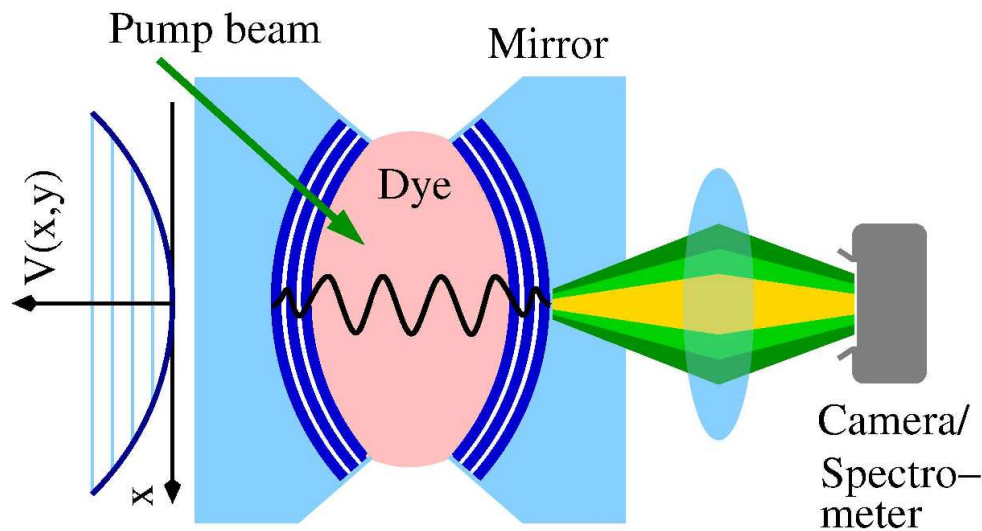
Greiner group (Harvard)

2.8 Photon Bose-Einstein Condensates



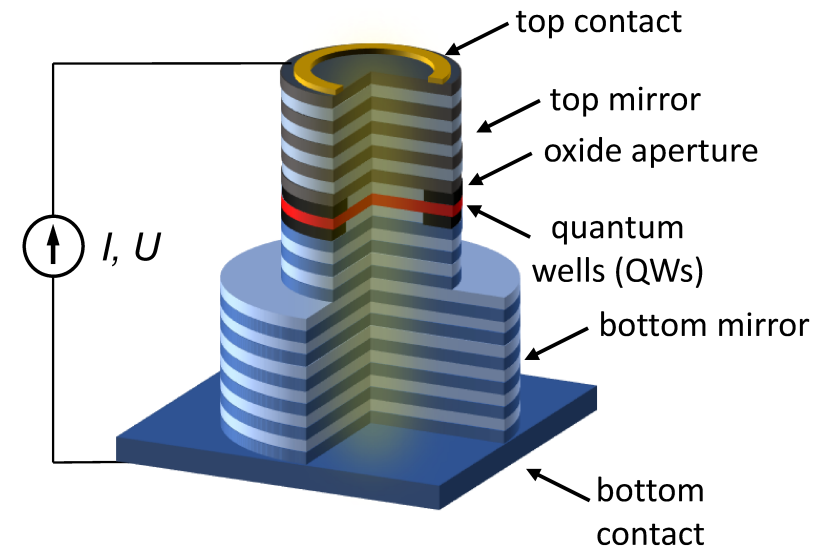
Wrocław University
of Science and Technology

Bonn, Kaiserslautern



**Dye filled
microcavity**

Weitz group (Bonn)



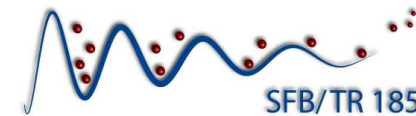
**Vertical-Cavity
Surface-Emitting Laser**

Pieczarka group (Wrocław)

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3.1 Homepage

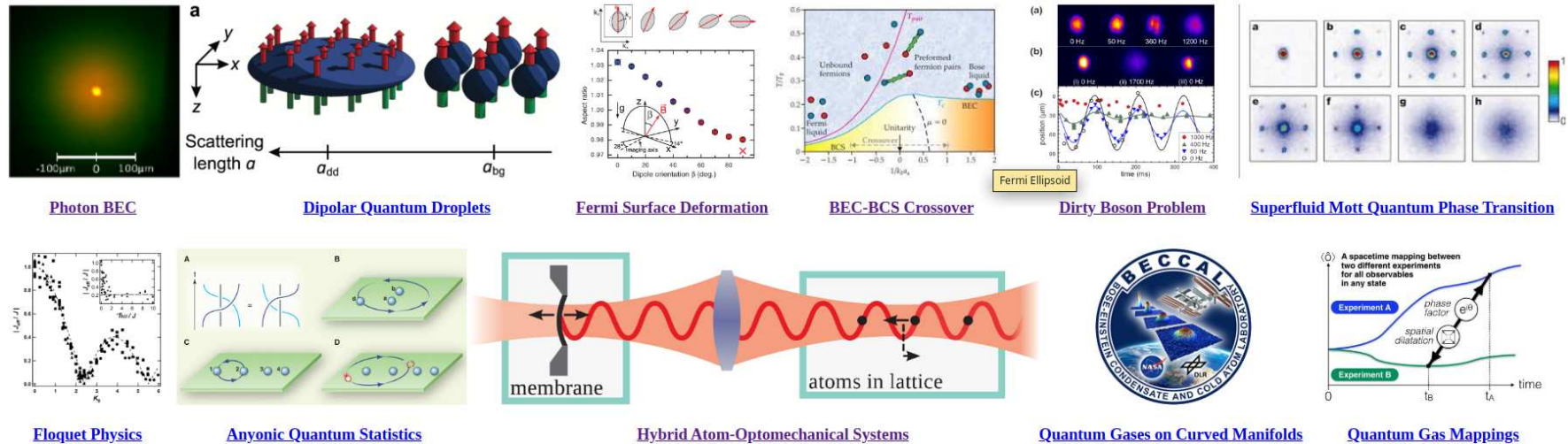


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<https://orcid.org/0000-0002-5215-0348>

Theory of Ultracold Quantum Gases:



<https://apelster.physik.rptu.de>
axel.pelster@rptu.de

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

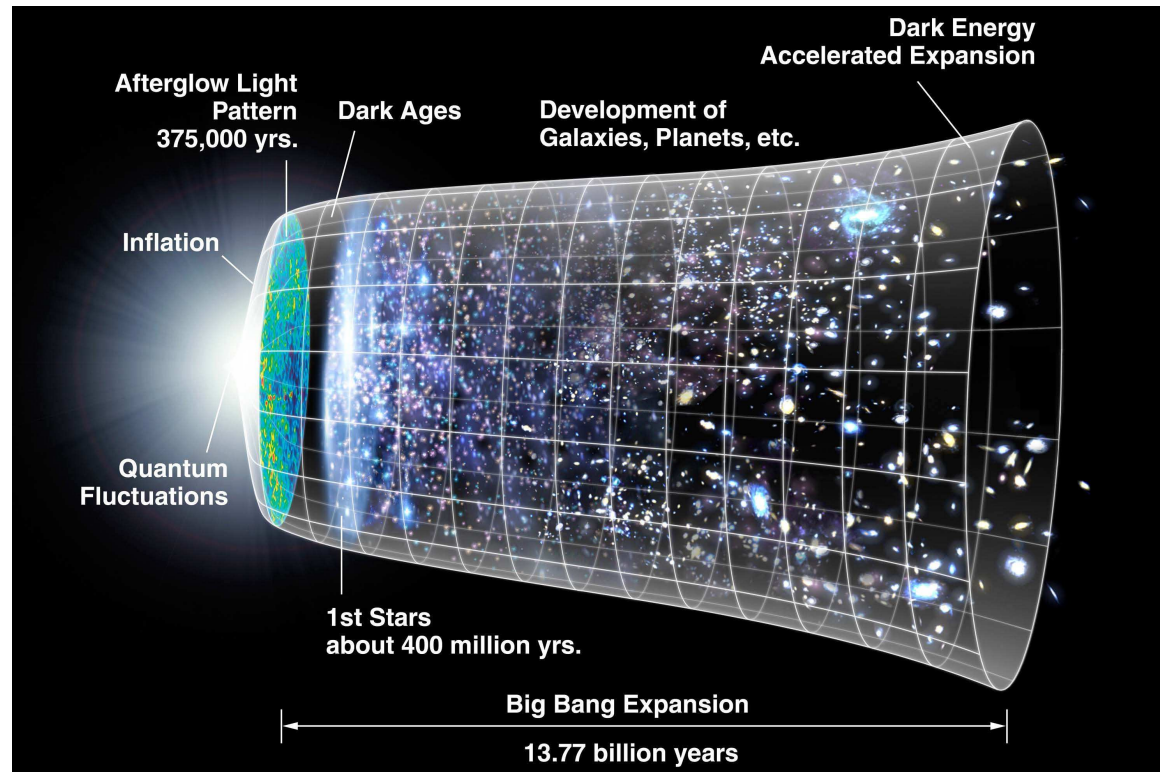


WILHELM UND ELSE
HERAEUS-STIFTUNG



DAAD

3.3 Summer Term 2025: Cosmology



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