The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

1859-20

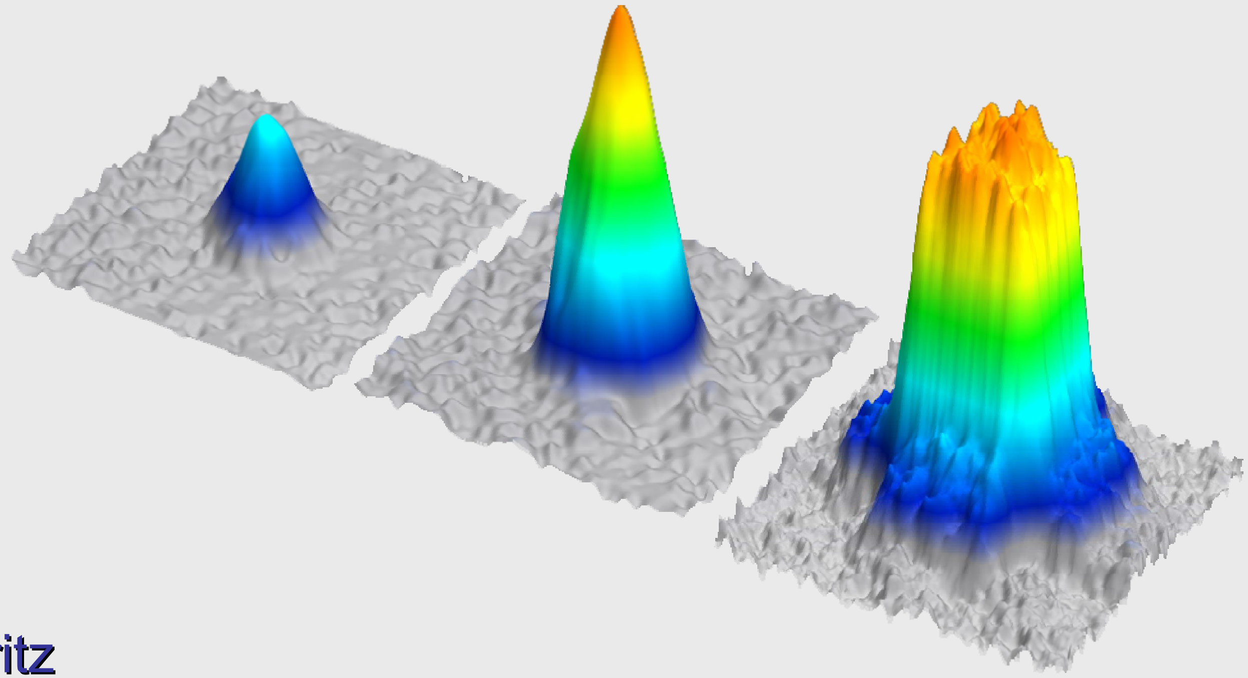
Summer School on Novel Quantum Phases and Non-Equilibrium Phenomena in Cold Atomic Gases

27 August - 7 September, 2007

Fermions in optical lattices

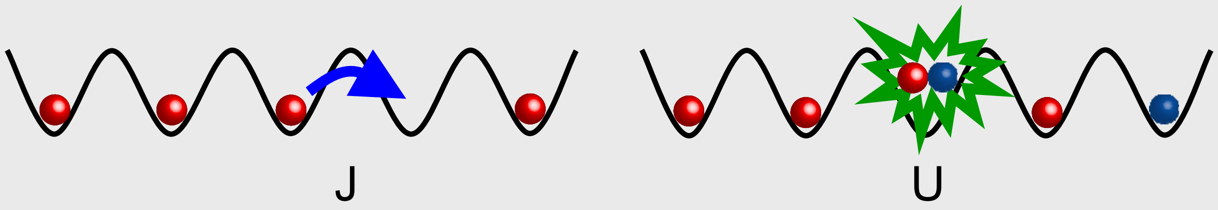
Henning Moritz
ETHZ Zurich

Fermions in Optical Lattices



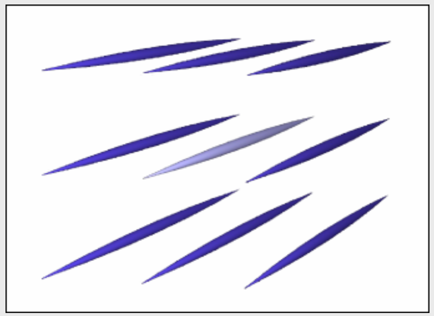
Henning Moritz
N. Strohmaier, R. Jördens, K. Günter
Y. Takasu, T. Stöferle, M. Köhl, T. Esslinger
ETH Zürich

Fermi-Hubbard model



$$H = -J\sum_{i,\sigma}(\hat{c}^{\dagger}_{i\sigma}\hat{c}_{i+1\sigma} + h.c.) + U\sum_{i}\hat{n}_{i\uparrow}\hat{n}_{i\downarrow} - \sum_{i,\sigma}(\mu - \varepsilon_i)\hat{n}_{i\sigma}$$

- Interaction U → molecule formation
- Tunneling J
- Dimensionality
- Filling

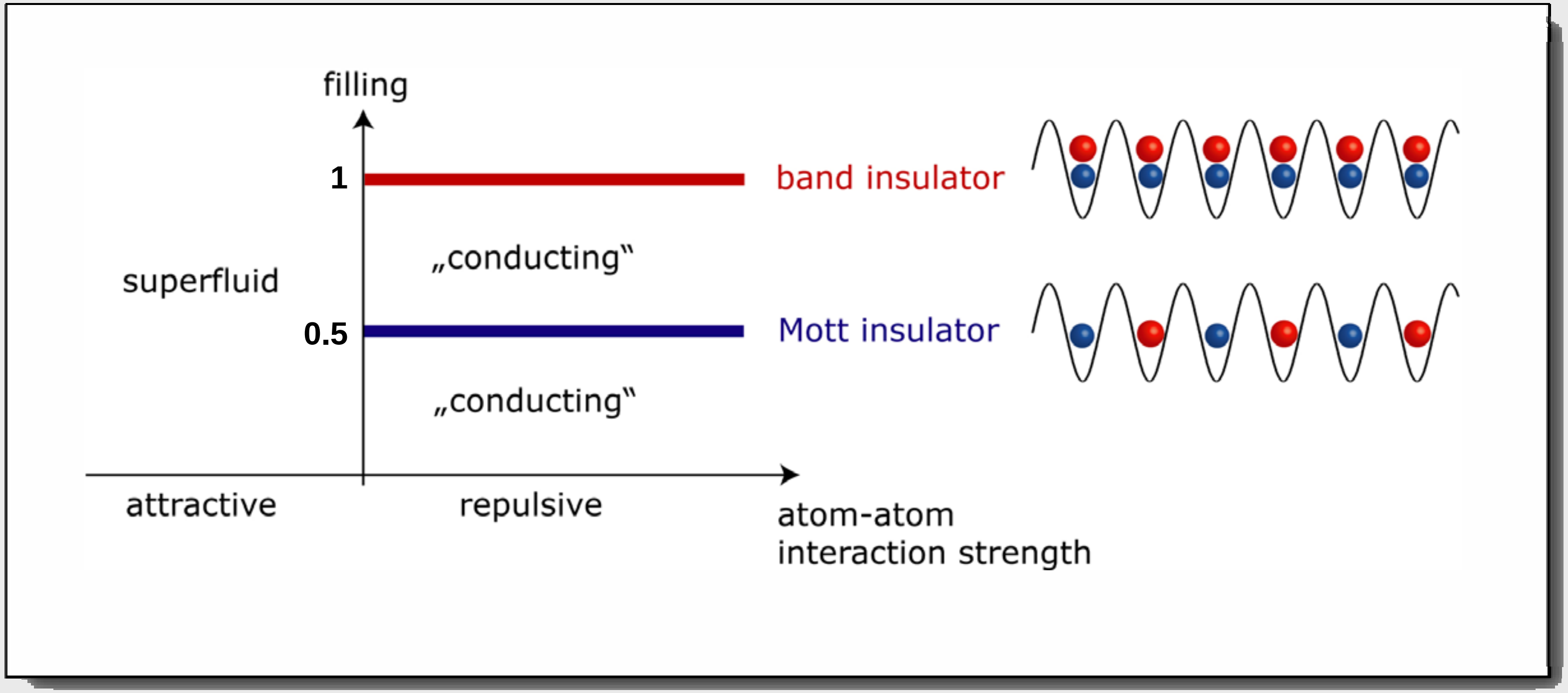


D. Jaksch et al., PRL 81, 3108 (1998) .

W. Hofstetter et al., PRL 89, 220407 (2002).

Quantum phases in the lattice

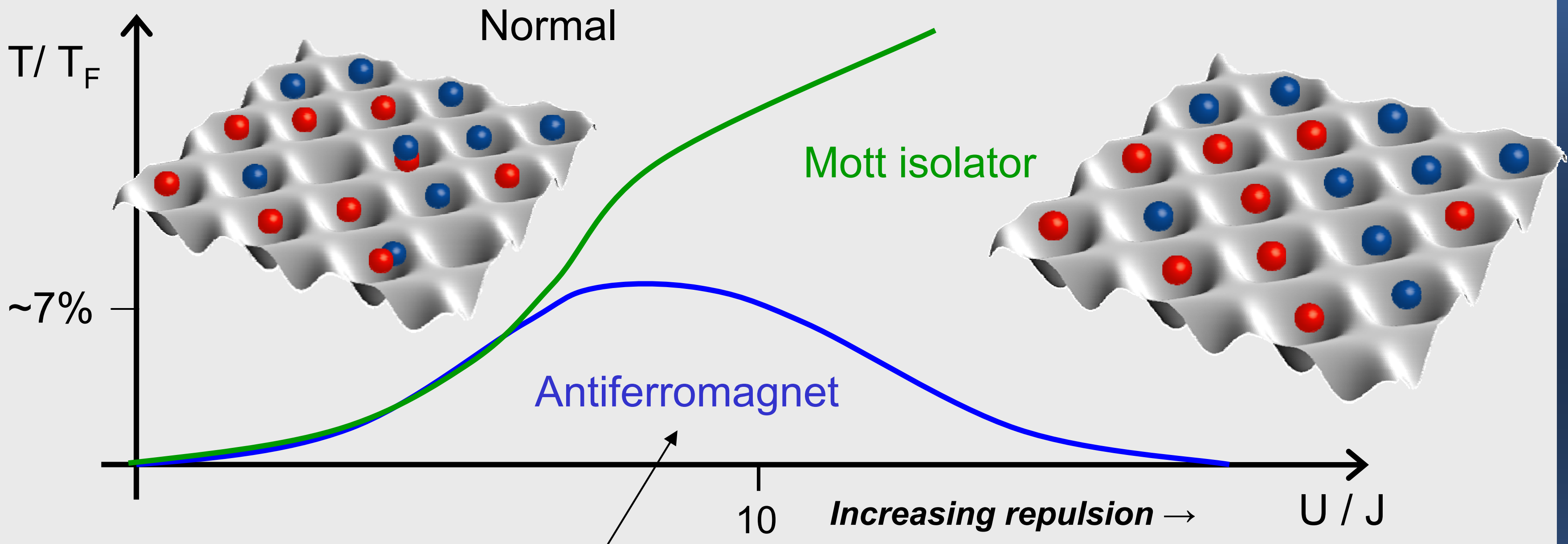
ETH

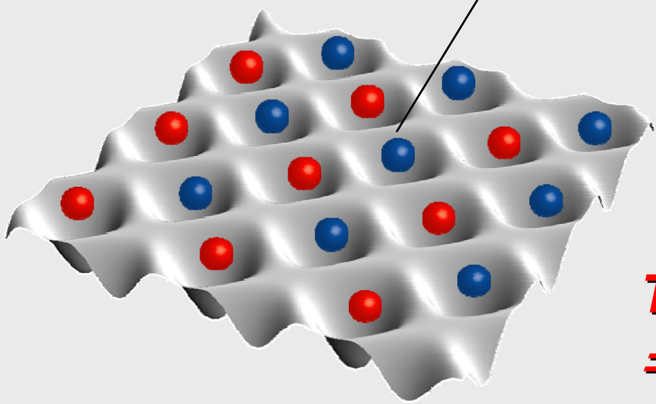


Repulsive Phases

ETH

Half filling





Antiferromagnetic order favorable because atoms can virtually hop to next site (paying U). This delocalisation minimises kinetic energy.

Take away a few particles
⟹ High T_c Superconductivity ?

Outline

ETH

Ideal Fermi gas in a 3D lattice

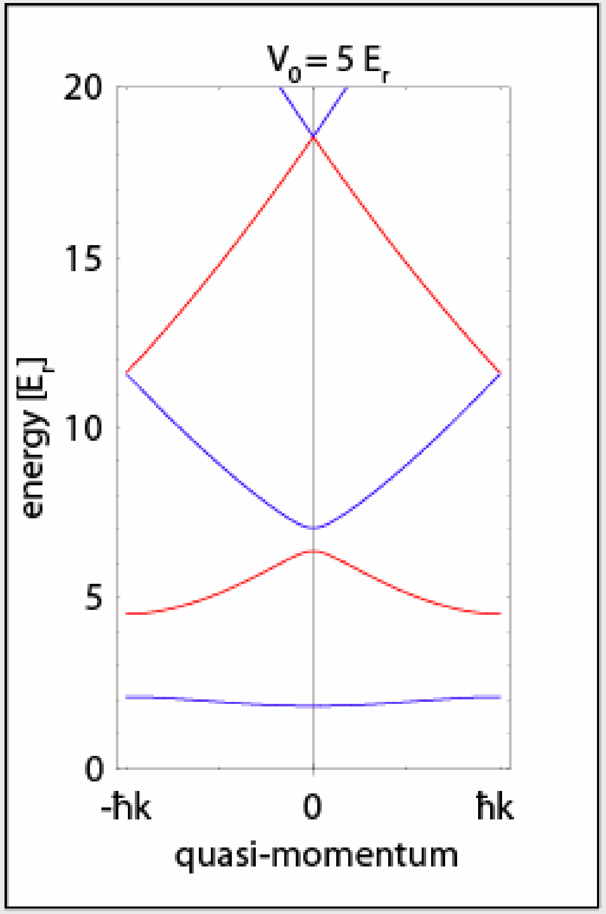
Strong interactions in the lattice

Transport of interacting fermions

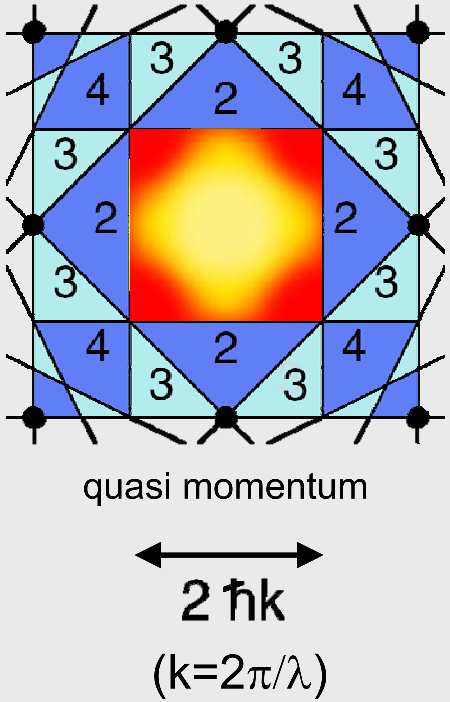
1D Fermi gas

Filling the lattice

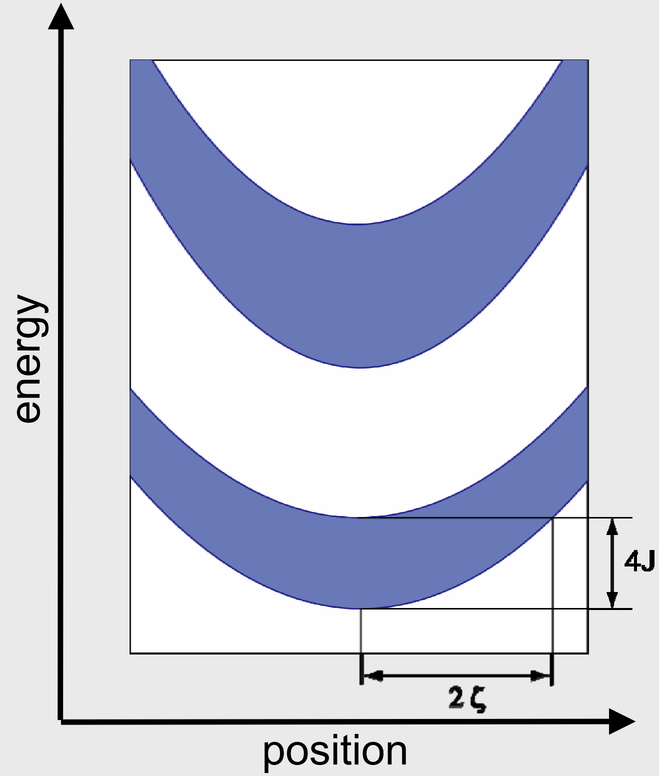
ETH



Brillouin zones
of a square lattice



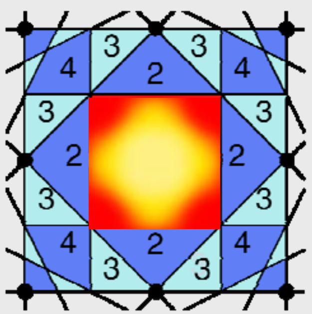
The inhomogeneous lattice



characteristic filling:

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

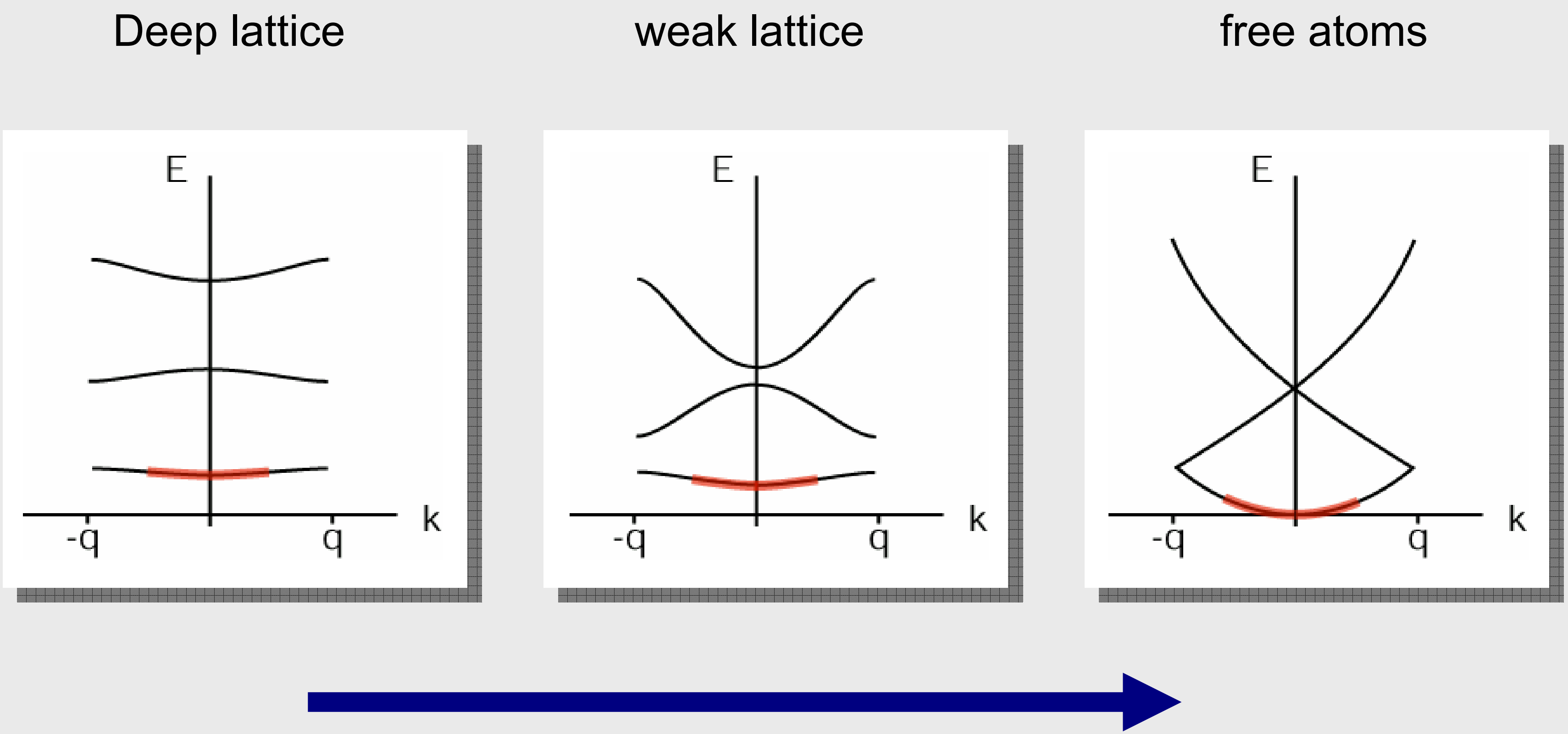
$$\rho_c = \frac{N}{(\zeta/d)^3}$$



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

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

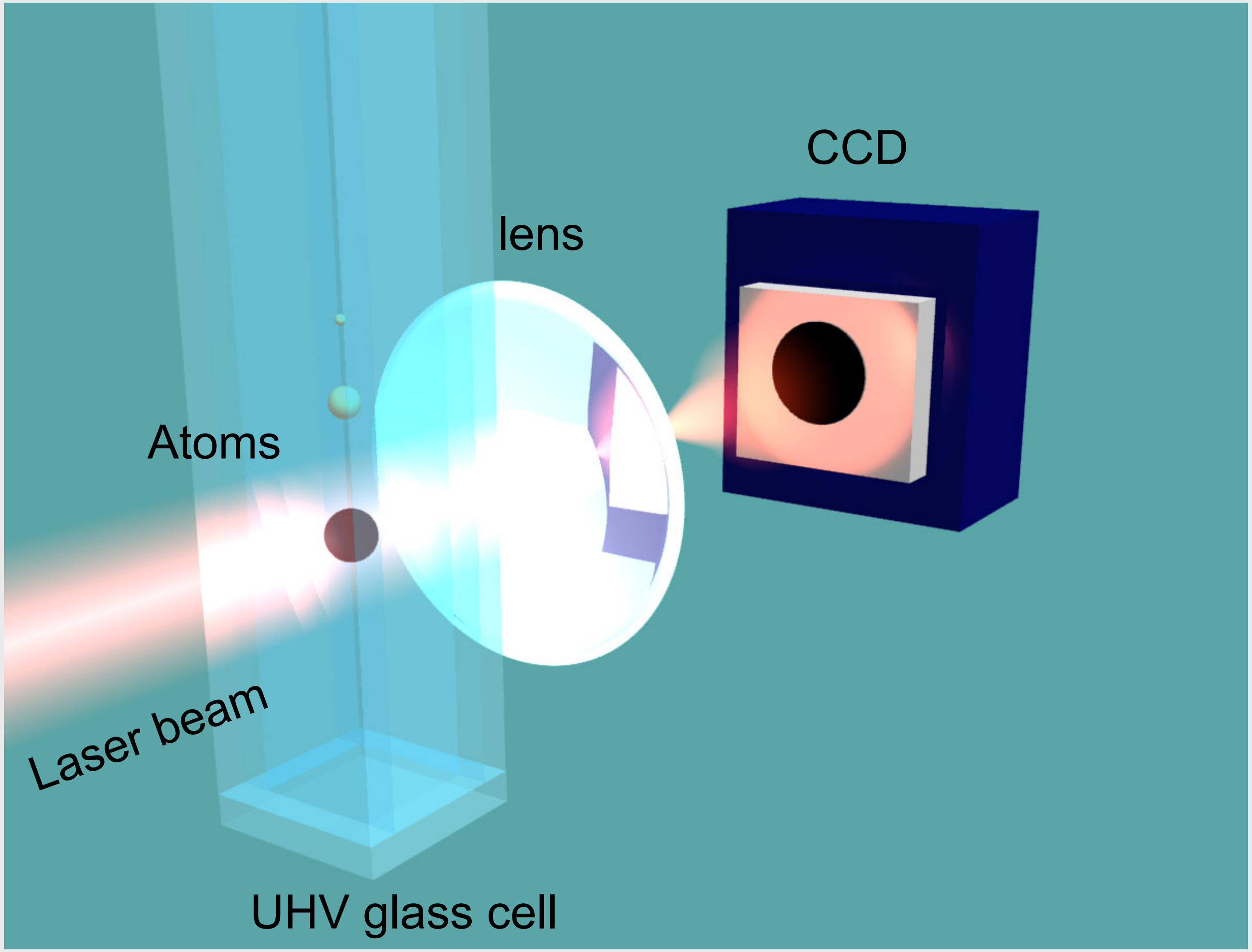
Adiabatic Expansion



- no transitions to higher bands
- quasi-momentum conserved (nearly)
- not adiabatic for many-body wavefunction

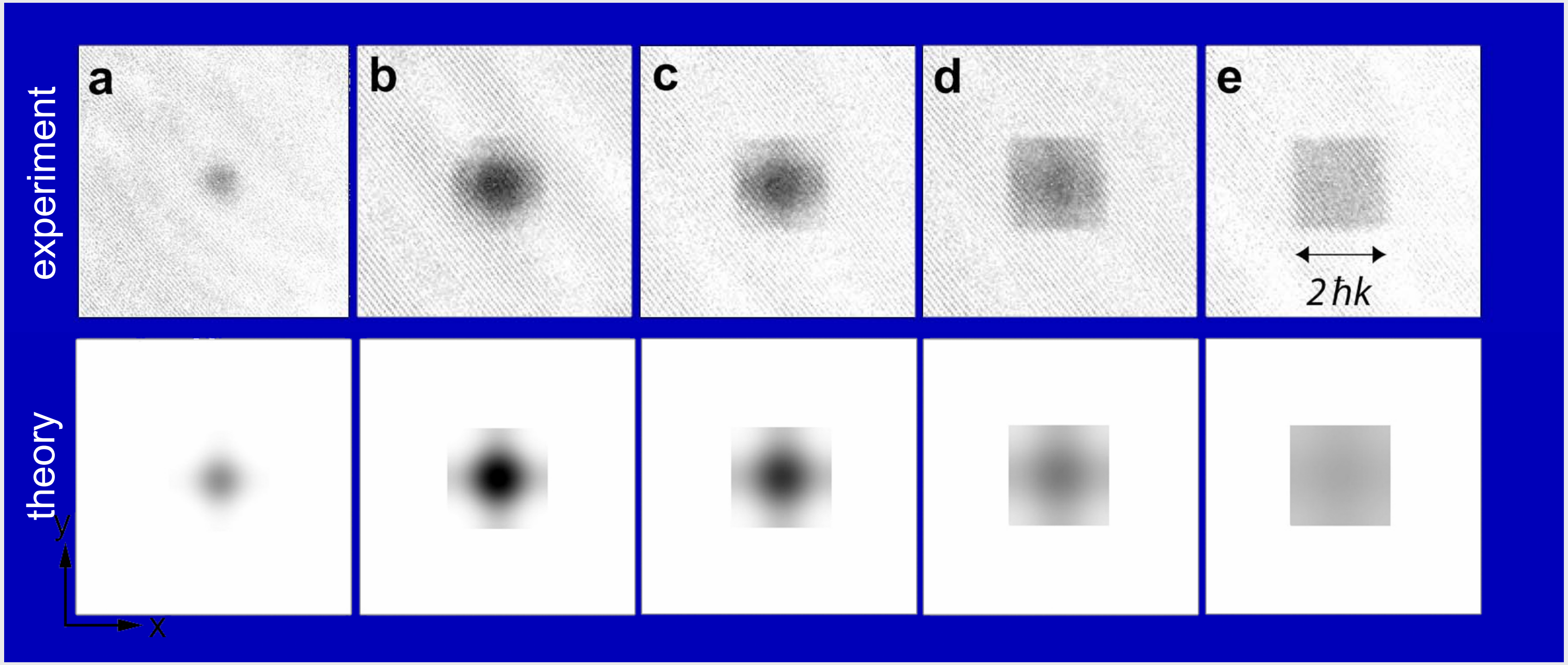
Absorption Imaging

ETH



Observed Fermi surfaces

ETH



"conductive state" → "band insulator"

characteristic filling

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

ETH

Ideal Fermi gas in a 3D lattice

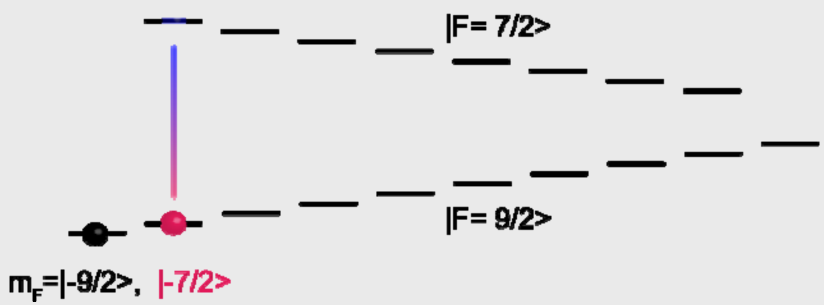
Strong interactions in the lattice

Transport of interacting fermions

1D Fermi gas

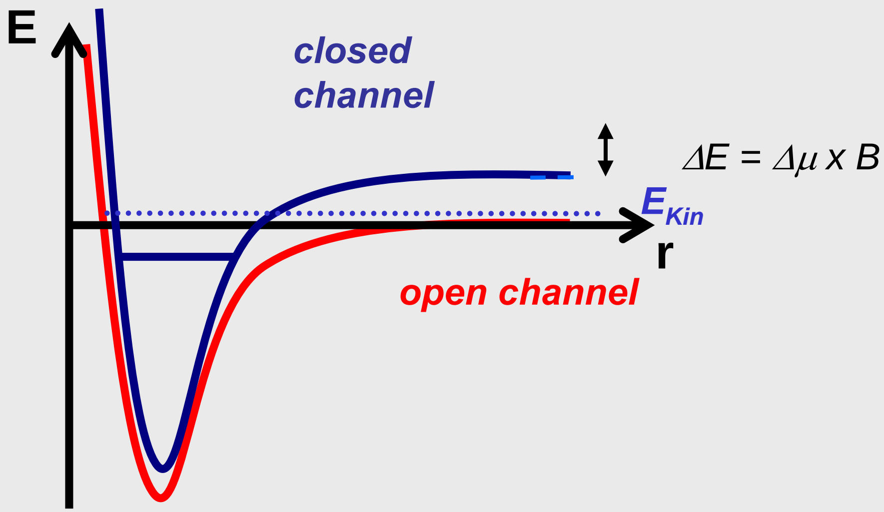
Feshbach resonance

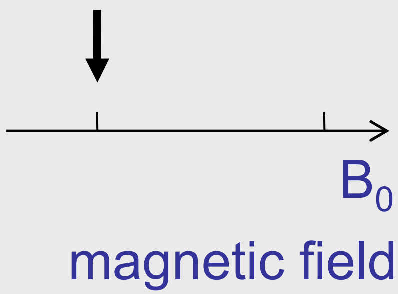
ETH



Interaction between spins of atoms at close distance may couple states
m_{tot} conserved

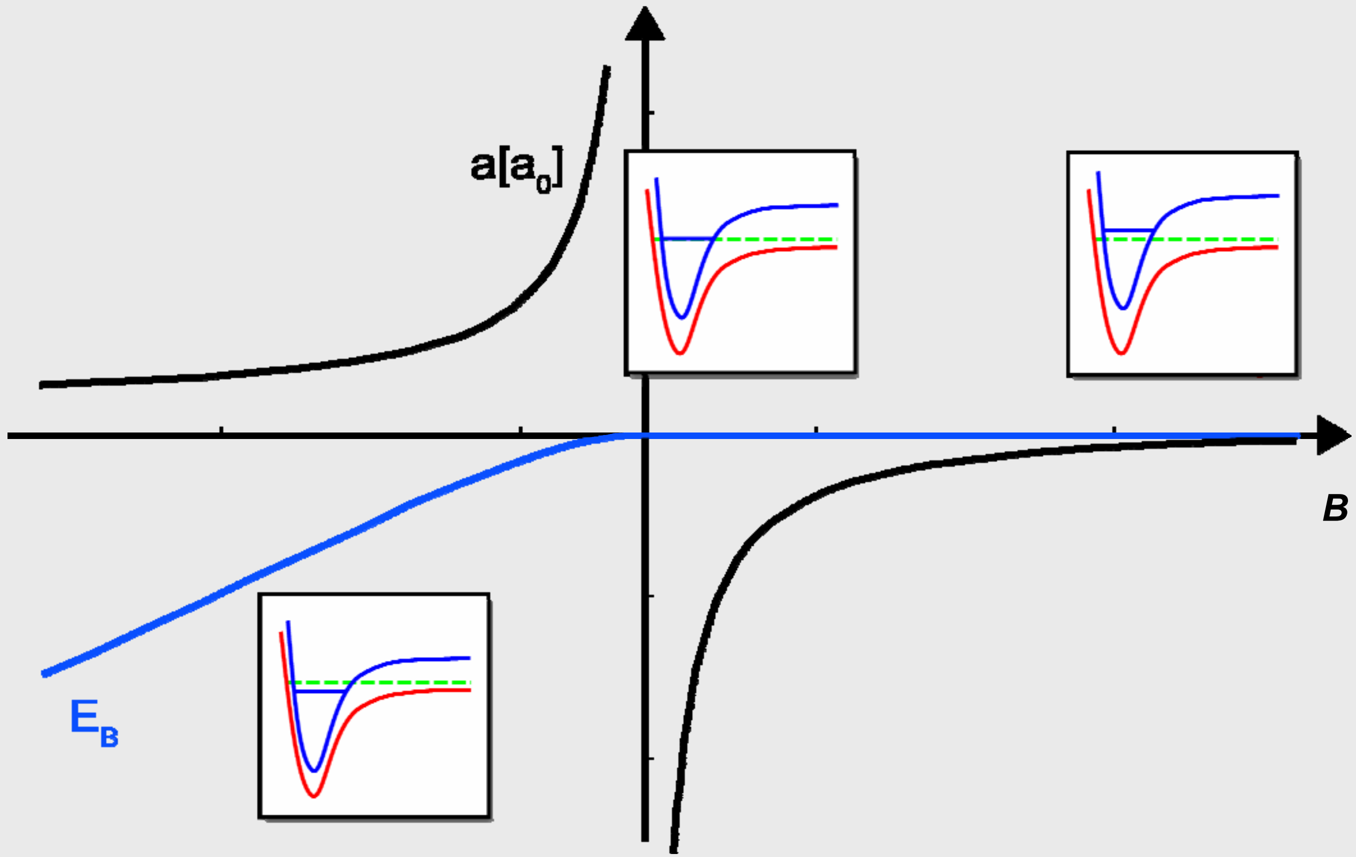
- *Tune bound state of a "closed channel" into degeneracy with the continuum*
- *Convenient tuning by mag. field: the two states have different mag. moment*





Free space: Feshbach resonance

ETH

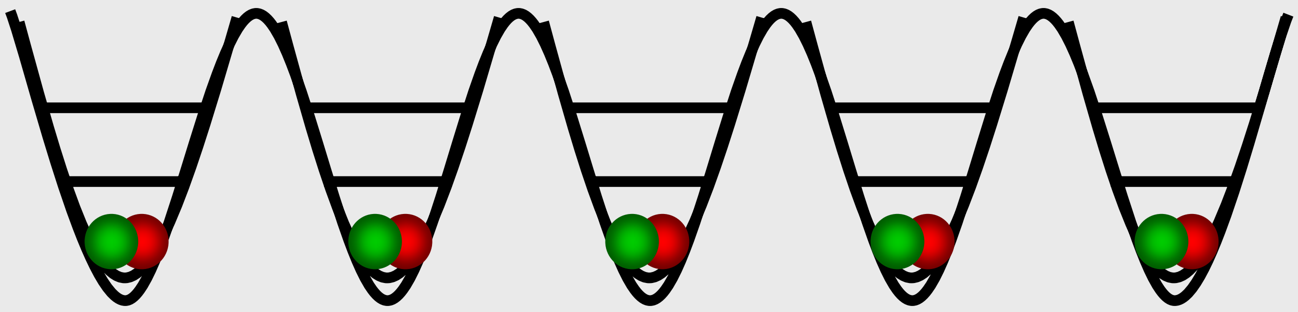


Composite Bosons

Free Fermions

Interactions in the lattice

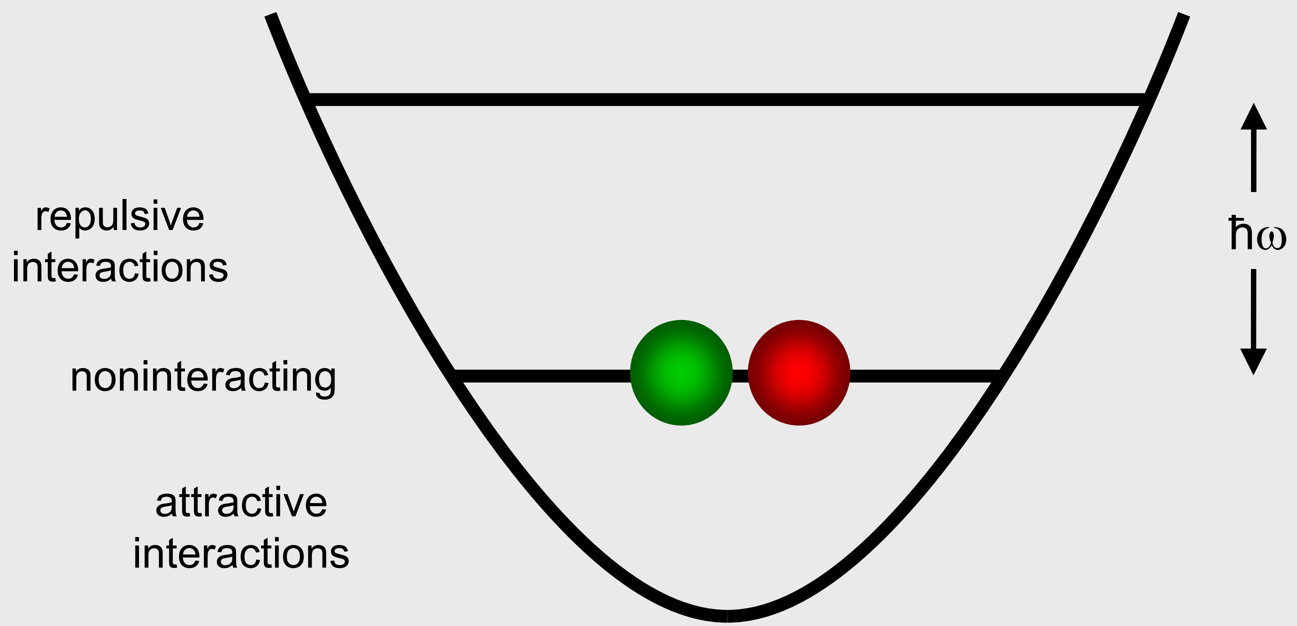
ETH



deep lattice = array of harmonic oscillators

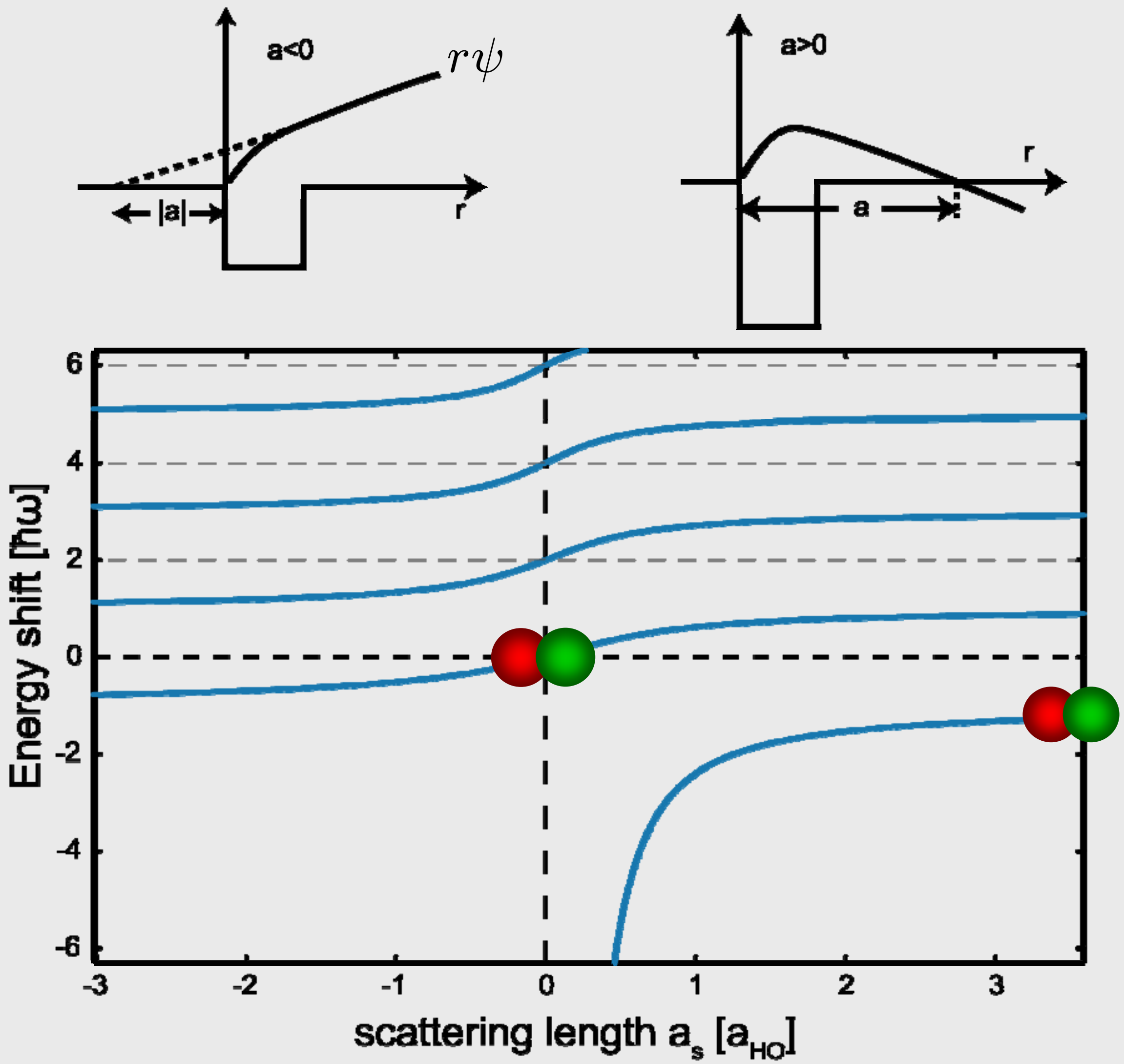
Interacting harmonic oscillator

ETH



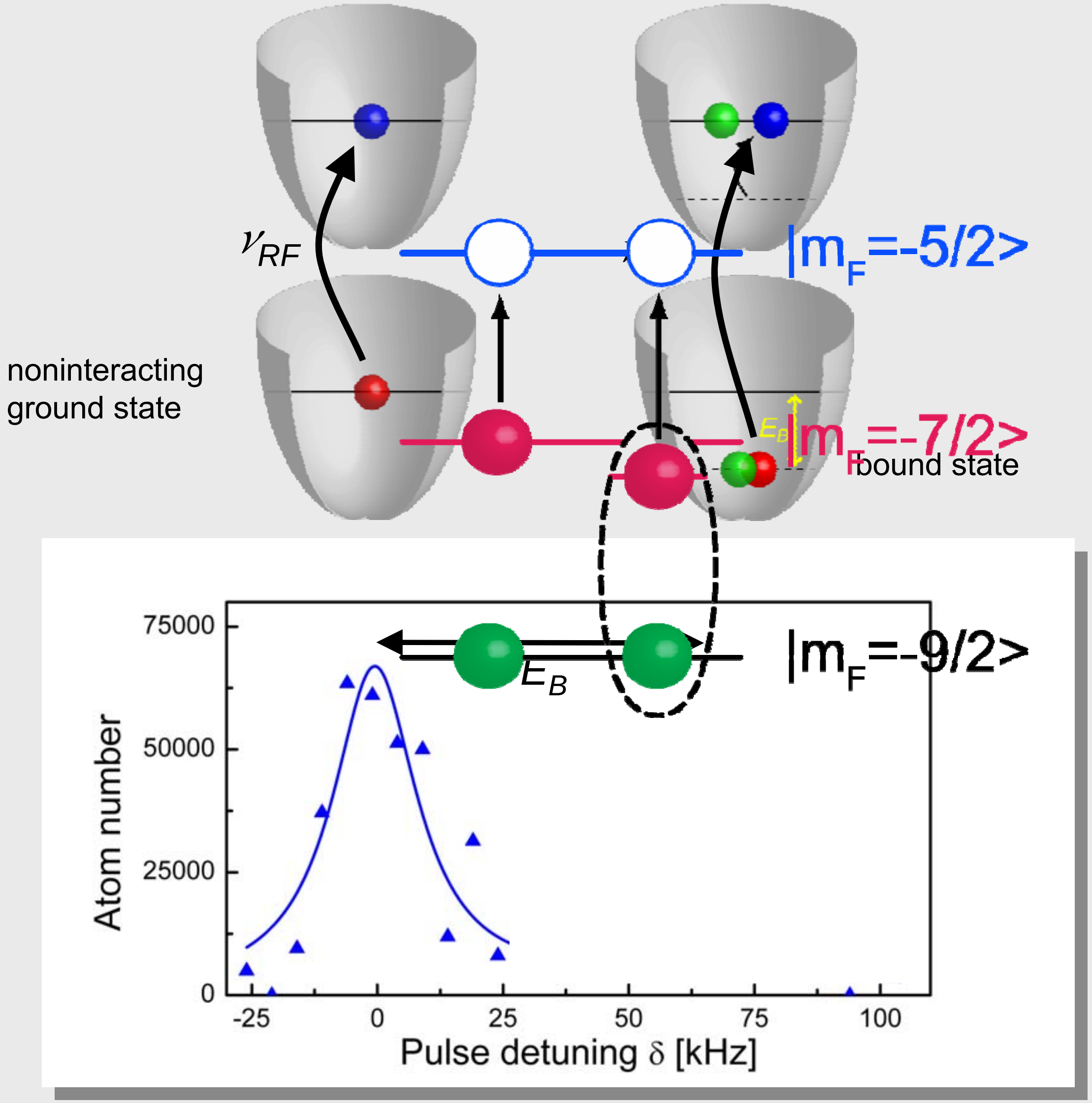
Harmonic oscillator spectrum

ETH



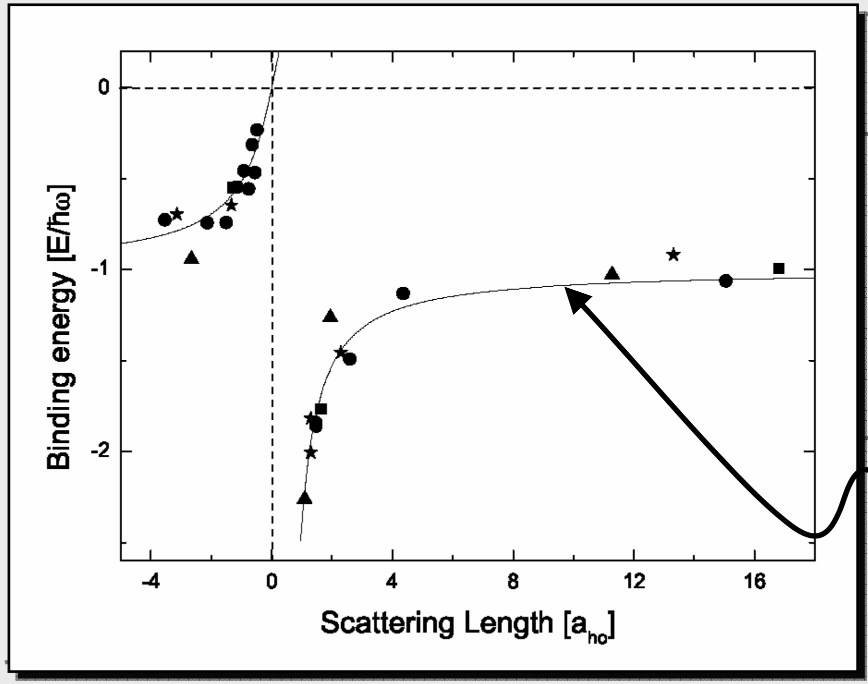
T. Busch et al., Found. Phys. 28, 549 (1998)

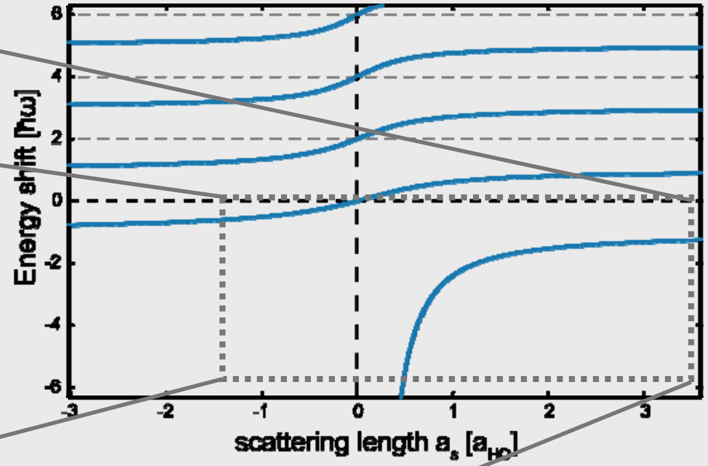
RF spectroscopy in the lattice



Measuring the binding energy

ETH





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

Exact theory
(no free parameters)

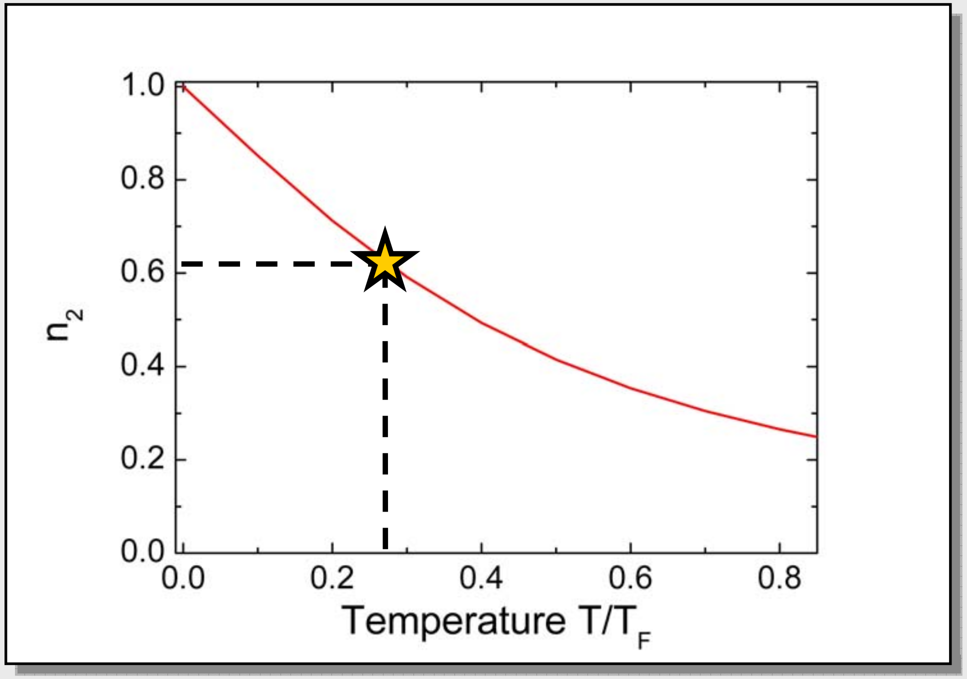
Fermionic atoms transform into bosonic molecules!

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

Thermometry in the lattice

ETH

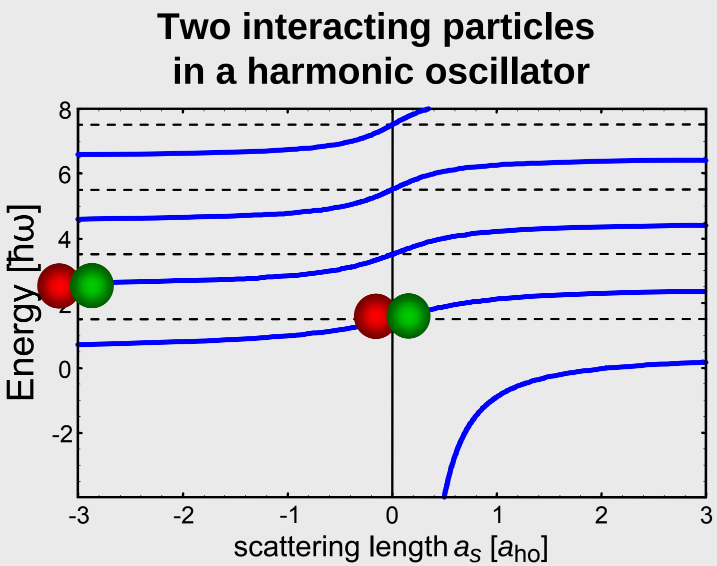
Temperature determines the fraction of doubly occupied lattice sites n_2.



M. Köhl, cond-mat/0510567.

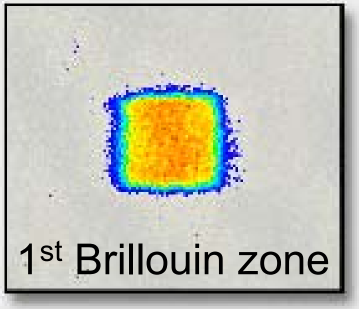
see also: H. G. Katzgraber et al., cond-mat/0510194 and for bosons: G. Pupillo et al., cond-mat/0407075.

Going the other direction …

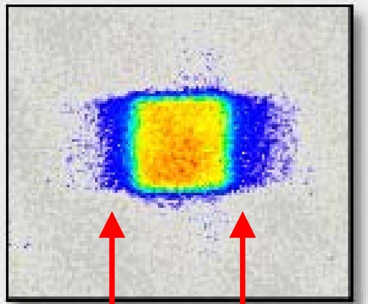


Physics beyond the single band Hubbard model.

noninteracting



sweep across
Feshbach resonance

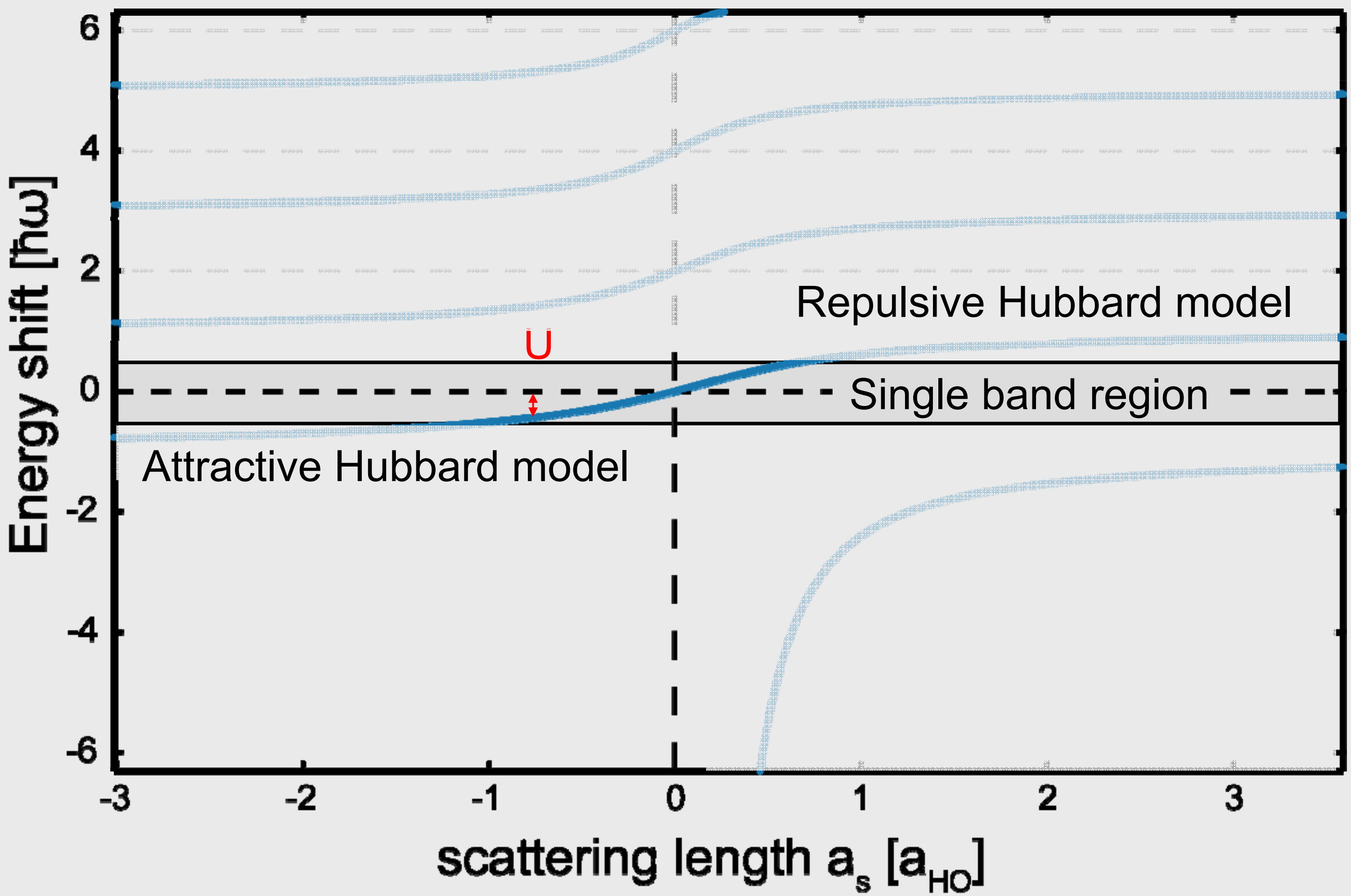


observe atoms in
higher bands

M. Köhl et al., Phys. Rev. Lett. 94, 080403 (2005).

Theory: Diener & Ho, PRL 96, 010402 (2006), H. G. Katzgraber et al., PRA 74, 043602 (2006).

Connection to Hubbard model



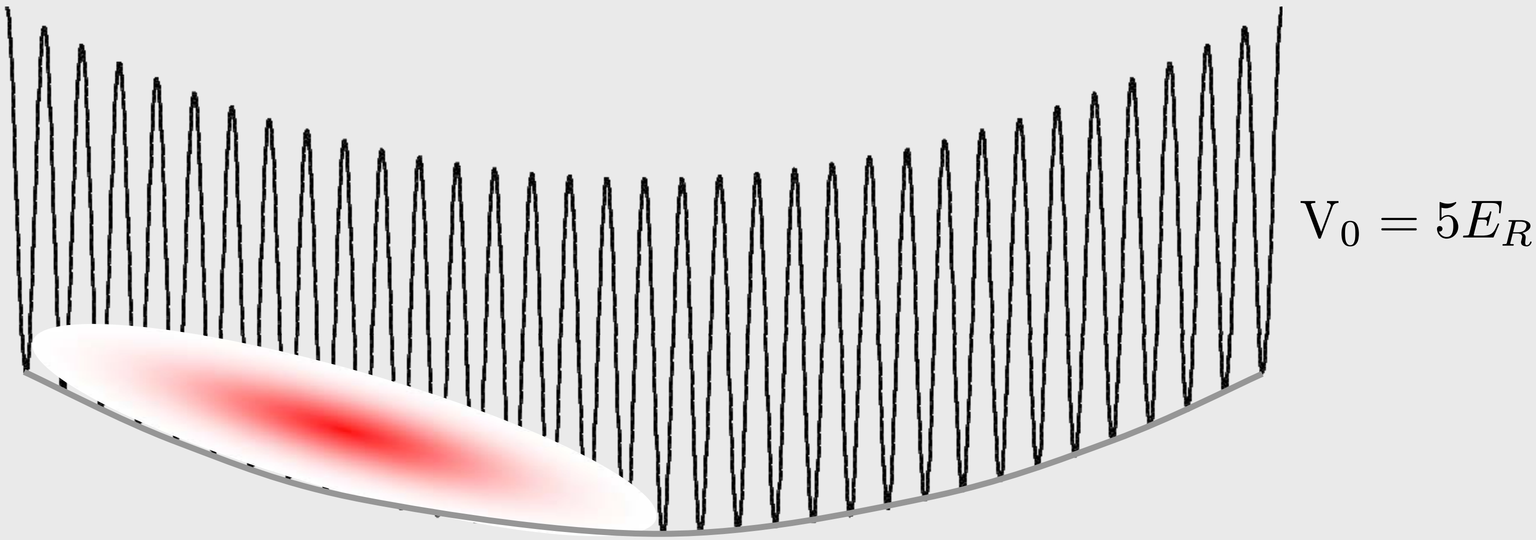
Ideal Fermi gas in a 3D lattice

Strong interactions in the lattice

Transport of interacting fermions

1D Fermi gas

Observing transport

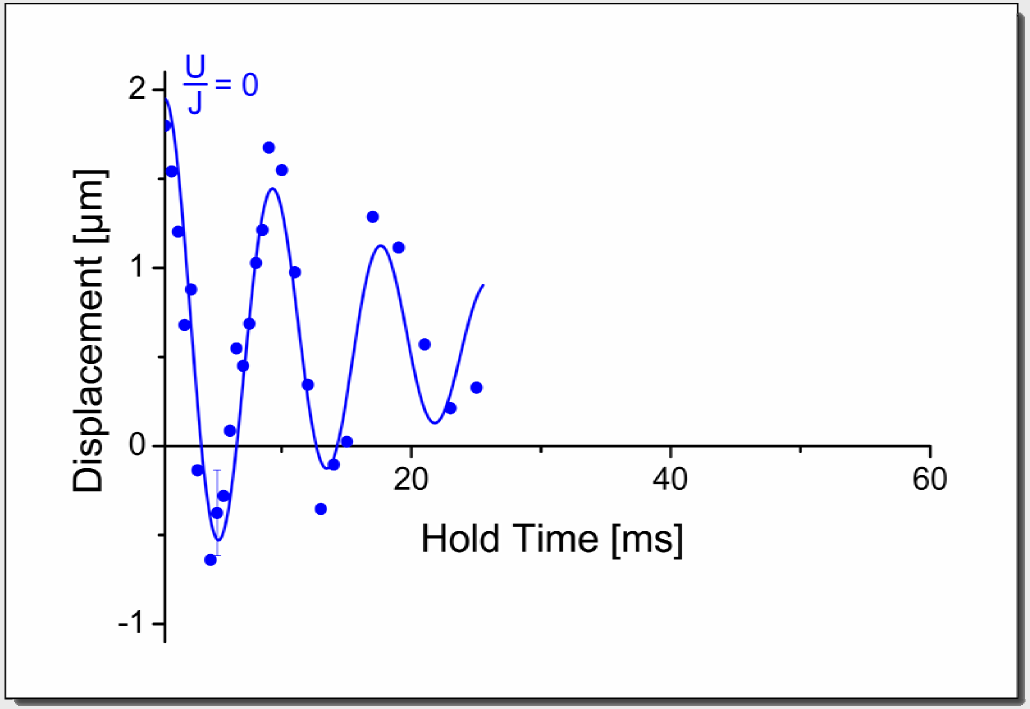


C. D. Fertig et. al, Phys. Rev, Lett, 92, 120403 (2005)
H. Ott, E. de Mirandes, F. Ferlaino, G. Roati, G. Modugno, and M. Inguscio, Phys. Rev, Lett, 92, 160601 (2004)

Observing transport

ETH

Lattice depth 5 E_R, ~half filling in the center

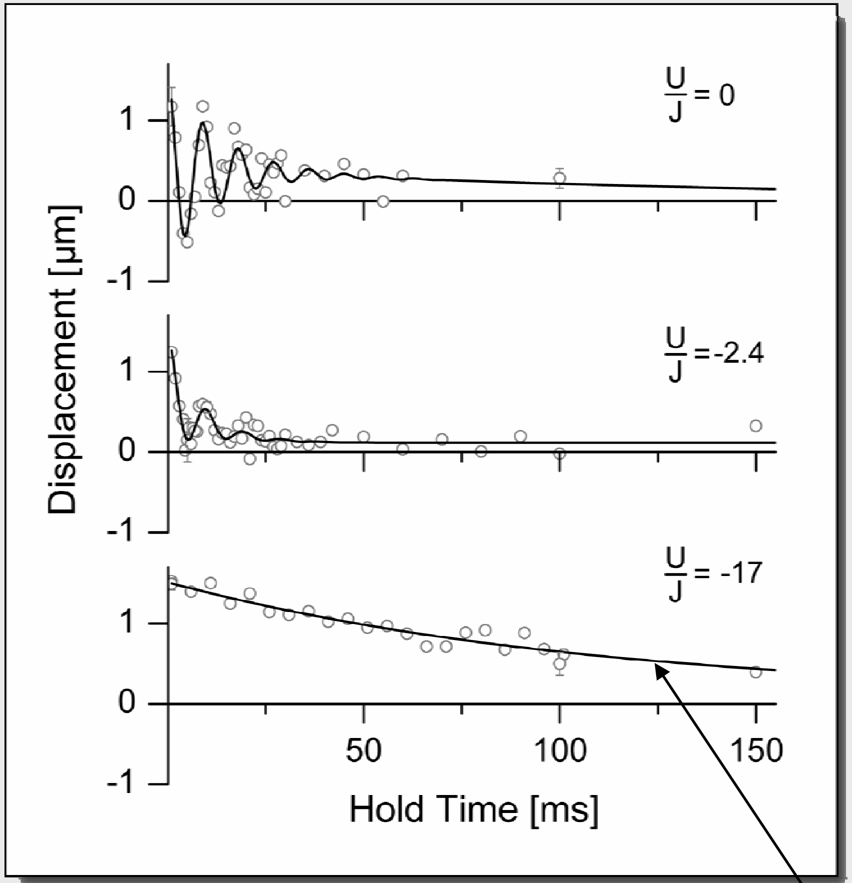


Inhibited Transport

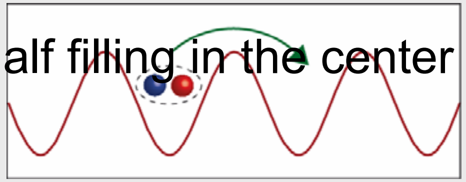
ETH

No interaction

Strong attraction

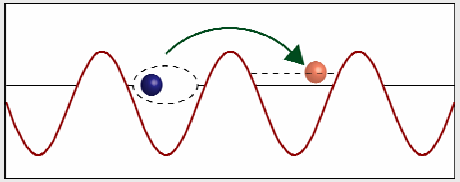


~ half filling in the center



pair tunneling

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



effective tunneling

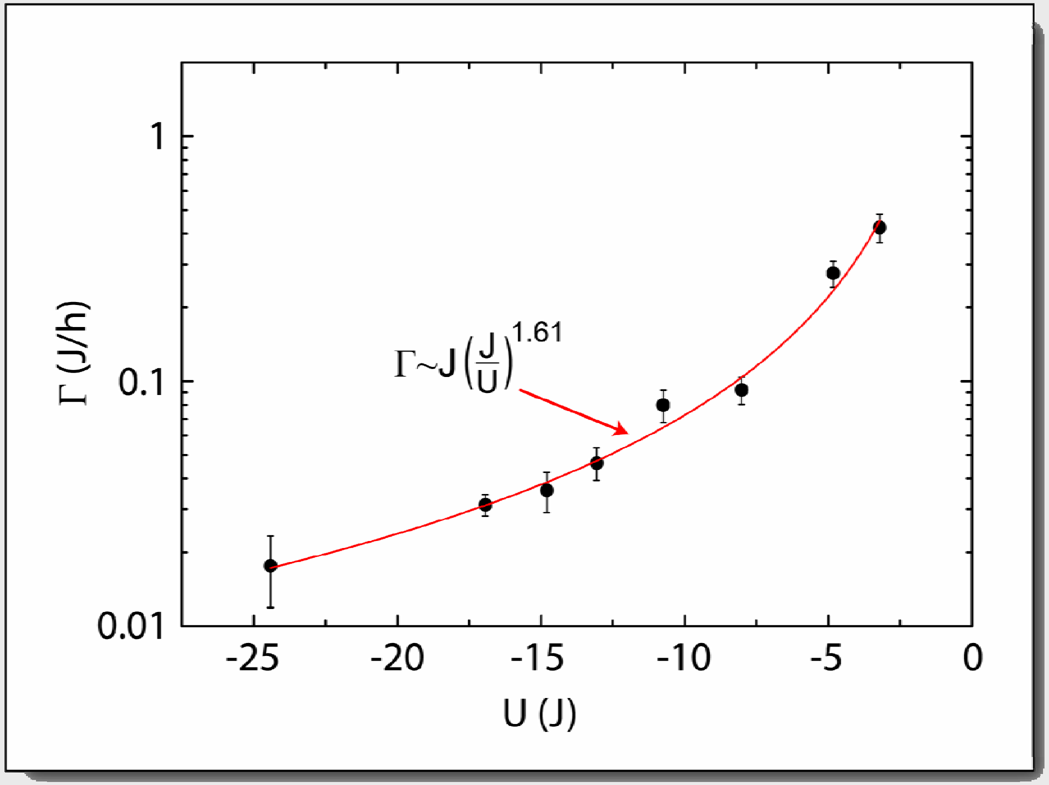
$J_{eff} = 2J \cdot \frac{J}{U}$

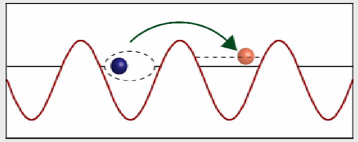
$$y(t) = y_0 + A\, e^{-\Gamma \cdot t}$$

Drift Rate

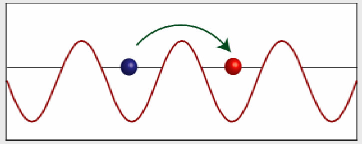
fast

slow

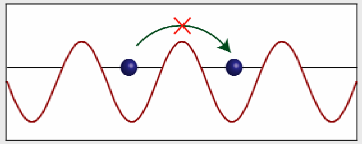




$$J_{eff} = 2J \cdot \frac{J}{U}$$



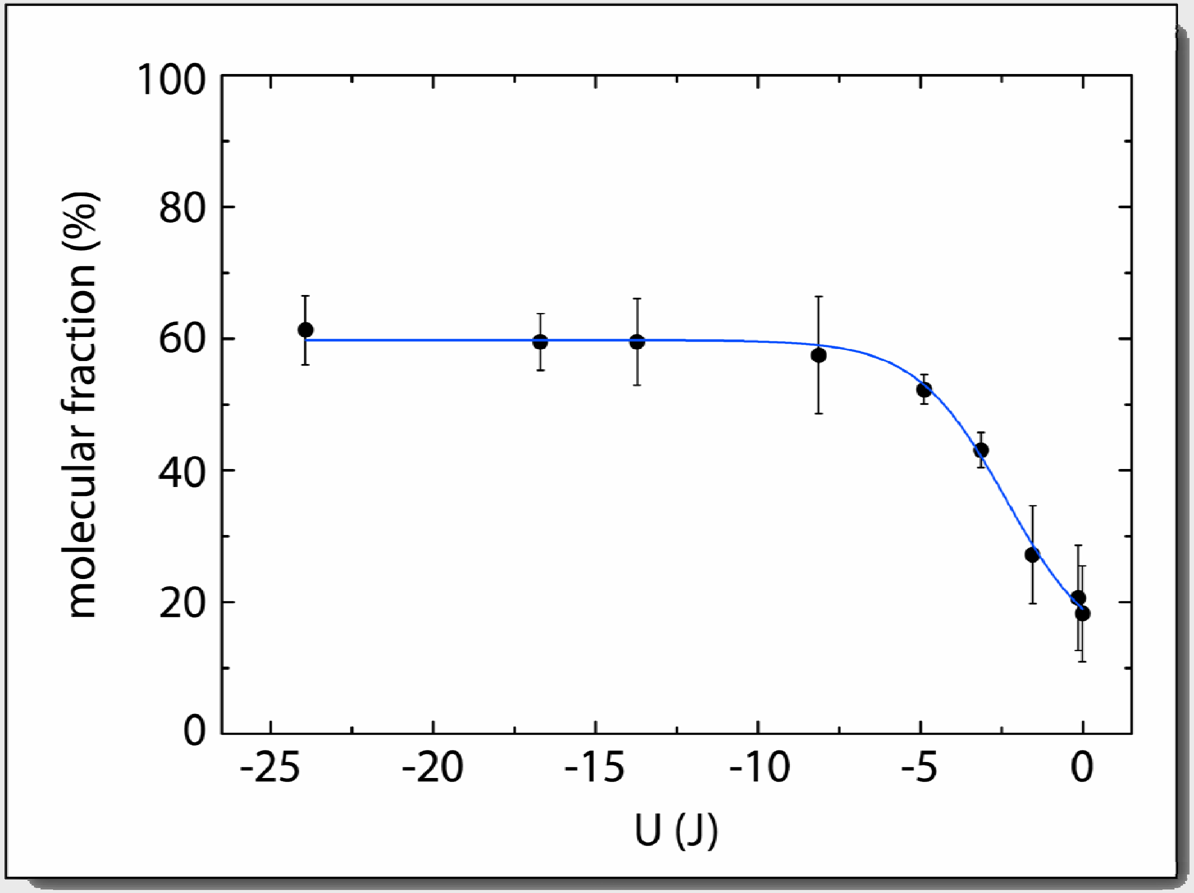
Normal tunneling J



No tunneling

← Increasing attraction

Pair formation increases



Ideal Fermi gas in a 3D lattice

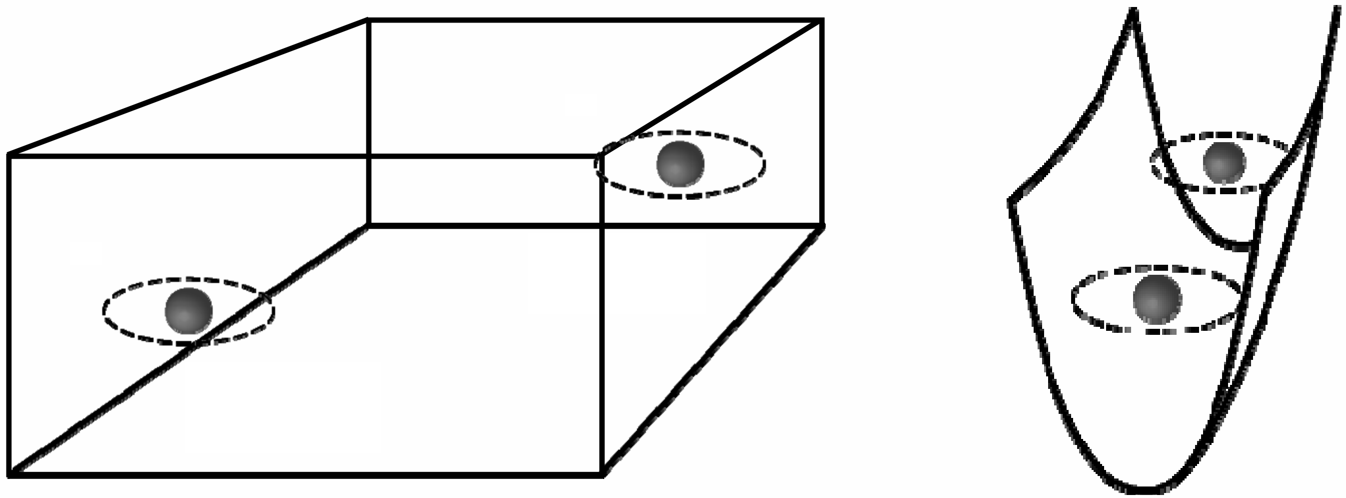
Strong interactions in the lattice

Transport of interacting fermions

1D Fermi gas

Scattering and confinement

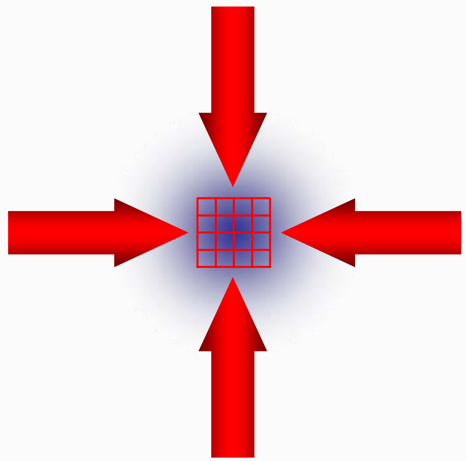
ETH



Bound state for a>0
(Wigner, 1933)

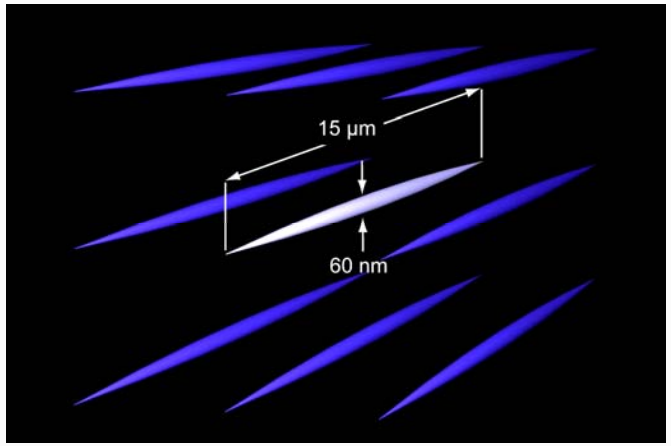
1D is different!
(Olshanii, 1998)

1D Fermi Gas



fermionic ^{40}K

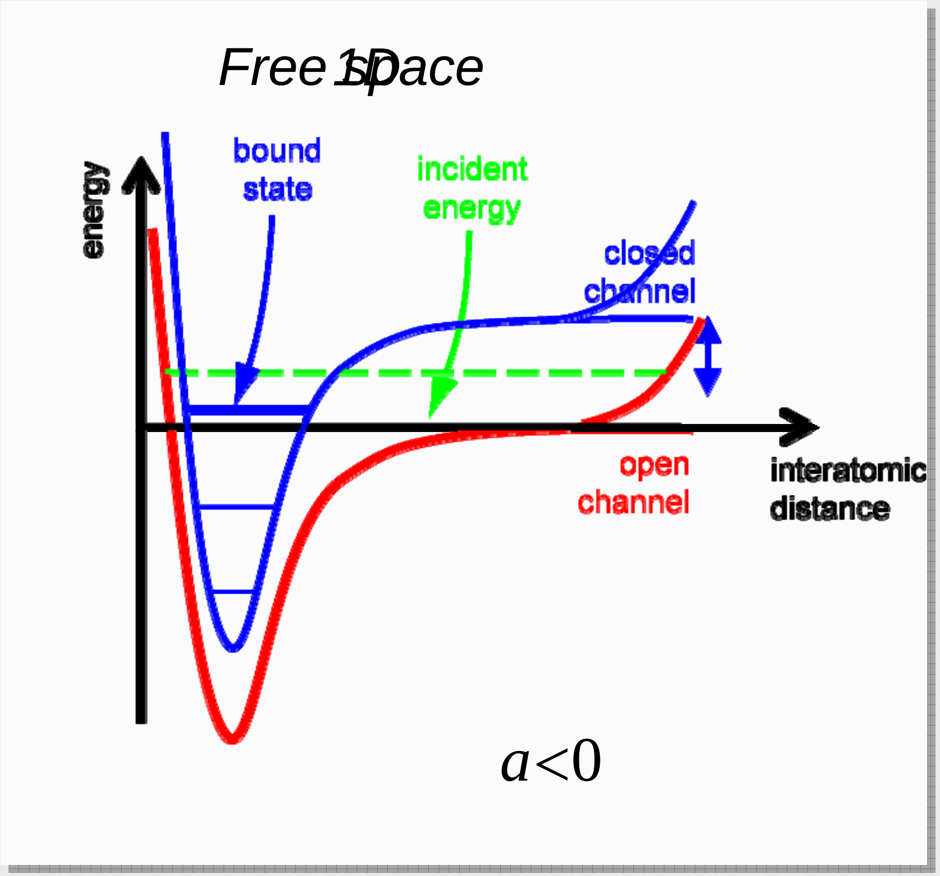
red-detuned standing waves
$V = 25\ E_R$, $\lambda = 826$ nm



- *aspect ratio* $\omega_\perp / \omega_z \simeq 270$
- $E_F = N\hbar\omega_z << \hbar\omega_\perp$
- $k_B T < E_F$

Molecules in 1D

ETH



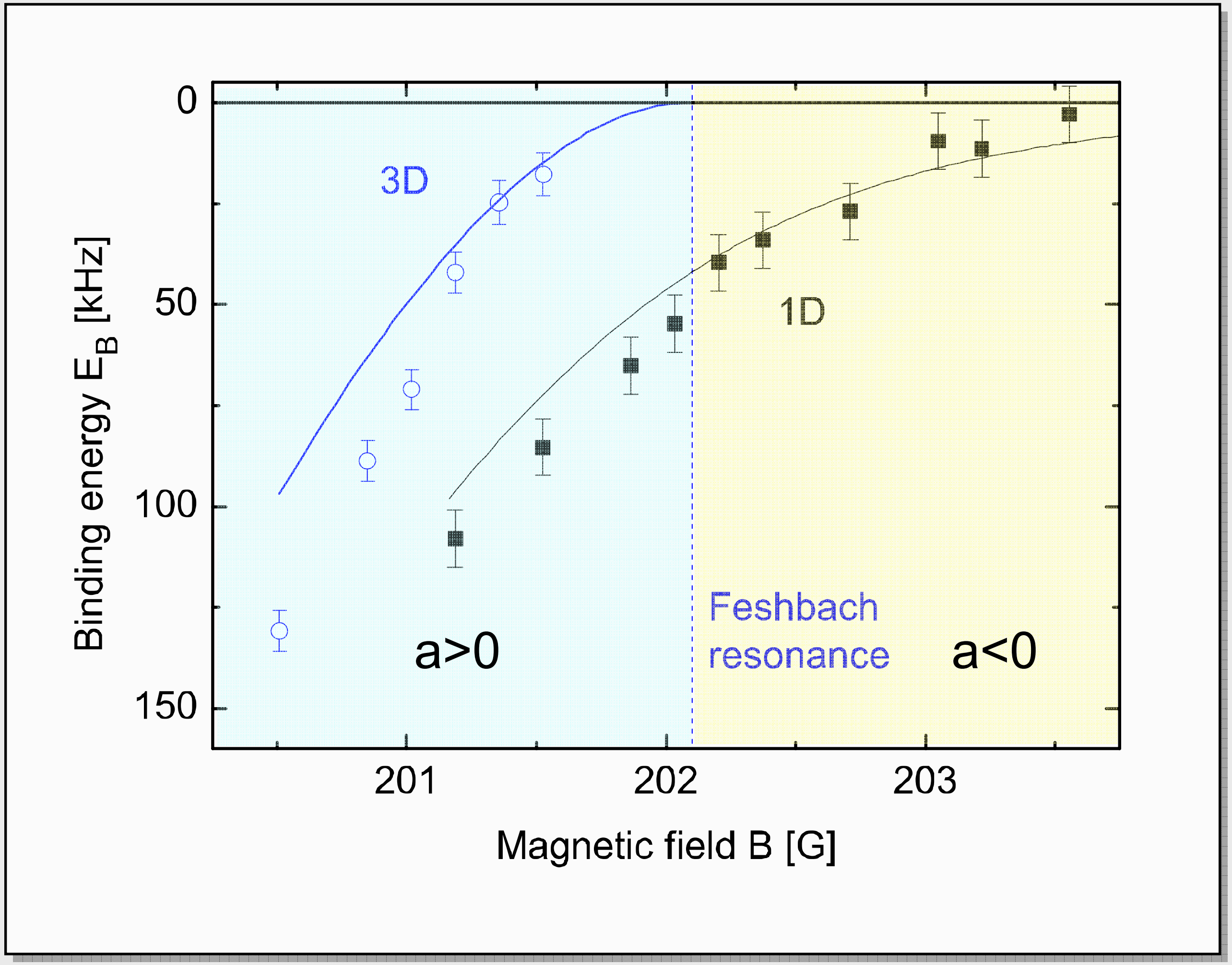
$$\frac{a}{l_\perp} = -\frac{\sqrt{2}}{\Gamma(1/2, -E_B/2\hbar\omega_\perp)}$$

T. Bergemann, M.G. Moore, M. Olshanii

Phys. Rev. Lett. 91, 163201 (2003)

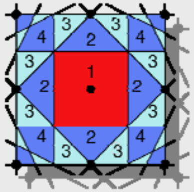
1D versus 3D

ETH

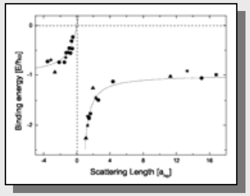


H. M., T. Stöferle, K. Günter, M. Köhl, T. Esslinger, Phys. Rev. Lett. 94, 210401 (2005).

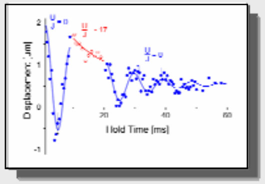
Conclusions



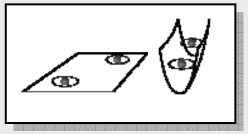
Fermi surfaces



Strong interactions & molecules

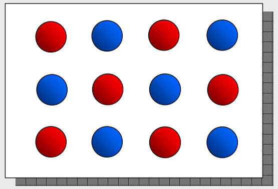


Transport of interacting fermions



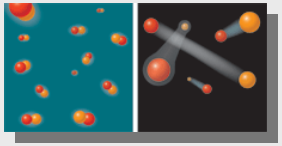
1D Fermi Gas

Outlook



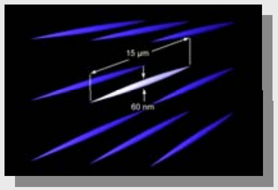
Mott insulating & antiferromagnetic phase

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



Superfluidity in the lattice

W. Hofstetter et al., PRL 89, 220407 (2002)



Low-dimensional systems

Exactly solvable BEC-BCS Crossover
J.N. Fuchs et al., PRL 93, 090408 (2004)
I.V. Tokatly, Phys. PRL 93, 090405 (2004)