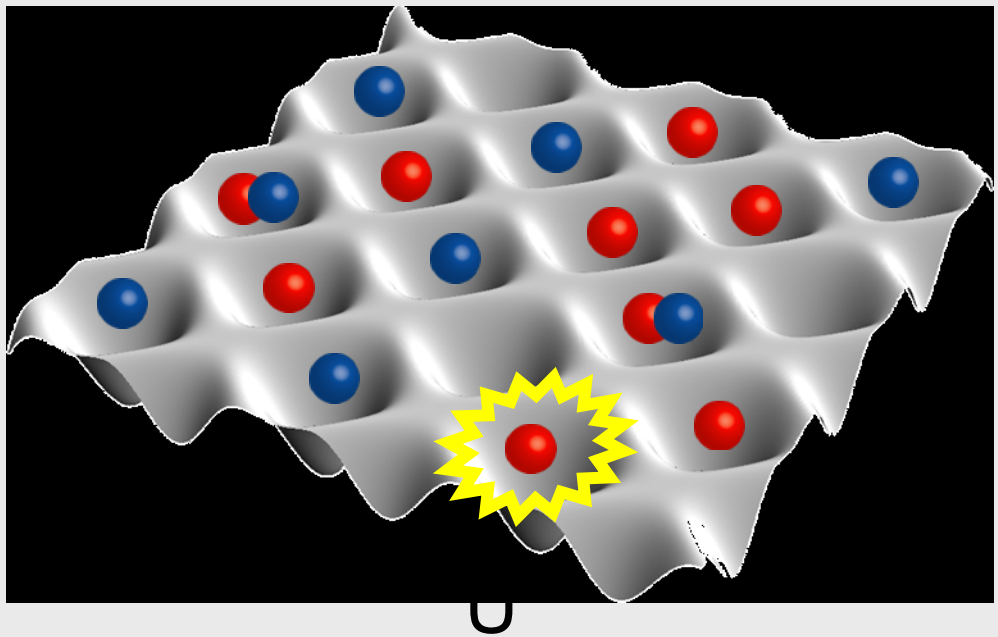
Interacting Fermions in Optical Lattices



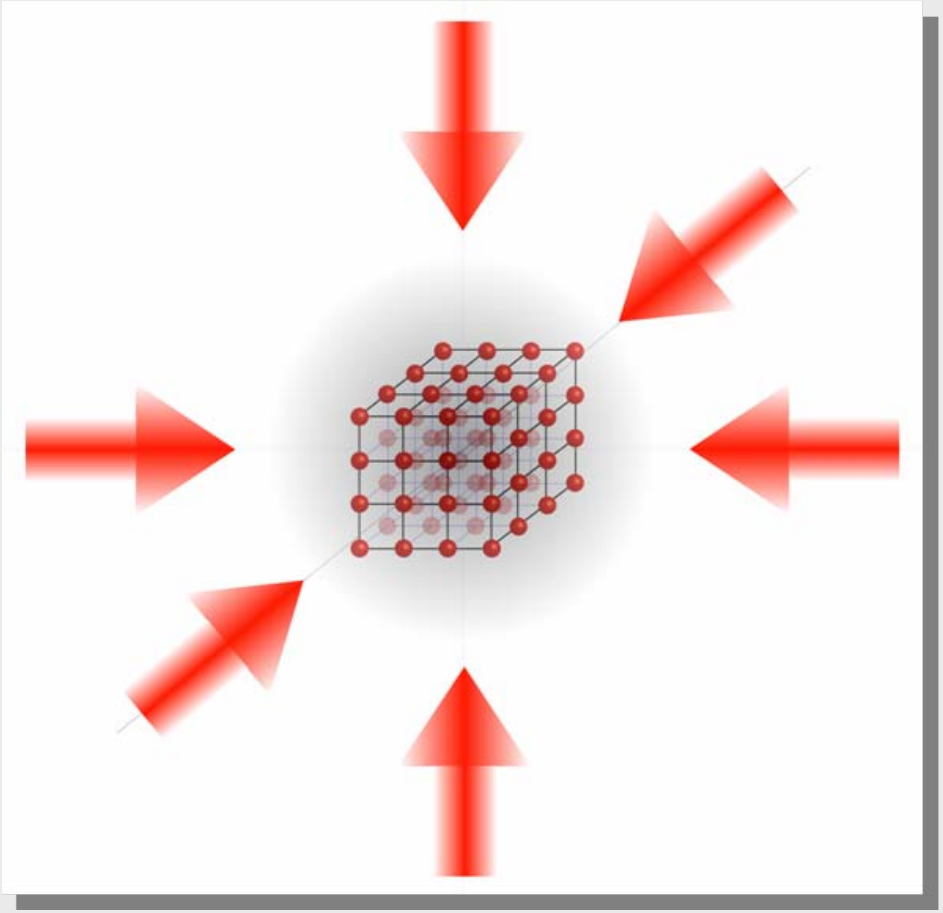
Henning Moritz

K. Günter, N. Strohmaier, R. Jördens,

Y. Takasu, T. Stöferle, M. Köhl, T. Esslinger

ETH Zürich

3D Optical Lattice



Fermions: ^{40}K (typically ~10^5)

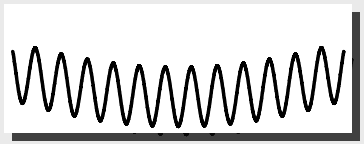
Bosons: ^{87}Rb

Optical Lattice: 826nm

3D lattice with fermions: ETH, Hamburg, MIT, Mainz, Lens

3D lattice with bosons: Munich/Mainz, ETH, NIST, Innsbruck, LENS, MIT, Penn, MPQ, Hamburg,

•Potential = simple cubic lattice + confining potential =



Outline

ETH

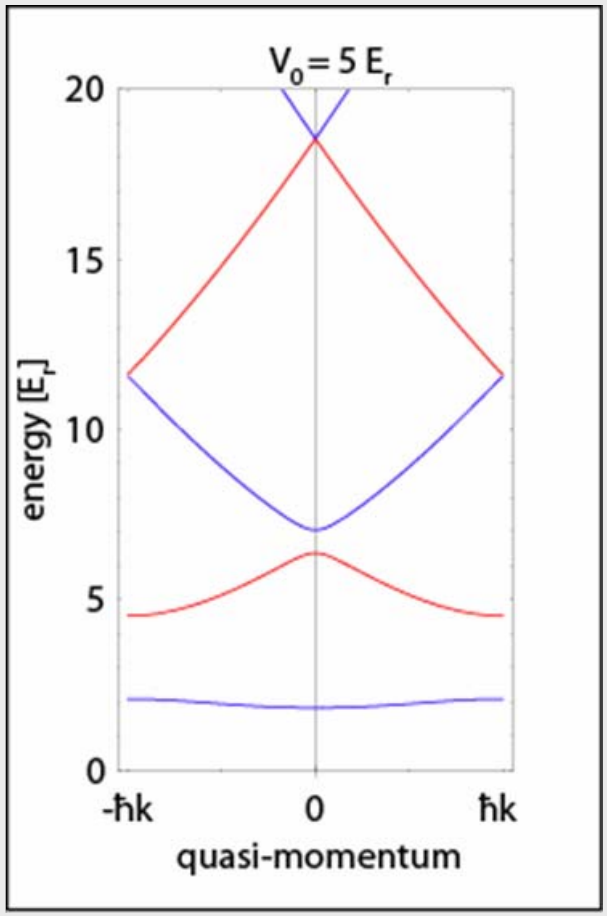
Ideal Fermi gas in a 3D lattice

Strong interactions & molecules

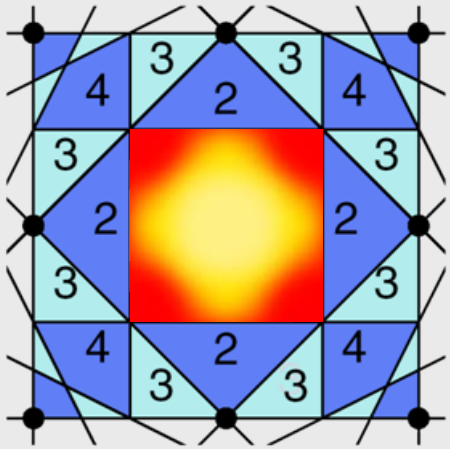
Transport of interacting fermions

Bose-Fermi mixtures

Filling the lattice



Brillouin zones
of a square lattice

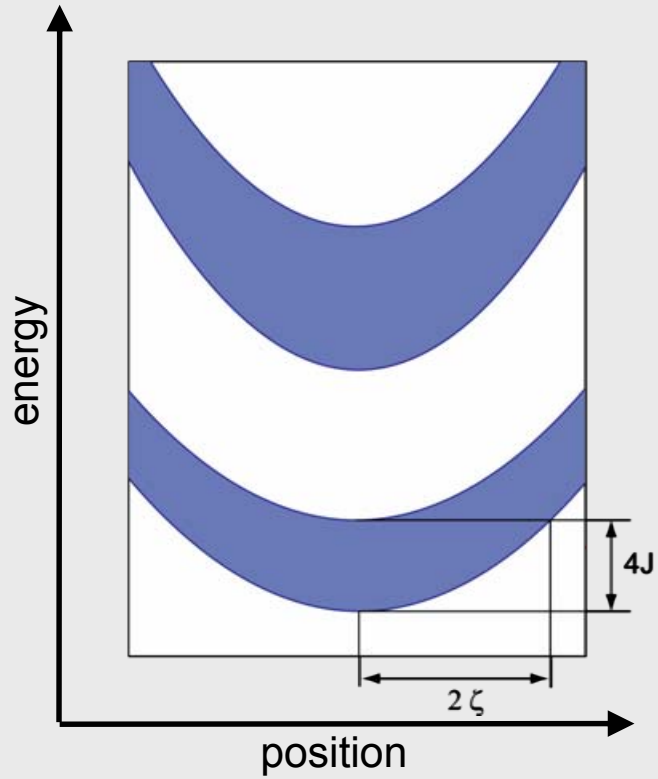


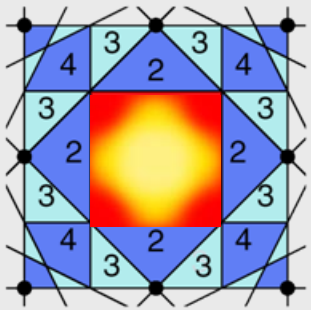
quasi momentum

$2\ \hbar k$

$(k=2\pi/\lambda)$

The inhomogeneous lattice





characteristic filling:

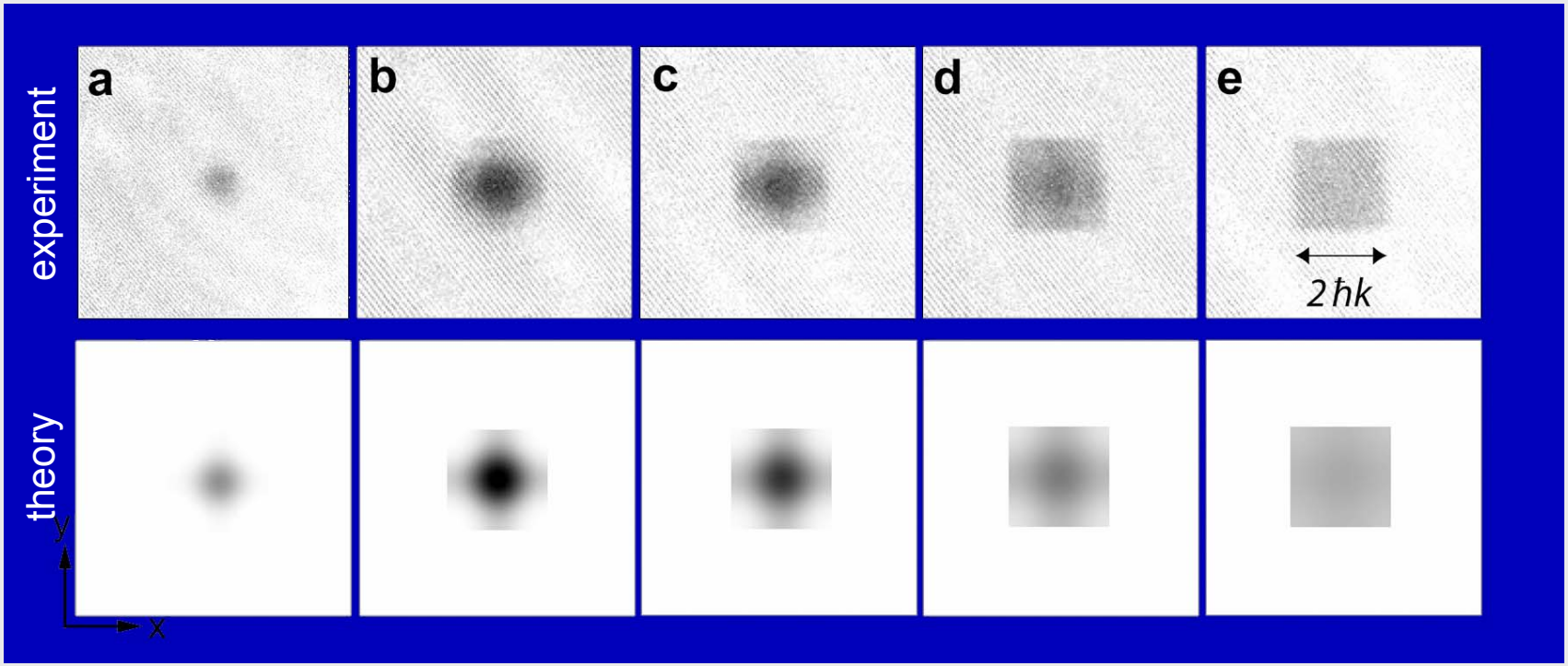
$$\frac{1}{2}m\omega^2 = J$$

$$n = \frac{N}{(\lambda/2)^3}$$

→ atom number *N*
→ external confinement ω
→ tunneling *J*

M. Rigol and A. Muramatsu PRA 70,043627 (2004)

Observed Fermi surfaces



“conductive state“ → characteristic filling → “band insulator“

M. Köhl, H. M, T. Stöferle, K. Günter and T. Esslinger, PRL 94, 080403 (2005).

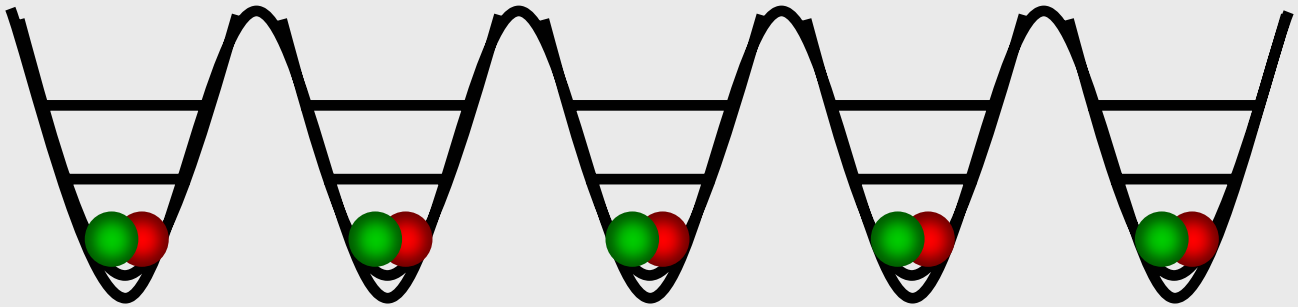
Ideal Fermi gas in a 3D lattice

Strong interactions & molecules

Transport of interacting fermions

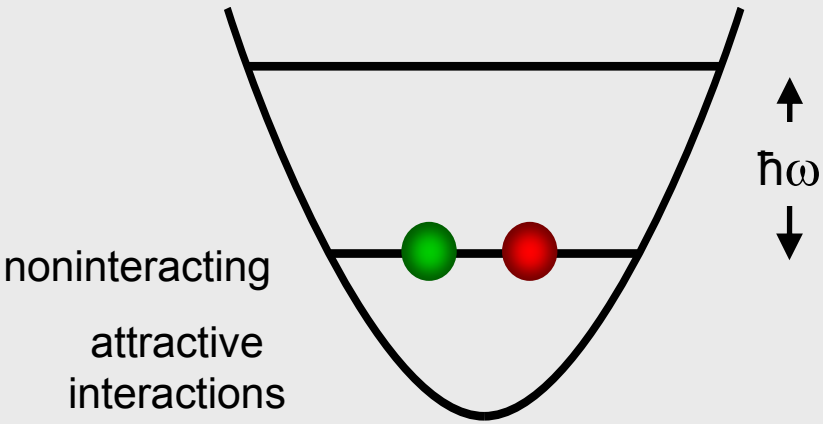
Bose-Fermi mixtures

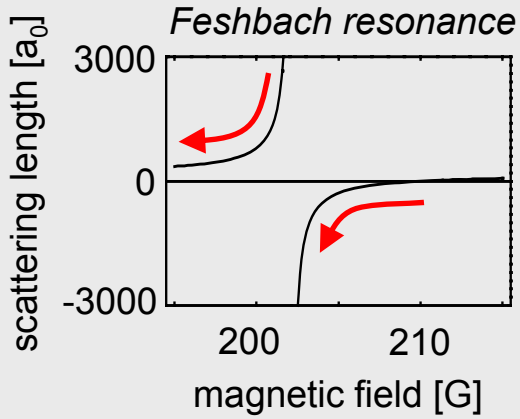
Interacting harmonic oscillator

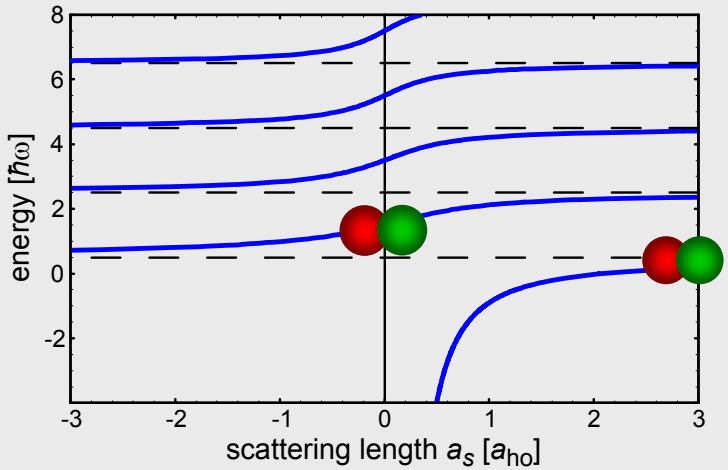


deep lattice = array of harmonic oscillators

Creating molecules

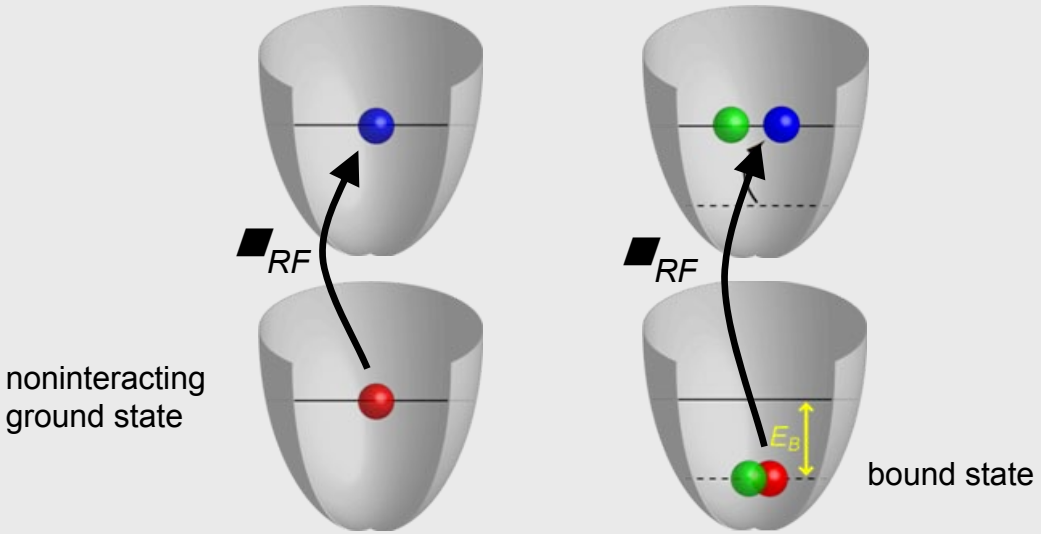


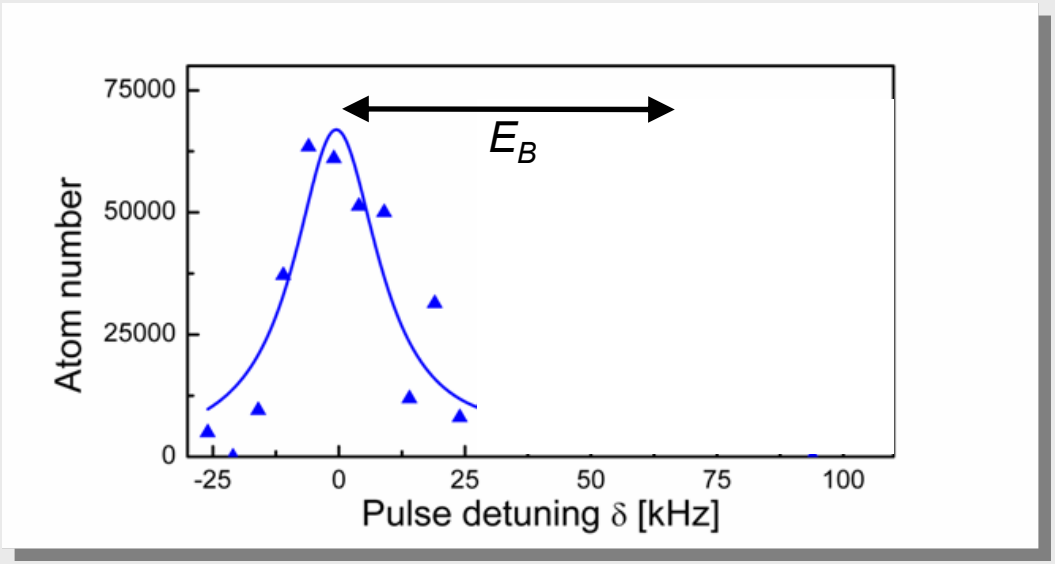




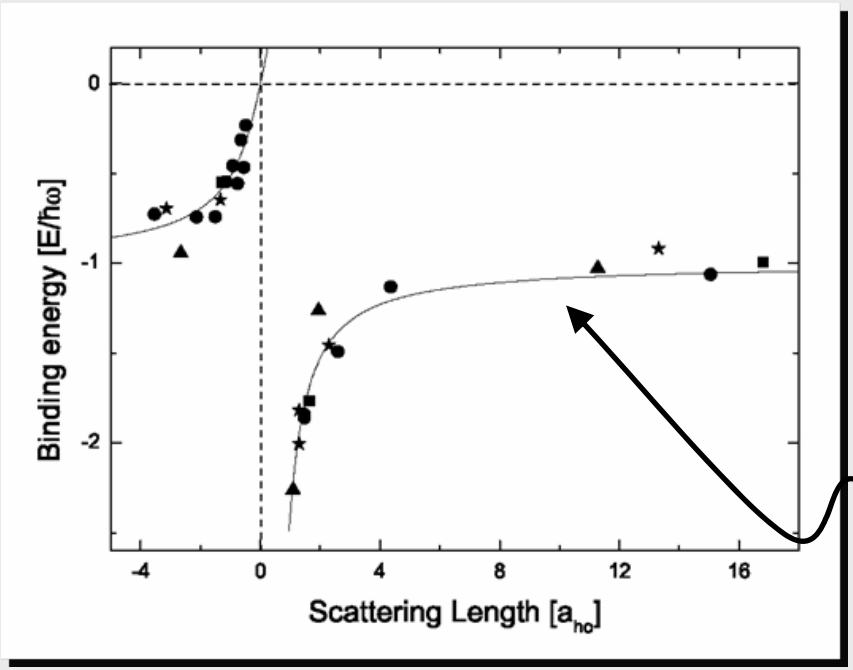
T. Busch et al., Found. Phys. 28, 549 (1998)

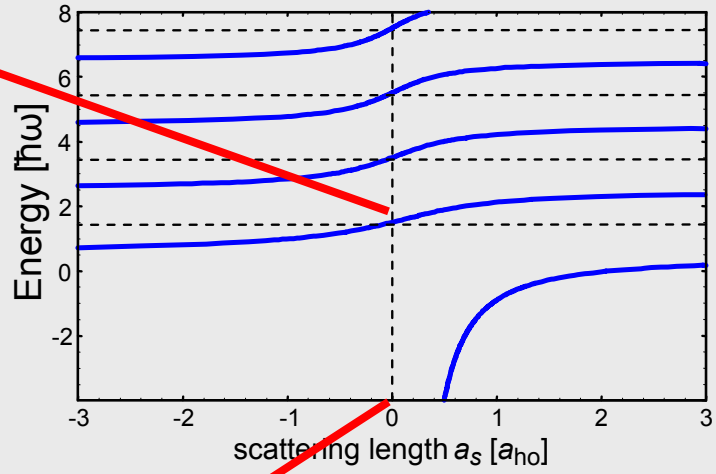
RF spectroscopy in the lattice





Measuring the binding energy





T. Busch et al., Found. Phys. 28, 549 (1998)

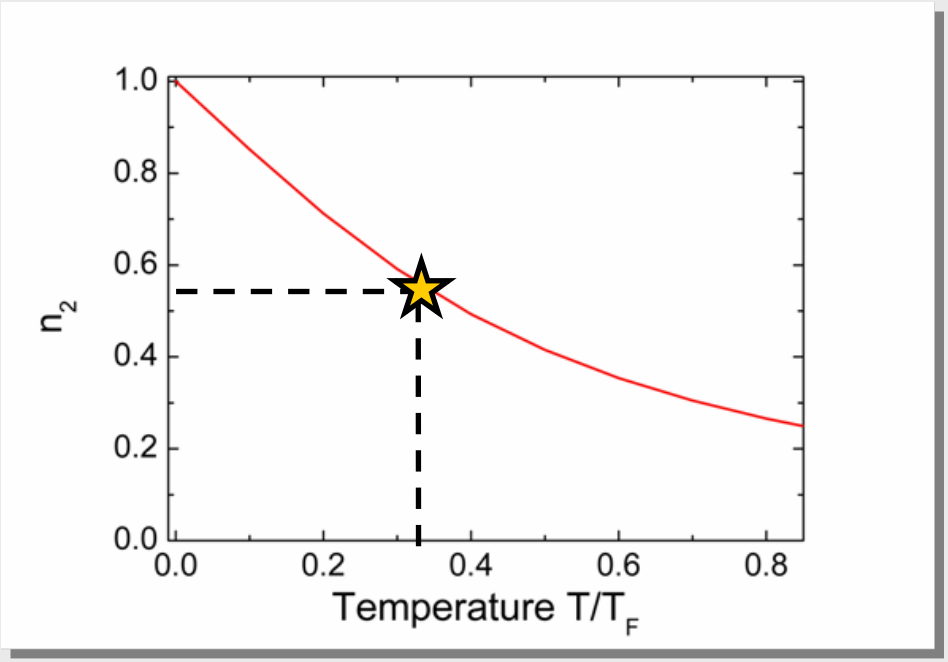
Exact theory
(no free parameters!)

Fermionic atoms transform into bosonic molecules!

Thilo Stöferle, H. M., K. Günter, M. Köhl, T. Esslinger, Phys. Rev. Lett. 96, 040301 (2006)

Thermometry in the lattice

Temperature determines the fraction of doubly occupied lattice sites.



M. Köhl, cond-mat/0510567.

see also: H. G. Katzgraber et al., cond-mat/0510194 and for bosons: G. Pupillo et al., cond-mat/0407075.

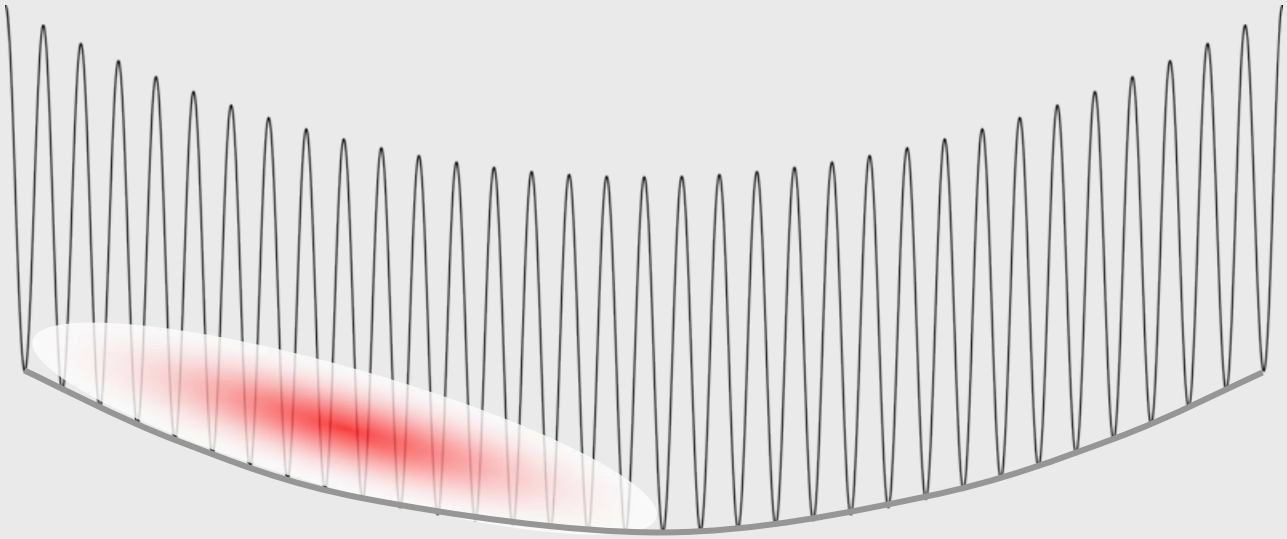
Ideal Fermi gas in a 3D lattice

Strong interactions & molecules

Transport of interacting fermions

Bose-Fermi mixtures

Observing transport



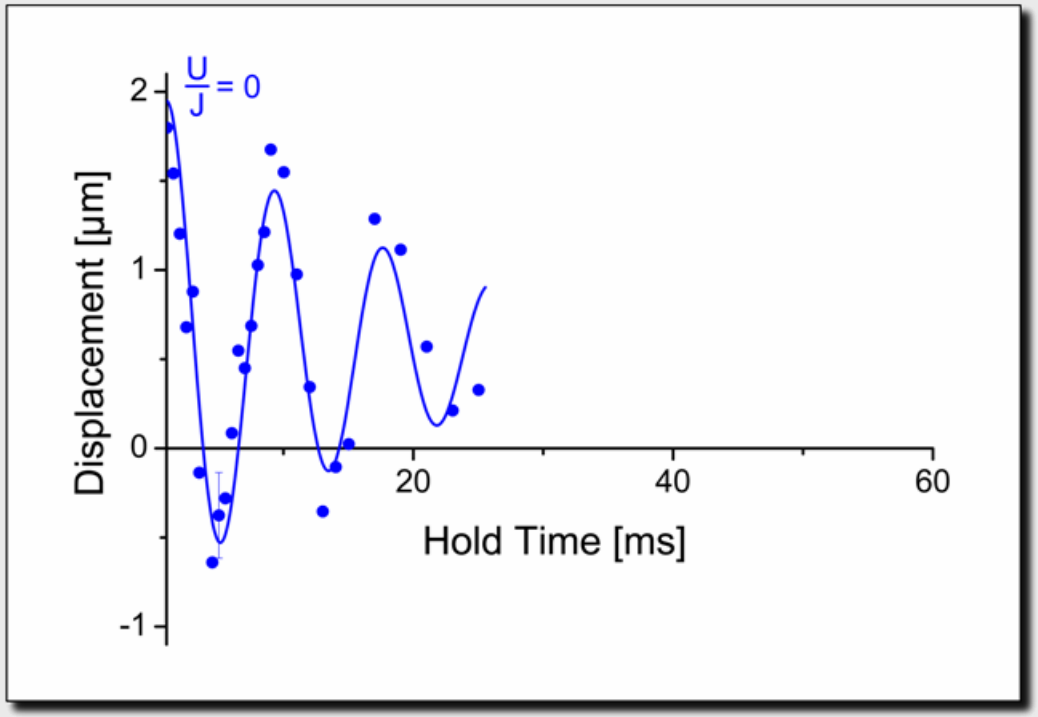
$V_0 = 5E_R$

C. D. Fertig et. al, Phys. Rev, Lett, 92, 120403 (2005)

H. Ott, E. de Mirandes, F. Ferlaino, G. Roati, G. Modugno, and M. Inguscio, Phys. Rev, Lett, 92, 160601 (2004)

Observing transport

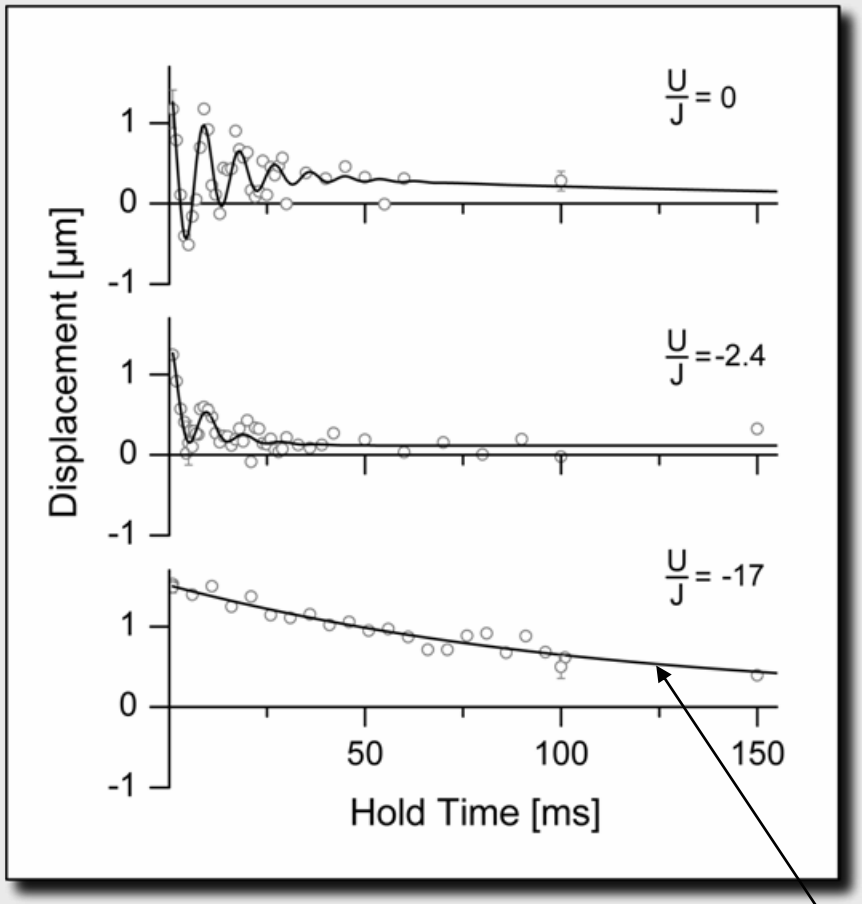
Lattice depth 5 E_R, ~half filling in the center



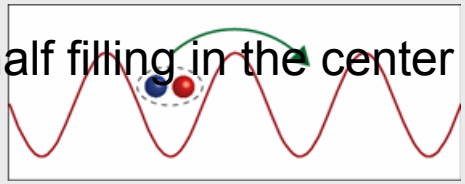
Inhibited Transport

No interaction

Strong attraction

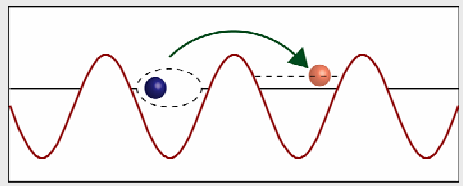


~ half filling in the center



pair tunneling

$J_{pair} \approx \frac{J}{60}$

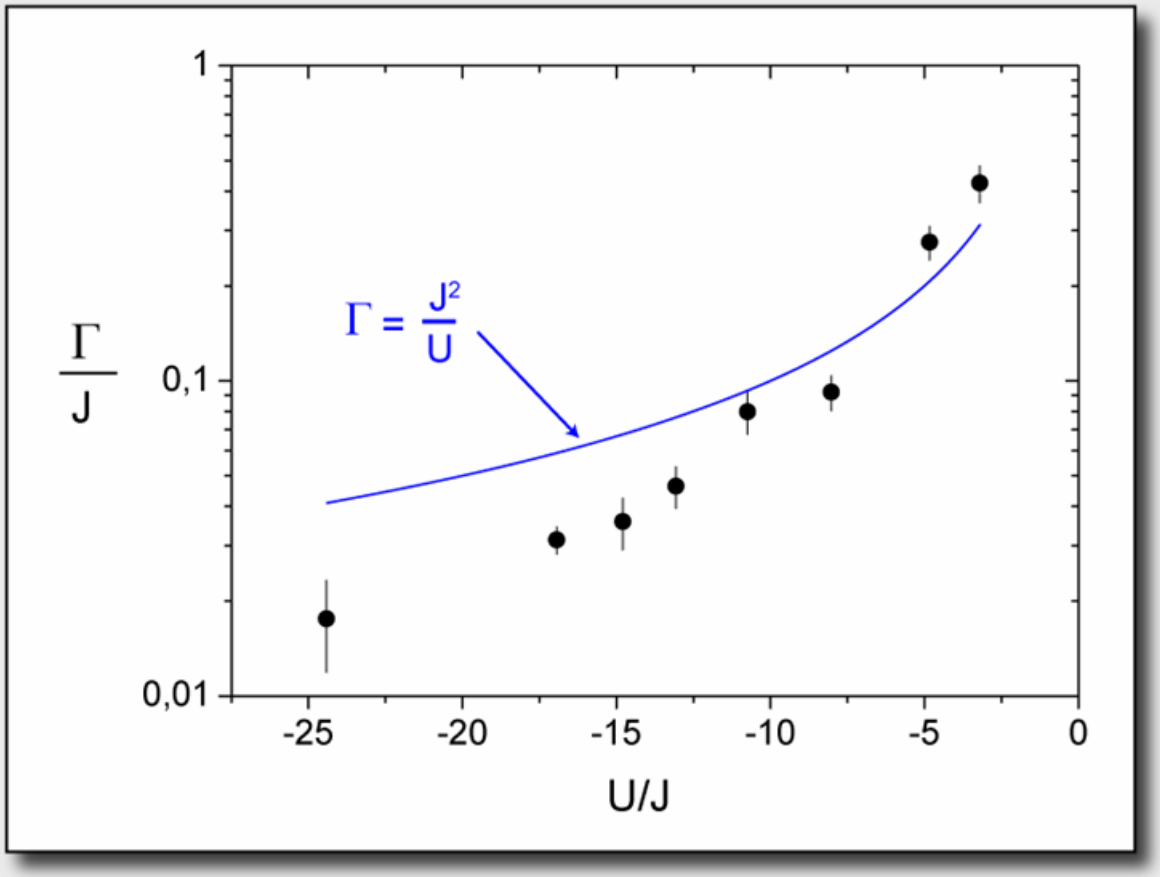


effective tunneling

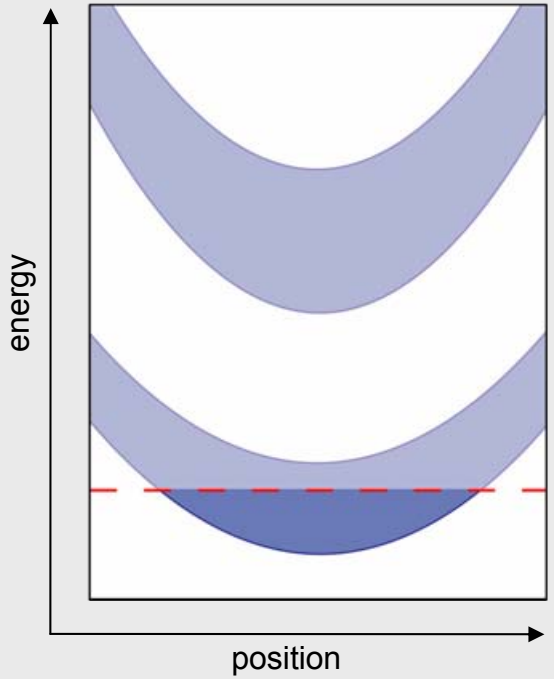
$J_{eff} \approx J \frac{J}{U}$

$$y(t) = y_0 + A e^{i \omega t}$$

Drift Rate



Characteristic filling



characteristic filling:

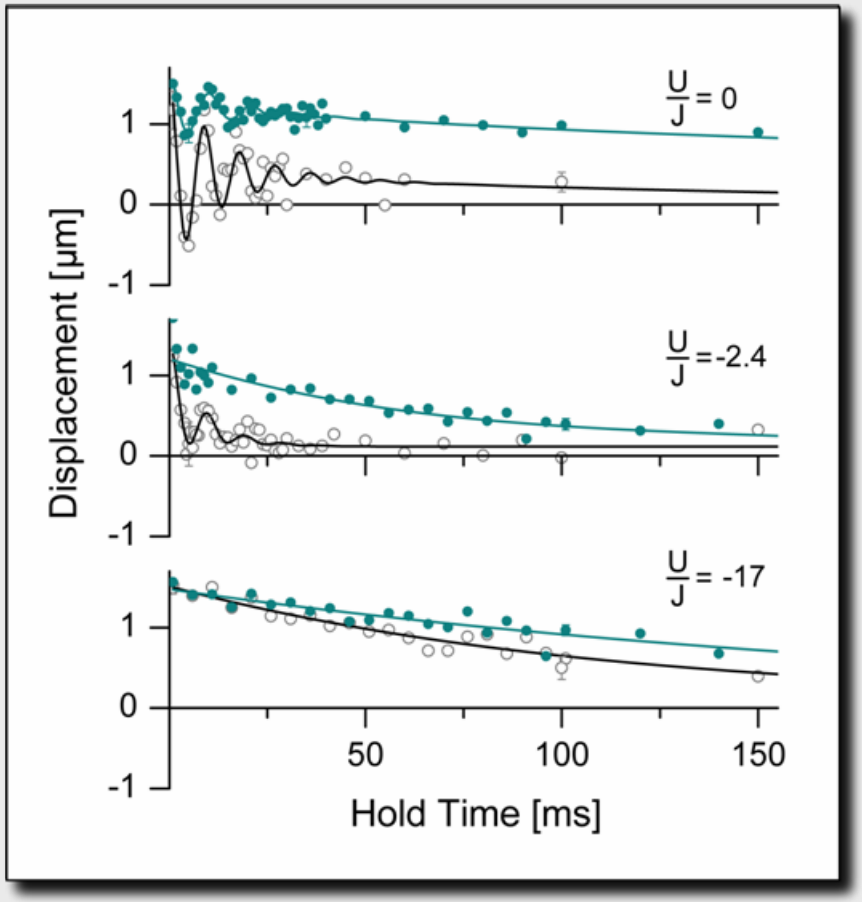
$$\frac{1}{2} m!^{2 \text{ ³ } 2} = J_{ef\ f}$$

$$\frac{1}{2} = \frac{N}{(\text{³} = d)^3} \Big/ \frac{1}{J_{ef\ f}^{3=2}}$$

Full filling

No interaction

Strong attraction



full filling in the center

~ half filling in the center

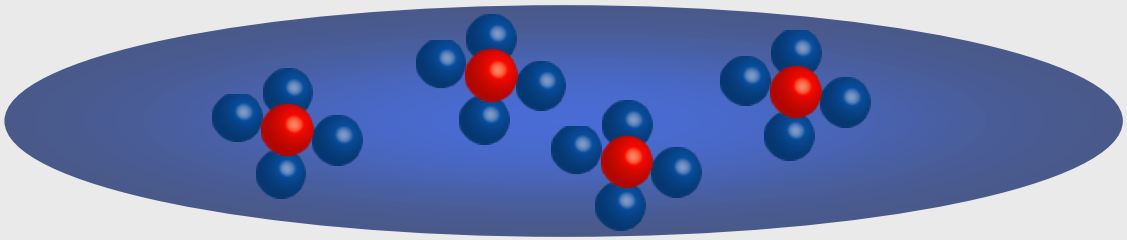
Ideal Fermi gas in a 3D lattice

Strong interactions & molecules

Transport of interacting fermions

Bose-Fermi mixtures

Adding fermions to a Bose condensate



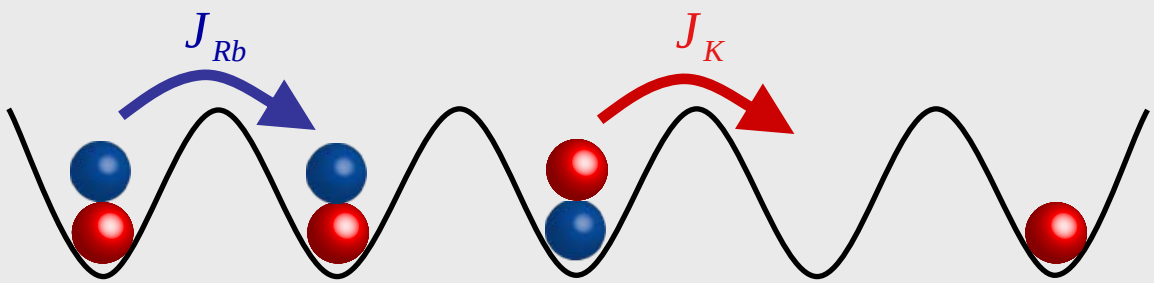
^{87}Rb

^{40}K

- Depletion of the Bose-Einstein condensate
- Polarons, fermion-phonon coupling with $v_F=v_S$
- Composite fermions
- Similiar to ^{3}He/^{4}He mixtures but on a lattice

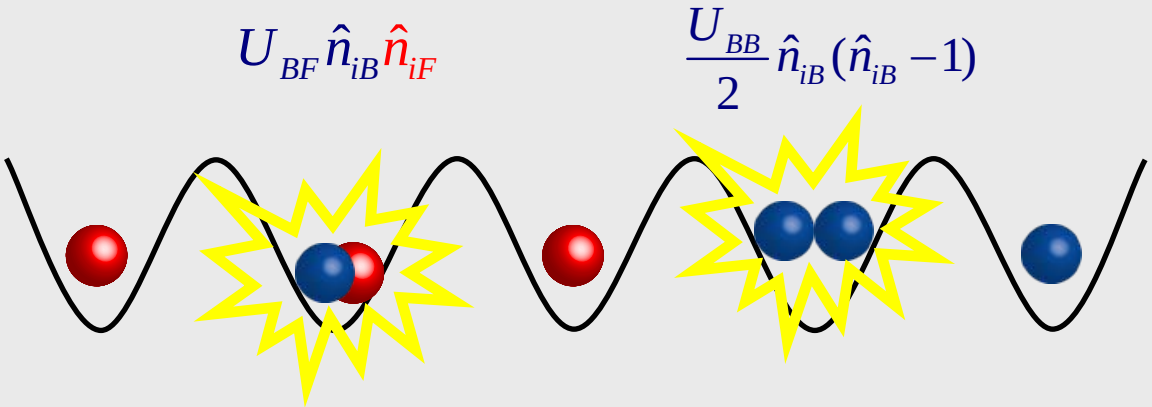
Theory: Blatter, Cazallila, Demler, Hofstetter, Kuklov, Lewenstein, Lukin, Santos, Troyer, …

Bosons and fermions in a lattice



tunneling

$$\frac{J_F}{J_B} \gg 1$$



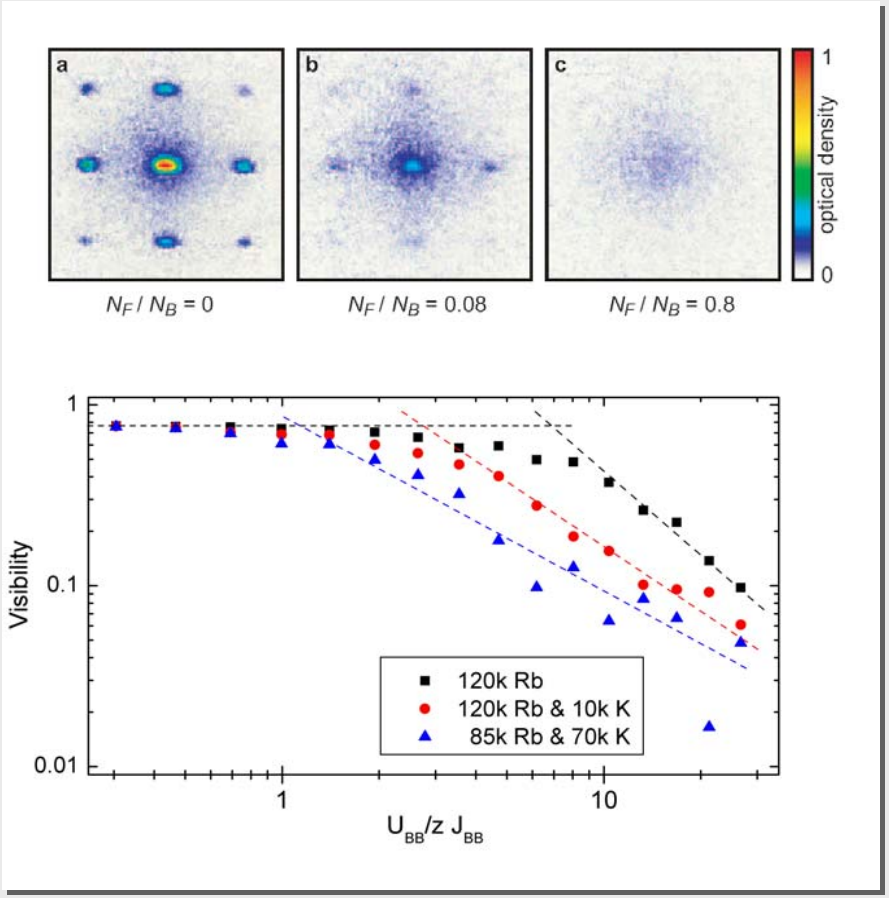
interactions

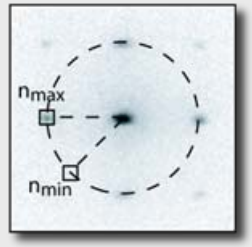
U_{BF} : attractive

U_{BB} : repulsive

$$\frac{U_{BF}}{U_{BB}} \approx -2$$

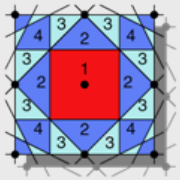
Experimental results



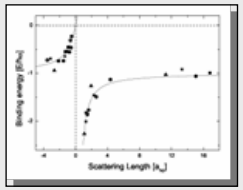


K. Günter, T. Stöferle, H. Moritz, M. Köhl, T. Esslinger, Phys. Rev. Lett. 96, 180402 (2006)
see also: S. Ospelkaus et al., Phys. Rev. Lett. 96, 180403 (2006)
1D Quantum monte Carlo Simulation: L. Pollet et al. cond-mat/0609604, (2006)

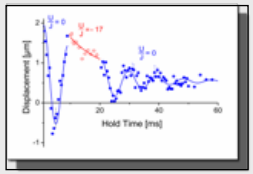
Conclusions



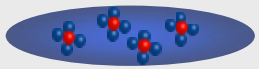
Fermi surfaces



Strong interactions & molecules

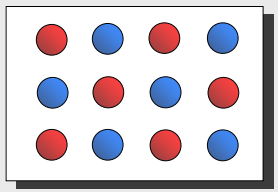


Transport of interacting fermions



Bose-Fermi Mixtures

Outlook



Mott insulating & antiferromagnetic phase

W. Hofstetter et al., PRL 89, 220407 (2002)
F. Werner et al., PRL 95, 056401 (2005)
E. Altman et al., PRA 70, 013603 (2004)

Thanks !

A. Frank, V. Bürgisser, Tilman Esslinger, B. Zimmermann,
H. M., Michael Köhl, Kenneth Günter, A. Öttl, Stephan Ritter, T. Donner, Thilo Stöferle, T. Bourdel,
Not shown: Niels Strohmaier, Robert Jördens, Yosuke Takasu

Funding: ETH, EU (OLAQUI), QSIT, SNF