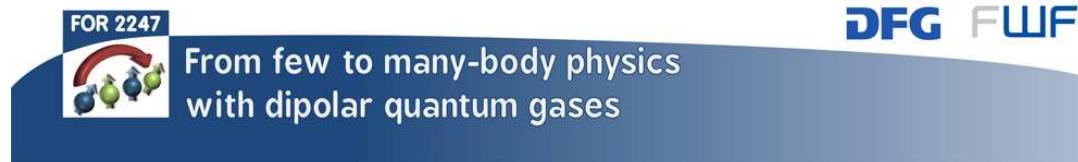
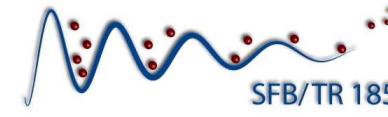


# Bose-Einstein Condensation in Microgravity – Challenges and Perspectives

Axel Pelster



TECHNISCHE UNIVERSITÄT  
KAISERSLAUTERN



## 1. Ultracold Quantum Gases

## 2. BEC in Bubble Traps

## 3. Open Problems



# 1.1 Identical Quantum Particles

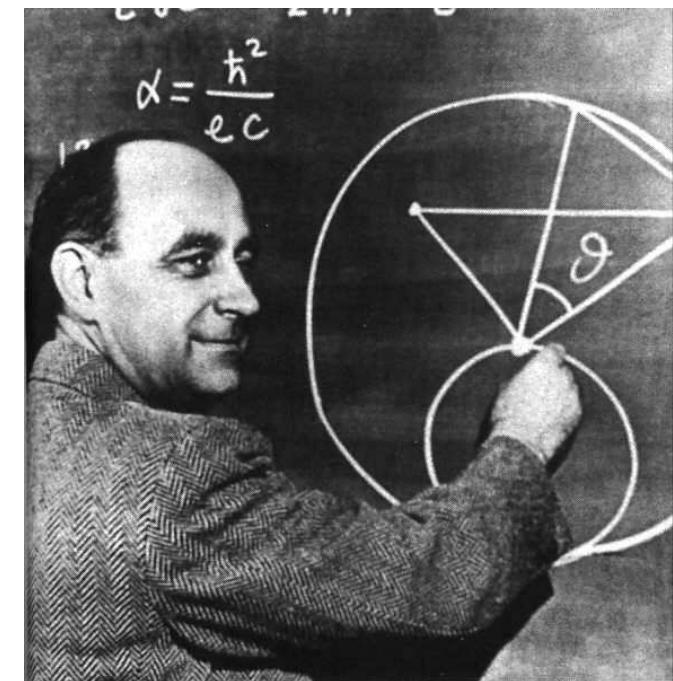
## Bosons:

- Integer spin
- Symmetric wave function

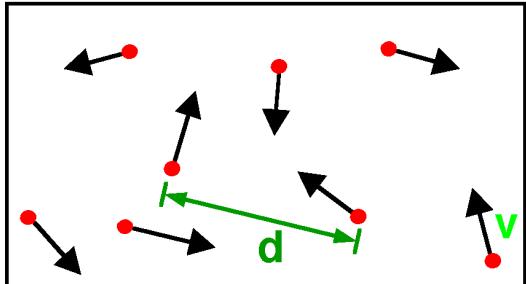


## Fermions:

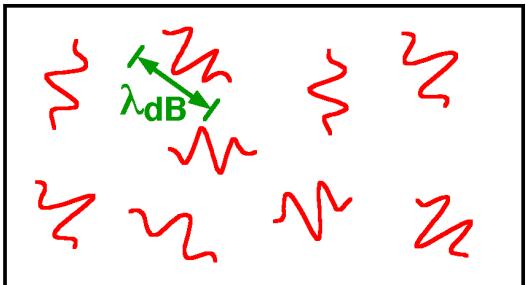
- Half-integer spin
- Anti-symmetric wave function



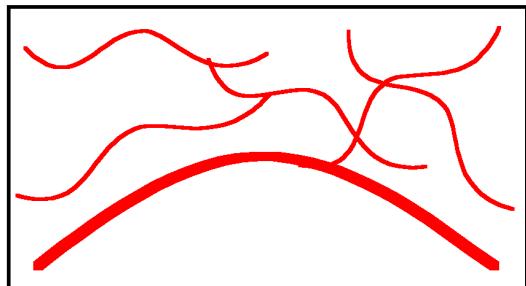
# 1.2 What is Bose-Einstein Condensation?



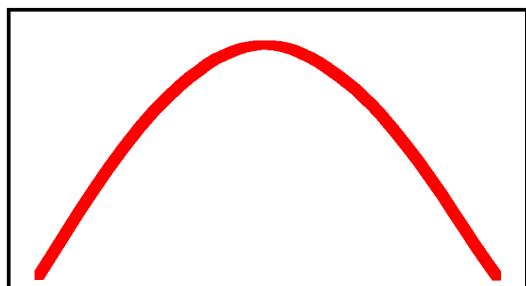
**High Temperature T:**  
thermal velocity  $v$   
density  $d^{-3}$   
"Billiard balls"



**Low Temperature T:**  
De Broglie wavelength  
 $\lambda_{dB} = \hbar/mv \propto T^{-1/2}$   
"Wave packets"



**T=T<sub>crit</sub>:**  
Bose-Einstein  
Condensation  
 $\lambda_{dB} \approx d$   
"Matter wave overlap"



**T=0:**  
Pure Bose  
condensate  
"Giant matter wave"

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

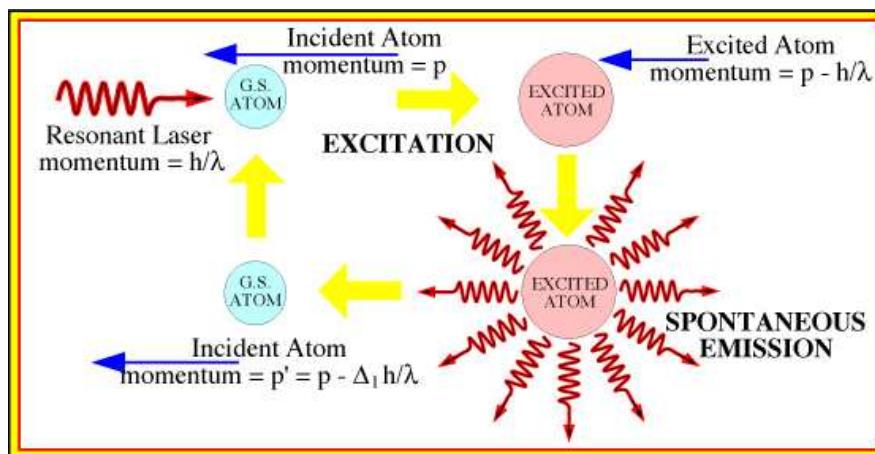
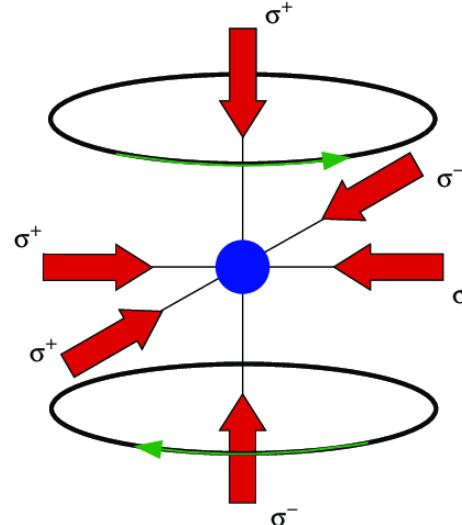
- $n = \frac{1}{d^3}$

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

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

# 1.3 Cooling Techniques

## Magneto-optical trap

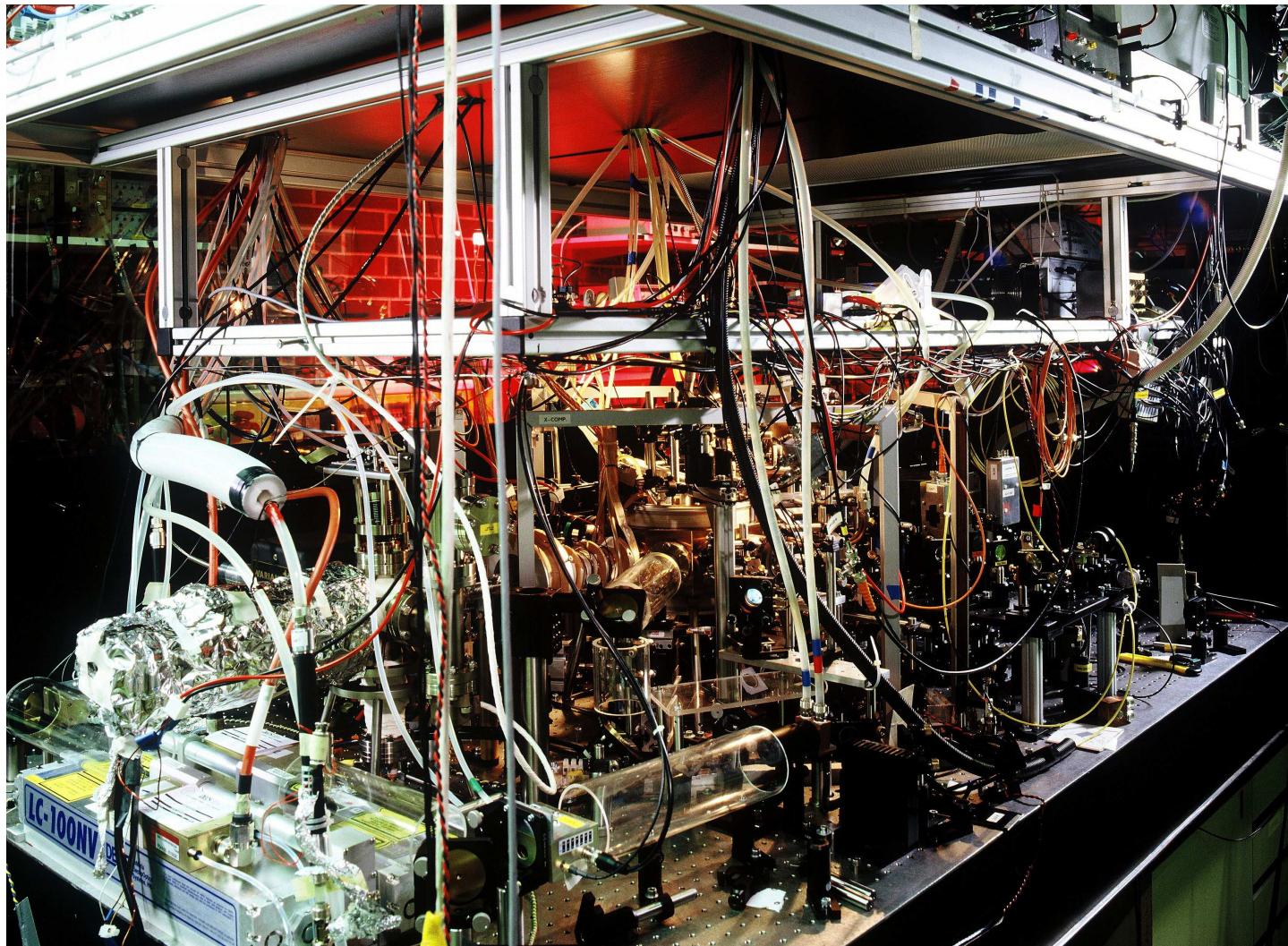


## Laser cooling

## Evaporative cooling

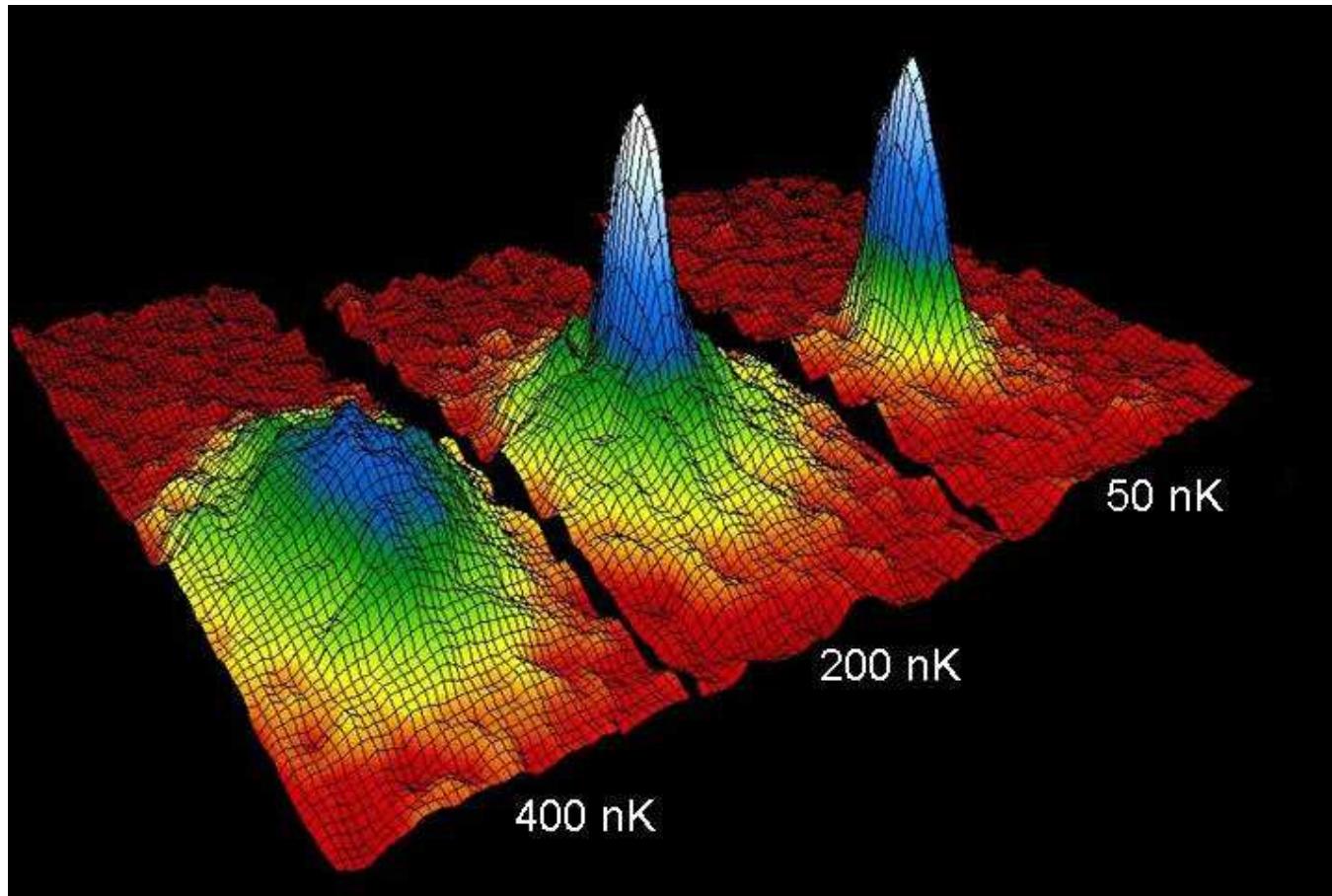


## 1.4 Experimental Apparatus



Costs about 1.000.000 EUR

## 1.5 Time-of-Flight Absorption Pictures



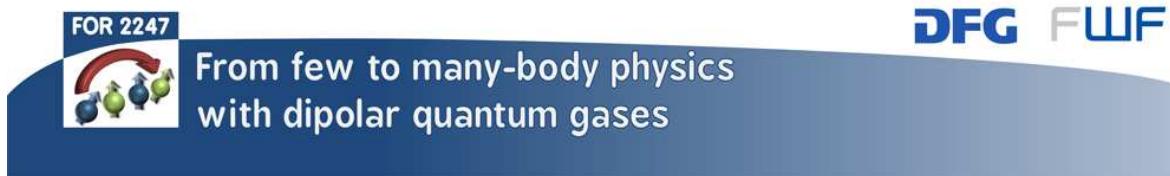
JILA (1995):  $^{87}\text{Rb}$ ,  $N=20\,000$ ,  $\omega_1 = \omega_2 = \omega_3/\sqrt{8} = 2\pi \times 120 \text{ Hz}$

# 1.6 Periodic Table of Chemical Elements

|             |   |             |   |
|-------------|---|-------------|---|
| <b>1</b>    | <b>H</b><br>Wasserstoff<br>$1s^1$<br>0.0899*                  | <b>2</b>    | <b>He</b><br>Helium<br>$1s^2$<br>0.18*                      |
| <b>3</b>    | <b>Li</b><br>Lithium<br>$[He]2s^1$<br>0.53                    | <b>4</b>    | <b>Be</b><br>Beryllium<br>$[He]2s^2$<br>1.85                |
| <b>11</b>   | <b>Na</b><br>Natrium<br>$[Ne]3s^1$<br>0.97                    | <b>12</b>   | <b>Mg</b><br>Magnesium<br>$[Ne]3s^2$<br>1.74                |
| <b>19</b>   | <b>K</b><br>Kalium<br>$[Ar]4s^1$<br>0.86                      | <b>20</b>   | <b>Ca</b><br>Calcium<br>$[Ar]4s^2$<br>1.55                  |
| <b>37</b>   | <b>Rb</b><br>Rubidium<br>$[Kr]5s^1$<br>1.53                   | <b>38</b>   | <b>Sr</b><br>Strontium<br>$[Kr]5s^2$<br>2.63                |
| <b>55</b>   | <b>Cs</b><br>Cäsium<br>$[Xe]6s^1$<br>1.90                     | <b>56</b>   | <b>Ba</b><br>Barium<br>$[Xe]6s^2$<br>3.62                   |
| <b>[87]</b> | <b>Fr</b><br>Francium<br>$[Rn]7s^1$<br>1.55                   | <b>[88]</b> | <b>Ra</b><br>Radium<br>$[Rn]7s^2$<br>2                      |
| <b>21</b>   | <b>Sc</b><br>Scandium<br>$[Ar]3d^14s^2$<br>2.99               | <b>22</b>   | <b>Ti</b><br>Titan<br>$[Ar]3d^24s^2$<br>4.50                |
| <b>23</b>   | <b>V</b><br>Vanadium<br>$[Ar]3d^34s^2$<br>6.11                | <b>24</b>   | <b>Cr</b><br>Chrom<br>$[Ar]3d^44s^1$<br>7.14                |
| <b>25</b>   | <b>Mn</b><br>Mangan<br>$[Ar]3d^54s^2$<br>7.43                 | <b>26</b>   | <b>Fe</b><br>Eisen<br>$[Ar]3d^64s^2$<br>7.87                |
| <b>27</b>   | <b>Co</b><br>Kobalt<br>$[Ar]3d^74s^2$<br>8.90                 | <b>28</b>   | <b>Ni</b><br>Nickel<br>$[Ar]3d^84s^2$<br>8.91               |
| <b>29</b>   | <b>Cu</b><br>Kupfer<br>$[Ar]3d^94s^2$<br>8.92                 | <b>30</b>   | <b>Zn</b><br>Zink<br>$[Ar]3d^{10}4s^2$<br>7.14              |
| <b>31</b>   | <b>Ga</b><br>Gallium<br>$[Ar]3d^{10}4s^1$<br>8.98             | <b>32</b>   | <b>Ge</b><br>Germanium<br>$[Ar]3d^{10}4s^24p^1$<br>9.90     |
| <b>33</b>   | <b>As</b><br>Arsen<br>$[Ar]3d^{10}4s^24p^3$<br>10.32          | <b>34</b>   | <b>Se</b><br>Selen<br>$[Ar]3d^{10}4s^24p^4$<br>4.82         |
| <b>35</b>   | <b>Br</b><br>Brom<br>$[Ar]3d^{10}4s^24p^5$<br>3.75*           | <b>36</b>   | <b>Kr</b><br>Krypton<br>$[Ar]3d^{10}4s^24p^6$<br>3.8        |
| <b>39</b>   | <b>Y</b><br>Yttrium<br>$[Xe]4d^15s^2$<br>4.47                 | <b>40</b>   | <b>Zr</b><br>Zirconium<br>$[Xe]4d^25s^2$<br>6.50            |
| <b>41</b>   | <b>Nb</b><br>Niob<br>$[Xe]4d^35s^3$<br>10.28                  | <b>42</b>   | <b>Mo</b><br>Molybdän<br>$[Xe]4d^45s^3$<br>11.5             |
| <b>43</b>   | <b>Tc</b><br>Technetium<br>$[Xe]4d^55s^1$<br>-3 bis 7         | <b>44</b>   | <b>Ru</b><br>Ruthenium<br>$[Xe]4d^65s^1$<br>12.37           |
| <b>45</b>   | <b>Rh</b><br>Rhodium<br>$[Xe]4d^75s^1$<br>12.38               | <b>46</b>   | <b>Pd</b><br>Palladium<br>$[Xe]4d^85s^0$<br>11.99           |
| <b>47</b>   | <b>Ag</b><br>Silber<br>$[Xe]4d^{10}5s^1$<br>0.24              | <b>48</b>   | <b>Cd</b><br>Cadmium<br>$[Xe]4d^{10}5s^2$<br>8.65           |
| <b>49</b>   | <b>In</b><br>Indium<br>$[Xe]4d^{10}5s^35p^1$<br>7.31          | <b>50</b>   | <b>Sn</b><br>Zinn<br>$[Xe]4d^{10}5s^35p^2$<br>5.77          |
| <b>51</b>   | <b>Sb</b><br>Antimon<br>$[Xe]4d^{10}5s^35p^3$<br>6.70         | <b>52</b>   | <b>Te</b><br>Tellur<br>$[Xe]4d^{10}5s^35p^4$<br>6.24        |
| <b>53</b>   | <b>I</b><br>Iod<br>$[Xe]4d^{10}5s^35p^5$<br>4.94              | <b>54</b>   | <b>Xe</b><br>Xenon<br>$[Xe]4d^{10}5s^35p^6$<br>5.90*        |
| <b>72</b>   | <b>Hf</b><br>Hafnium<br>$[Xe]4d^45d^16s^2$<br>13.28           | <b>73</b>   | <b>Ta</b><br>Tantal<br>$[Xe]4d^55d^16s^2$<br>4.65           |
| <b>74</b>   | <b>W</b><br>Wolfram<br>$[Xe]4d^65d^26s^2$<br>16.65            | <b>75</b>   | <b>Re</b><br>Rhenium<br>$[Xe]4d^75d^26s^2$<br>19.3          |
| <b>76</b>   | <b>Os</b><br>Osmium<br>$[Xe]4d^85d^26s^2$<br>21.0             | <b>77</b>   | <b>Ir</b><br>Iridium<br>$[Xe]4d^95d^26s^2$<br>22.59         |
| <b>78</b>   | <b>Pt</b><br>Platin<br>$[Xe]4d^{10}5d^16s^1$<br>21.45         | <b>79</b>   | <b>Au</b><br>Gold<br>$[Xe]4d^{10}5d^16s^1$<br>19.32         |
| <b>80</b>   | <b>Hg</b><br>Quecksilber<br>$[Xe]4d^{10}5d^16s^2$<br>13.55    | <b>81</b>   | <b>Tl</b><br>Thallium<br>$[Xe]4d^{10}5d^16s^26p^1$<br>11.85 |
| <b>82</b>   | <b>Pb</b><br>Blei<br>$[Xe]4d^{10}5d^16s^26p^2$<br>11.34       | <b>83</b>   | <b>Bi</b><br>Bismuth<br>$[Xe]4d^{10}5d^16s^26p^3$<br>9.78   |
| <b>84</b>   | <b>Po</b><br>Polonium<br>$[Xe]4d^{10}5d^16s^26p^4$<br>2.3     | <b>85</b>   | <b>At</b><br>Astat<br>$[Xe]4d^{10}5d^16s^26p^5$<br>1.3      |
| <b>88</b>   | <b>Rf</b><br>Rutherfordium<br>$[Rn]5f^146d^17s^2$<br>10.07    | <b>89</b>   | <b>Dy</b><br>Dysprosium<br>$[Xe]4f^15d^16s^2$<br>1.56       |
| <b>104</b>  | <b>Db</b><br>Dubnium<br>$[Rn]5f^146d^17s^2$<br>11.72          | <b>105</b>  | <b>Tb</b><br>Terbium<br>$[Xe]4f^25d^16s^2$<br>1.56          |
| <b>106</b>  | <b>Sg</b><br>Seaborgium<br>$[Rn]5f^146d^17s^2$<br>15.37       | <b>107</b>  | <b>Gd</b><br>Gadolinium<br>$[Xe]4f^35d^16s^2$<br>1.56       |
| <b>108</b>  | <b>Bh</b><br>Bohrium<br>$[Rn]5f^146d^17s^2$<br>19.16          | <b>109</b>  | <b>Eu</b><br>Europium<br>$[Xe]4f^45d^16s^2$<br>1.56         |
| <b>110</b>  | <b>Hs</b><br>Hassium<br>$[Rn]5f^146d^17s^2$<br>20.45          | <b>111</b>  | <b>Sm</b><br>Samarium<br>$[Xe]4f^55d^16s^2$<br>1.56         |
| <b>112</b>  | <b>Mt</b><br>Meitnerium<br>$[Rn]5f^146d^17s^2$<br>13.67       | <b>113</b>  | <b>Am</b><br>Americium<br>$[Rn]5f^65d^16s^2$<br>13.51       |
| <b>114</b>  | <b>Ds</b><br>Darmstadtium<br>$[Rn]5f^146d^17s^2$<br>14.78     | <b>115</b>  | <b>Cm</b><br>Curium<br>$[Rn]5f^75d^16s^2$<br>15.1           |
| <b>116</b>  | <b>Rg</b><br>Roentgenium<br>$[Rn]5f^146d^17s^2$<br>15.1       | <b>117</b>  | <b>Cf</b><br>Californium<br>$[Rn]5f^85d^16s^2$<br>(2,3)     |
| <b>118</b>  | <b>Cn</b><br>Copernicium<br>$[Rn]5f^146d^17s^2$<br>15.1       | <b>119</b>  | <b>Ho</b><br>Holmium<br>$[Xe]4f^95d^16s^2$<br>1.56          |
| <b>120</b>  | <b>Uut</b><br>Ununtrium<br>$[Rn]5f^146d^17s^27p^1$<br>11.72   | <b>121</b>  | <b>Er</b><br>Erbium<br>$[Xe]4f^{10}5d^16s^2$<br>1.56        |
| <b>122</b>  | <b>Uuq</b><br>Ununquadium<br>$[Rn]5f^146d^17s^27p^2$<br>15.37 | <b>123</b>  | <b>Tm</b><br>Thulium<br>$[Xe]4f^{11}5d^16s^2$<br>1.56       |
| <b>123</b>  | <b>Uup</b><br>Ununpentium<br>$[Rn]5f^146d^17s^27p^3$<br>19.82 | <b>124</b>  | <b>Yb</b><br>Ytterbium<br>$[Xe]4f^{12}5d^16s^2$<br>1.56     |
| <b>125</b>  | <b>Uuh</b><br>Ununhexium<br>$[Rn]5f^146d^17s^27p^4$<br>24.05  | <b>126</b>  | <b>Lu</b><br>Lutetium<br>$[Xe]4f^{13}5d^16s^2$<br>1.56      |
| <b>126</b>  | <b>Uus</b><br>Ununseptium<br>$[Rn]5f^146d^17s^27p^5$<br>24.05 | <b>127</b>  | <b>No</b><br>Nobelium<br>$[Rn]5f^146d^17s^27p^6$<br>1.56    |
| <b>127</b>  | <b>Uuo</b><br>Ununoctium<br>$[Rn]5f^146d^17s^27p^6$<br>24.05  | <b>128</b>  | <b>Lr</b><br>Lawrencium<br>$[Rn]5f^146d^17s^27p^6$<br>1.56  |

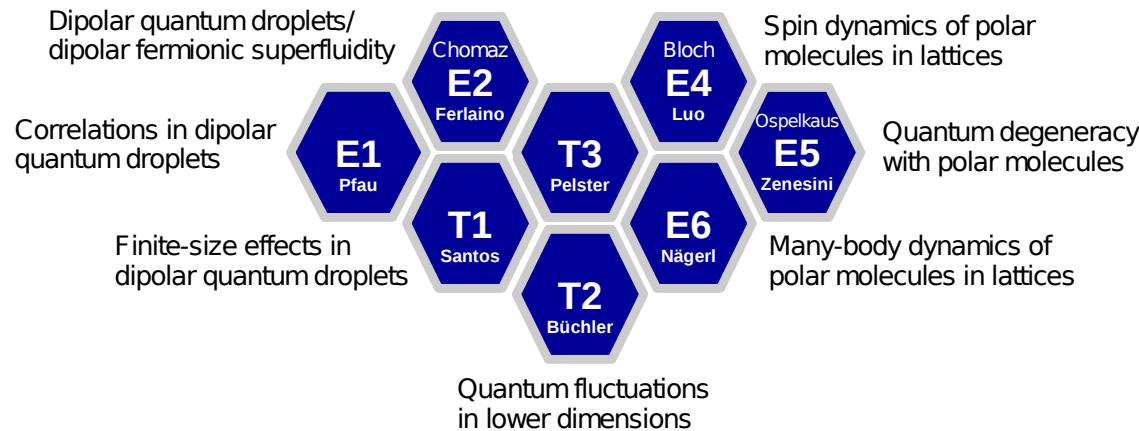
Quantum degenerate **bosons** and **fermions**

# 1.7 Research Unit 2247 (2019-2022)

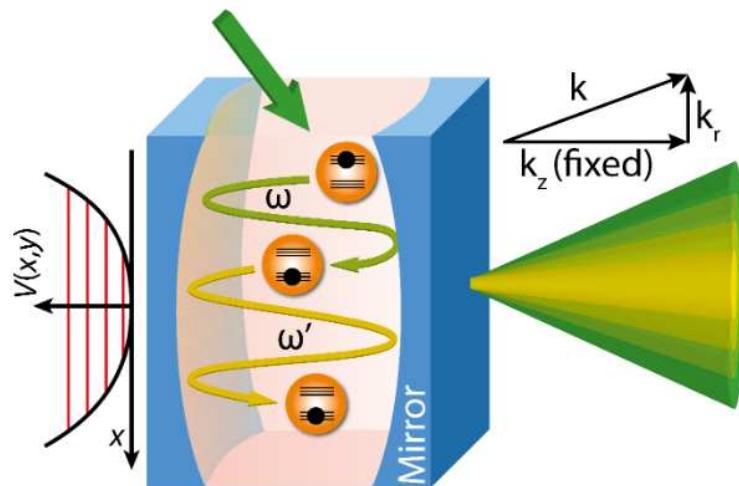


Hannover, Innsbruck, Kaiserslautern, Munich, Stuttgart

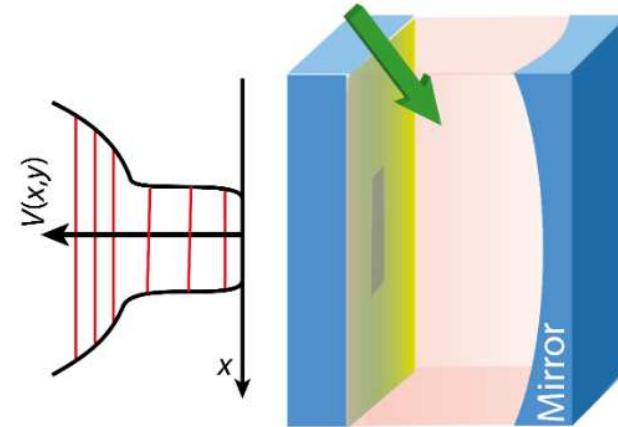
- Project T3: Superfluidity in strong dipolar quantum gases
  - Dipolar Fermi gases: deformation of Fermi sphere  
Veljić, ... , Ferlaino, ..., Pelster, Balaž, NJP **20**, 093016 (2018)
  - Dipolar Bose gases: quantum droplets  
Pelster, Physik-Journal **18**, Nr. 6, 20 (2019)
- Collaborations



# 1.8 CRC/TR185 (2020-2024, decided end of May 2020)



**Project B1**  
Schmitt, Kroha, Weitz  
**Dynamics in 2D**



**Project B6N**  
Pelster, Vewinger, von Freymann  
**Statics in 1D**

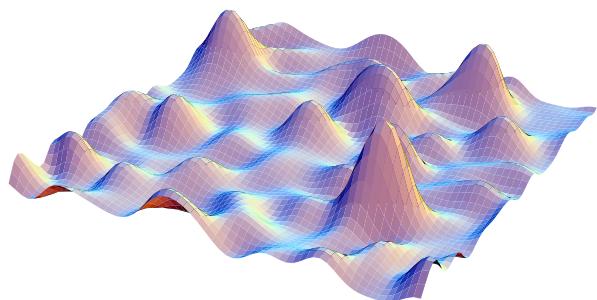
⇒ New center for photon BEC research in Kaiserslautern

Klärs, Schmitt, Vewinger, and Weitz, Nature **468**, 545 (2010)

**Overview:** Pelster, Physik-Journal **10**, Nr. 1, 20 (2011)

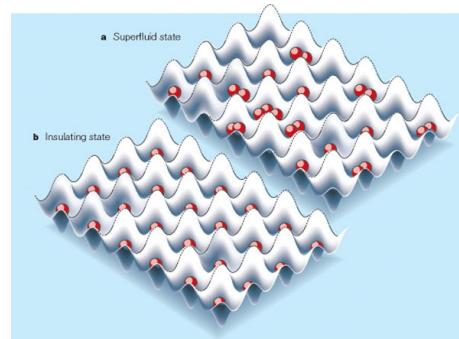
Pelster, Physik-Journal **13**, Nr. 3, 20 (2014)

## 1.9 Other Research Areas (Selection, Since 2015)



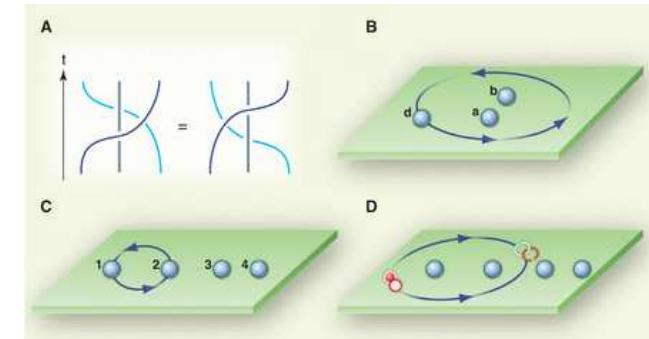
**Dirty boson problem**

NJP (2016), arXiv (2019)



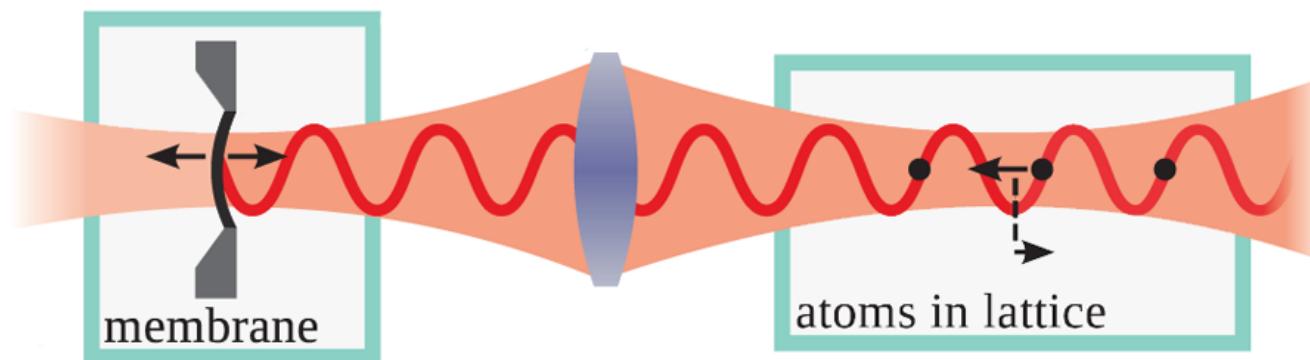
**Optical lattices**

PRB (2015), PRL (2016)



**Anyonic statistics**

NJP (2015)



**Hybrid atom-optomechanical systems**

PRL (2018), NJP (2019)



**BECCAL**

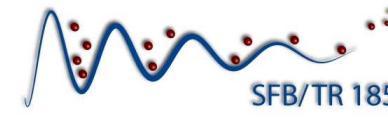
arXiv (2020)

# Bose-Einstein Condensation in Microgravity – Challenges and Perspectives

Axel Pelster



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KAISERSLAUTERN



From few to many-body physics  
with dipolar quantum gases

DFG FWF

## 1. Ultracold Quantum Gases

## 2. BEC in Bubble Traps

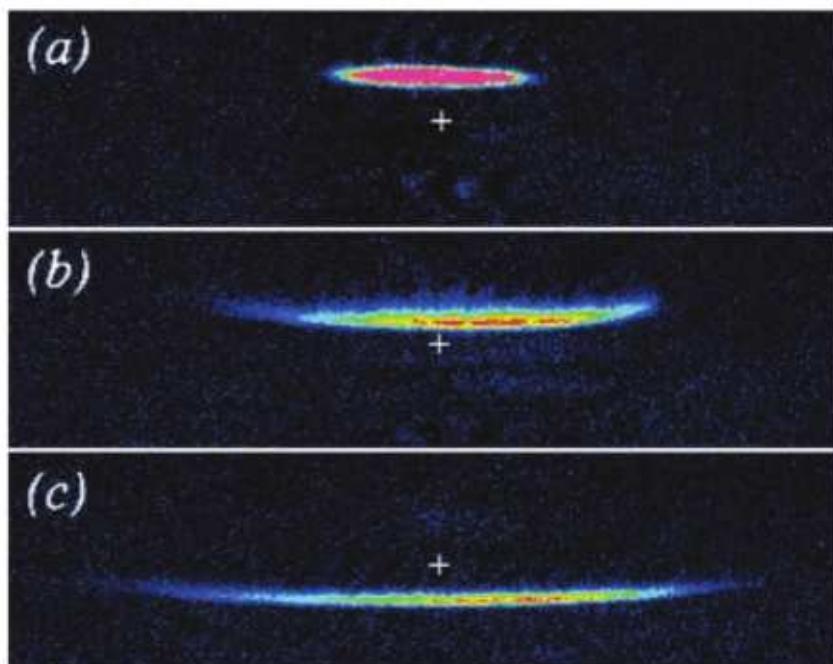
Möller, Santos, Bagnato, and Pelster,  
arXiv:2001.07443

## 3. Open Problems



## 2.1 Bubble Traps

On earth



Colombe et al., EPL **67**, 593 (2004)

Guo et al., PRL **124**, 025301 (2020)

In microgravity

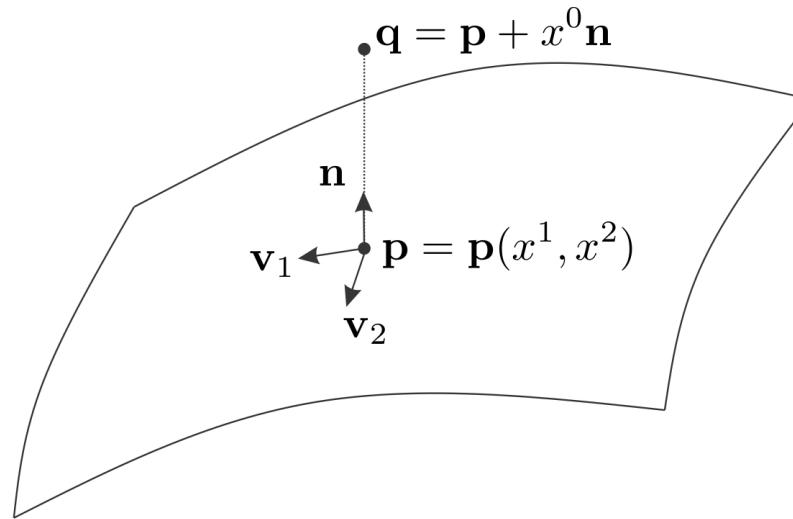


Gibney, Nature **557**, 151 (2018)

Freye et al., arXiv:1912.04849

## 2.2 Manifold

- Gaussian normal coordinate system:



- Metric:

$$G = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \sqrt{g} & \\ 0 & & g \end{pmatrix}$$

- Potential confinement:  $V = \frac{M}{2} \omega^2 (x^0)^2$

## 2.3 Reducing Dimensionality

- **Particle number:**  $N = \int dV |\Psi(x^0, x^1, x^2)|^2$
- **Energy:**
$$E = \int dV \Psi^* \left[ -\frac{\hbar^2}{2M} \Delta + \frac{M}{2} \omega^2 (x^0)^2 + \frac{1}{2} g |\Psi|^2 - \mu \right] \Psi$$
- **Ansatz:**
$$\Psi(x^0, x^1, x^2) = \frac{e^{-(x^0)^2/2\sigma^2(x^1, x^2)}}{\sqrt[4]{\pi} \sqrt{\sigma(x^1, x^2)}} \psi(x^1, x^2)$$
- **Integrate variable  $x^0$  perpendicular to manifold**
- **Extremize energy with respect to  $\psi^*(x^1, x^2)$  and  $\sigma(x^1, x^2)$**

**Inspired by** L. Salasnich et al., PRA 65, 043614 (2002)

## 2.4 Quasi Two Dimensions

- **Particle number:**  $N = \int d^2x \sqrt{\det g} |\psi(x^1, x^2)|^2$
- **Two-dimensional Gross-Pitaevskii equation:**
$$\left[ -\frac{\hbar^2}{2M} \Delta_{\text{LB}} + V_{\text{eff}}(x^1, x^2) + \frac{\hbar^2}{4M\sigma^2} + \frac{M\omega^2\sigma^2}{4} + \frac{g|\psi|^2}{\sqrt{2\pi}\sigma} \right] \psi = \mu \psi$$
- **Laplace-Beltrami operator:**
$$\Delta_{\text{LB}} = \frac{1}{\sqrt{\det g}} \frac{\partial}{\partial x^i} \left( \sqrt{\det g} g^{ij} \frac{\partial}{\partial x^j} \right)$$
- **Width:**

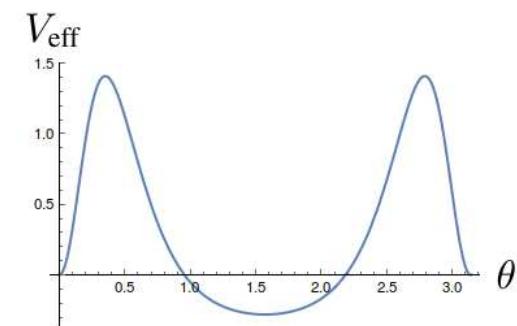
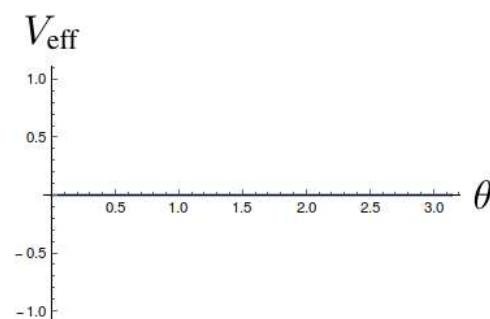
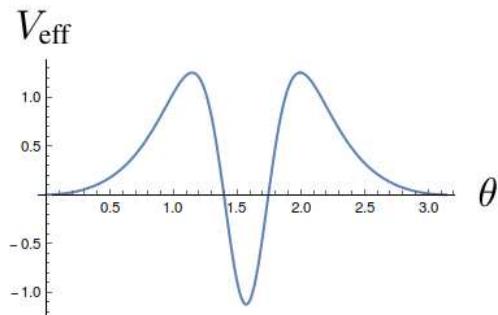
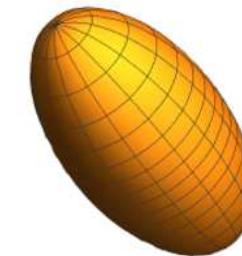
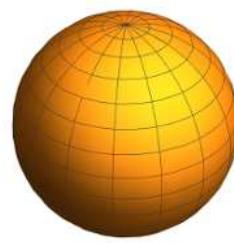
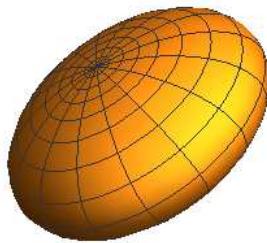
$$\frac{\sigma^4}{\sigma_{\text{osc}}^4} = 1 + \frac{gM}{\sqrt{2\pi}\hbar^2} \sigma |\psi|^2, \quad \sigma_{\text{osc}} = \sqrt{\frac{\hbar}{M\omega}}$$

## 2.5 Effective Potential

- General expression:

$$V_{\text{eff}}(x^1, x^2) = \frac{\hbar^2}{4M} \left[ \frac{1}{2} \left( \frac{\partial \ln \sqrt{\det g}}{\partial x^0} \right)^2 + \frac{\partial^2 \ln \sqrt{\det g}}{\partial x^{02}} \right] \Big|_{x^0=0}$$

- Examples:

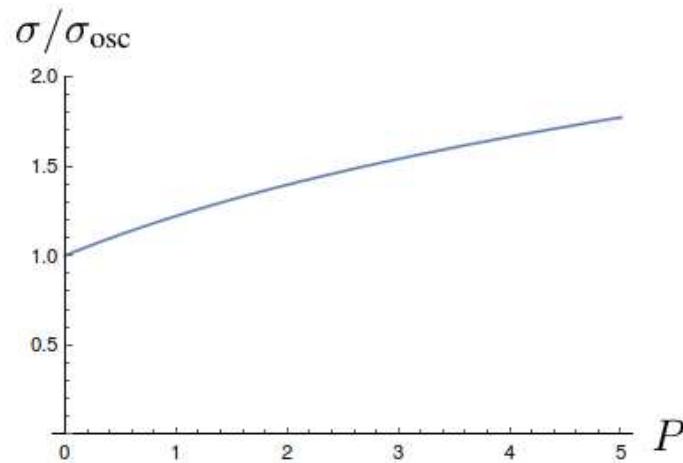


## 2.6 Equilibrium on Quasi Sphere

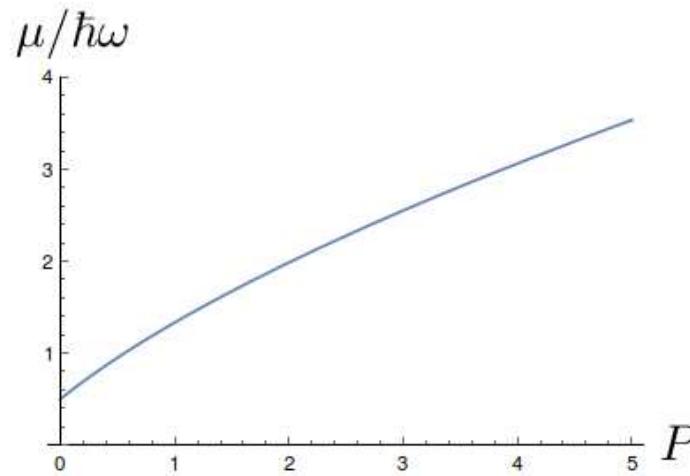
- Wave function from normalization:

$$\psi = \sqrt{\frac{N}{4\pi R^2}}$$

- Width:



Equation of state:



$$\left(\frac{\sigma}{\sigma_{\text{osc}}}\right)^4 = 1 + P \frac{\sigma}{\sigma_{\text{osc}}}$$

$$\frac{\mu}{\hbar\omega} = \frac{1}{4} \left( \frac{1}{\sigma^2/\sigma_{\text{osc}}^2} + \frac{\sigma^2}{\sigma_{\text{osc}}^2} \right) + \frac{P}{\sigma/\sigma_{\text{osc}}}$$

- Dimensionless interaction strength:

$$a_s = 100 \text{ } a_B, \sigma_{\text{osc}} = 1 \text{ } \mu\text{m}, R = 10 \text{ } \mu\text{m}, N = 10^5 \implies P = 2.1$$

$$P = \frac{a_s \sigma_{\text{osc}} N}{\sqrt{2\pi} R^2}$$

## 2.7 Low-Lying Excitations on Quasi Sphere

- **Action:**

$$S = \int dt \int dV \Psi^* \left[ i\hbar \frac{\partial}{\partial t} + \frac{\hbar^2}{2M} \Delta - \frac{M}{2} \omega^2 (x^0)^2 - \frac{1}{2} g |\Psi|^2 \right] \Psi$$

- **Ansatz:**

$$\Psi(x^0, x^1, x^2, t) = \frac{\exp \left\{ -\frac{1}{2} \left[ \frac{1}{\sigma^2(x^1, x^2, t)} + iB(x^1, x^2, t) \right] (x^0)^2 \right\}}{\sqrt[4]{\pi} \sqrt{\sigma(x^1, x^2, t)}} \psi(x^1, x^2, t)$$

- **Linear stability analysis**

- **Lower frequencies:**

$$\Omega'_l = \frac{\hbar}{2MR^2} l(l+1) + \mathcal{O}(P)$$

- **Higher frequencies:**

$$\Omega''_l = 2\omega - \frac{\hbar}{2MR^2} l(l+1) + \mathcal{O}(P)$$

## 2.8 Outlook for Bubble Traps

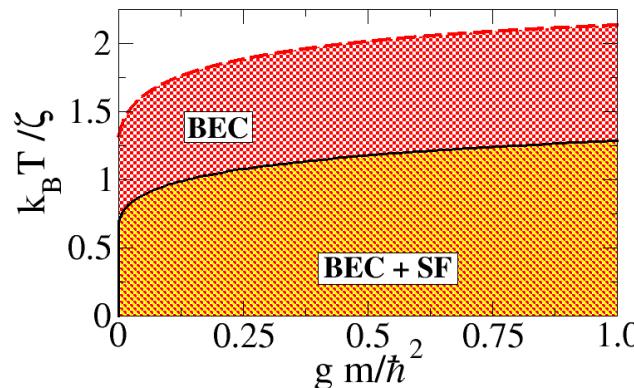
- Taking levitation into account

Breathing and quadrupole mode: Diniz et al., arXiv:1911.03513

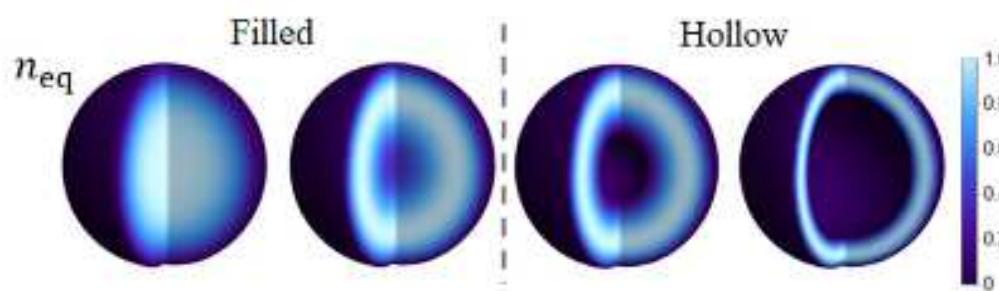
- Phase diagram for sphere: Tononi and Salasnich, PRL **123**, 160403 (2019)

– Mermin-Wagner-Hohenberg theorem:  $\lim_{R \rightarrow \infty} T_c(R) = 0$

– Berezinski-Kosterlitz-Thouless physics:



- Dimensional crossover: K. Sun et al.. PRA **98**. 013609 (2018)

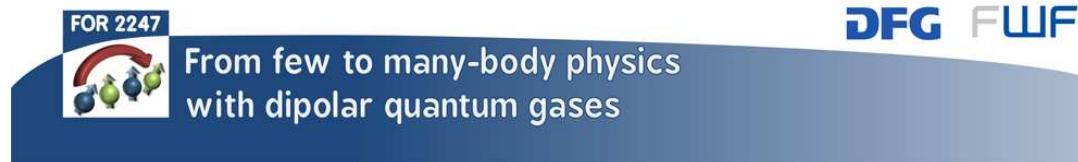
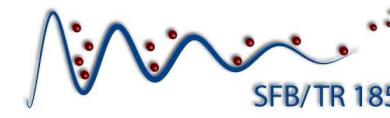


# Bose-Einstein Condensation in Microgravity – Challenges and Perspectives

Axel Pelster



TECHNISCHE UNIVERSITÄT  
KAISERSLAUTERN



## 1. Ultracold Quantum Gases

## 2. BEC in Bubble Traps

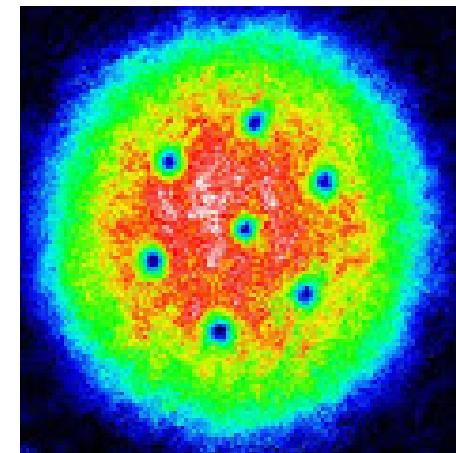
## 3. Open Problems



## 3.1 Vortex Dynamics in Bubble Traps

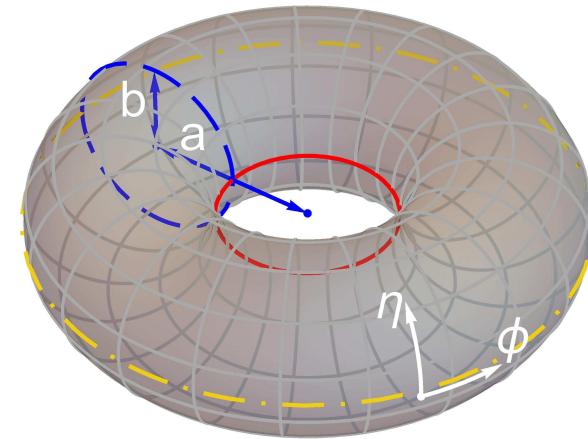
- Far-field vortex dynamics in plane:
  - Hamiltonian equations
  - Vortex precession about trap center
  - Vortex-vortex interaction

Navarro et al., PRL **110**, 225301 (2013)



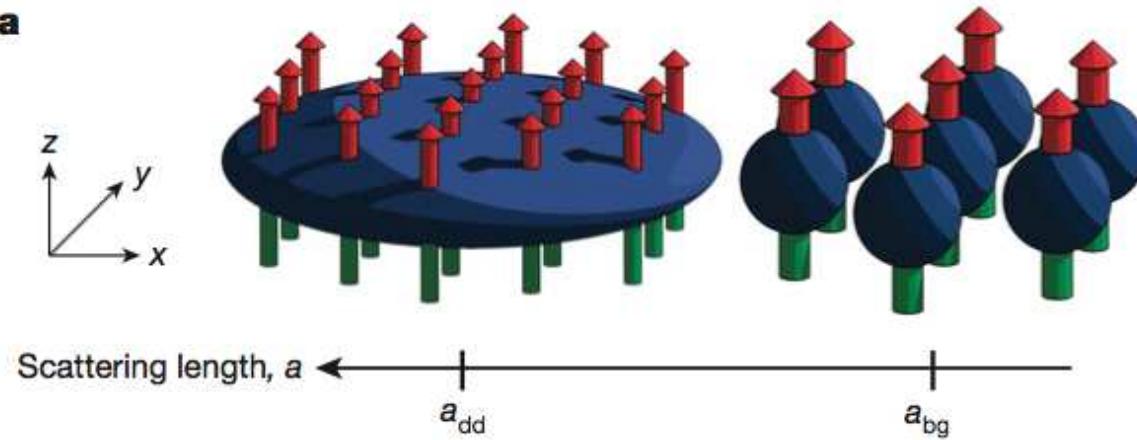
- Vision for CAL at ISS:  
**Vortex precession in bubble trap as gyroscope**
- Preliminary studies

- Vortex on cylinder:  
Günther et al., PRA **96**, 063608 (2017)
- Dynamics of two vortices on cone:  
Massignan and Fetter, PRA **99**, 063602 (2019)
- Vortex dynamics on torus:  
Günther et al., arXiv:1911.11794



## 3.2 Quantum Droplets in Bubble Traps

- Physical notion:
  - Mean-field instability
  - Stabilization due to quantum fluctuations
  - Extended Gross-Pitaevskii equation
- Experiments:
  - Dipolar Bose gas (Dy, Er: Stuttgart, Innsbruck, Pisa)



- Bose-Bose mixture (K: Barcelona, K-Rb: Florence)
- Vision for BECCAL:  
Quantum droplets for K-Rb mixture

### 3.3 Critical Exponents

- **Superfluid helium (homogeneous case)**

- **On earth:**

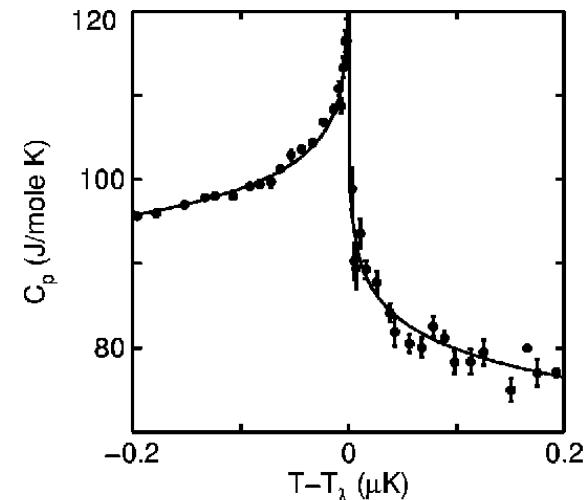
$$\alpha = -0.026 \pm 0.004$$

Ahlers, PRA **3**, 696 (1971)

- **In microgravity:**

$$\alpha = -0.0127 \pm 0.0003$$

Lipa et al., PRB **68**, 174518 (2003)



- **Bose-Einstein condensate (harmonically trapped case)**

- **On earth:**

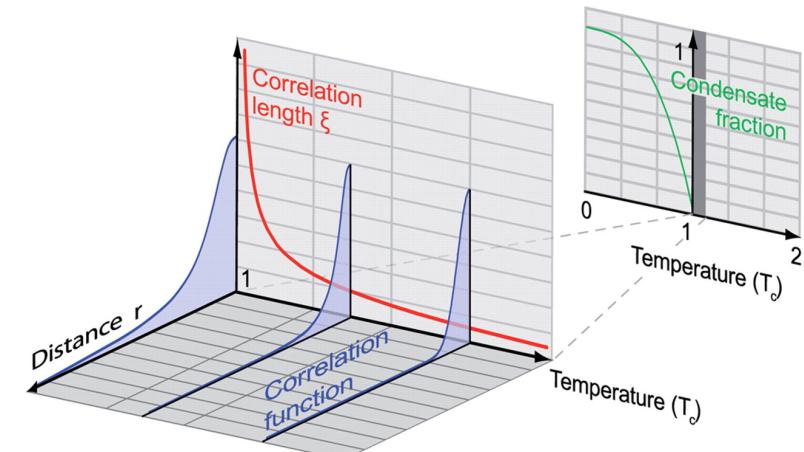
$$\xi \sim |(T - T_c)/T_c|^{-\nu}$$

$$\nu = 0.67 \pm 0.13$$

Donner et al., Science **315**, 1556 (2007)

- **In microgravity:**

**BECCAL?**



## 3.4 Optical Lattices

- Flat optical lattice:

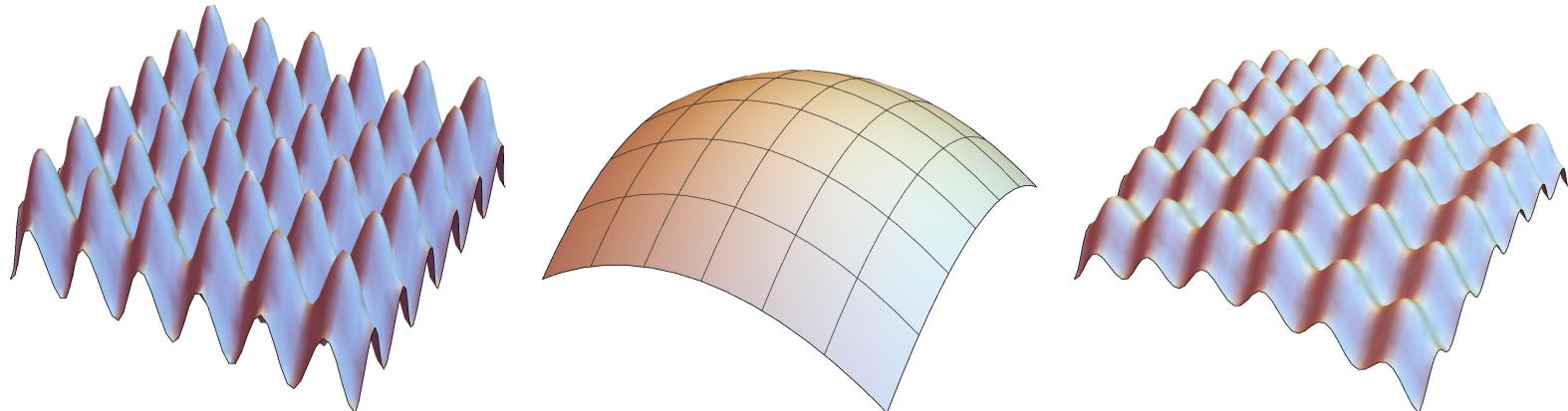
- Continuum many-body Hamiltonian:

$$\hat{H} = \int d^3x \left\{ \hat{\psi}^\dagger \left[ -\frac{\hbar^2}{2M} \Delta + V_0 \sum_{k=1}^3 \sin^2 \left( \frac{\pi}{a} x_k \right) \right] \hat{\psi} + \frac{g}{2} \hat{\psi}^\dagger 2 \hat{\psi}^2 \right\}$$

- Bose-Hubbard model:

$$\hat{H} = -J \sum_{\langle i,j \rangle} \hat{b}_i^\dagger \hat{b}_j + \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i - 1) ; \quad \hat{n}_i = \hat{b}_i^\dagger \hat{b}_i$$

- Curved optical lattice: Inhomogeneous hopping



Gödtel, diploma thesis, TU Kaiserslautern, 2017

# **3.5 Wilhelm and Else Heraeus Seminar**

## **Exploring Quantum ManyBody Physics with Ultracold Atoms and Molecules**

**organized by Carlos Sá de Melo and Axel Pelster**

**Bad Honnef (Germany); December 14 – 18, 2020**

**Invited Speakers:** Monika Aidelsburger (Germany), Alain Aspect (France), Waseem Bakr (USA), Nicholas Bigelow (USA), Doerte Blume (USA), Georg Bruun (Denmark), Andreas Buchleitner (Germany), Jean Dalibard (France), Francesca Ferlaino (Austria), Thomas Gasenzer (Germany), Tin-Lun Ho (USA), Michael Köhl (Germany), Giovanni Modugno (Italy), Cristiane Morais Smith (Netherlands), Jian-Wei Pan (China), Dmitry Petrov (France), Ernst Rasel (Germany), Monika Schleier-Smith (USA), Peter Schmelcher (Germany), Sandro Stringari (Italy), Päivi Törmä (Finland), Christof Weitenberg (Germany), Artur Widera (Germany), Jun Ye (USA), Wei Zhang (China)

**WILHELM UND ELSE  
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