Universität Hamburg

Department Physik

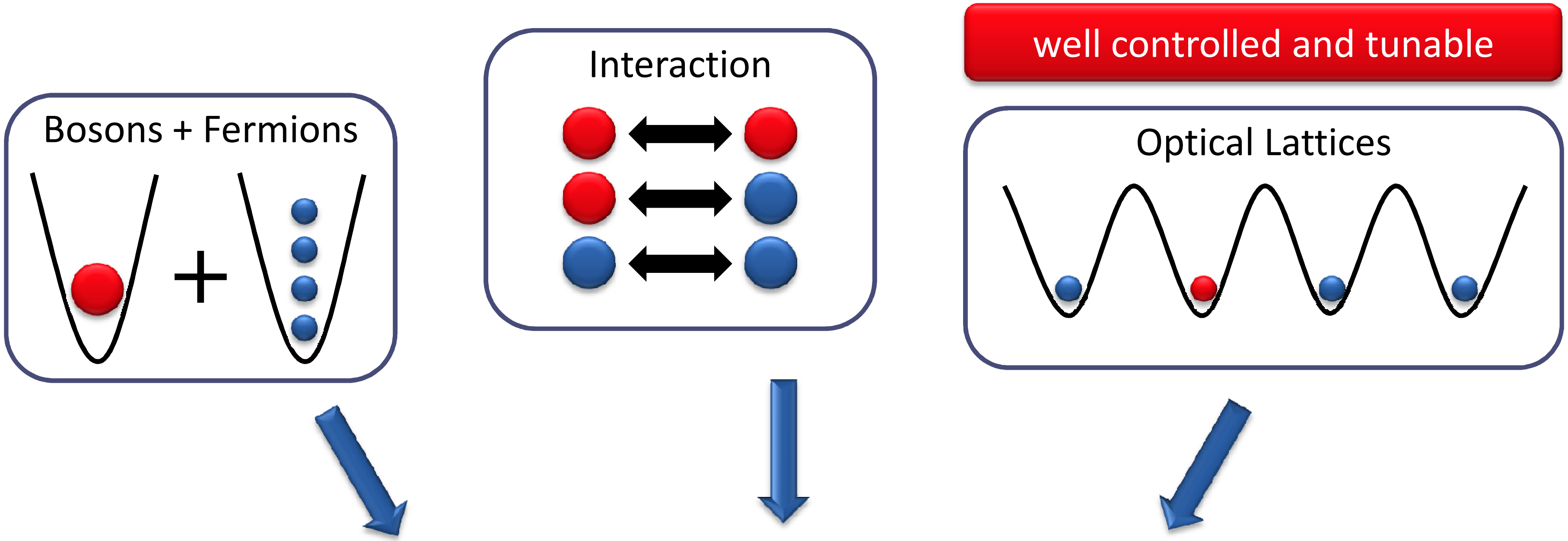
Analysis of Bose-Fermi Mixtures in Optical Lattices

Philipp T. Ernst, Sören Götze, Jannes Heinze,
Jasper Krauser, Christoph Becker & Klaus Sengstock

Project within FerMix collaboration

European Science Foundation
SETTING SCIENCE AGENDAS FOR EUROPE

Motivation



Bose-Fermi Mixtures in Optical Lattices

Motivation

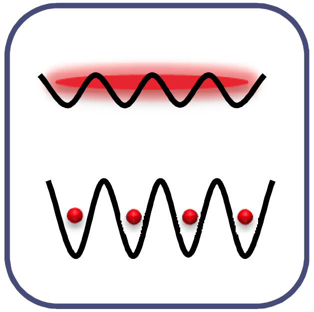
Testing ground solid state theories

Bose-Fermi Mixtures in Optical Lattices

Quantum simulators

Cold molecules

Mott-Insulator



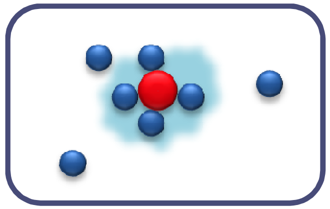
Exotic Superfluids

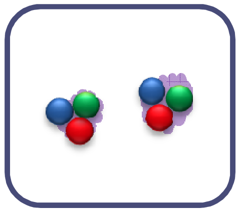
aMI

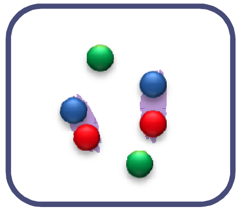
CDW

Supersolids

Composite particles







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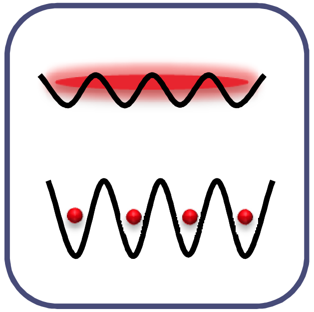
Mott-Insulator



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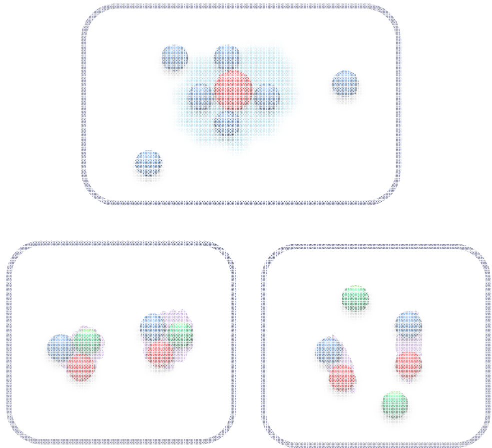
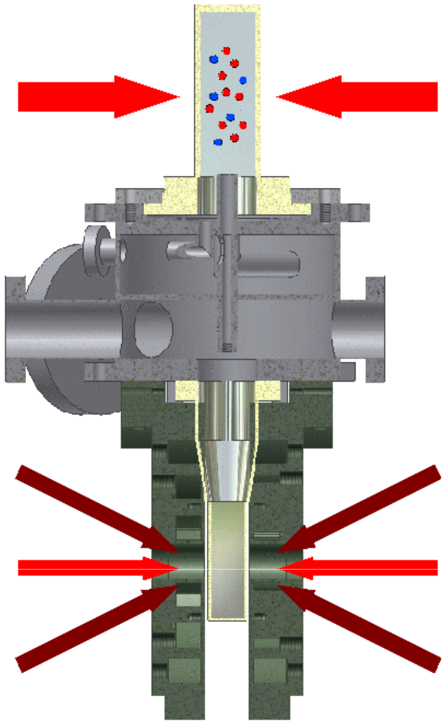


Outline

Bosonic Mott-Insulator Transition in Presence of Fermions (recent aspects)

Momentum-Resolved Bragg Spectroscopy in Optical Lattices

Bose-Fermi Mixture Experiment I



^{87}Rb ^{40}K

Rb ⟷ Rb: $\approx$ 100 a_B

Rb ⟷ K: $\approx$ - 205 a_B

K K: no s-wave scattering

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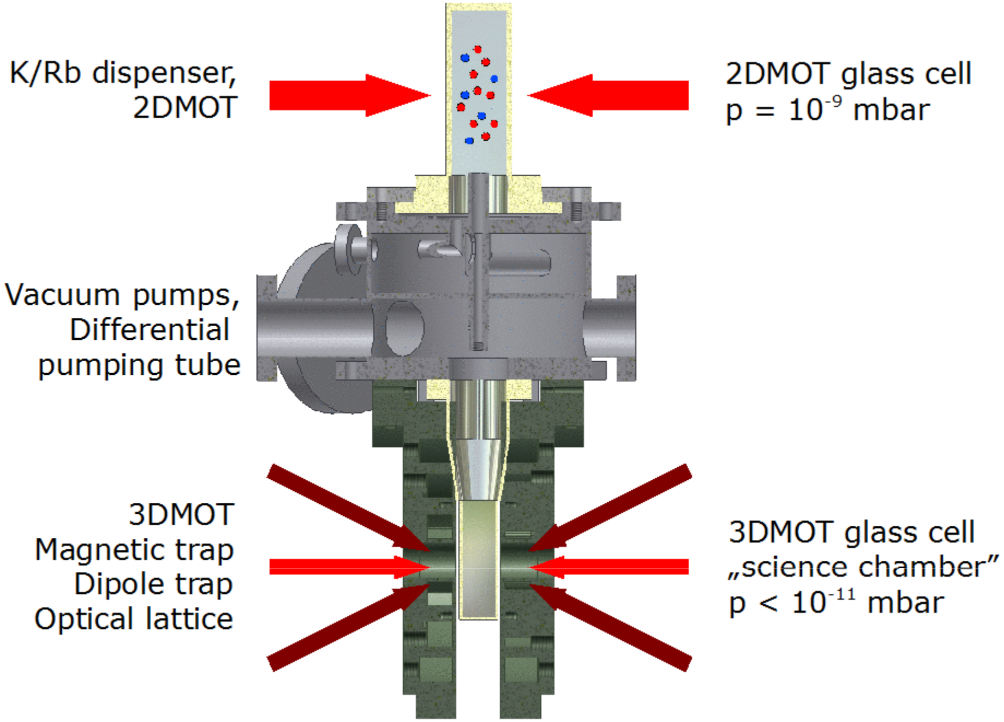


^{87}Rb ^{40}K

Rb ↔ Rb ≈ 100 a_B

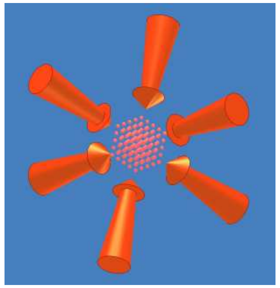
Rb ↔ K ≈ - 205 a_B

K K no s-wave scattering

- Laser cooling 2D MOT, 3D MOT
- Magnetic trap
- Sympathetical evaporation cooling

  → quantum degeneracy (BEC & T/TF ≈ 0.15)

  → $N_b \approx 1 \cdot 10^6$ & $N_f \approx 5 \cdot 10^5$
- Transfer to Crossed dipole trap
- Optical lattice
- TOF & Absorption Imaging

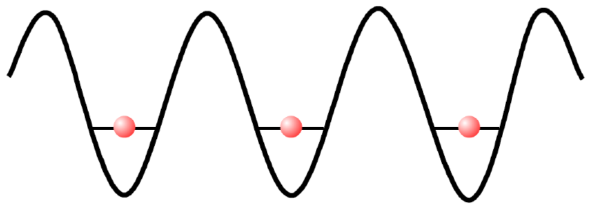


Crossed dipole trap @ 808nm

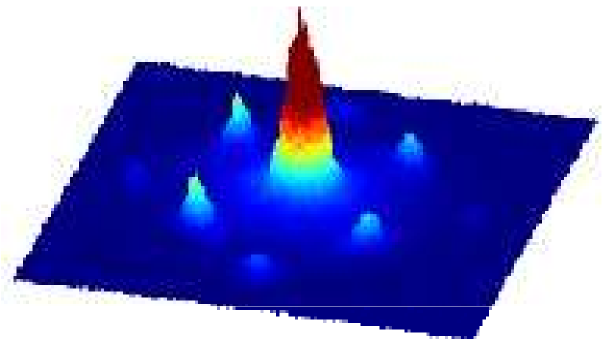
3D optical lattice @ 1030nm

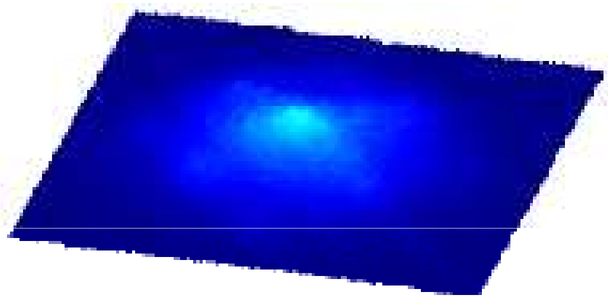
Bose-Fermi Mixture Experiment II

Superfluid phase



Mott-Insulator phase





For shallow lattices: delocalized coherent state → Interference peaks
For deep lattices: localized number states → broad incoherent distribution

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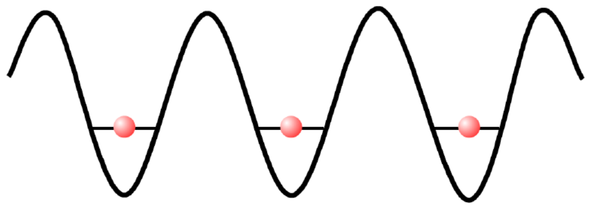

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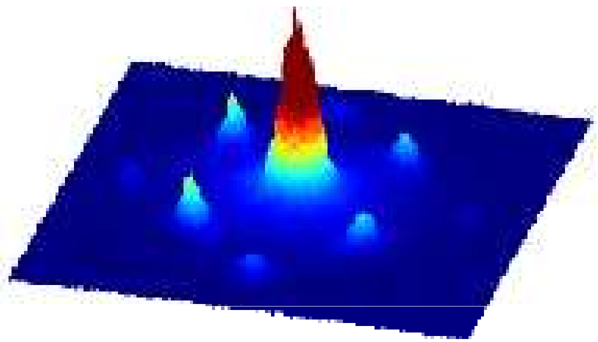
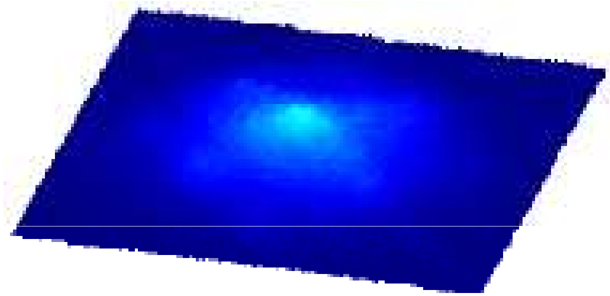




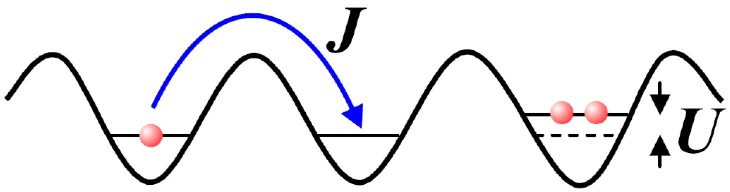
For shallow lattices: delocalized coherent state → Interference peaks
For deep lattices: localized number states → broad incoherent distribution

Several evaluation methods e.g.

- Visibility of interference peaks
- Width of central peak
- Linear increase of incoherent background
- Signs of MI in excitation spectra
- …

Reminder: Bose-Hubbard model

Description of ultracold gases in optical lattices by Bose-Hubbard model
*Jaksch et al. PRL **81**, 3108 (1998)*



- On-site interaction **U** (preferably calculated in **single band** approx.)
- Tunneling / hopping integral **J** (nearest neighbours)

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

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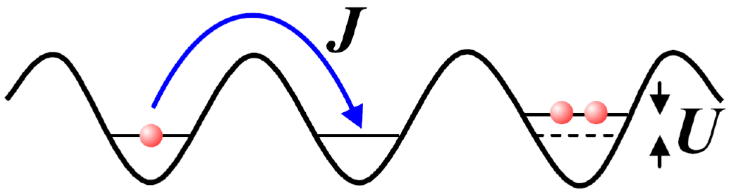

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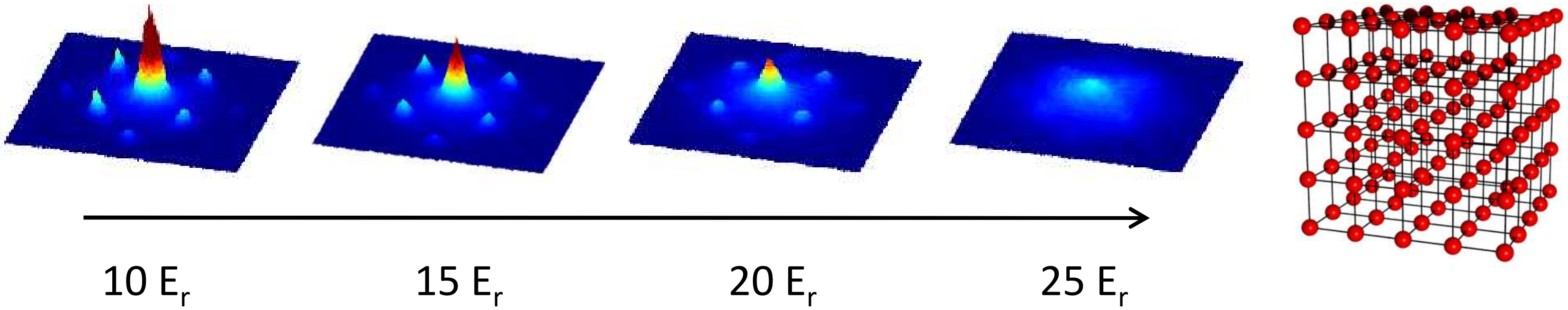
- Calculate critical points for quantum phase transition depending on density at lattice site and number of nearest neighbours

$$(U/J)_c = z(2n_\mathrm{B} + 1 + 2\sqrt{n_\mathrm{B}(n_\mathrm{B} + 1)})$$

Mott-Insulator transition experiments

Pure bosonic system



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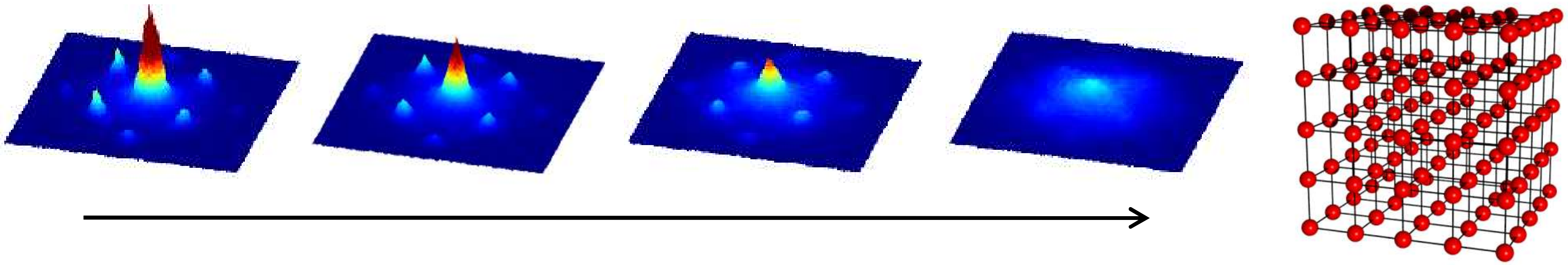
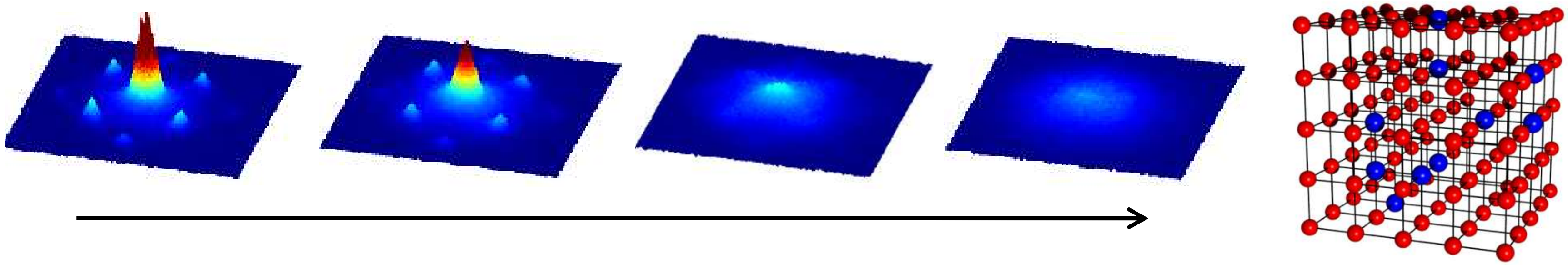


$10\ E_r$ $15\ E_r$ $20\ E_r$ $25\ E_r$

With small admixture of fermions



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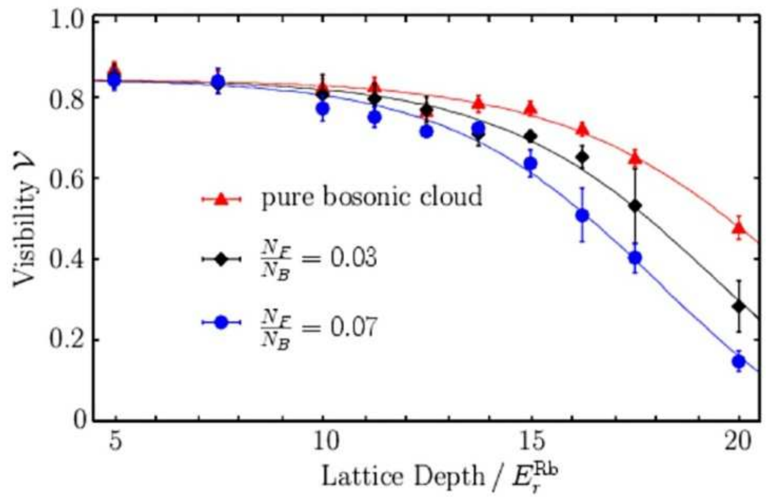
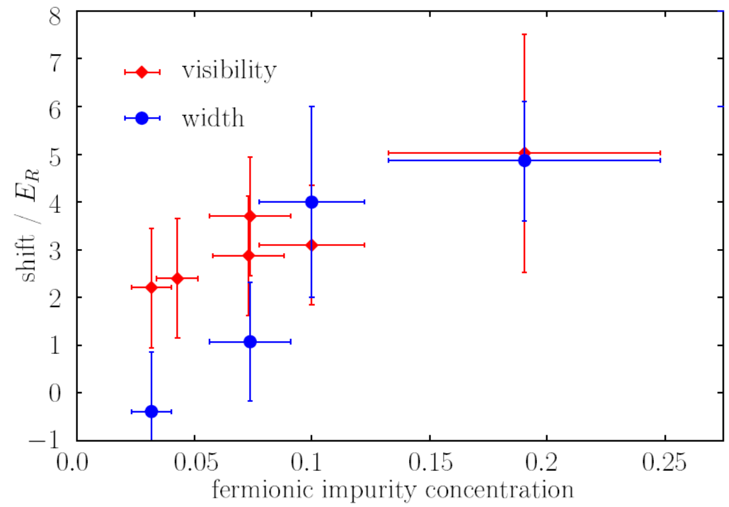
Experimental findings





Data above:
S. Ospelkaus et al., PRL 96, 180403 (2006)

Similiar experiments:
- ETH Zürich
  PRL 96, 180402 (2006)
- Florence
  Bose-Bose mixture
  Phys. Rev. A 77, 011603 (2008)
- Mainz
  Feshbach resonance
  PRL 102, 030408 (2009)

- Unexpected large shift of the critical potential depth
- even for small fermionic fractions (few percent)
- Seen in all experiments with different parameters

Discussion I

Lag of understanding

- Inspiration for further investigation
  (attraction to theoriticians)
- Controversial discussion

Which effects can be predicted in presence of the interspecies interaction?
In which way / which part does the interspecies interaction „dominate“?

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PHYSICAL REVIEW A **77**, 023608 (2008)

Mixture of bosonic and spin-polarized fermionic atoms in an optical lattice

Lode Pollet,[1] Corinna Kollath,[2] Ulrich Schollwöck,[3] and Matthias Troyer[1]
[1]*Theoretische Physik, ETH Zürich, CH-8093 Zürich, Switzerland*
[2]*Université de Genève, 24 Quai Ernest-Ansermet, CH-1211 Genève, Switzerland*
[3]*Institute of Theoretical Physics C, RWTH Aachen University, D-52056 Aachen, Germany*
(Received 23 September 2006; published 6 February 2008)

We investigate the properties of trapped Bose-Fermi mixtures for experimentally relevant parameters in one dimension. The effect of the attractive Bose-Fermi interaction onto the bosons is to deepen the parabolic trapping potential, and to reduce the bosonic repulsion in higher order. This leads for many situations to an increase in bosonic coherence. The opposite effect was observed in ^{87}Rb-^{40}K experiments, most likely due to a sharp rise in temperature. We also discuss low-temperature features, such as a bosonic Mott insulator transition driven by the fermion concentration, and the formation of composite particles such as polarons and molecules.

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Effective reduction of bose-bose repulsion by bose-fermi attraction
→ delayed shift of transition

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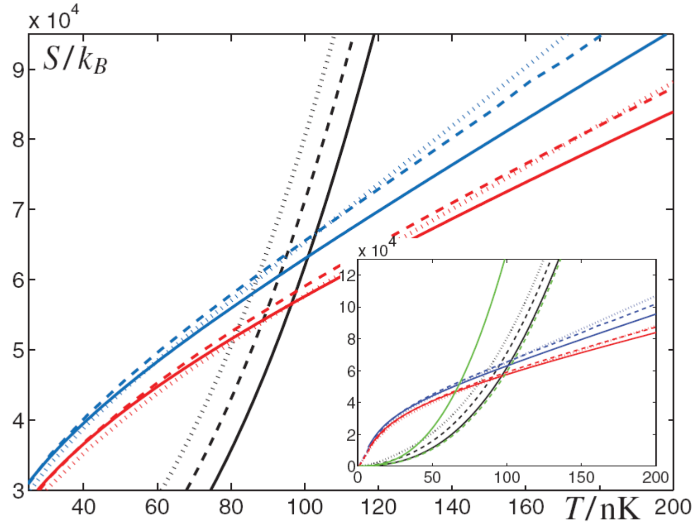
Discussion II

2

Discussion II - Thermal effects

Reduction of visibility by thermal effect:
Higher temperature after ramp up of optical lattice with additional fermions compared to ramp up of lattice with bosons only
(see e.g. studies by Ho, Blakie et al., Bloch et al., …)



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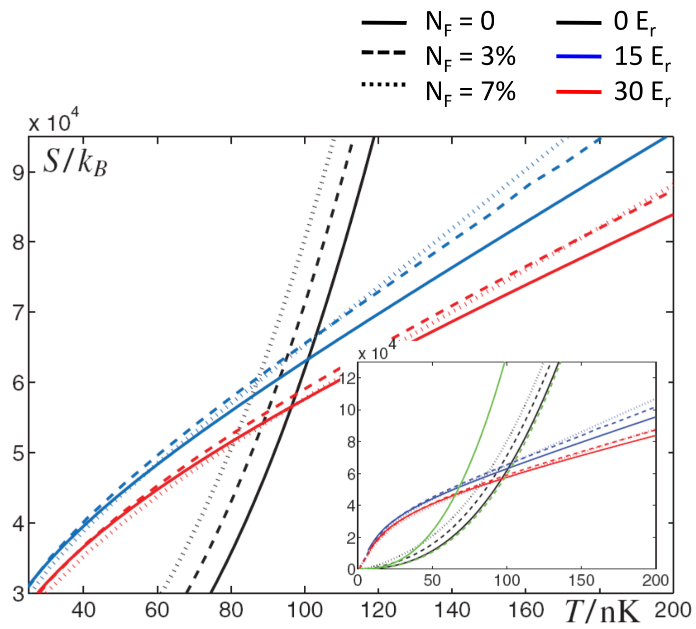
<u>Argument:</u>

- adiabatic ramp up → change of temperature due to change in density of states
- change of density of states in presence of fermions
- reduced adiabatic cooling in presence of fermions

Calculation for Fermi-Bose mixture with our parameters done by M. Cramer et al.:
M. Cramer, S. Ospelkaus, C. Ospelkaus,K. Bongs, K. Sengstock, J. Eisert,Phys. Rev. Lett., 100, 140409 (2008)



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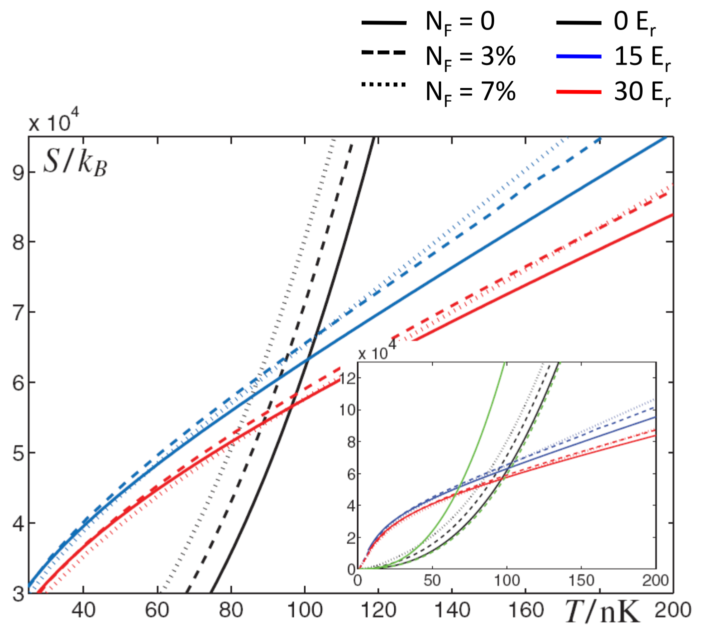

Slightly higher **T**(mixture) > **T**(bosons only)

Effect on change of visibility?

→ Still ongoing work

Discussion III

3

Discussion III – On-site interaction

Detailed study of on-site interaction
in cooperation with D. Pfannkuche and D. S. Lühmann
*D.-S. Lühmann, K. Bongs, K. Sengstock & D. Pfannkuche, PRL **101**, 050402 (2008)*

- Exact diagonalization using a many-particle basis
- Examination of a single lattice site
- Inclusion of the orbital degrees of freedom
- Repulsive interaction between bosons
- Attractive boson-fermion interaction via effective potentials

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$$V_B^{eff}(\rho_F) = V(\vec{r}) + g_{BF}\,\rho_F(\vec{r})$$

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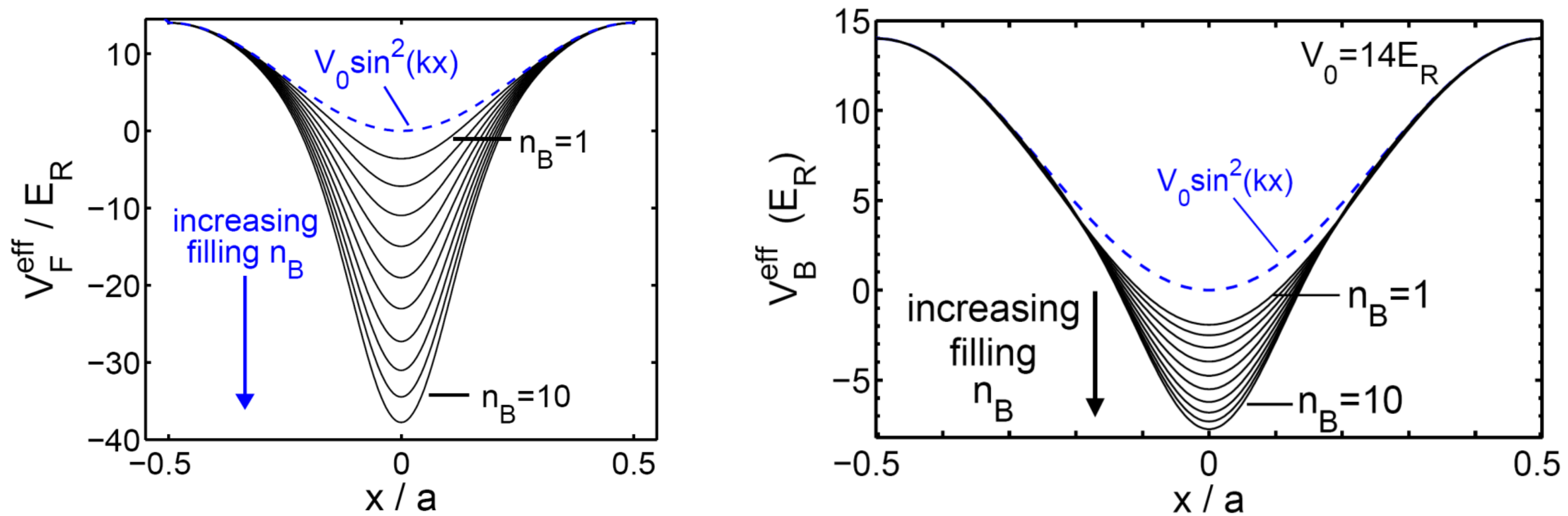

Discussion III – On-site interaction

- Bosonic repulsion $\propto n_B^2$
  is overcompensated by nonlinear boson-fermion interaction effect
- Lowering of the bosonic effective potential
  with an increasing n_B

Leads to:

- A decreased hopping **J** between neighboring sites
- An increase of the on-site interaction energy **U**

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Leads to:

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The ratio **U**/**J** increases!

New effective Bose-Hubbard parameters!

- $\mathbf{U_{eff}}$ directly from V_B^{eff}
- $\mathbf{J_{eff}}$ from band structure of the periodic continuation of V_B^{eff}

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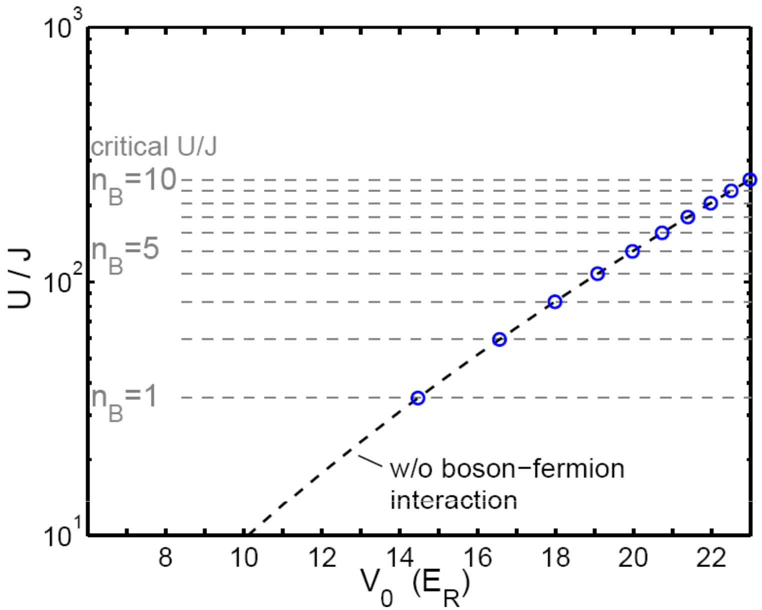

Comparison:

- Dashed line bosonic system only
- Circles critical value for phase transition

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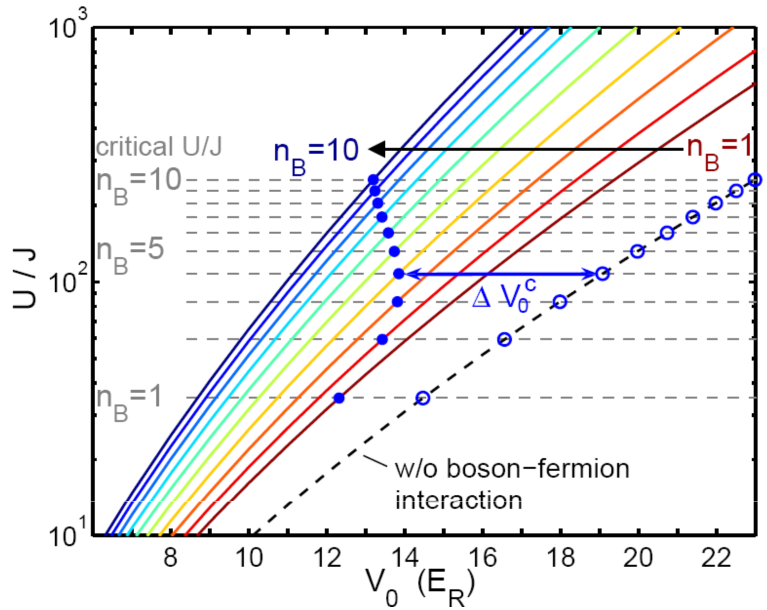

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- Solid lines new (U_{eff}/J_{eff}) for different filling factors from n_B = 1 to n_B = 10
- Difference in ΔV_0^c
- Shift of approx. 5 E_r for our filling factors
- Good agreement with experiments

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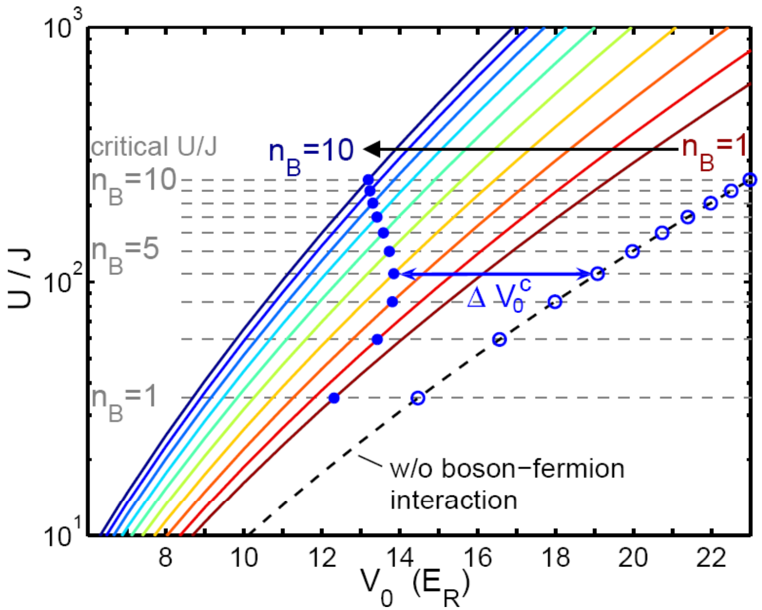
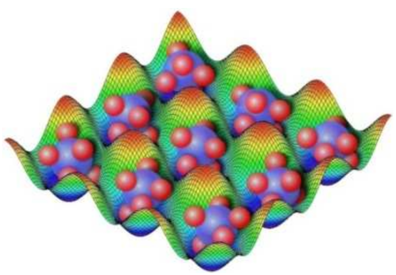


Fundamental importance for quantum gas mixtures in optical lattices



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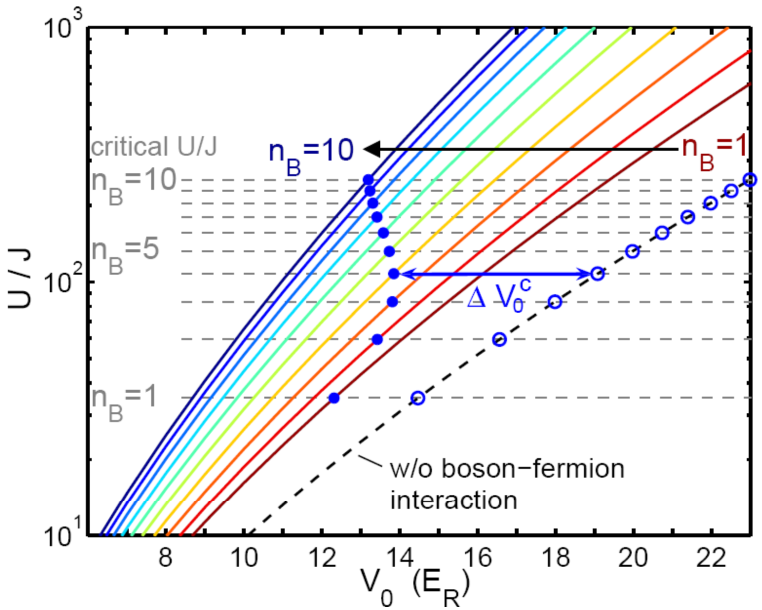

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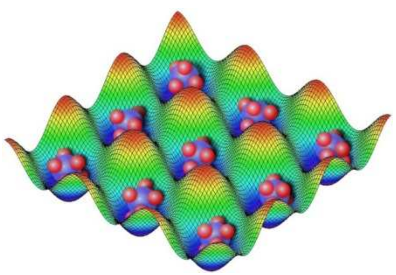

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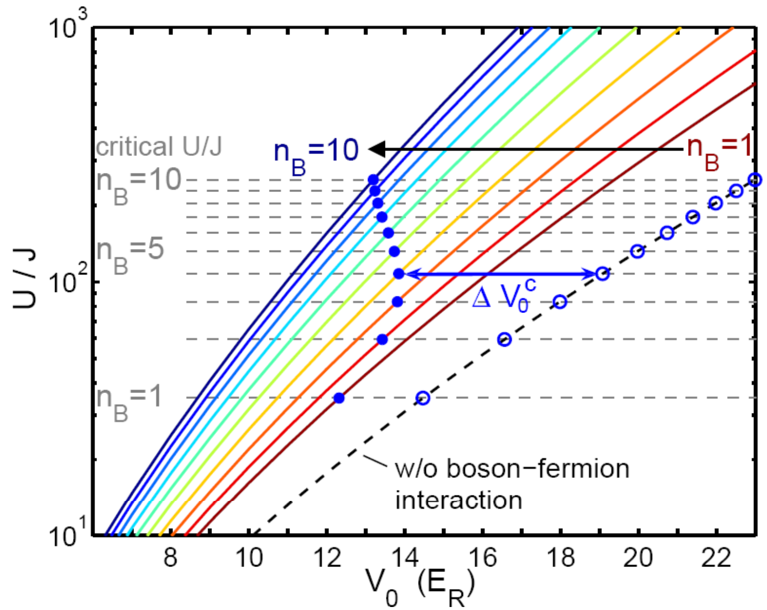

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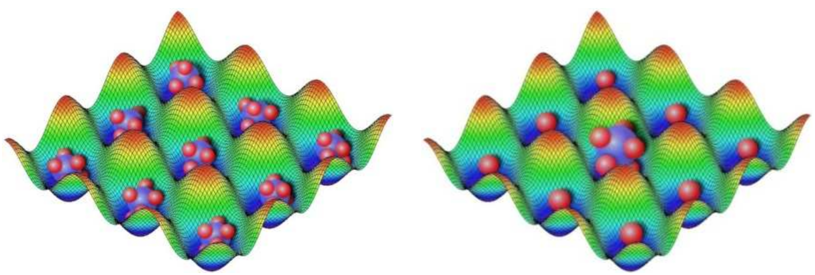

<u>Comparison:</u>

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- Solid lines new (**U_{eff}**/**J_{eff}**) for different filling factors from n_B = 1 to n_B = 10
- Difference in ΔV_0^c
- Shift of approx. 5 E_r for our filling factors
- Good agreement with experiments

Calculations show self-trapping behaviour of the bosons (1 fermion, 6 bosons)
*D. S. Lühmann et al., PRL **101**, 050402 (2008)*

Experimentally tuned interaction see:
*Th. Best et al., PRL **102**, 030408 (2009)*

Conclusion

Conclusion:

- Bose-Fermi mixtures in optical lattices are exciting new systems
- Still ongoing and in part controversal discussion of the change in bosonic coherence properties due to fermionic admixtures
  - → finite T effects may play a role (but expected to be small)
  - → interaction might deform wavefunctions significantly
- Demands for further calculations including contribution of higher bands
- Effective new single-band BH-parameters U_{eff} and J_{eff}

- Interest in further experimental (and theoretical) studies
- (excitations? , measurement of fermionic system, …)

Outline

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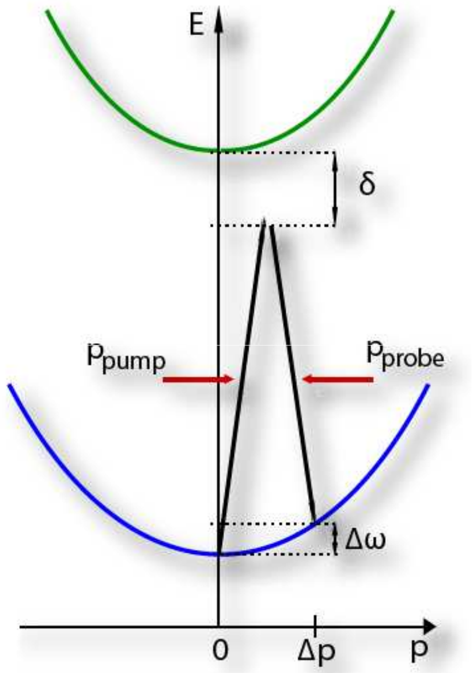
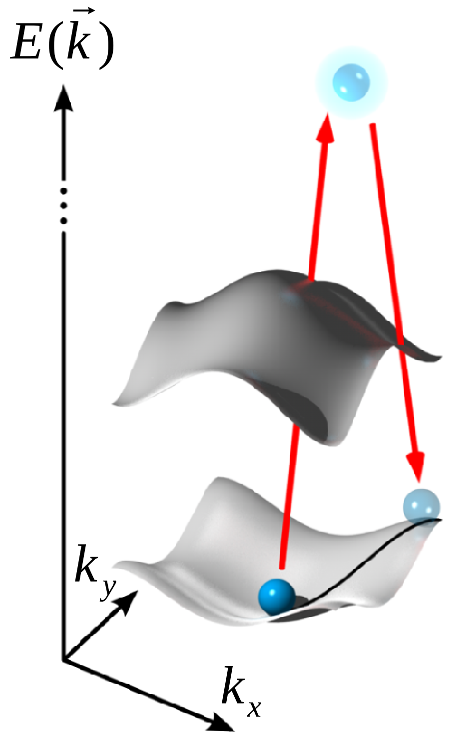
Momentum-Resolved Bragg Spectroscopy in Optical Lattices

Bragg spectroscopy I



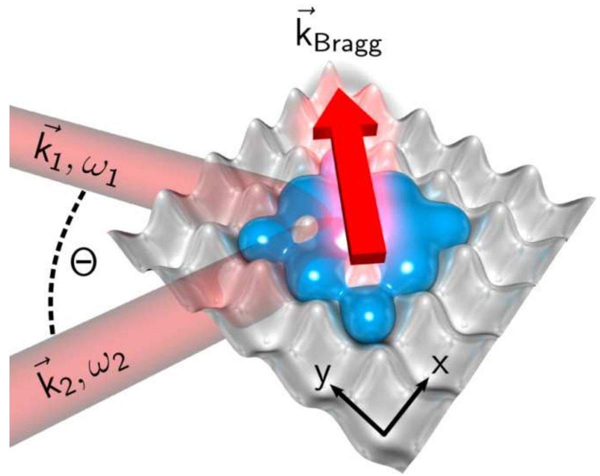
- Coherent two photon process
- Detuning to excited state δ ≈ 5 GHz
- Absorption of pump-photon
- Stim. emission of probe-photon
- Redistribution between pump and probe
- Energy and momentum conservation
  momentum Δp = laser k-vector difference
  relative energy difference Δω

Bragg spectroscopy II

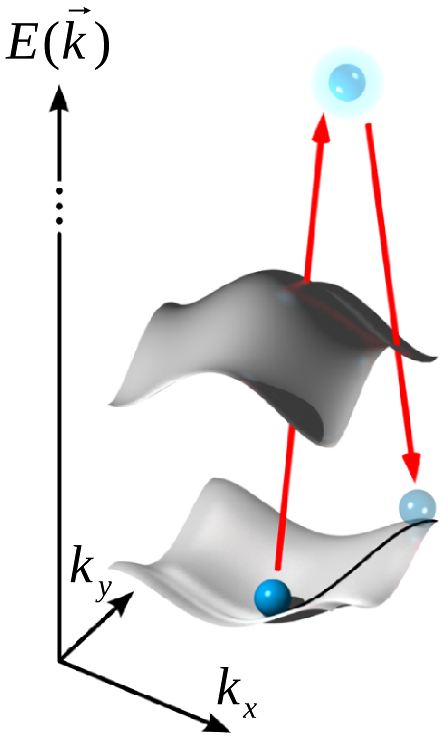


- Arbitrary momentum direction possible
- Value of momentum-transfer given by Bragg laser angle Θ
- Energy difference $\Delta\omega = \omega_2 - \omega_1$

- „Scan“ of momentum value
  → Complete first Brillouin zone
- Scan of energy difference yield resonance spectrum
  → first, second, … higher bands accessible



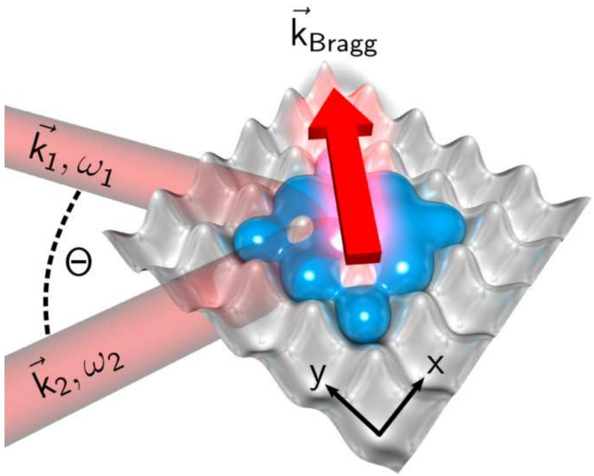
Bragg spectroscopy II



- Arbitrary momentum direction possible
- Value of momentum-transfer given by Bragg laser angle Θ
- Energy difference $\Delta\omega = \omega_2 - \omega_1$
- „Scan“ of momentum value
  → Complete first Brillouin zone
- Scan of energy difference yield resonance spectrum
  → first, second, … higher bands accessible

<u>See also:</u>

- „Using photoemission spectroscopy to probe a strongly interacting Fermi gas“ – J. T. Stewart, J. P. Gaebler & D. S. Jin
  *Nature **454**, 07172 (2008)*
- „Measuring the One-Particle Excitatoins of Ultracold Fermionic Atoms by Stimulated Raman Spectroscopy“ – T.-L. Dao, A. Georges, J. Dalibard, C. Salomon & I. Carusotto
  *PRL **98**, 240402 (2007)*



Experimental sequence

Lattice ramp up

↓

Bragg pulse

↓

Lattice and trap switch off

↓

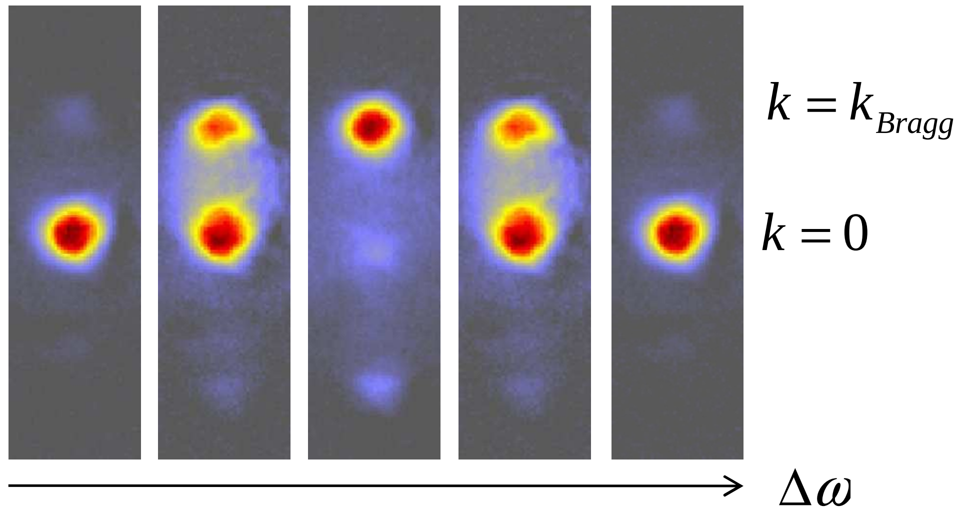
TOF & Imaging

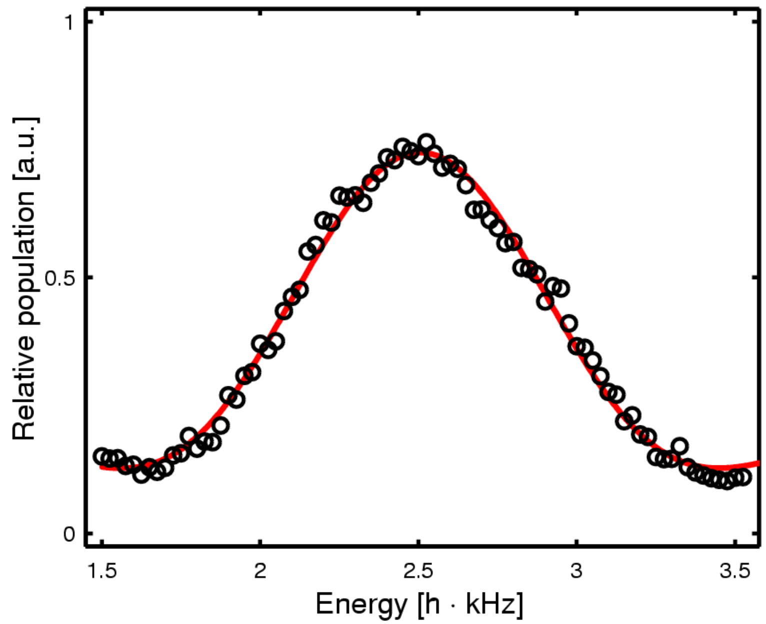
↓

Counting atoms

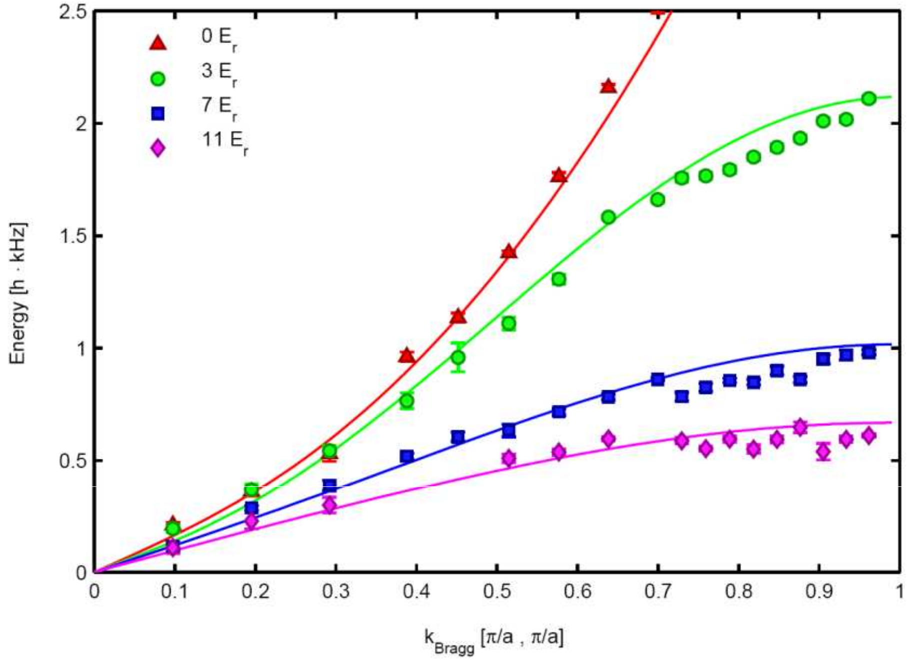
↓

Spectrum

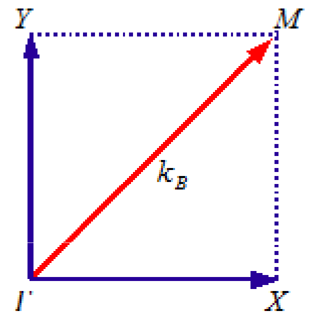




Bragg spectroscopy - Bandstructure

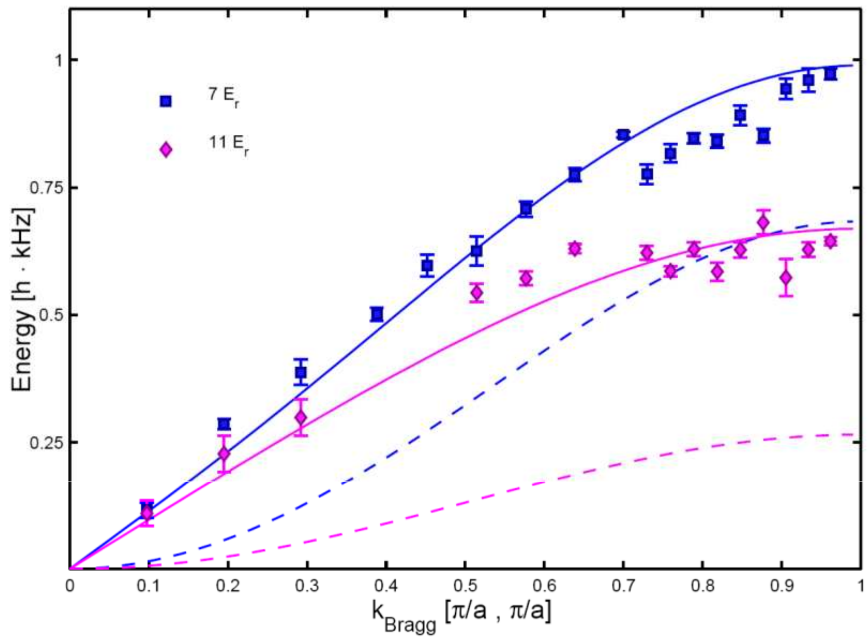


Measurements in 2D and 3D optical lattice in [1,1] nodal direction



- Mapping of first Brillouin zone for several lattice depths
- Identification of different regimes:
  - linear „phonon-like" regime (collective excitations)
  - particle-like excitations
  - lattice dominated regime at BZ edge (decreasing bandwidth, bragg reflection, etc.)

Bragg spectroscopy – Interaction effects



Dashed lines:
bandstructure w.o. interaction

Solid lines:
Bandstructure including interaction following van Oosten, Burnett, …
Bogoliubov approx. within BH frame

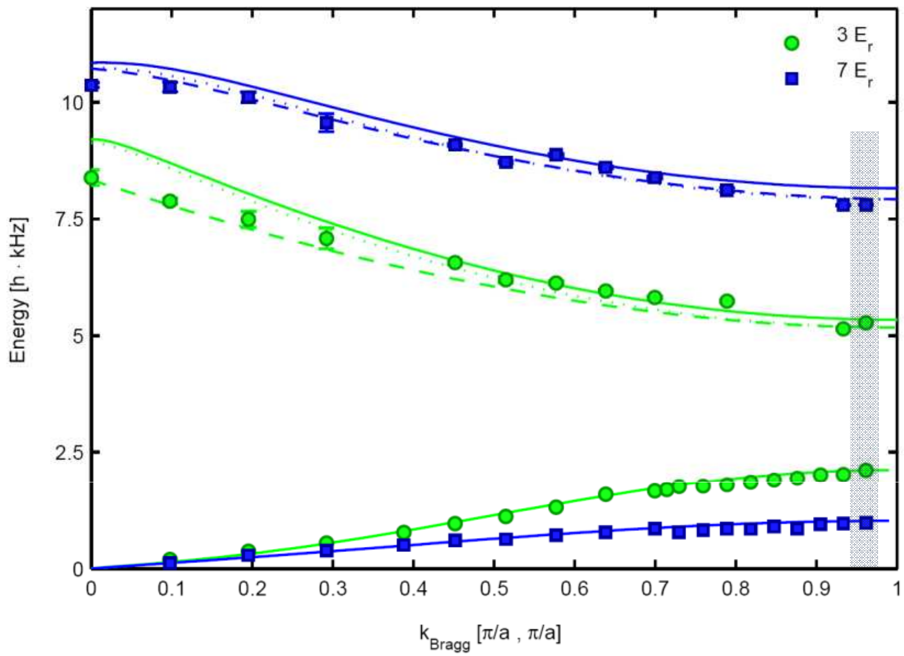
Interaction effects crucially important in first band!

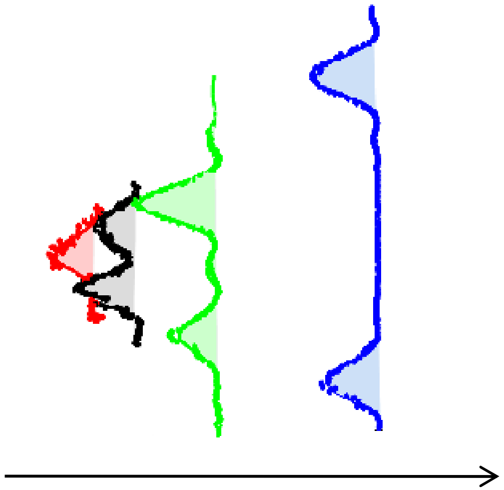
$$\hbar\omega_k = \sqrt{\varepsilon_k^2 + 2n_0U\varepsilon_k} \qquad \varepsilon_k = 4J\sin^2\left(\frac{ka}{2}\right)$$

Tight binding energy

Van Oosten et al., PRA 63, 053601 (2001)
Burnett et al., J.Phys. B: At. Mol. Opt. Phys., 35, 1671 (2002)

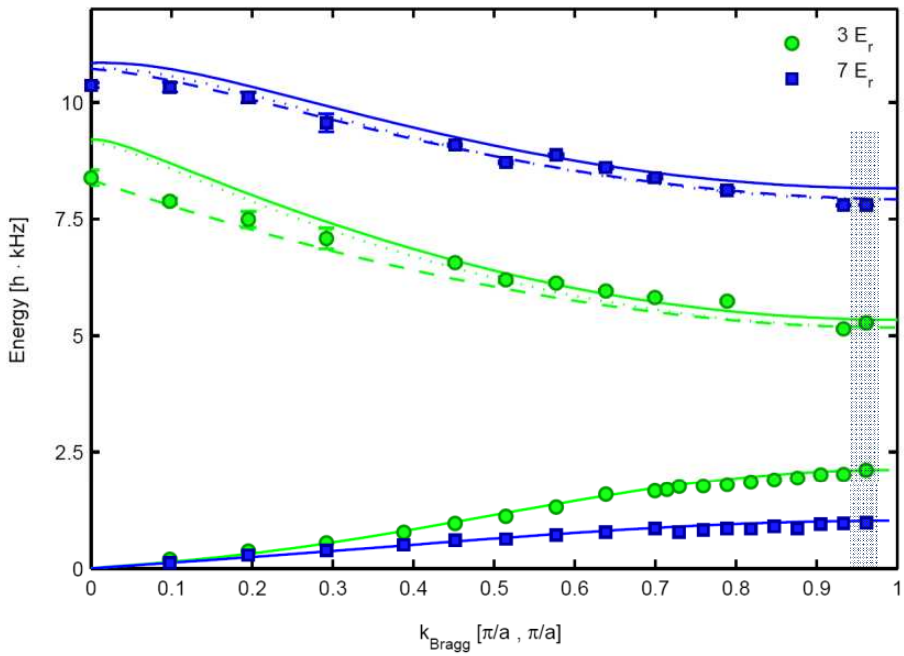
Bragg spectroscopy – Higher bands I

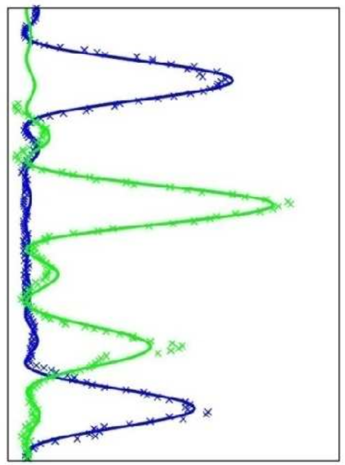




- Opening of Bandgap illustrated
- Dotted lines: non-interacting dispersion relation
- Solid lines: Bogoliubov approx. to Bose-Hubbard

Bragg spectroscopy – Higher bands II





Second band

First band

- Impact of interaction severly reduced in second band due to reduced overlap integral
- Data at small momenta deviate from interacting calculations
  Energies for 3 E_r above potential depth
- Bogoliubov-de Gennes calculation including harm. confinement fits nicely (dashed lines) in cooperation with D. S. Lühmann & D. Pfannkuche

Conclusion

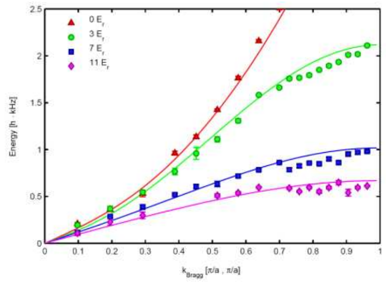
- Fully momentum-resolved excitation spectra in optical lattice
- Characterization of bandstructure
- Analysis of interaction effects

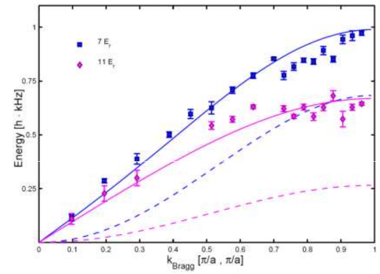
- Effective means of state preparation

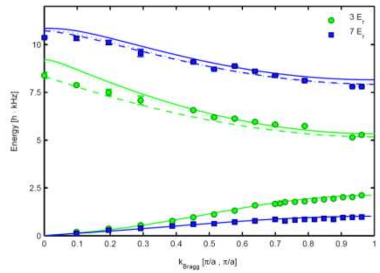
- Further investigation:

    o Strongly correlated regime, e.g. Mott insulator

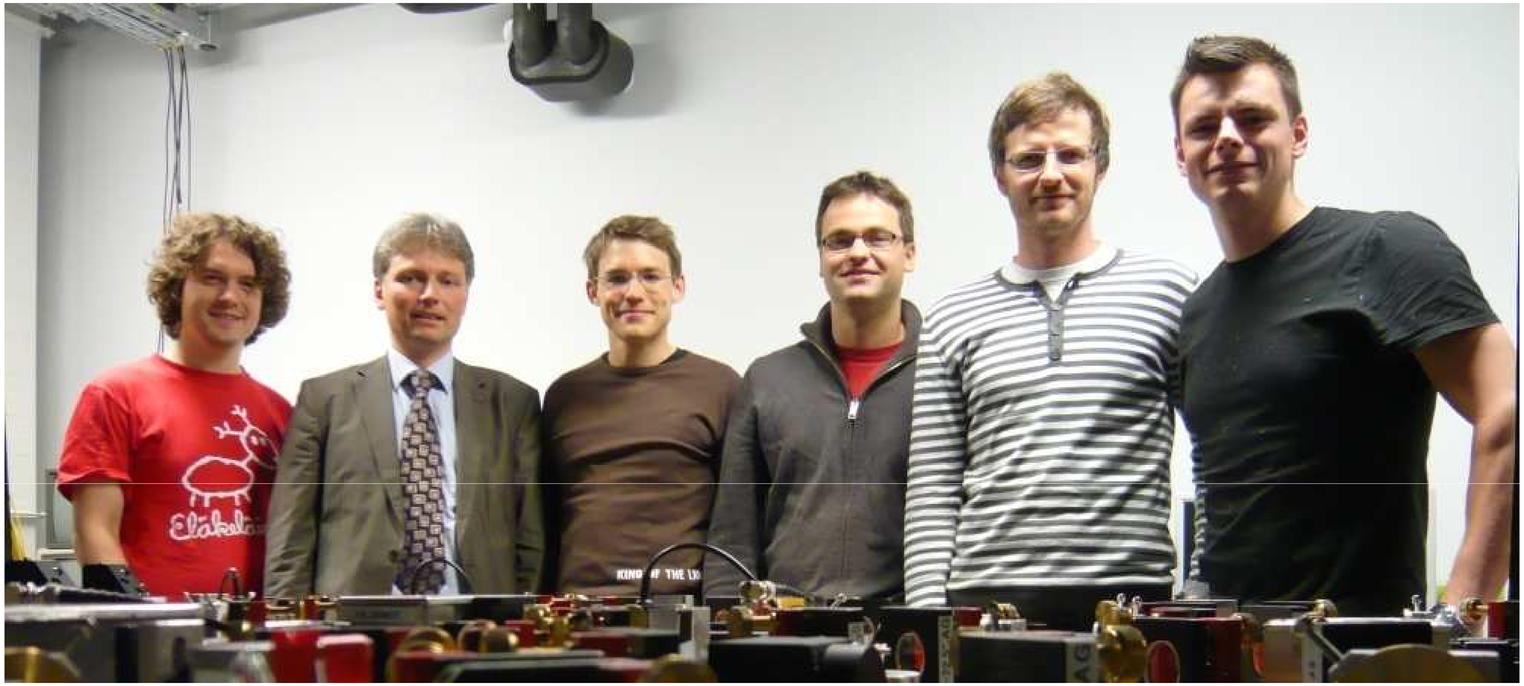
    o Fermionic and mixture system (including MI transition)





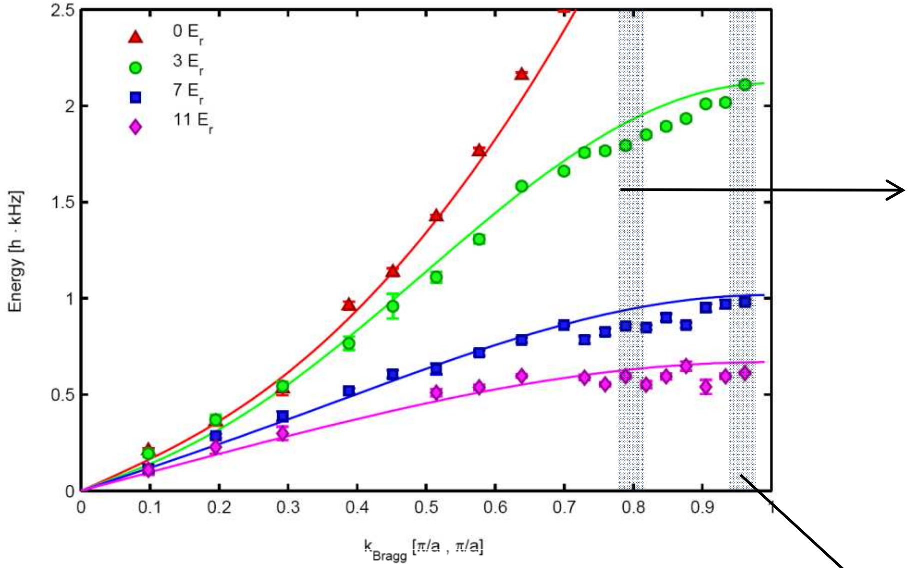


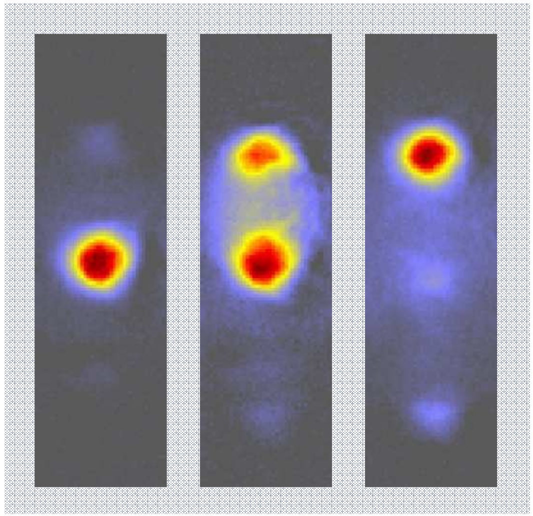
Team



Jannes Heinze, Klaus Sengstock, Philipp T. Ernst, Jasper Krauser, Christoph Becker, Sören Götze

Appendix – Bragg Reflection



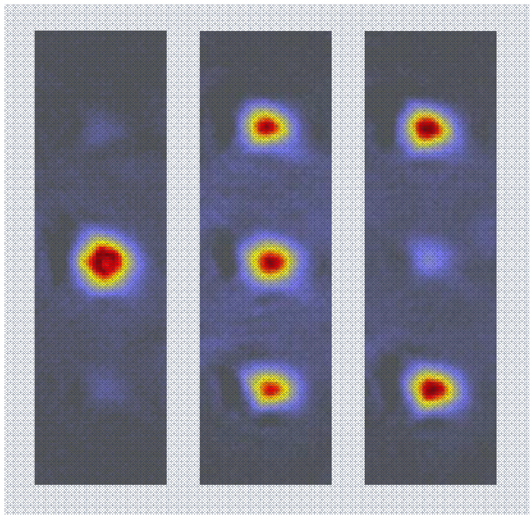


$k = k_{Bragg}$

$k = 0$

$$k_{Bragg} = 0.8 \frac{\pi}{a_{diag}}$$

$$k_{Bragg} = 0.96 \frac{\pi}{a_{diag}}$$

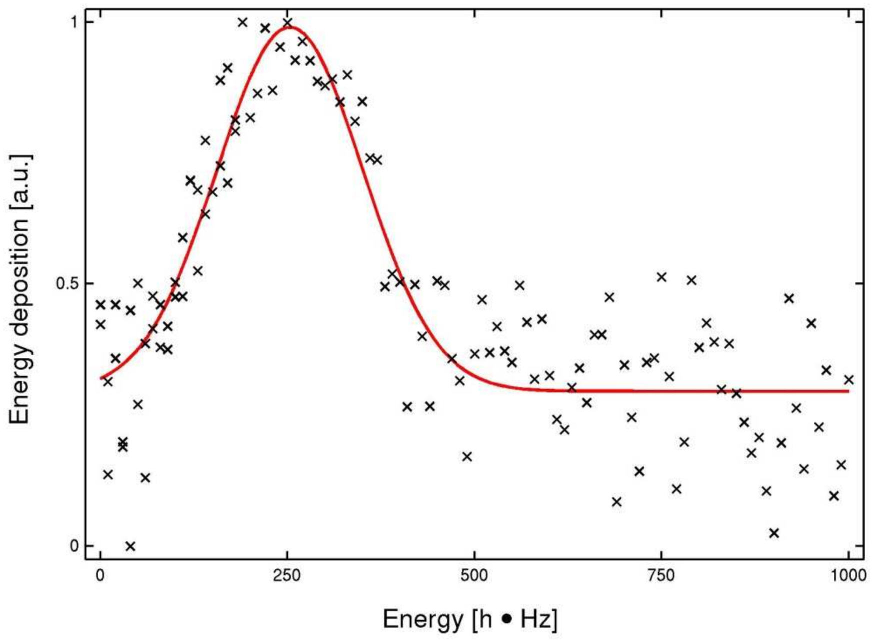


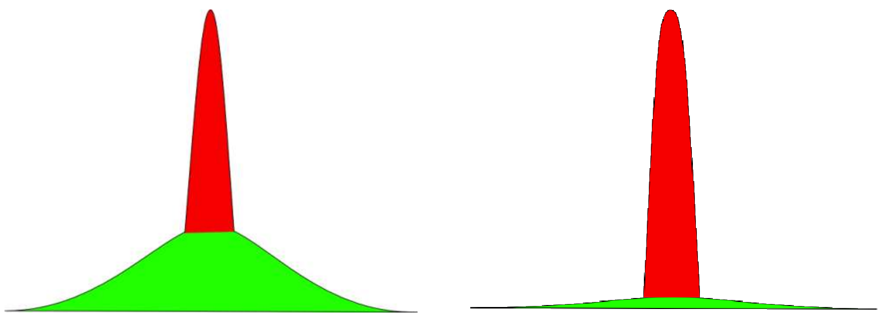
$k = k_{Bragg}$

$k = 0$

$k = k_{Bragg} - k_G$

Appendix – Energy transfer



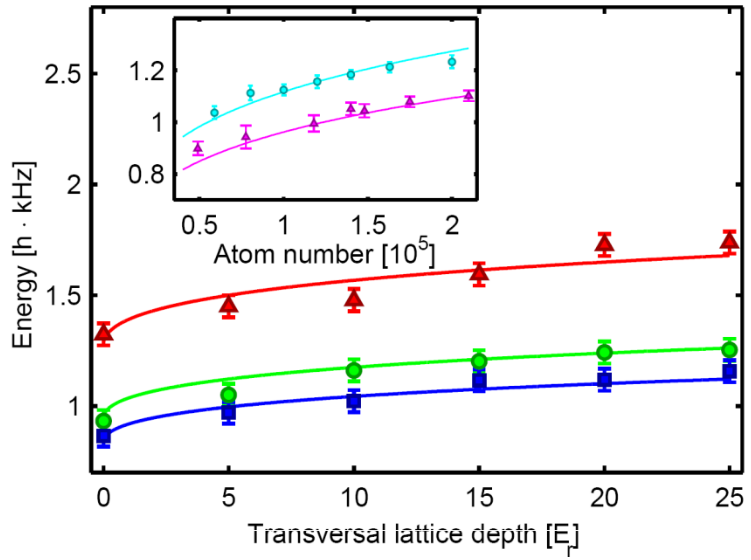


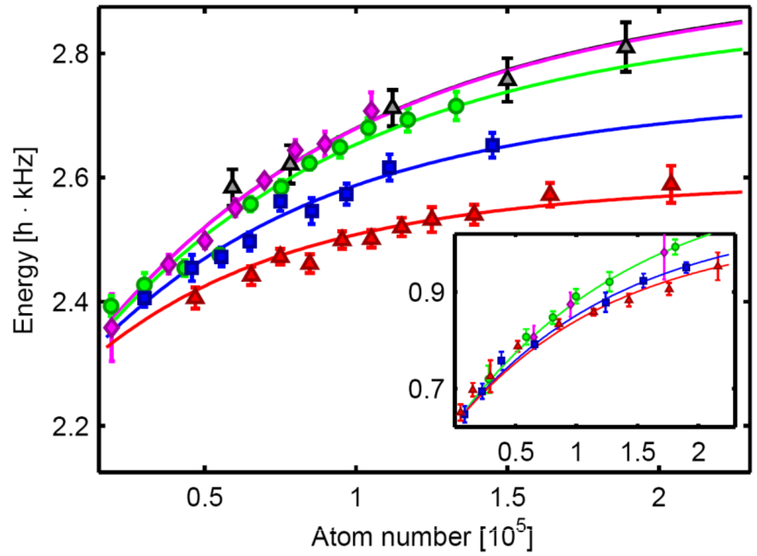
For small momentum transfers clouds don‘t separate anymore!

Impart momentum to atoms
Wait for thermalization

Measure energy deposition in system by fits to column-sums e.g. condensate fraction, width, visibility, etc.

Appendix – 2D & 3D, Excitation fraction





- Parallel shift of resonances due to increase in density at different angles
- Inset: particle number dependance
- Change in on-site interaction U
- For 2D and 3D experiment

- Influence reduced in optical lattice (inset) compared to h.t. BEC
- Energy decreases with higher excitation fraction in both cases
- Adiabacity? Trap modes?
- Work in progress