The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1957-5

Miniworkshop on Strong Correlations in Materials and Atom Traps

4 - 15 August 2008

Correlations in Ultracold Quantum Gas Mixtures.

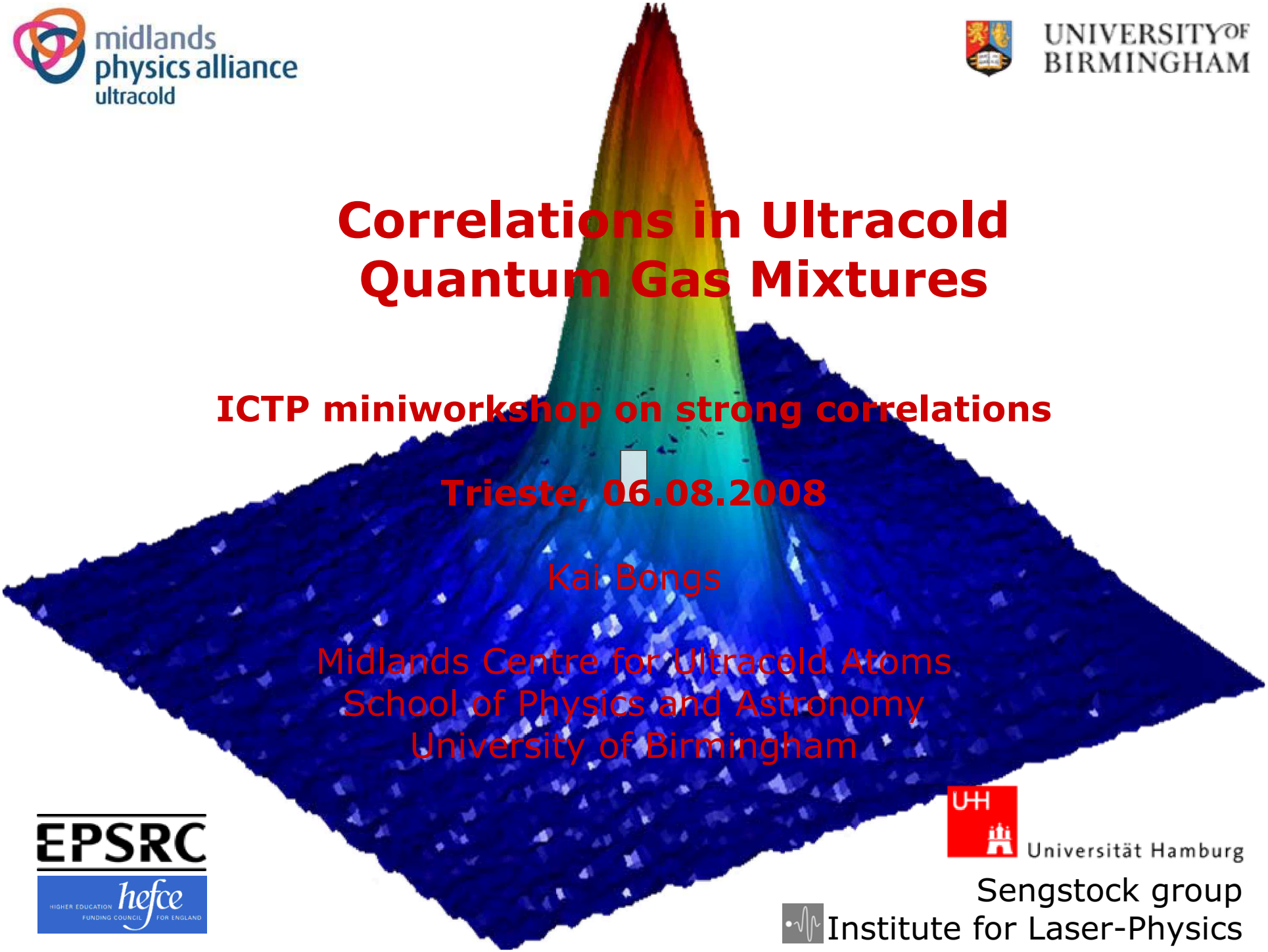
BONGS Kai

University of Birmingham
School of Physics & Astronomy
Theoretical Physics Res.Group, Edgbaston
B15 2TT Birmingham
United Kingdom

midlands physics alliance ultracold

UNIVERSITY OF BIRMINGHAM

Correlations in Ultracold Quantum Gas Mixtures



ICTP miniworkshop on strong correlations

Trieste, 06.08.2008

Kai Bongs

Midlands Centre for Ultracold Atoms
School of Physics and Astronomy
University of Birmingham

EPSRC

hefce HIGHER EDUCATION FUNDING COUNCIL FOR ENGLAND

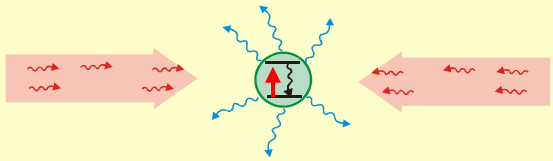
UH Universität Hamburg

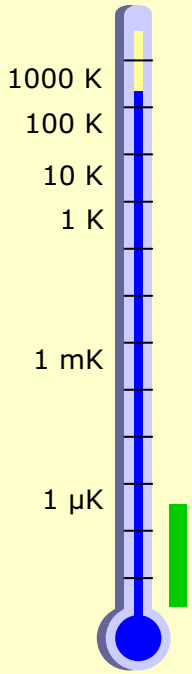
Sengstock group
Institute for Laser-Physics

Ultracold Quantum Gases

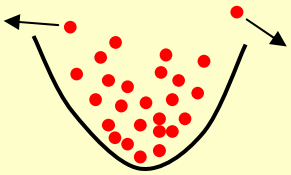
Preparation

- Laser cooling

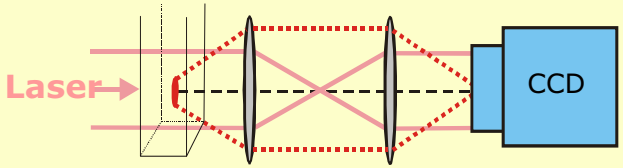


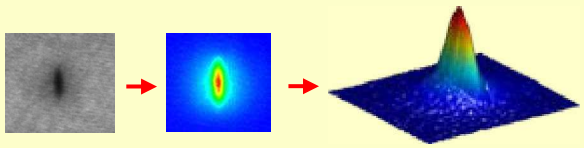


- Evaporative cooling



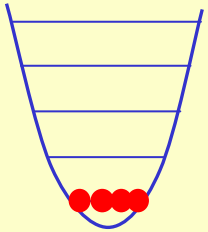
- Imaging



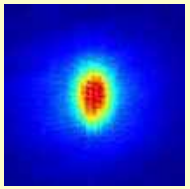


Typical Parameters

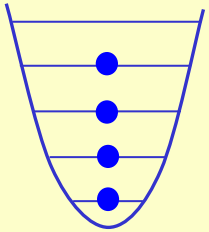
Bosons



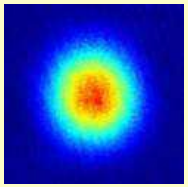
^{87}Rb



Fermions



^{40}K



T ~ 100 nK

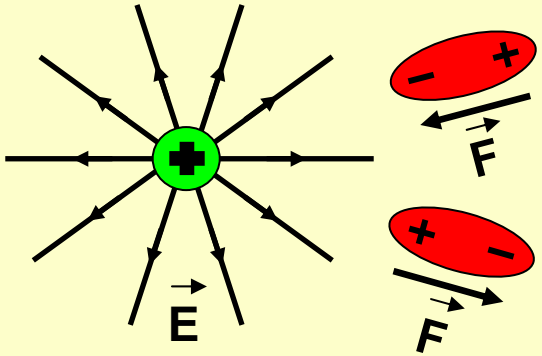
n ~ 10^{13}..10^{14} cm^{-3}

N ~ 10^{5}

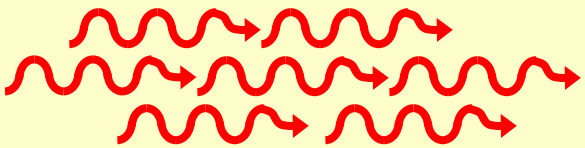
Manipulation with Lasers

Light-atom interaction

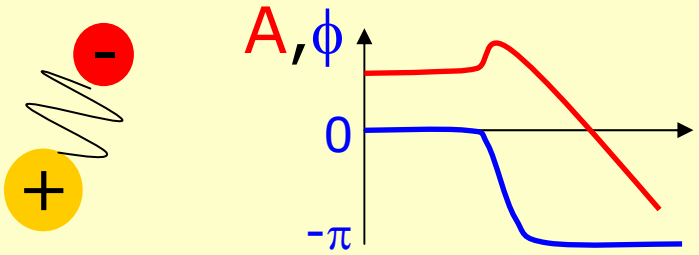
- Static dipole interaction



- Light -> oscillating electric field

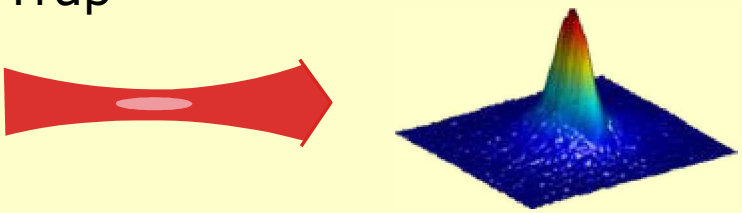


- Atom: spring model

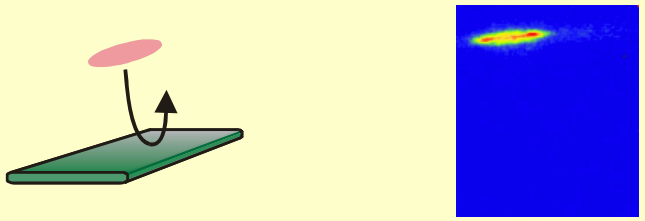


Coherent manipulation

- Trap

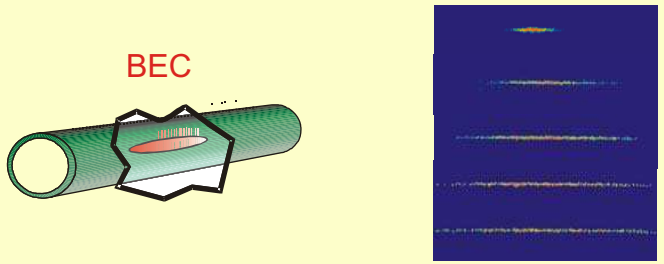


- Mirror



Phys. Rev. Lett. ***83****, 3577 (1999)*

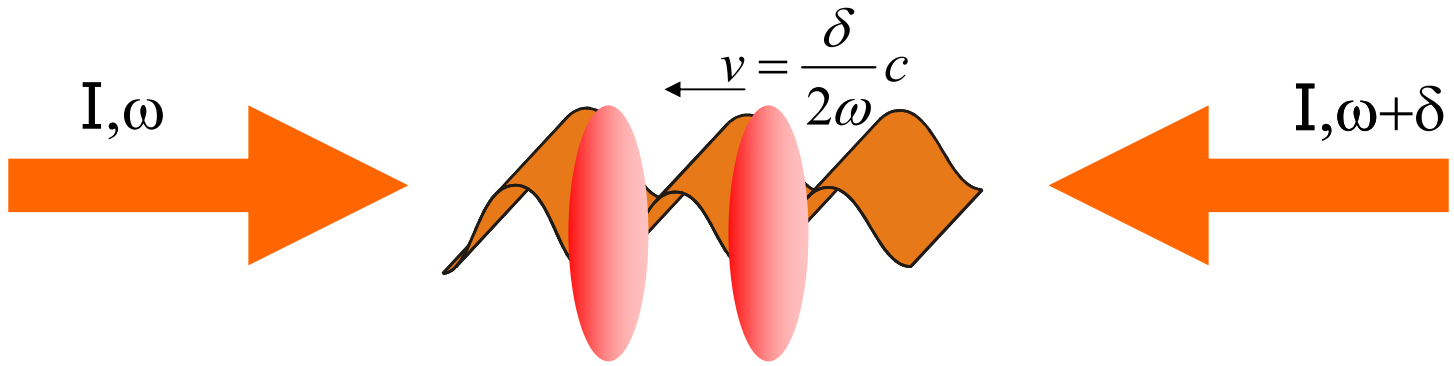
- Waveguide



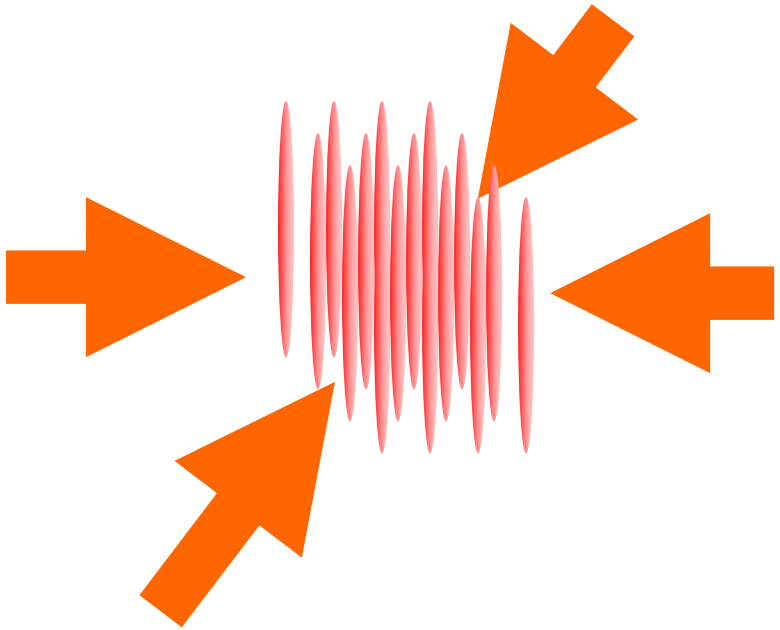
Phys. Rev. A ***63****, 031602 (2001)*

Optical Lattices

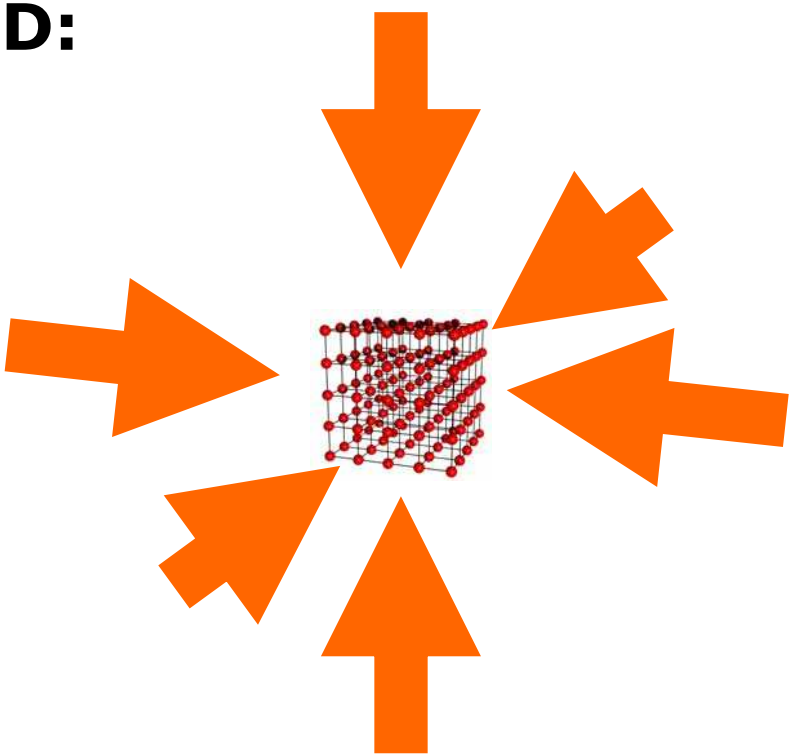
1D:



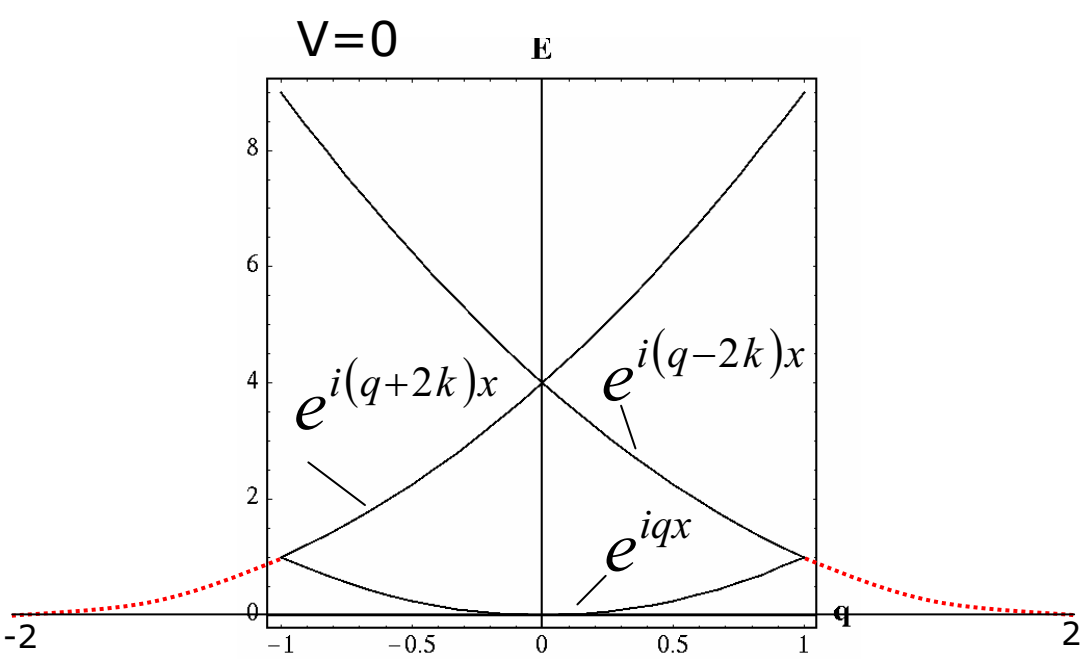
2D:

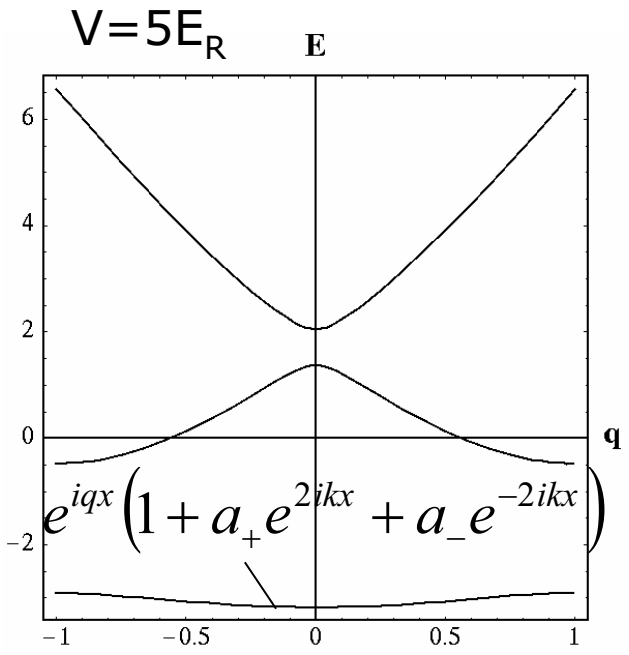


3D:

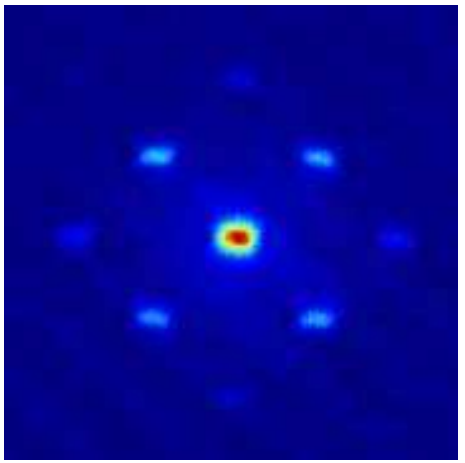


Momentum Distribution





TOF



Sudden switch off of lattice potential:

→ projection of in lattice quasimomenta to free space momenta

Bloch basis → plane waves

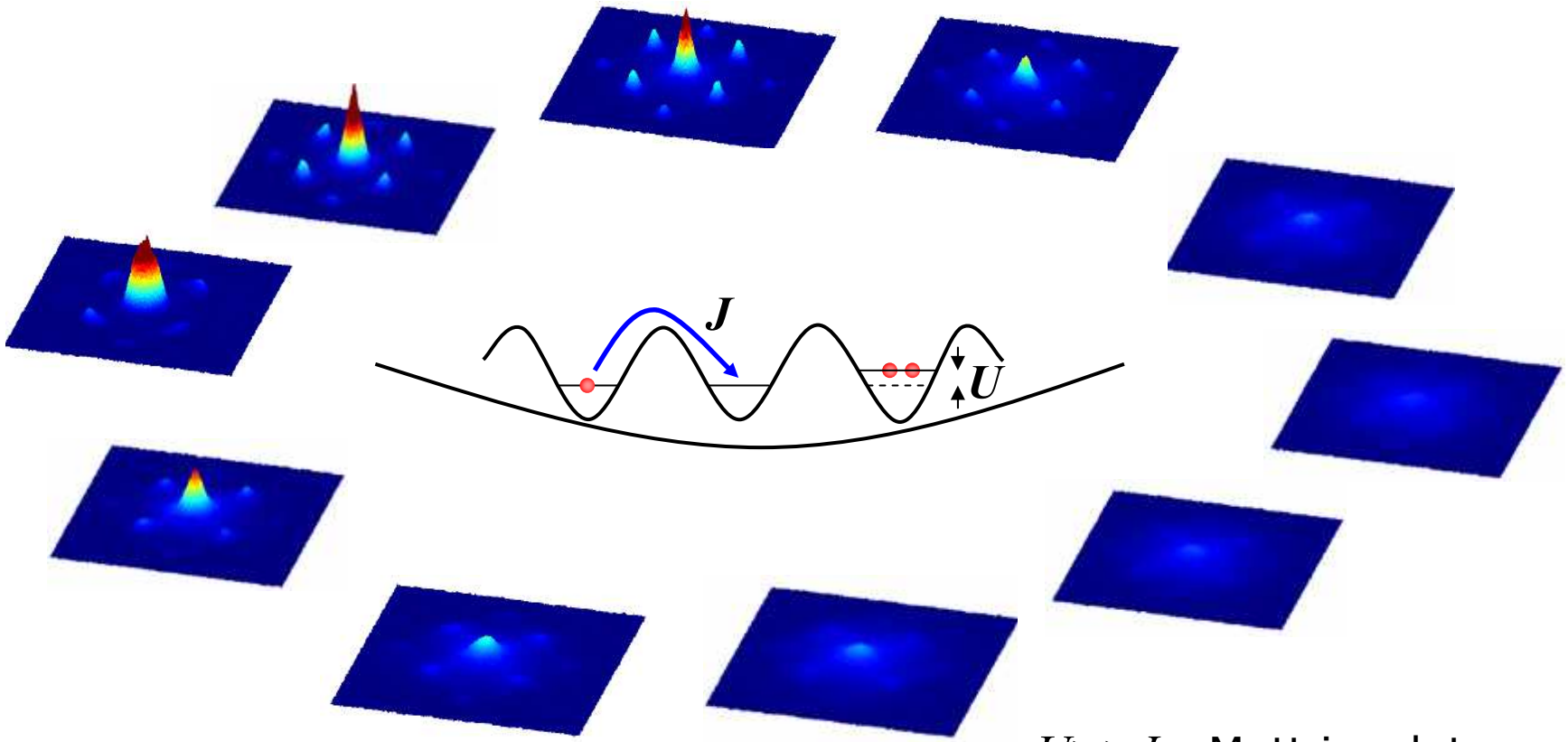
→ **coherence and correlations**

The Bosonic Mott Insulator Transition

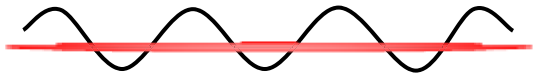
Bose-Hubbard physics:

Jaksch et al. PRL **81**, 3108 (1998)

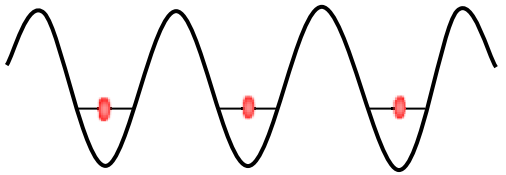
$$H = -J\sum_{(i,j)} \hat{a}_i^{+}\hat{a}_j + \sum_i \varepsilon_i n_i + \tfrac{1}{2}U\sum_i \hat{n}_i\left(\hat{n}_i - 1\right)$$



$U<<J$: superfluid

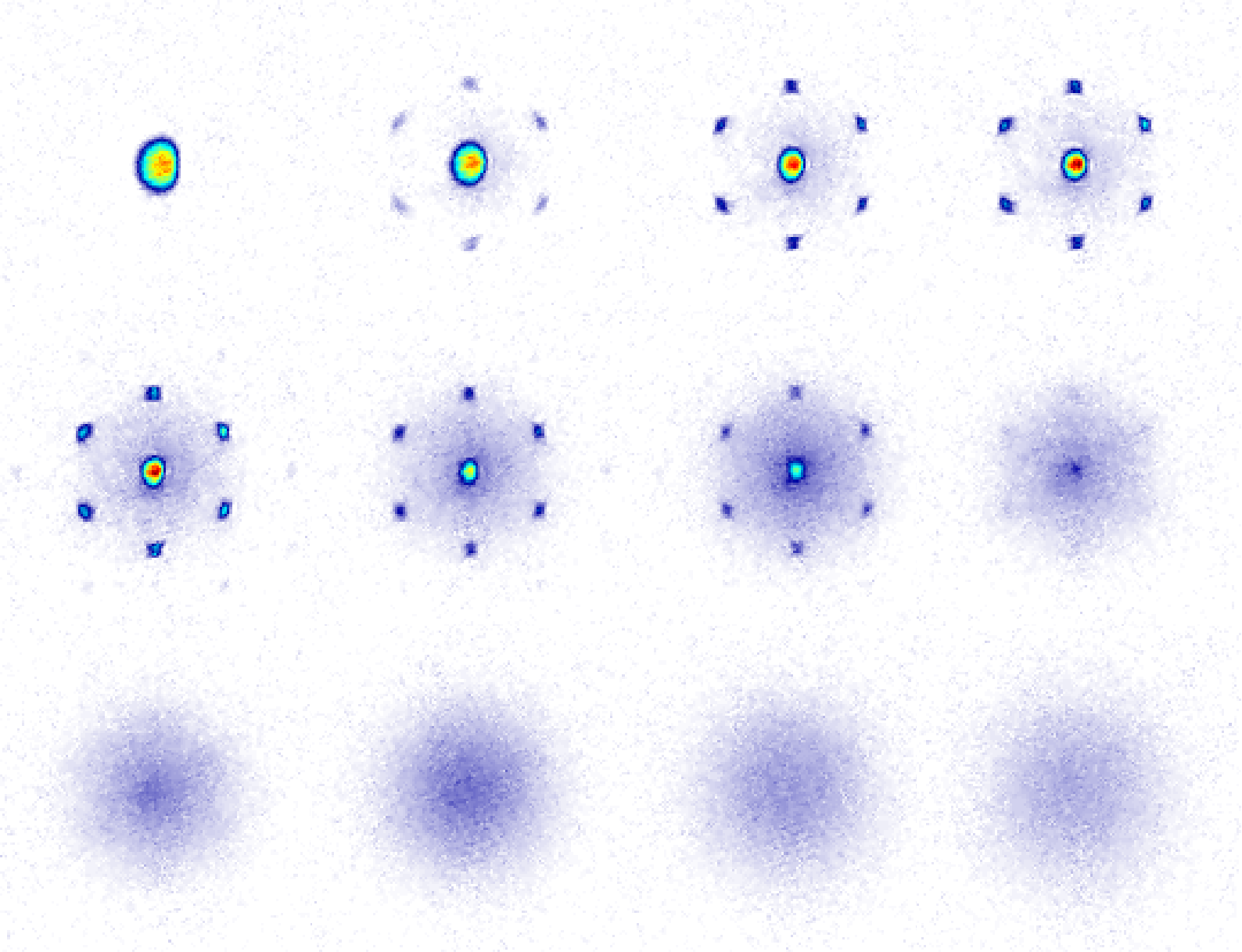


$U>>J$: Mott insulator

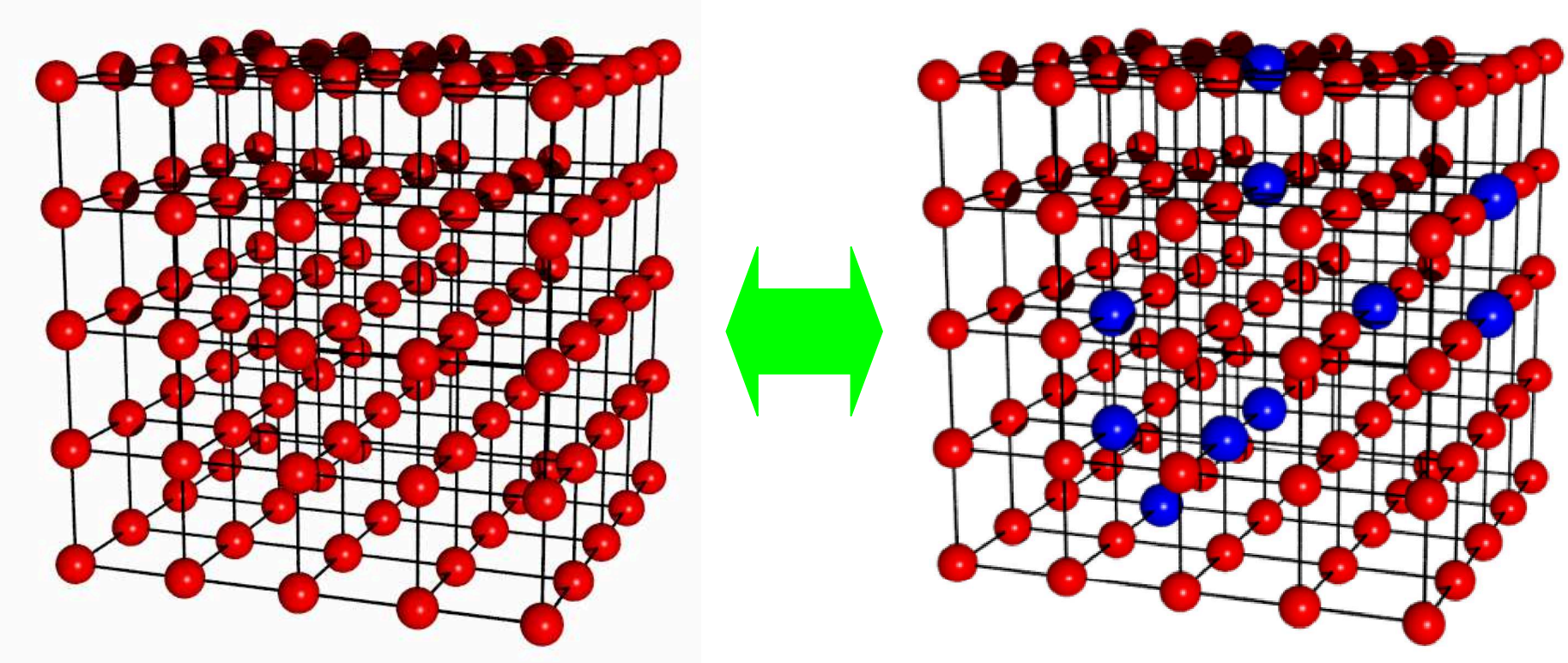


First observed by: M. Greiner et al., Nature **415**, 39 (2002)

Triangular Lattice Geometry



A New System in a 3D Optical Lattice



^{87}Rb $\Leftrightarrow$ ^{40}K/^{87}Rb Fermi-Bose mixture

Additional harmonic confinement for a lattice with 25 E_R depth:

ν_{rad} ~ 250 Hz
ν_{ax} ~ 200 Hz

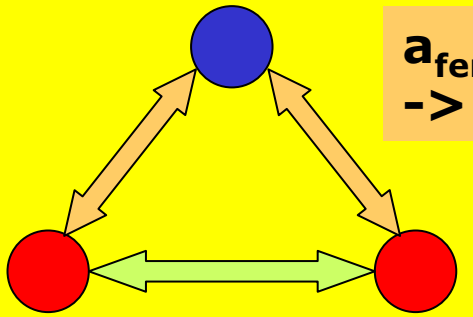
mass scaling

$$\nu_K = \sqrt{\frac{87}{40}}\nu_{Rb}$$

$$E_r(K) = \frac{87}{40} E_R(Rb)$$

Interactions in ^{40}K ^{87}Rb Fermi Bose Mixtures

Fermi-Bose Mixture

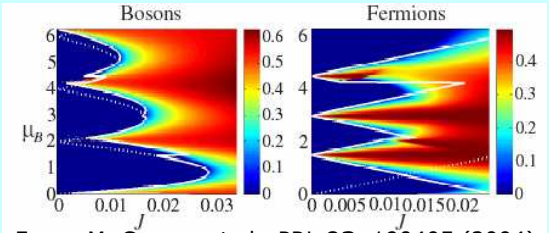


$a_{fermi\text{-}bose} \sim -205\ a_B$
-> attractive (tunable)

$a_{bose\text{-}bose} \sim +99\ a_B$
-> repulsive

Fermi Bose Mixtures

Mott transition



From: M. Cramer et al., PRL **93**, 190405 (2004)

CDW

Supersolid

Polarons

Glass phases

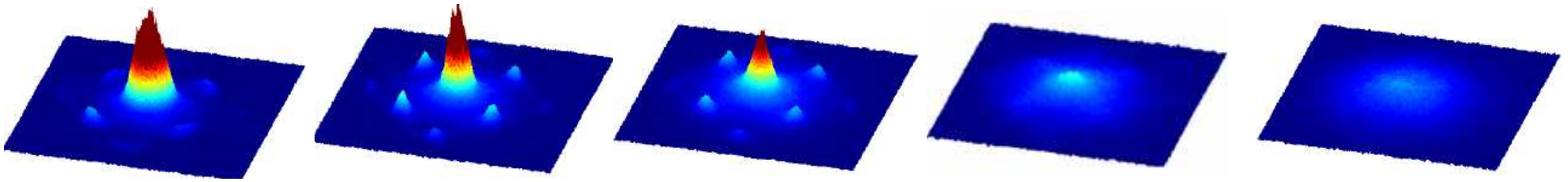
...

Boson mediated superfluidity

Composite fermions

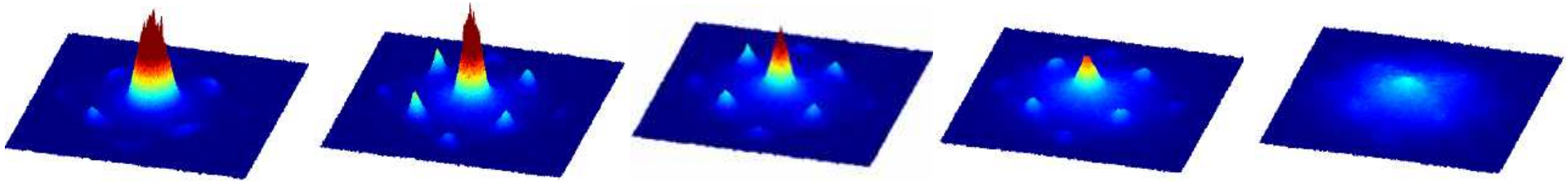
"Bosonic Mott Insulator" with Fermions

Fermi Bose mixture



5 E_R 10 E_R 15 E_R 20 E_R 25 E_R

Bosons only



5 E_R 10 E_R 15 E_R 20 E_R 25 E_R

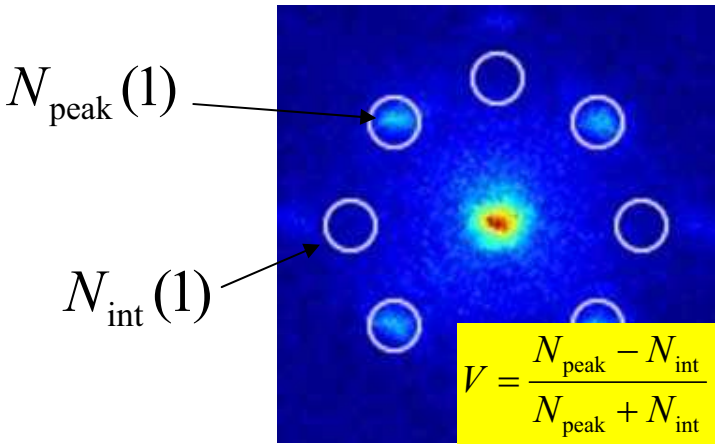
SHIFT OF THE TRANSITION !

Phys. Rev. Lett. 06

Similar observations at ETH Zürich, Phys. Rev. Lett. 06

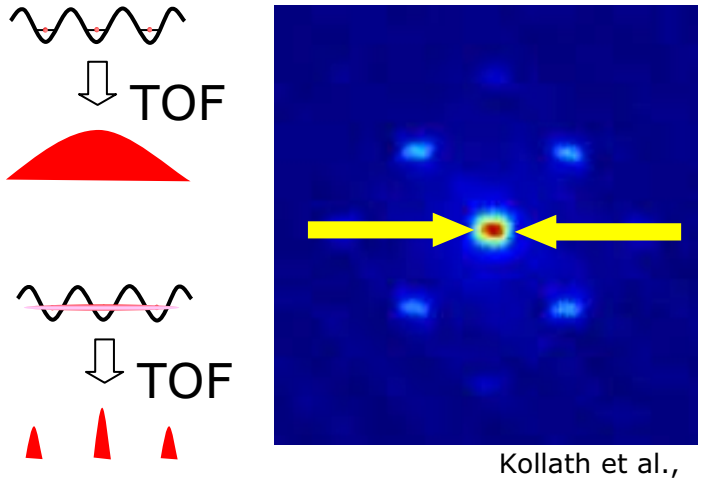
Quantification of the Shift

Visibility

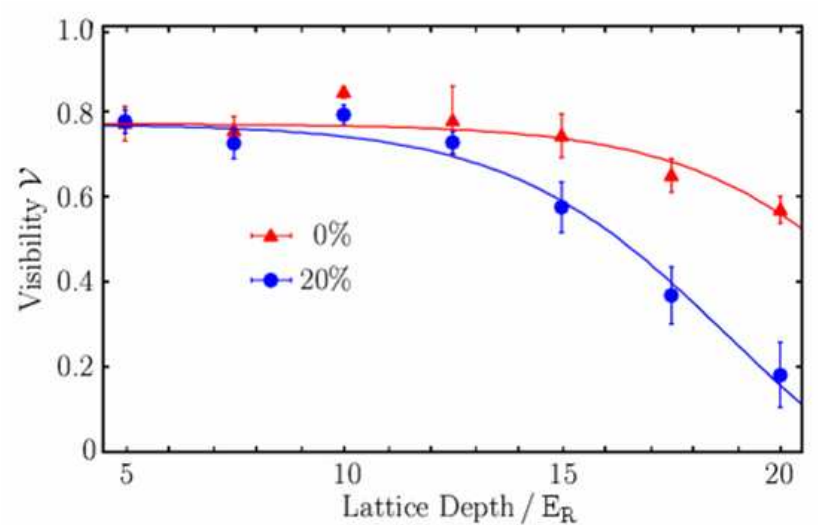


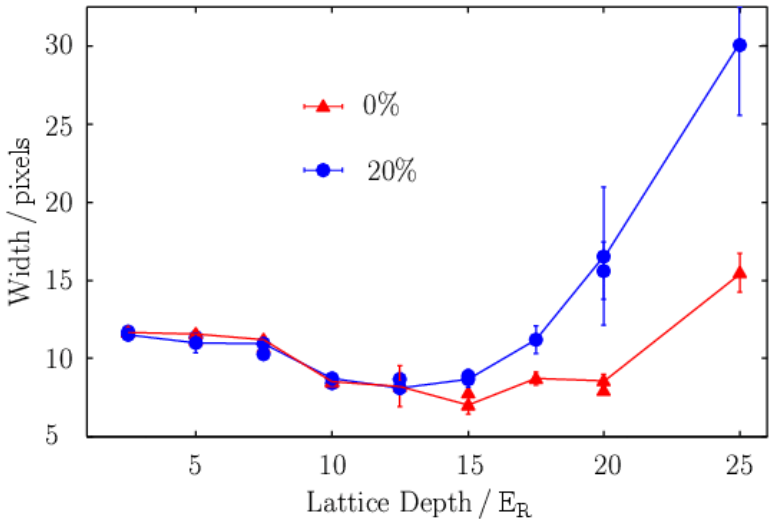
Widera et al,
PRA 72, 053606 (2005)

"Coherence Length"



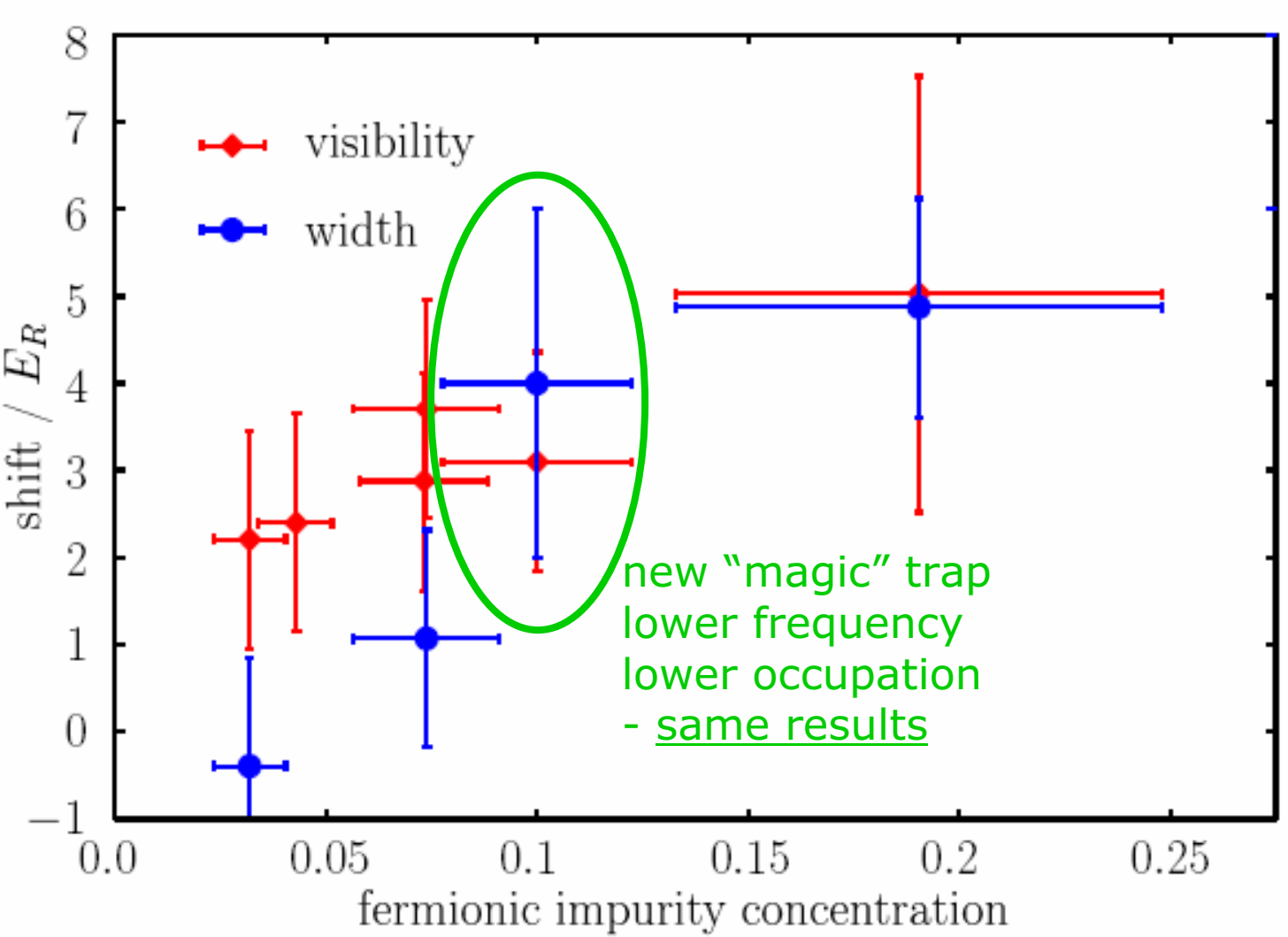
Kollath et al.,
PRA **69**, 031601(R) (2004)





Localized Fermi Bose Phase

Central result: Impurity dependent shift of the localization transition



MI Shift in Bose-Fermi Hubbard Model

Bose-Fermi Hubbard Hamiltonian (in **single band** approximation):
M. Cramer et al., PRL **93**, 190405 (2004)

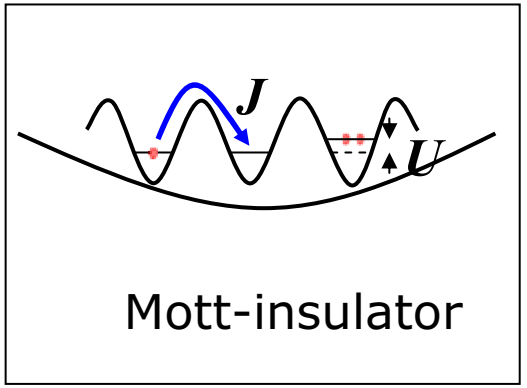
$$\hat{H} = -\sum_{\langle i,j \rangle} \left(J_B \hat{b}_i^+ \hat{b}_j + J_F \hat{f}_i^+ \hat{f}_j + h.c. \right) + U_{BF} \sum_i \hat{n}_B^i \hat{n}_F^i$$
$$+ U_{BB} \sum_i \hat{n}_B^i \left(\hat{n}_B^i - 1 \right) + \sum_i \hat{n}_B^i \tilde{V}_B^i + \sum_i \hat{n}_F^i \tilde{V}_F^i$$

const. const. const.

Maximum mean field effect for largest possible, i.e. unity fermion filling

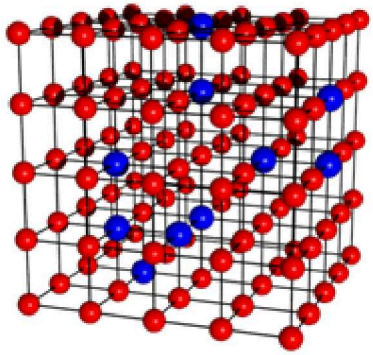
➔ Bose Hubbard Hamiltonian

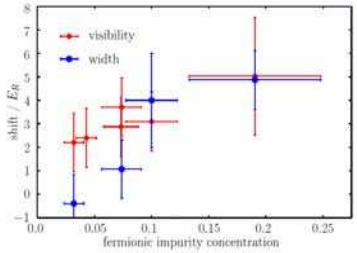
➔ no shift expected to first order!



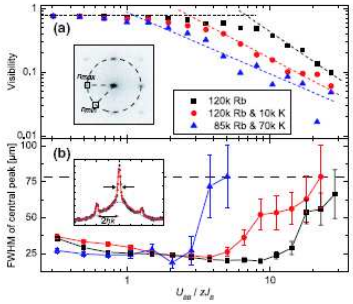
Experimental Observations

^{40}K ^{87}Rb Fermi-Bose mixtures



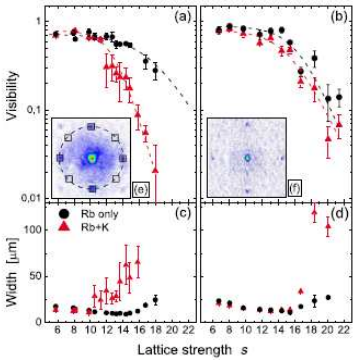


Hamburg
PRL **96**, 180403 (2006)



ETH Zürich
PRL **96**, 180402 (2006)

^{39}K ^{87}Rb Bose-Bose mixture



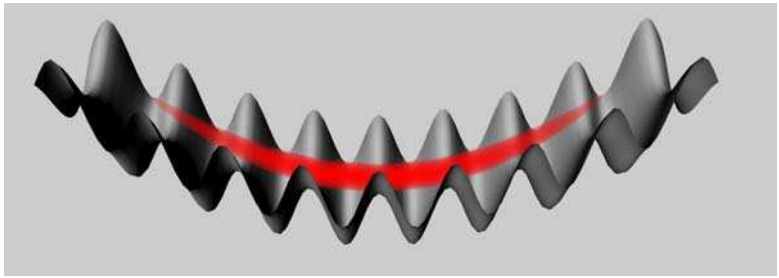
LENS, Florence
PRA **77**, 011603 (2008)

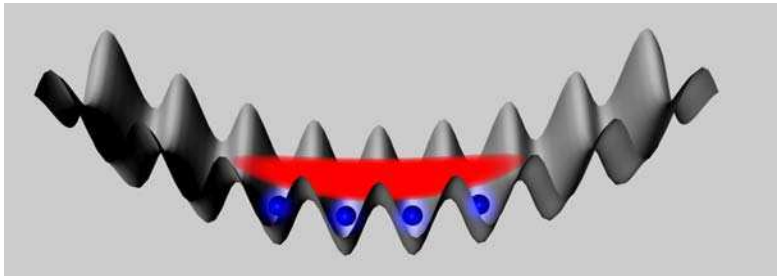
maximum shift ~ 5E_r

What is the origin of this shift ???

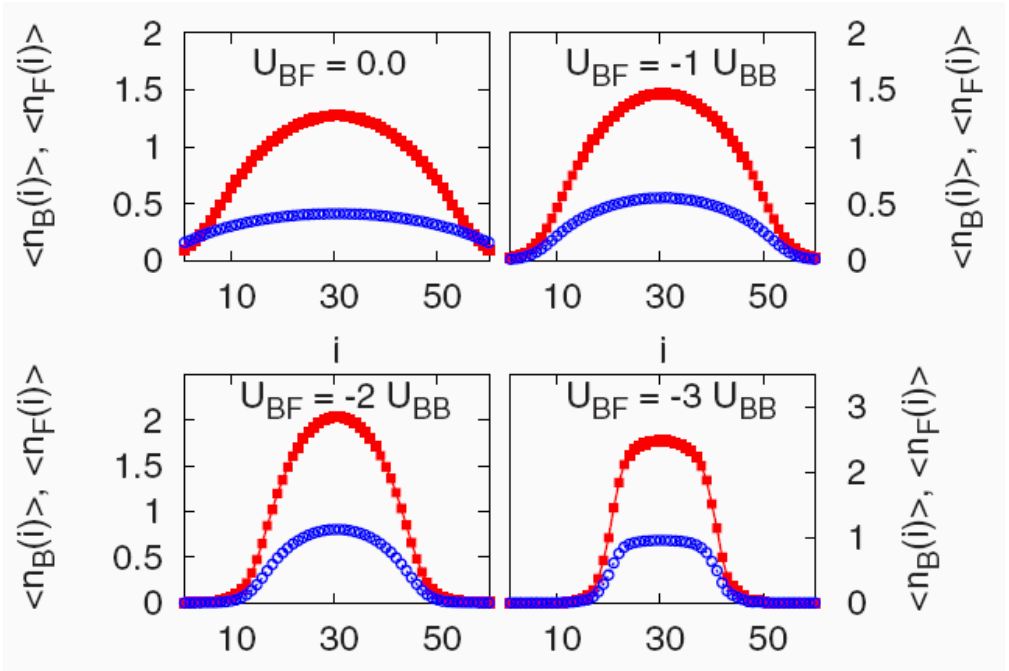
Influence of the Trap ?

Within lattice and harmonic trapping potential:
- Fermions in center of cloud (1/lattice-site)
- attractive interaction
-> increase of bosonic density





"exact" DMRG, QMC calculations (single band?)



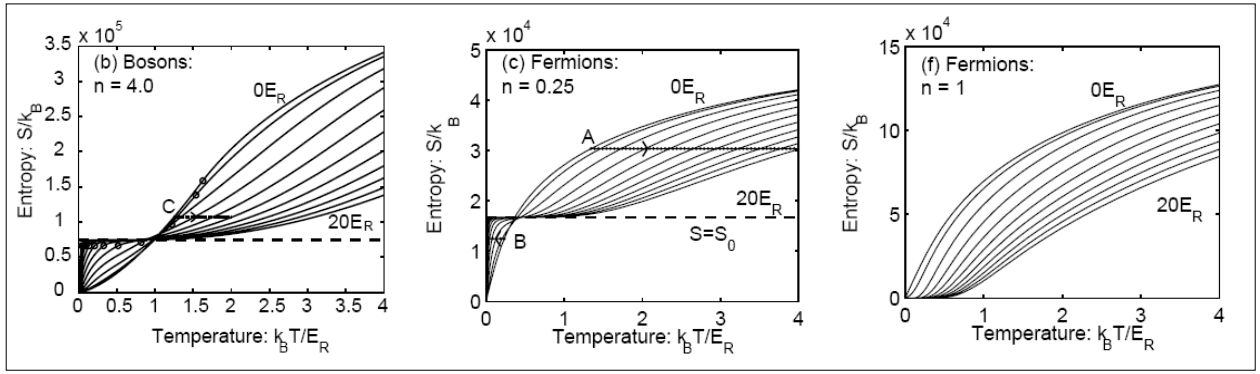
L. Pollet, C. Kollath, U. Schollwöck, and M. Troyer,
PRA 77, 023608 (2008)

-> Fermi-Bose interaction should lead to a shift in the **opposite** direction!

Thermodynamics?

Cooperation with J. Eisert and M. Cramer

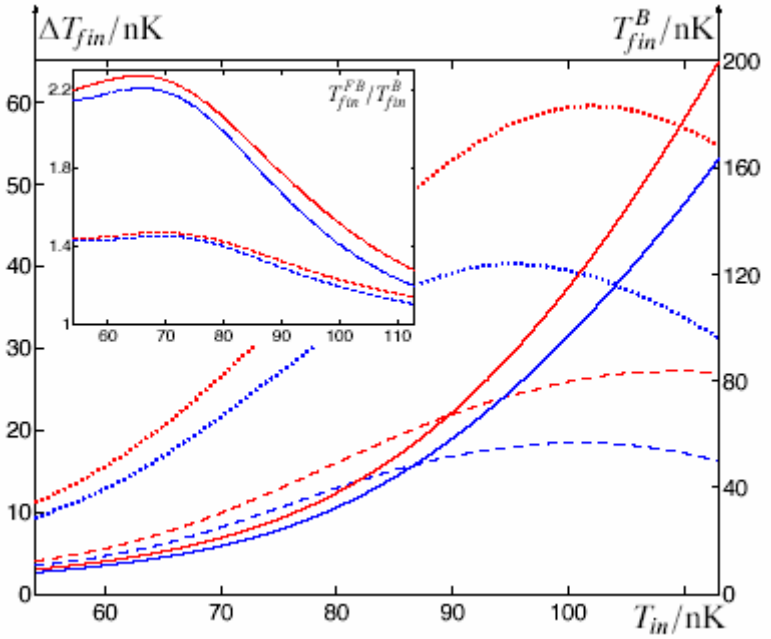
- **argument:** adiabatic lattice ramp → change in temperature due to change in density of states



P.B. Blakie et. al., Laser Physics **17**, 198 (2007)., see also T.L. Ho et al. (2007), ...

- **calculations for our lattice potential and Bose-Fermi mixture (work by J. Eisert, M. Cramer)**

  M. Cramer, S. Ospelkaus, C. Ospelkaus, K. Bongs, K. Sengstock, J. Eisert, Phys. Rev. Lett. **100**, 140409 (2008)

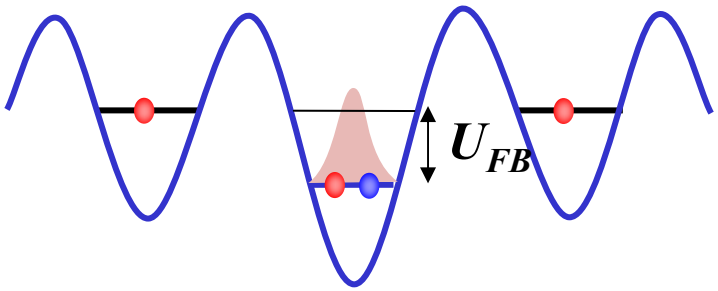


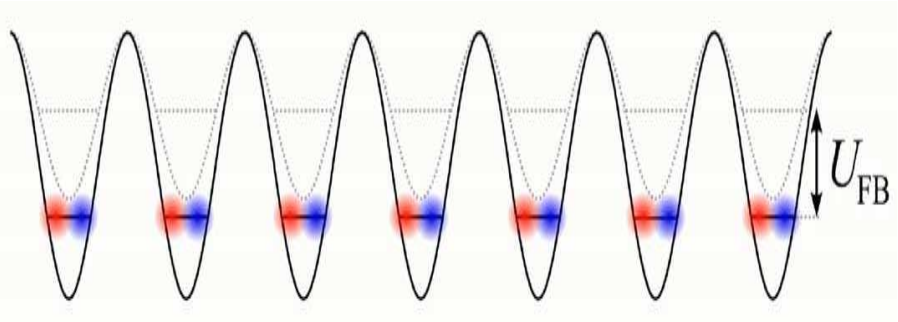
→cooling, even of mixture, BUT: T (mixture) > T (Bosons only)

→ effect on coherence not yet fully clear!

Effective Potential ?

"Intuitive" picture:





Fermi-Bose interaction matrix element from Fermi-Bose Hubbard model
(Albus et al., PRA **68**, 023606 (2003))

Interactions using wavefunctions from lowest band approximation:

$$U_{\mathrm{FB}} = \frac{2\pi\hbar^2 a_{\mathrm{FB}}}{\mu} \int d^3x \, w_{\mathrm{F}}^2(x) w_{\mathrm{B}}^2(x) \approx 1.1 E_r^{\mathrm{Rb}} \qquad @ \; V_{\mathrm{lat}} \sim 15 \, E_r$$

reduced mass $\mu = \dfrac{m_{\mathrm{Rb}} m_{\mathrm{K}}}{m_{\mathrm{Rb}} + m_{\mathrm{K}}}$

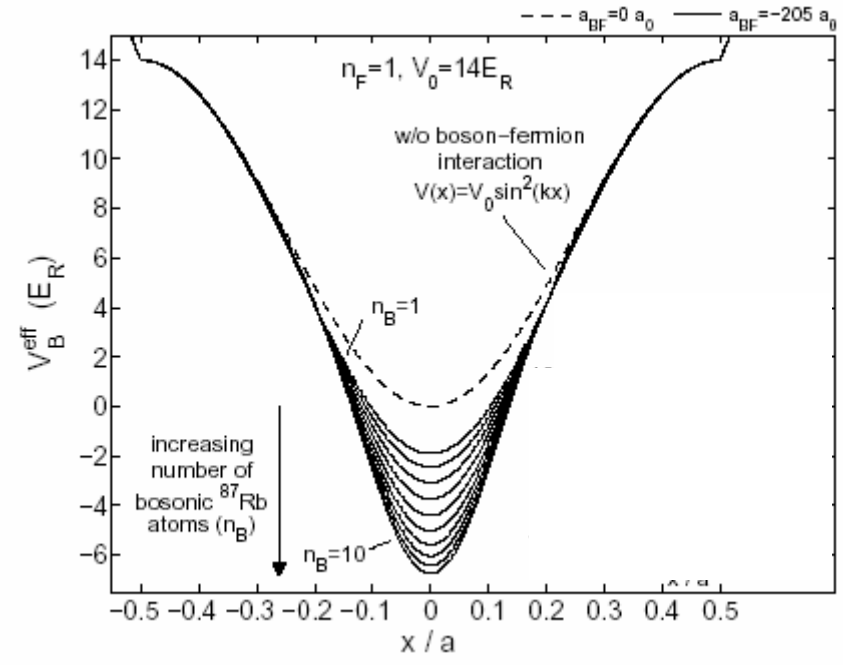
compare to shift of ~ 5 E_r

Multi Band Effects ?

Study of small systems via exact diagonalization

Cooperation with D. Pfannkuche et al.

Main result:
wave functions are strongly deformed for attractive interaction!
("admixture of higher bands")



attractive interaction

→ deformation of effective potential

→ reduced hopping and stronger on-site interaction

→ ‚shift' in MI-transition!!

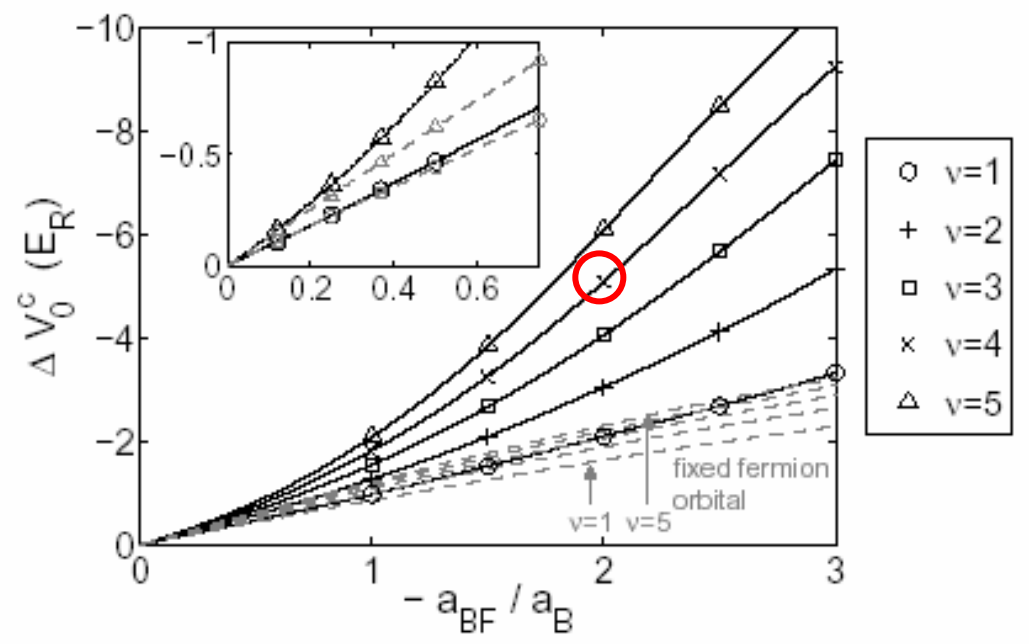
D.-S. Lühmann, K. Bongs, K. Sengstock, and D. Pfannkuche, cond-mat/0711 2975

Multi Band Effects 2

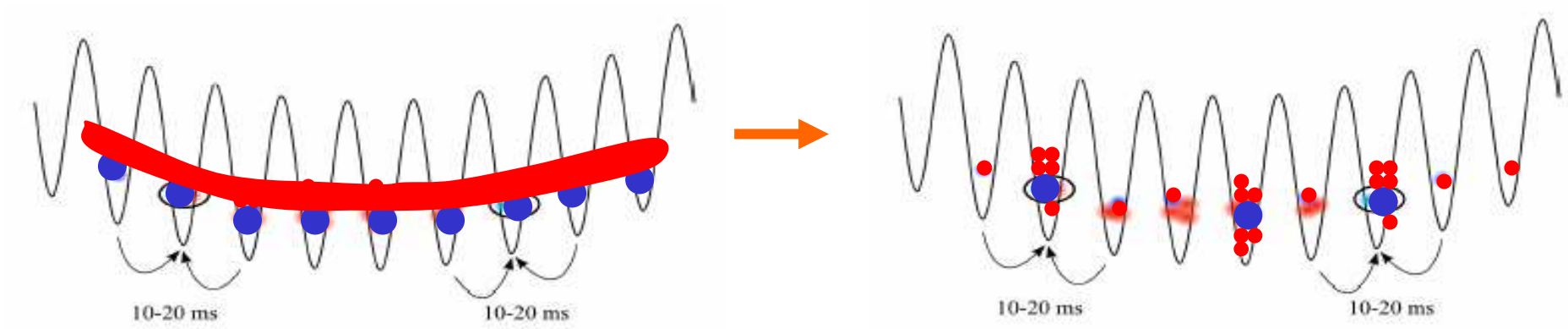
Cooperation with D. Pfannkuche et al.

attractive interaction

→ deformation of
effective potential
→ reduced hopping and
stronger on-site interaction
→ ‚shift' in MI-transition!!



Also: self-trapping of fermions and bosons
(one Fermion can attract up to 6 Bosons! → Polaron-like behaviour)



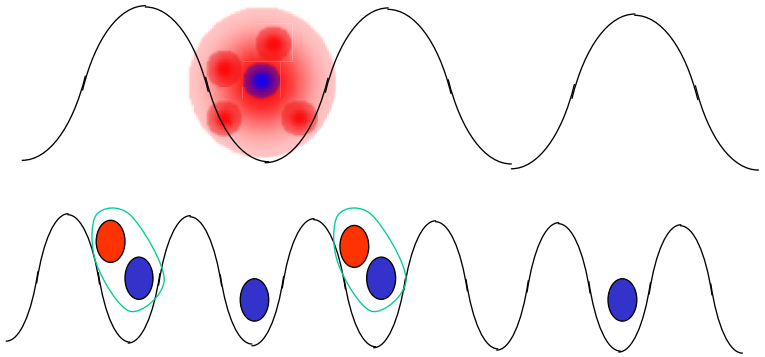
Trapping scenarios ?

Polaron-like dressing of fermions

L. Mathey, et al., PRL **93**, 1204040 (2004).
M. Bruderer, et al., PRA **76**, 011605(R) (2007).

Formation of composite fermions

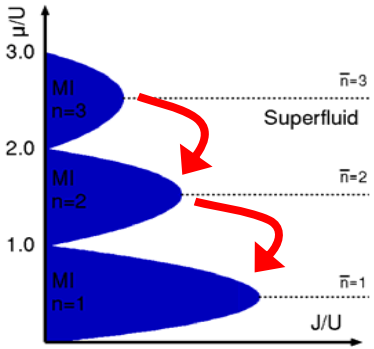
M. Lewenstein et al., PRL **92**, 050401 (2004).



Effects:

1. Depletion of the condensate wavefunction

➔ Incoherent background and shift of 1-3 E_R

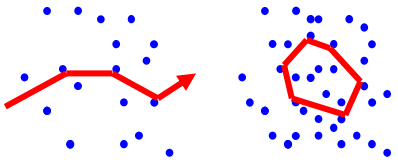


2. Localization of polarons/composites

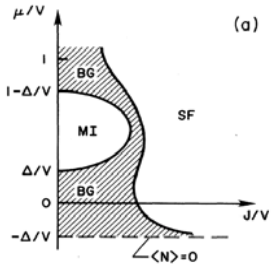
➔Disorder with localized impurities??

Disorder scenarios ?

Fermions act as impurity scatterers

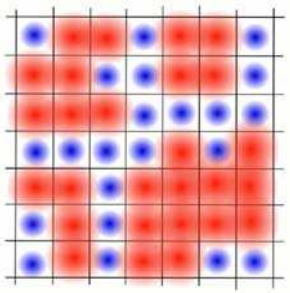


➔ Weak/strong localization,
Bose glass phase,… ? *(Fleischhauer et al.)*



Fisher et al., PRB 40, 546 (1989)

➔ Quantum percolation ?

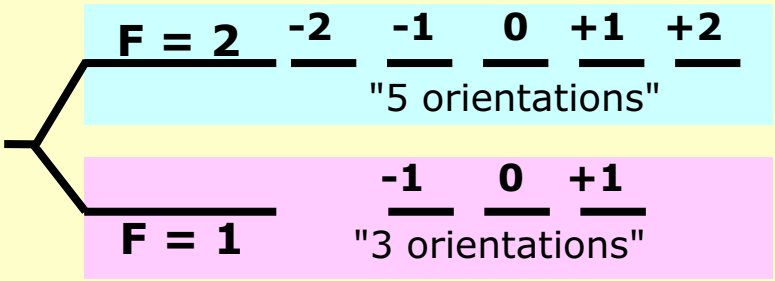


Localization possible for relatively small potential perturbations

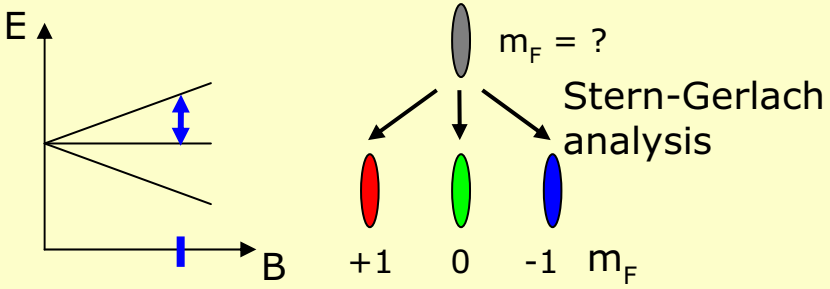
A Different System: Spin Mixtures

Control of the Spin

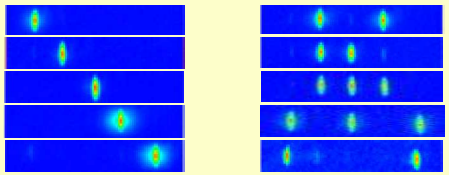
- the system: ^{87}Rb



- magnetic field: Zeeman-shift

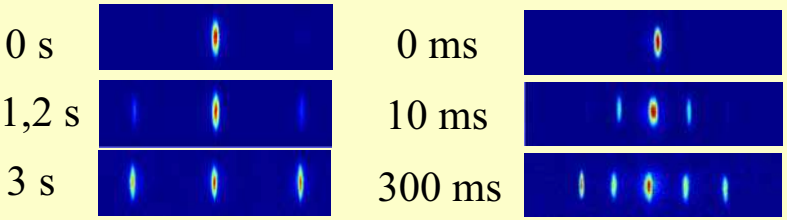


- state preparation using rf fields



Magnetism

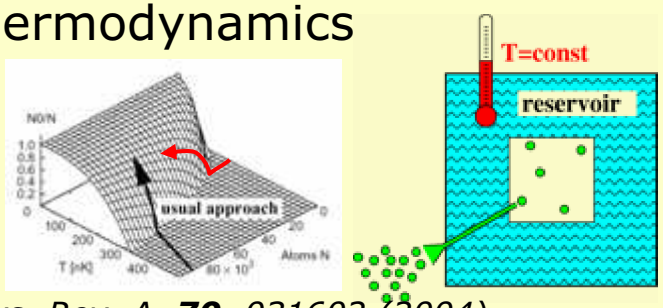
- ground states



F=1 ferromagnetic F=2 antiferromagnetic

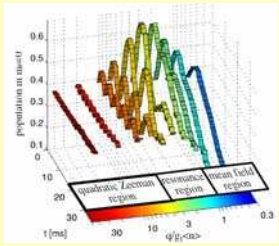
Phys. Rev. Lett. 92, 040402 (2004)
Phys. Rev. Lett. 100, 160405 (2008)

- thermodynamics



*Phys. Rev. A **70**, 031602 (2004)*

- coherent dynamics



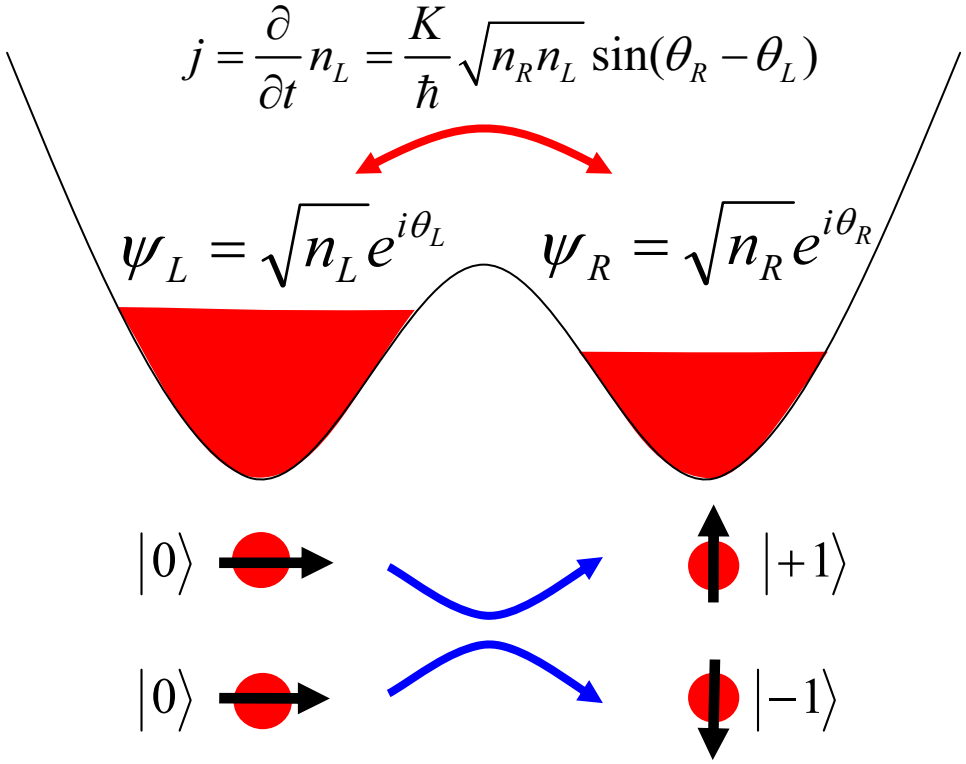
PRA 72, 063619 (2005)
PRA 73, 013629 (2006)
PRL 97, 110404 (2006)

F=1 Spinor BEC and Josephson Junction

$$H = E_L\psi_L^+\psi_L + E_R\psi_R^+\psi_R + H_T$$

$$H_T = K\left(\psi_R^+\psi_L + \psi_L^+\psi_R\right)$$

$$\theta_R - \theta_L = \Delta\theta_0 + \frac{E_L - E_R}{\hbar}t$$



Spinor BEC:

"internal Josephson junction"

with $L \to 00,\ R \to \pm 1$

➔ **Spinor BEC:**
competition of mean field and quadratic Zeeman energy shifts

Mean field

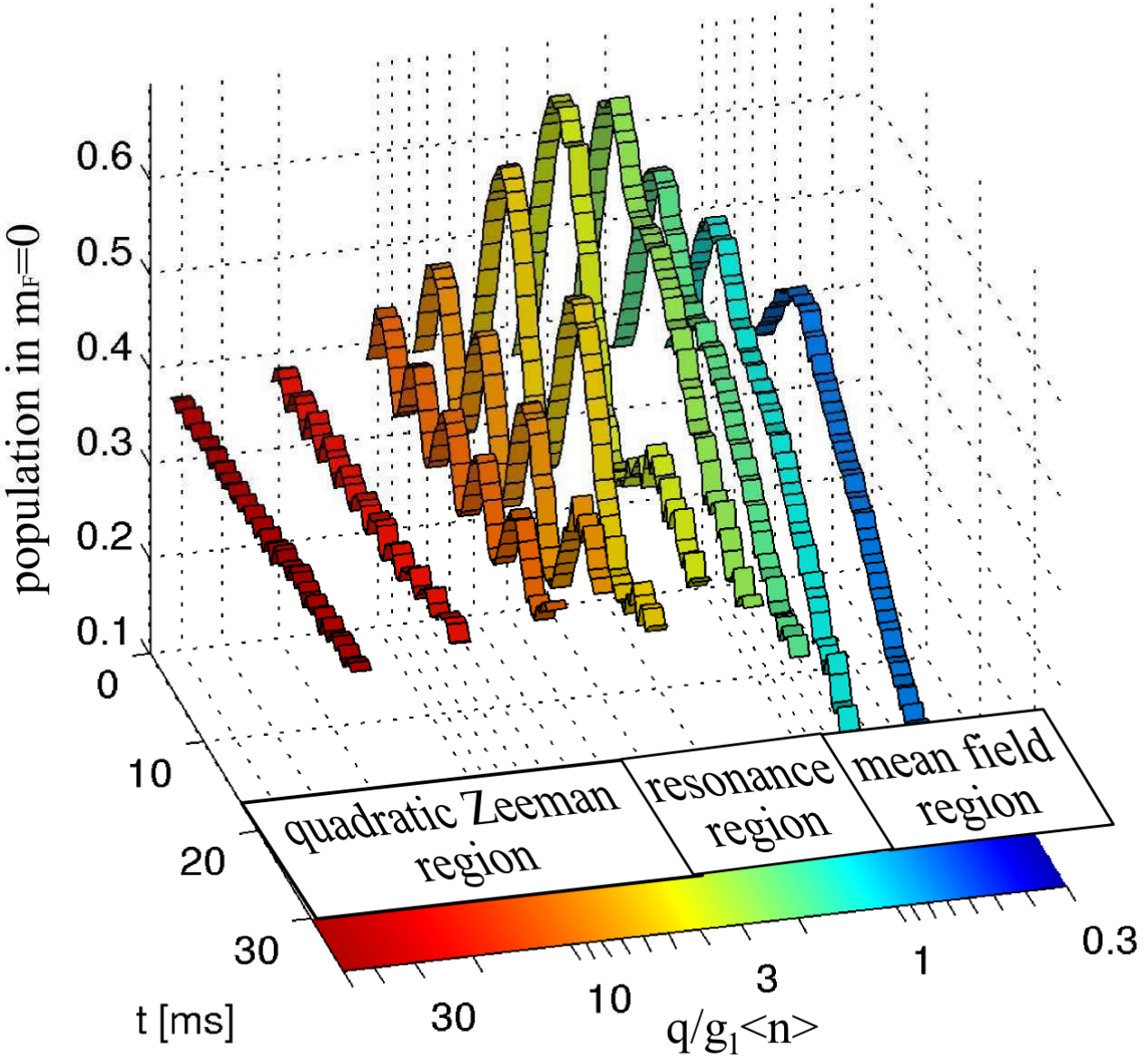
energy ~ population, density & interactions

Quadr. Zeeman

energy ~ B^2
→ tunable!

Resonant Spinor Dynamics

J. Kronjäger et al. Phys. Rev. Lett. **97**, 110404 (2006)

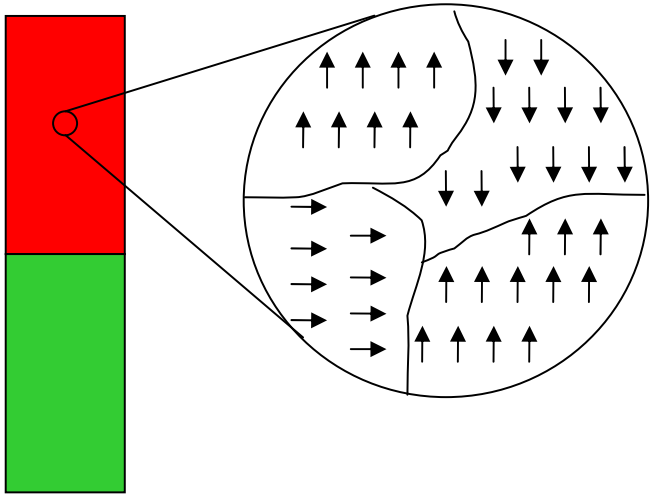


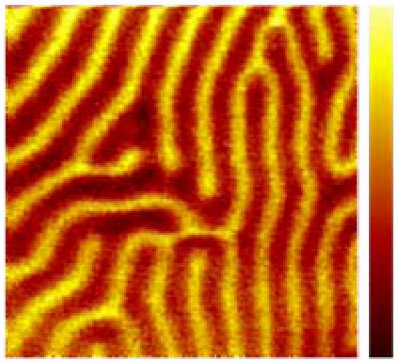
F=1 prediction of the resonance: W. Zhang et al., PRA 72, 013602 (2005)

F=1 observation of quadratic Zeeman regime: J. Kronjäger et al., Phys. Rev. A 73, 013629(2006)

Multimode Phenomena ?

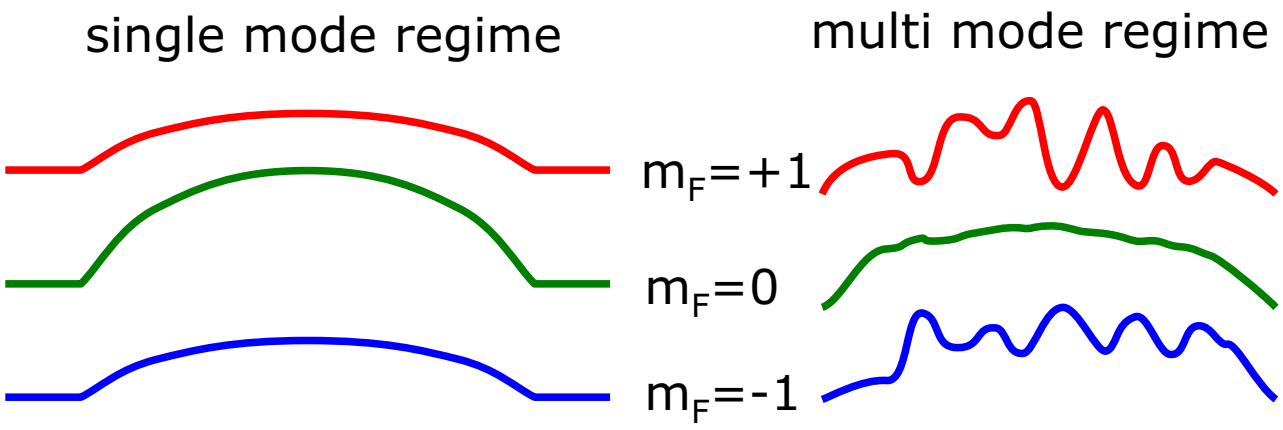
Condensed matter





http://www.kth.se/fakulteter/TFY/cmp/research/microscopy/scanning_examples.html#P5

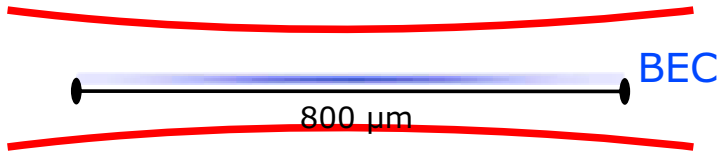
Spinor BEC



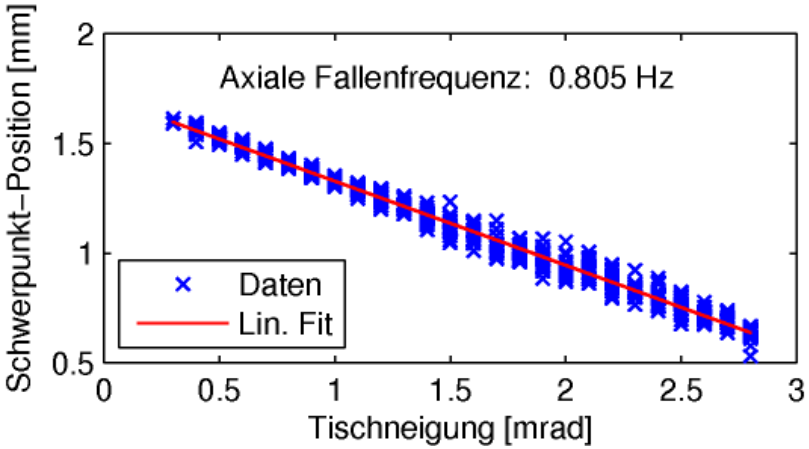
Elongated Bose-Einstein-Condensates

Single beam dipole trap

extremely elongated, quasi-1D BEC



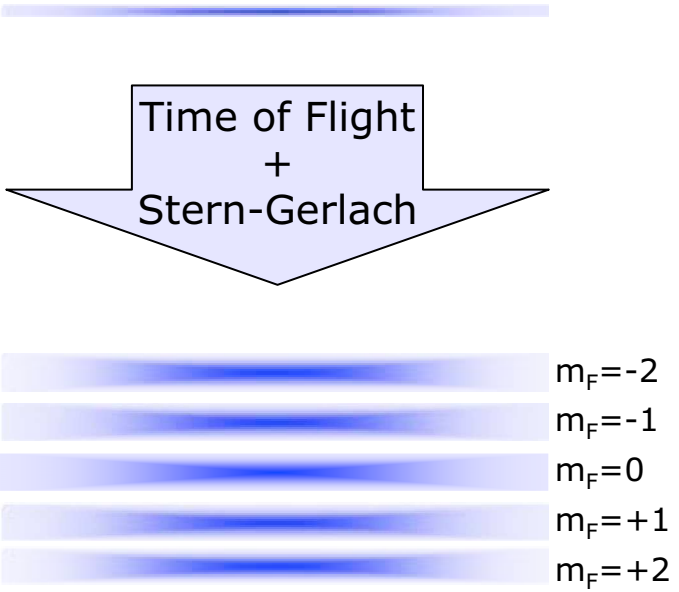
radial trap frequency: 120 Hz



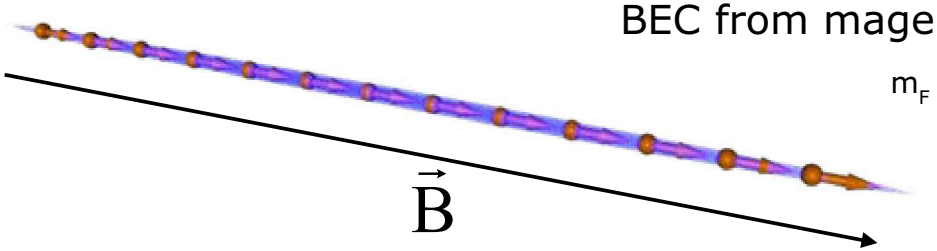
"atomic level"

Stern-Gerlach

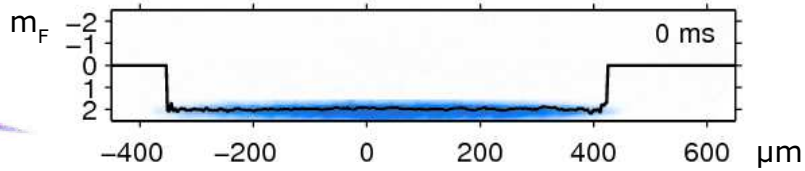
TOF separation of the spin components perp. to long axis

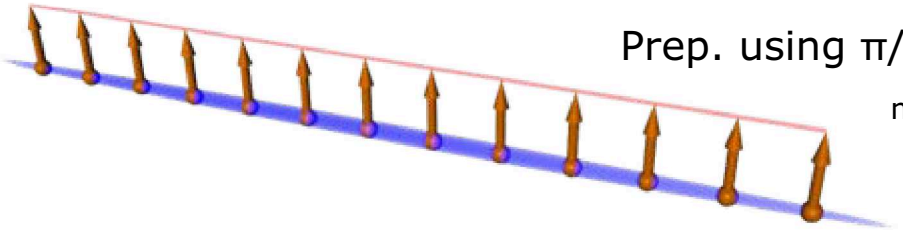


Spatial Ramsey: Phase Twist

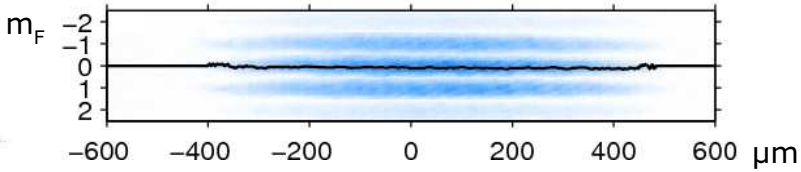


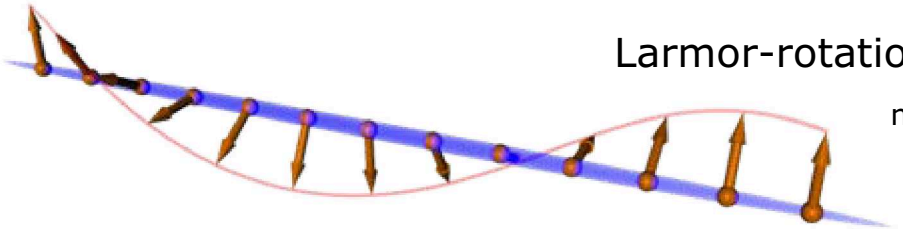
BEC from magentic trap: fully stretched axially



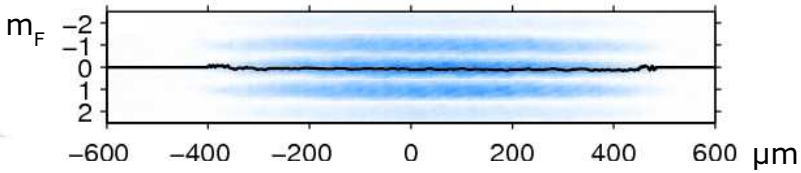


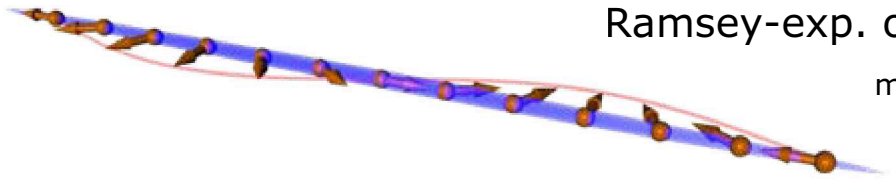
Prep. using π/2-pulse: fully stretched transversally



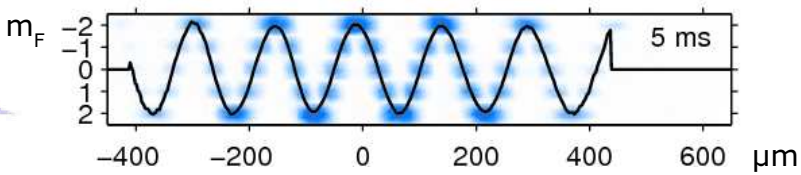


Larmor-rotation with B-field gradient: “twist”



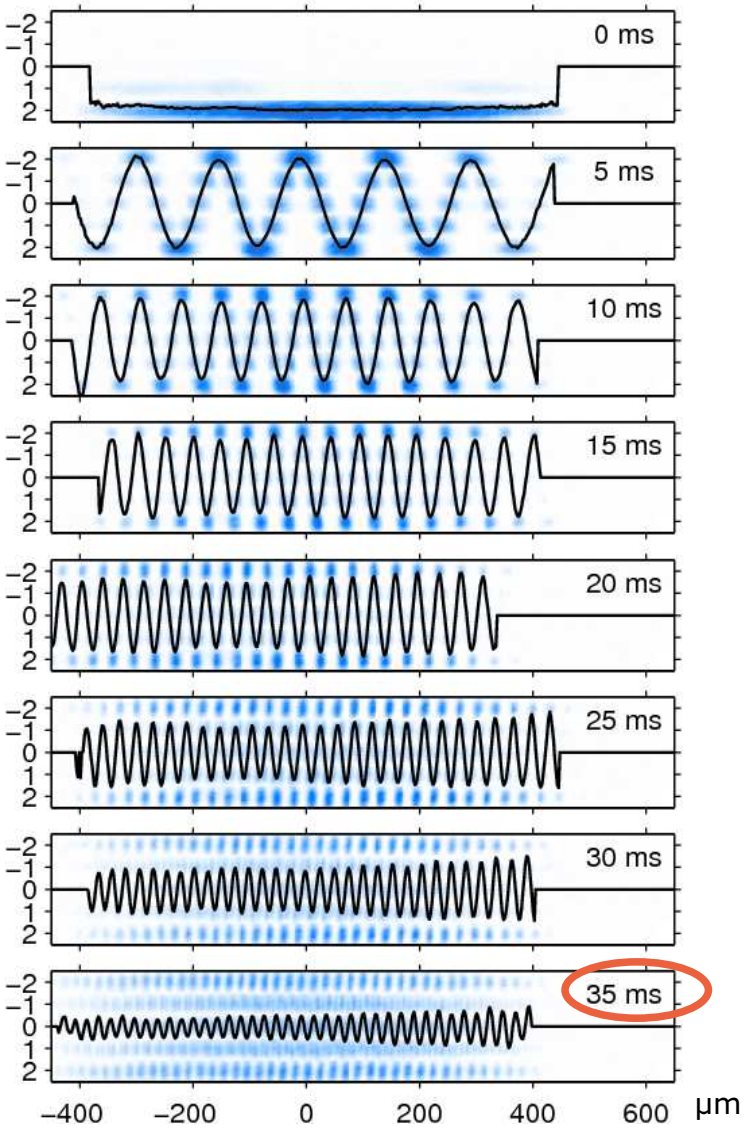


Ramsey-exp. observation: second π/2-pulse

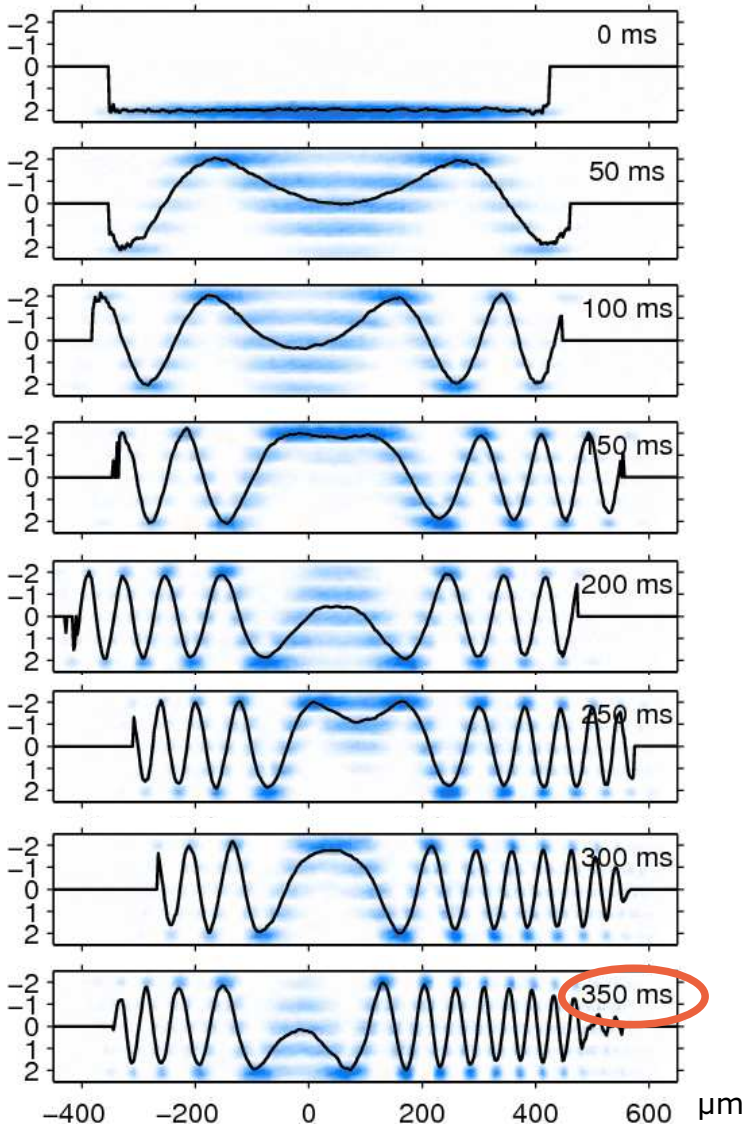


Compensation of Magnetic Field Gradients

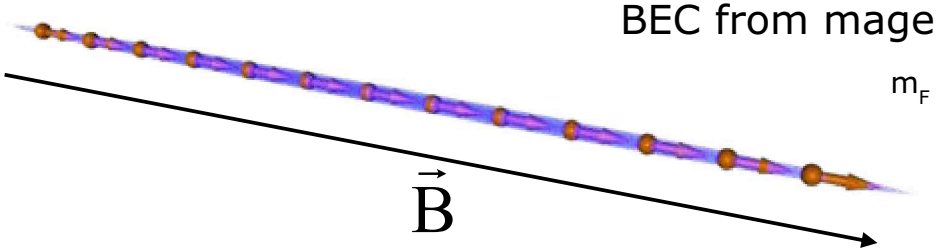
Gradient 1.9 mG/mm
Offset 82 mG
Relative 2.3% / mm



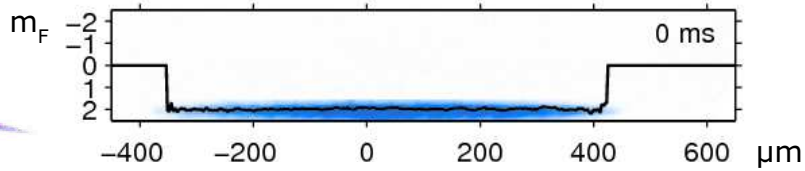
Zero gradient in trap centre
Curvature ~ 0.25 mG/mm^2

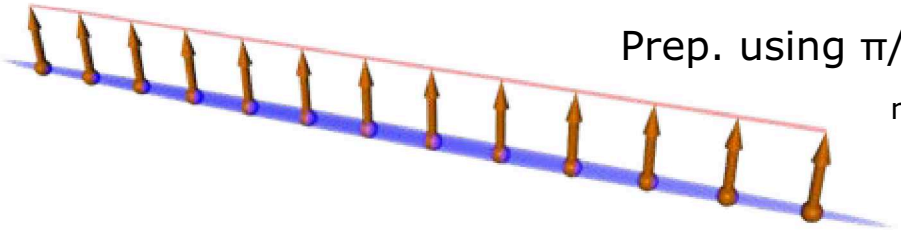


Local Dynamics in Magnetic Fields

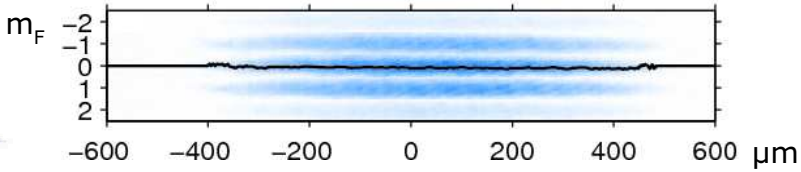


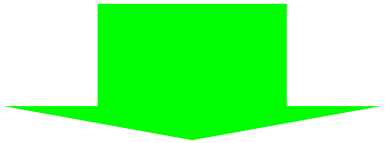
BEC from magentic trap: fully stretched axially





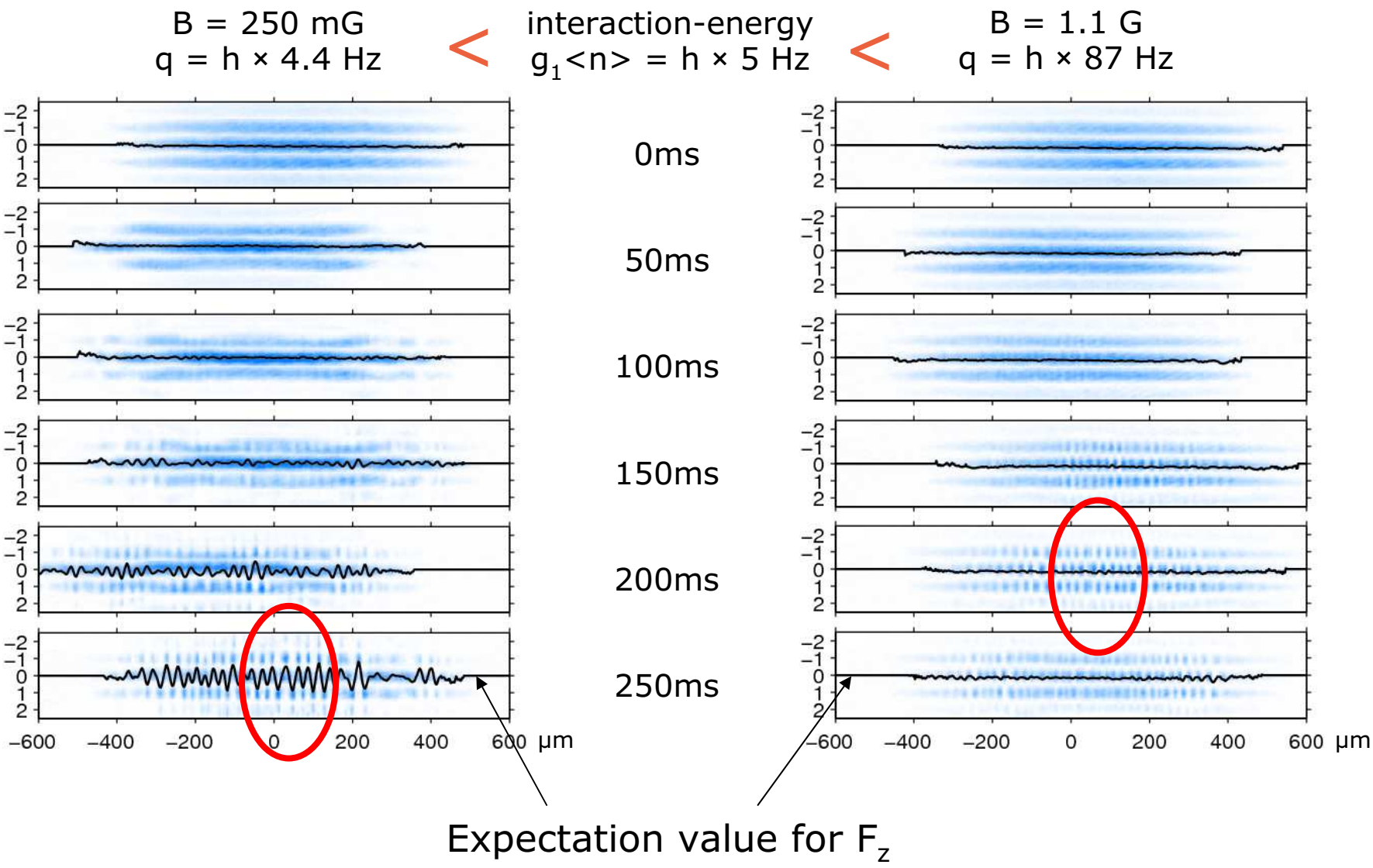
Prep. using π/2-pulse: fully stretched transversally





?

Spontaneous Pattern Formation!



Spontaneous Pattern Formation

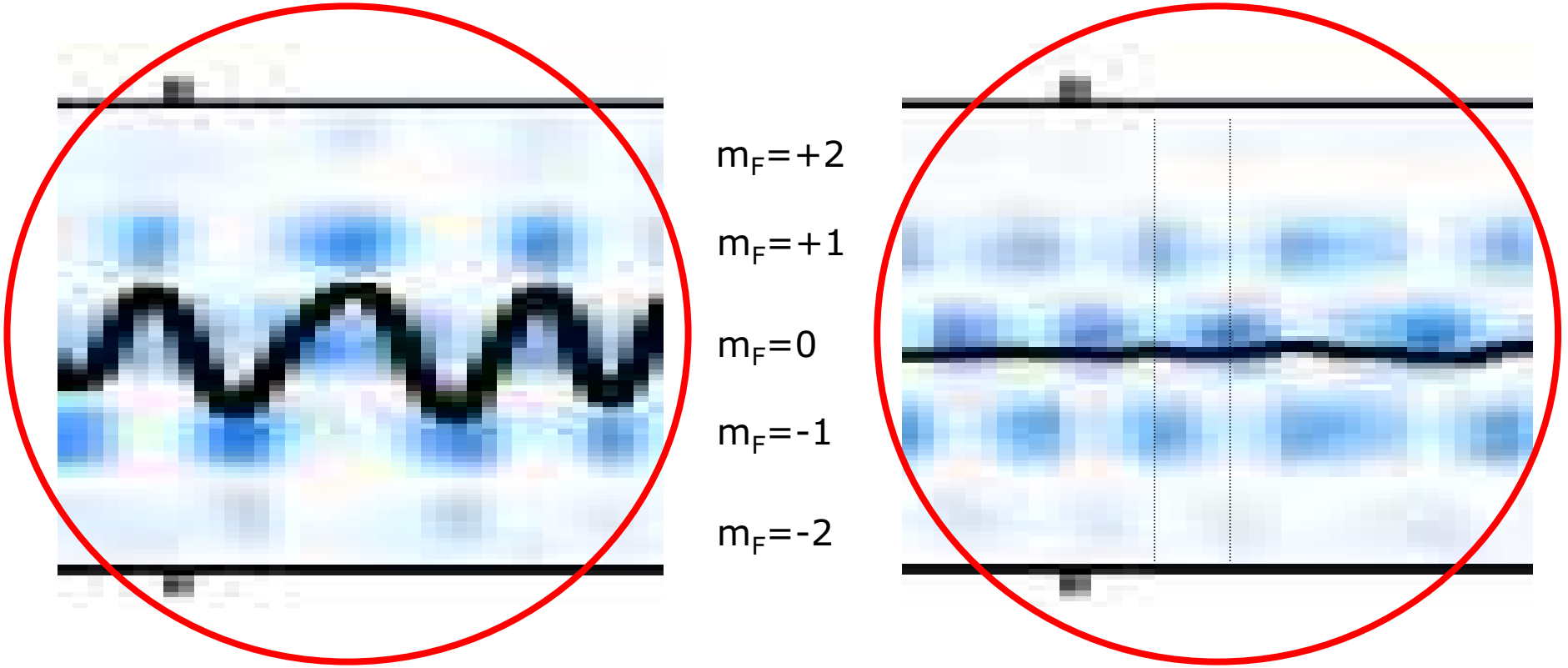
B = 250 mG
q = h × 4.4 Hz

<

Interaction energy
$g_1 \langle n \rangle$ = h × 5 Hz

<

B = 1.1 G
q = h × 87 Hz



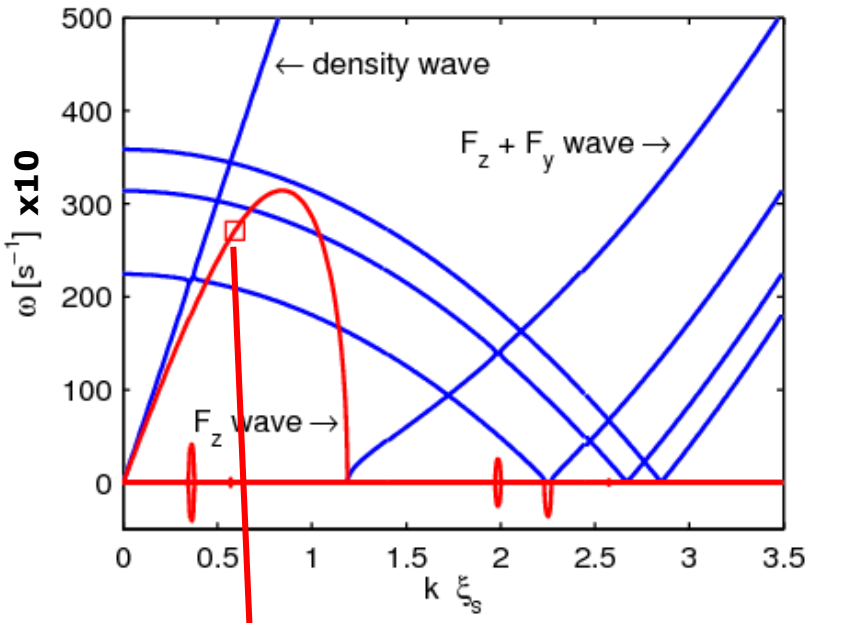
"Spin wave"

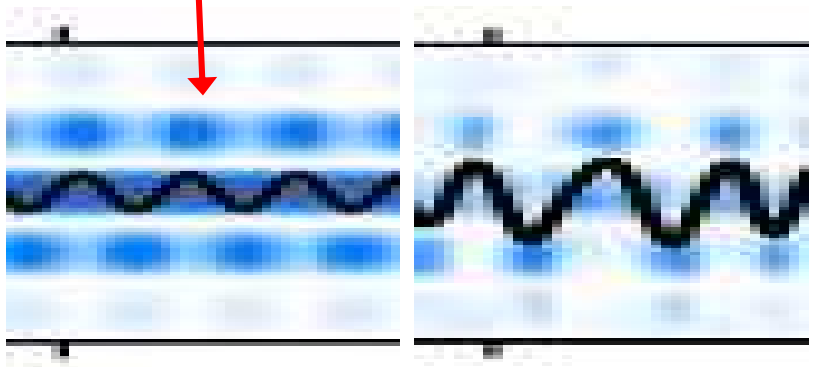
"Composition wave"

Bogoliubov-Simulation Dynamcal Instability

red: unstable modes

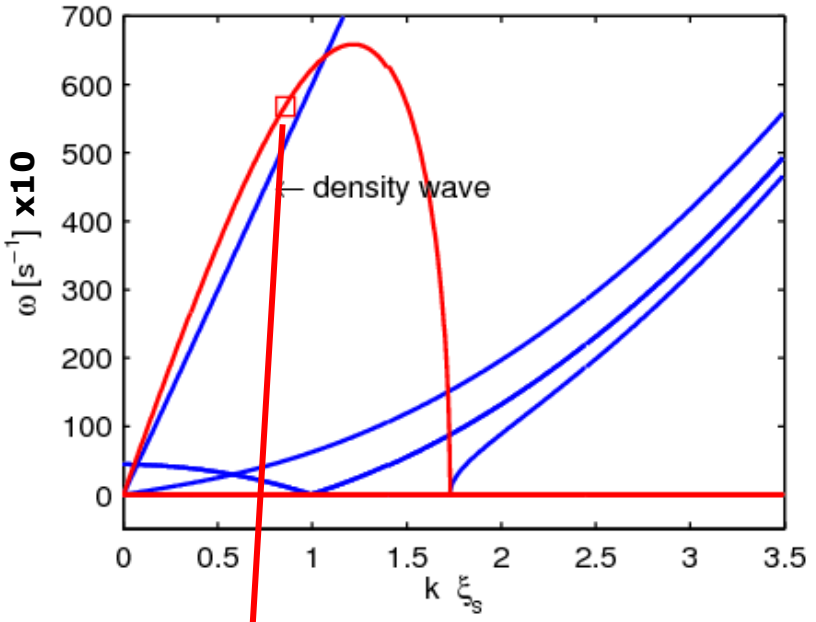
B = 250 mG





Simulation Experiment

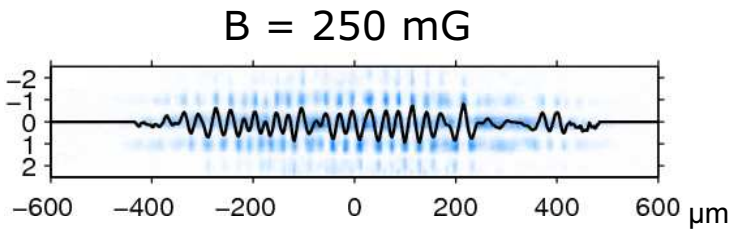
B = 1.1 G

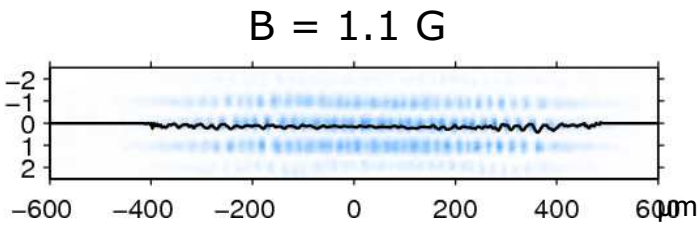


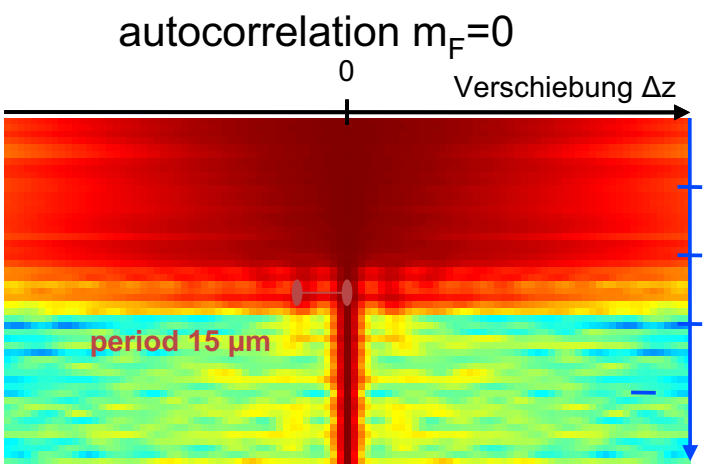
Simulation Experiment

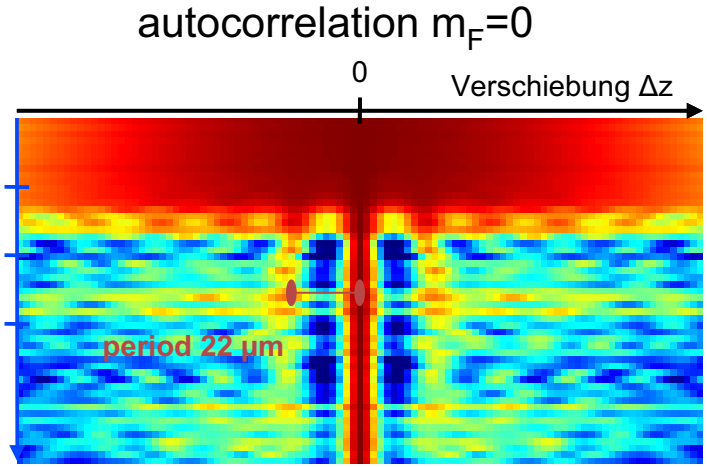
Qualitative agreement!

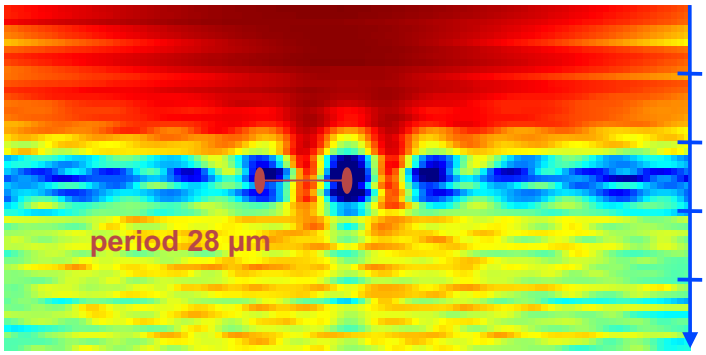
Spontaneous Pattern Formation - Correlations

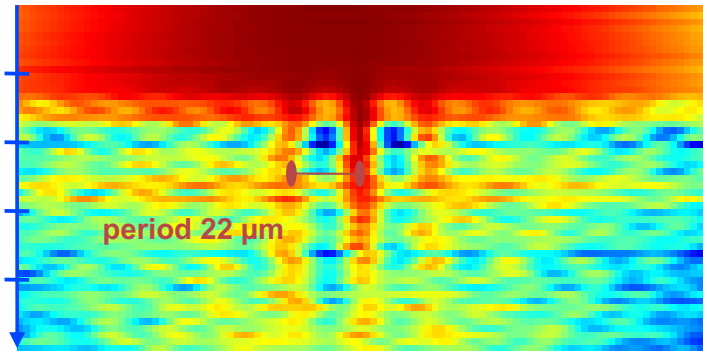


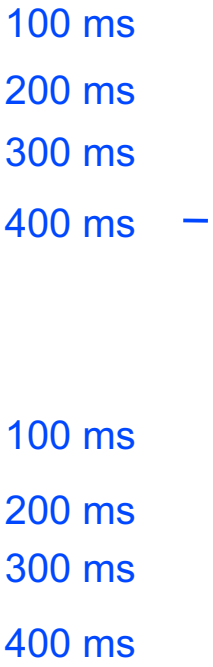


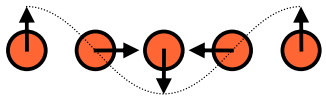


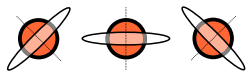








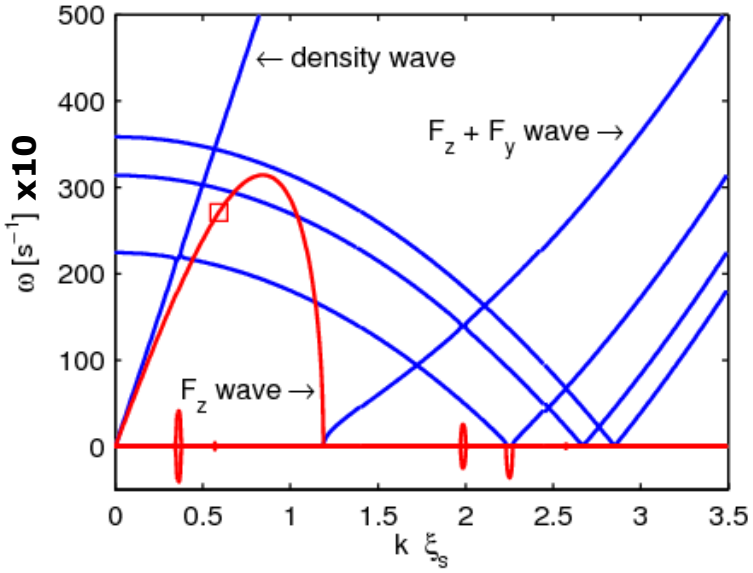




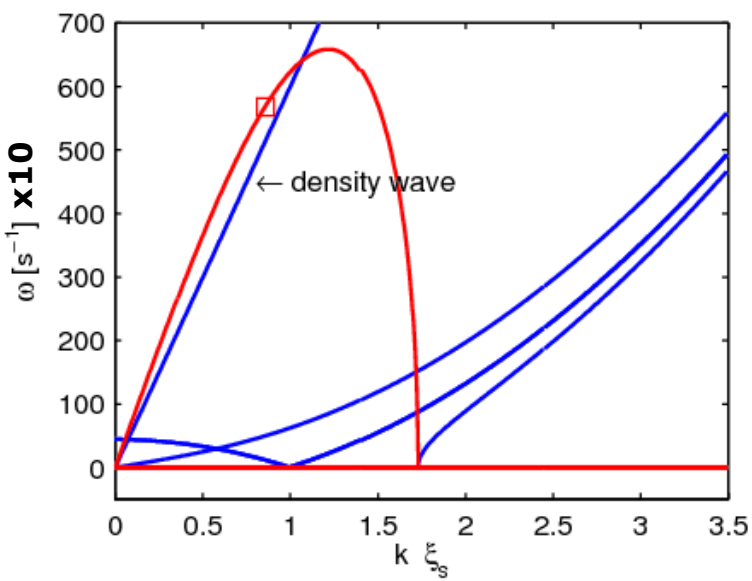
Timescales of Mode Buildup

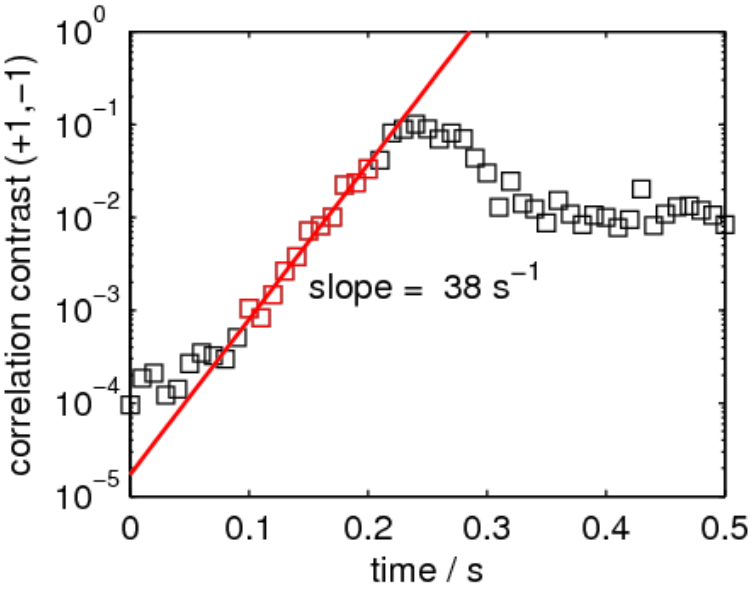
red: unstable modes

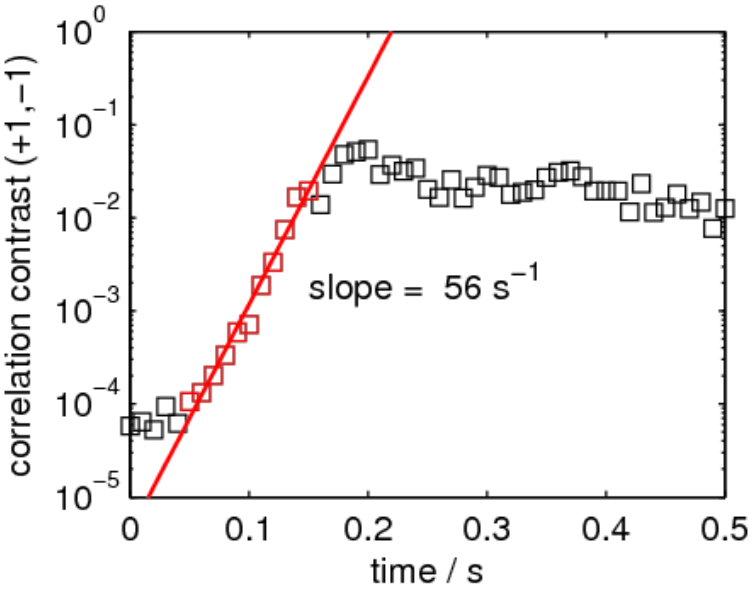
B = 250 mG



B = 1.1 G







Summary and Outlook

Correlations in Fermi-Bose mixtures in an optical lattice

→ "mobile" impurities

→ connections to disorder, polarons, composite fermions?

→ finite temperature effects

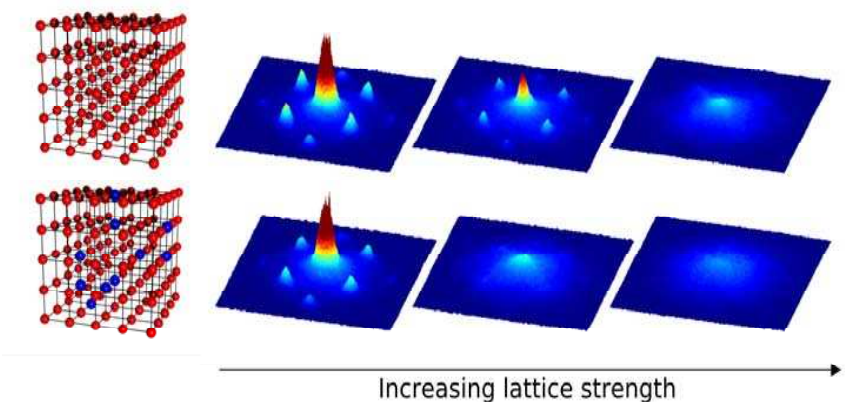
→multi band effects

→ excitations, mobilities

→ Bosons as impurities for Fermions

→ tuning of interactions

→ …



Correlations in Spinor Condensates

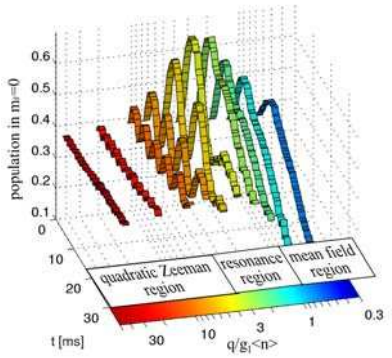
→ resonance spin dynamics

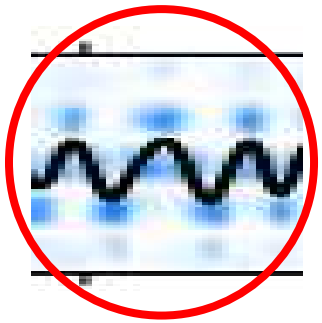
→ spontaneous pattern formation

→ local chaos

→ spins in optical lattices

→ …





The Hamburg Group

Universität Hamburg

K. Sengstock

KB – Quantum Gases

Magnetism in BEC:
Dr. Jochen Kronjäger
Christoph Becker
Parvis Soltan-Panahi
Simon Stellmer
Sören Dörscher
Matthis Baumert

Fermi-Bose mixtures:
Dr. Silke Ospelkaus-Schwarzer
Dr. Christian Ospelkaus
Philipp Ernst
Sören Götze
Carsten Pyka

BEC in space:
Anika Vogel
Nadine Meyer
Alexandra Dwenger
Julian Hofmann

Atom guiding in PCF:
Stefan Vorrath
Sönke Möller

Valery Baev – Laser development

RGB-fiber-lasers:
Ortwin Hellmig
Arnold Stark
Jörg Schwenke
Florian Engel

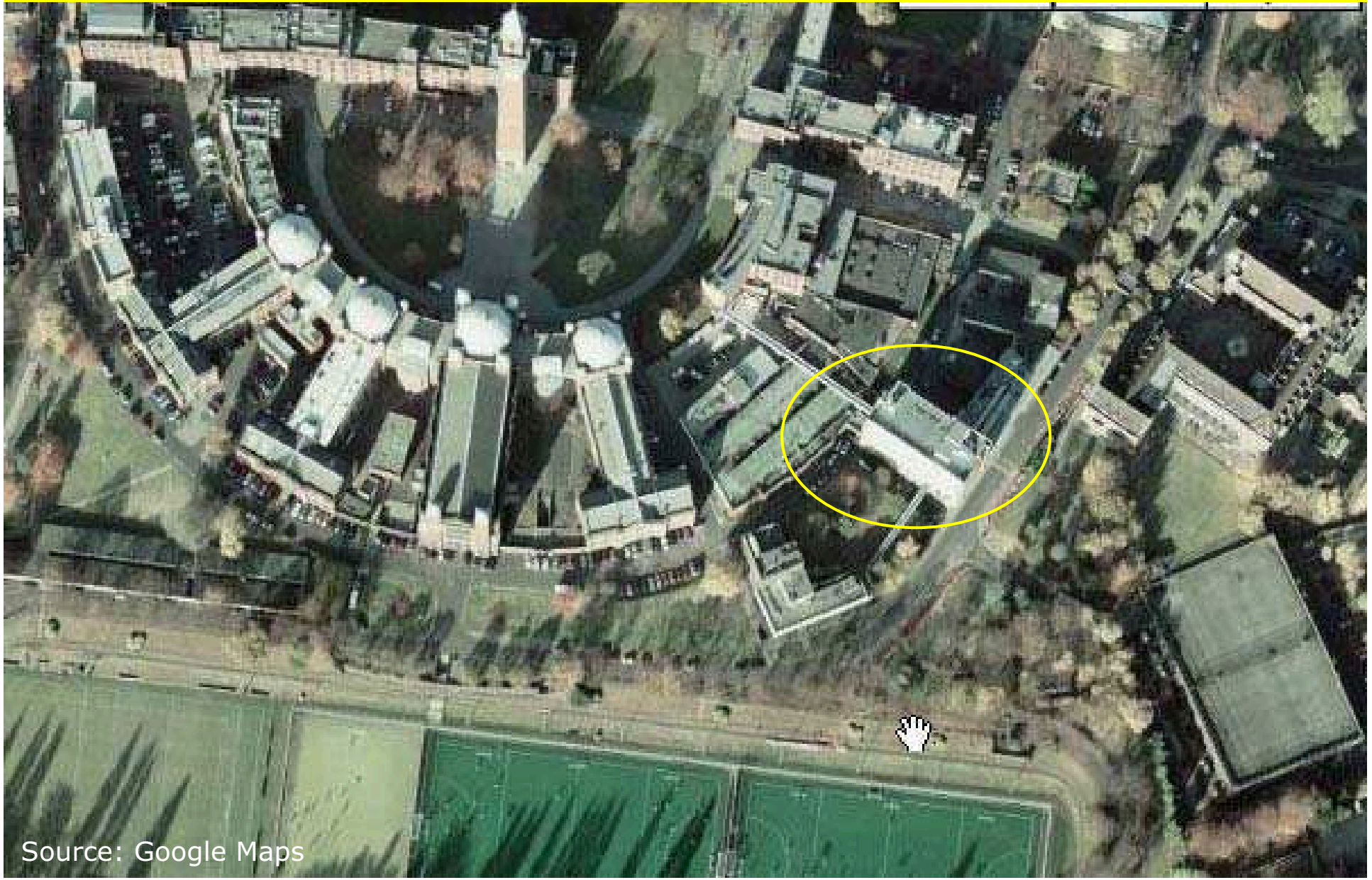
High resolution spectroscopy:
Benjamin Löhden
Philip v. Ende

Dynamics of multi-mode lasers:
Oliver Back
Tim Bonin

Technology and management:
Mariela Boevska
Dieter Barloesius
Reinhard Mielck

Midlands Centre for Ultracold Atoms

University of Birmingham



EPSRC

midlands physics alliance ultracold

HIGHER EDUCATION hefce FUNDING COUNCIL FOR ENGLAND

UNIVERSITY OF BIRMINGHAM

Theory


J.M.F. Gunn


N.K. Wilkin


D. Gangardt


R. Smith

Experiment


K. Bongs

NN1

NN2

The University of Nottingham

Theory


M. Fromhold


C. Lobo


K. Benedict


R. Scott

Experiment


P. Krüger

NN1

NN2

THE UNIVERSITY OF WARWICK

Theory


M. Szymanska


N. d'Ambrumenil


I. Lesanovsky
(from March 2009)

Thank you!