The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
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1957-22

Miniworkshop on Strong Correlations in Materials and Atom Traps

4 - 15 August 2008

Strongly correlated fermionic gases in optical lattices.

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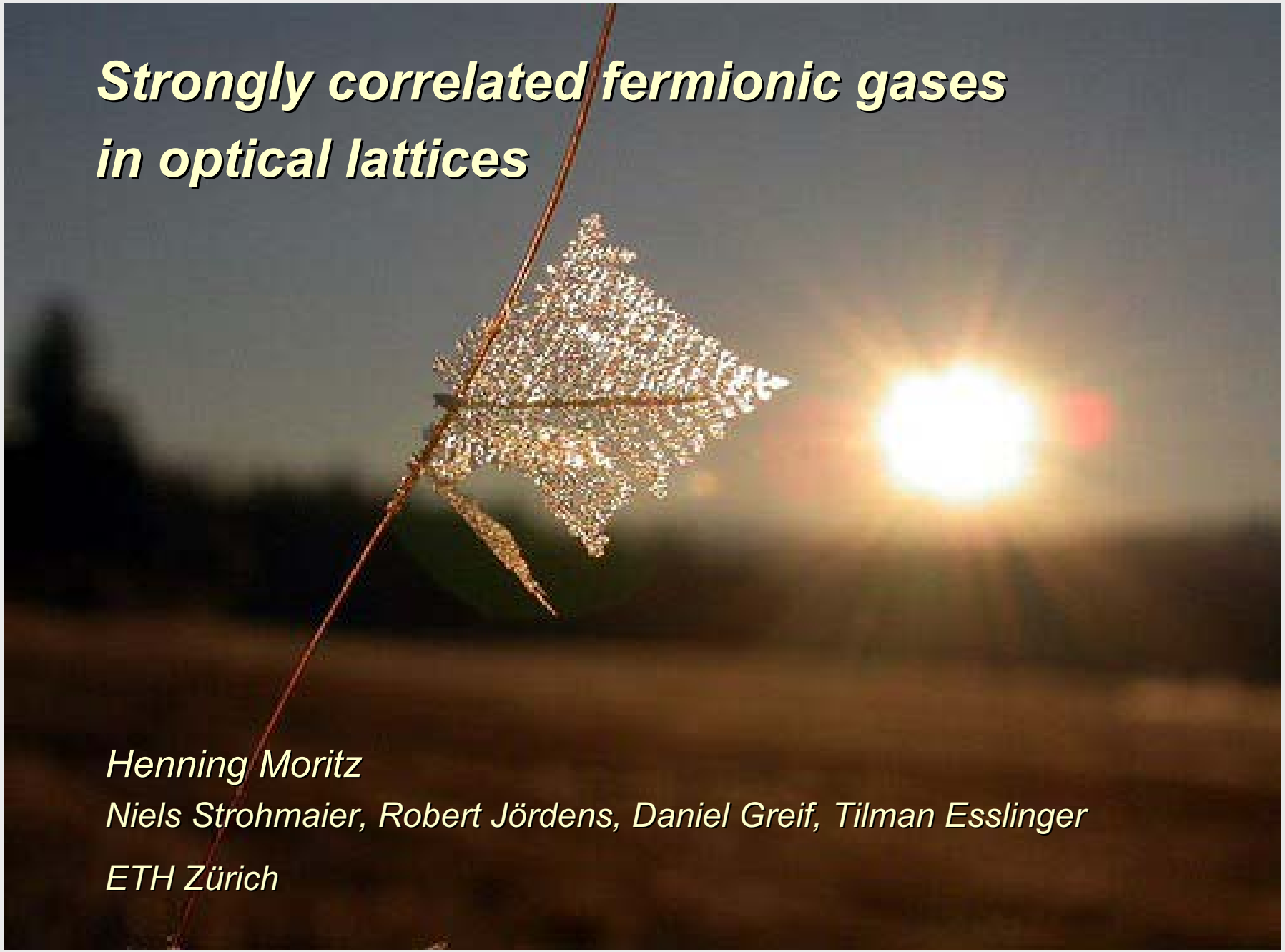


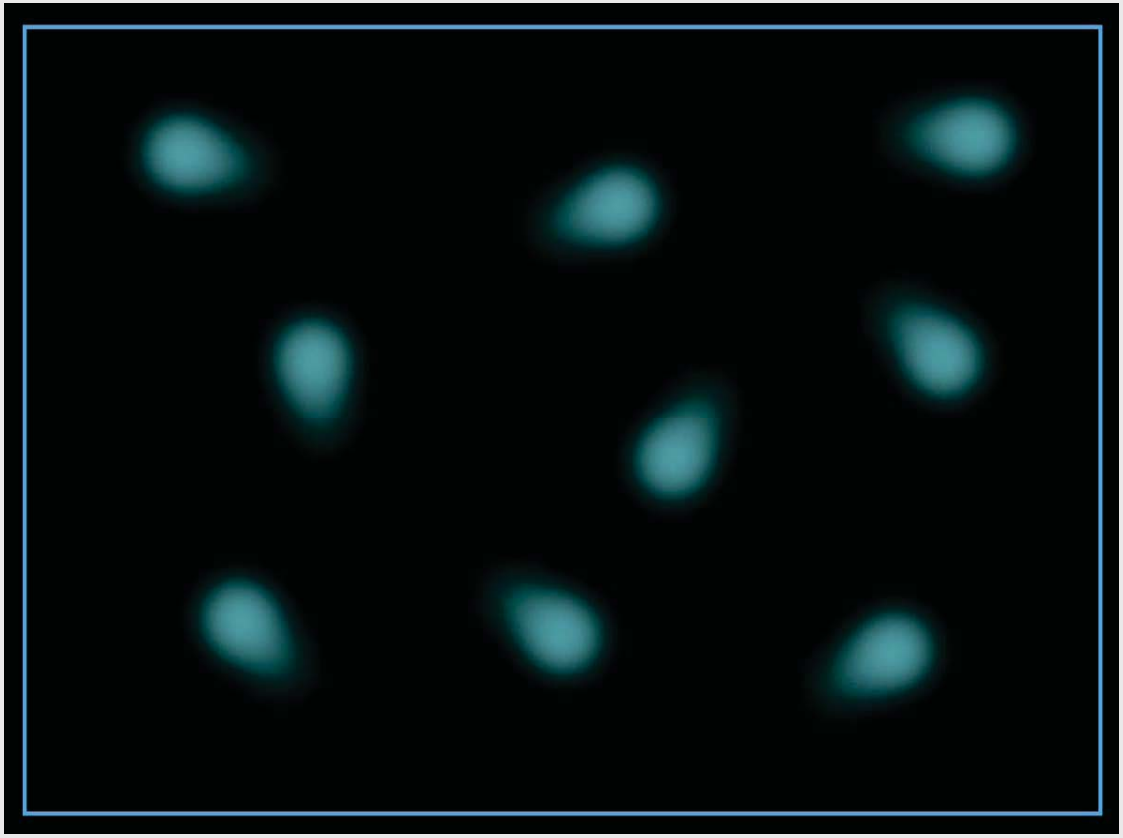
Strongly correlated fermionic gases in optical lattices

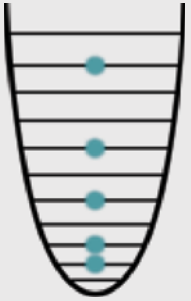
Henning Moritz

Niels Strohmaier, Robert Jördens, Daniel Greif, Tilman Esslinger

ETH Zürich

An ultracold gas

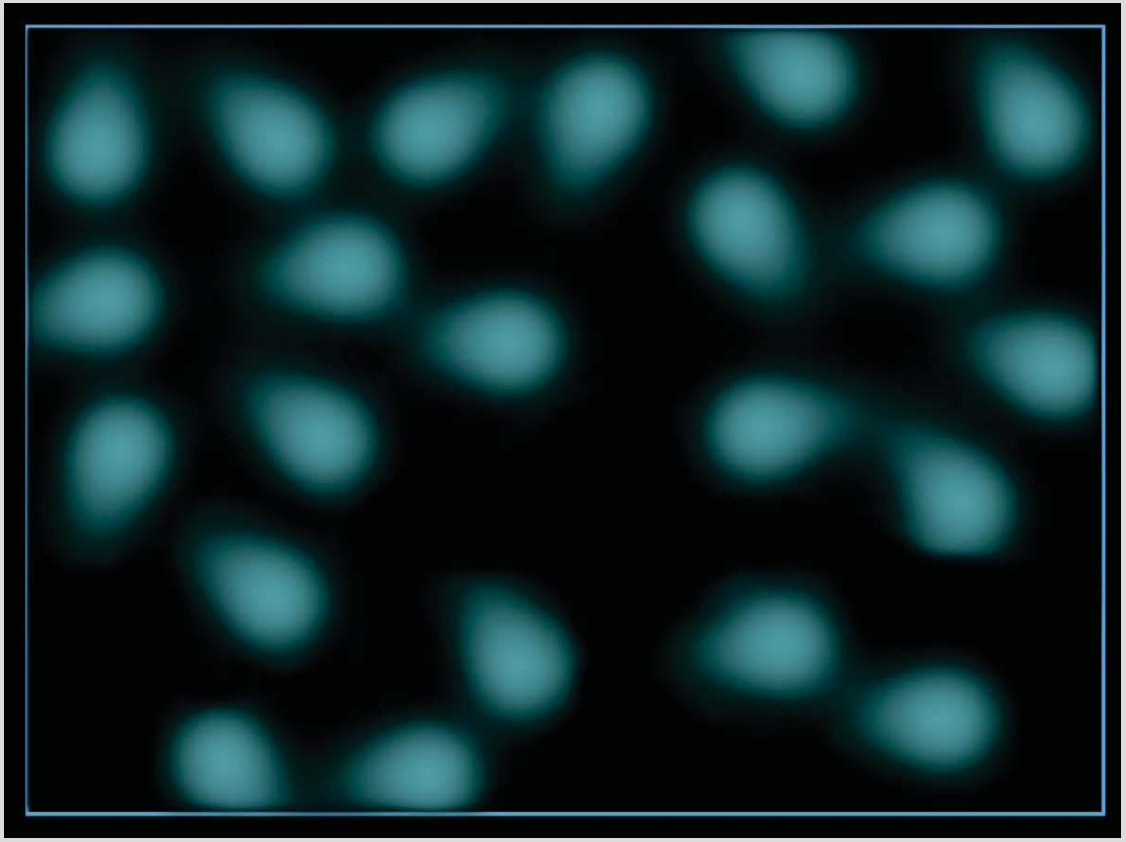


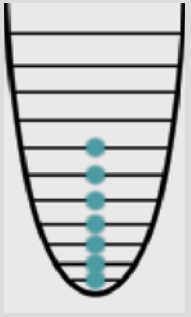


T ~ 10 μK

A quantum degenerate Fermi gas

ETH



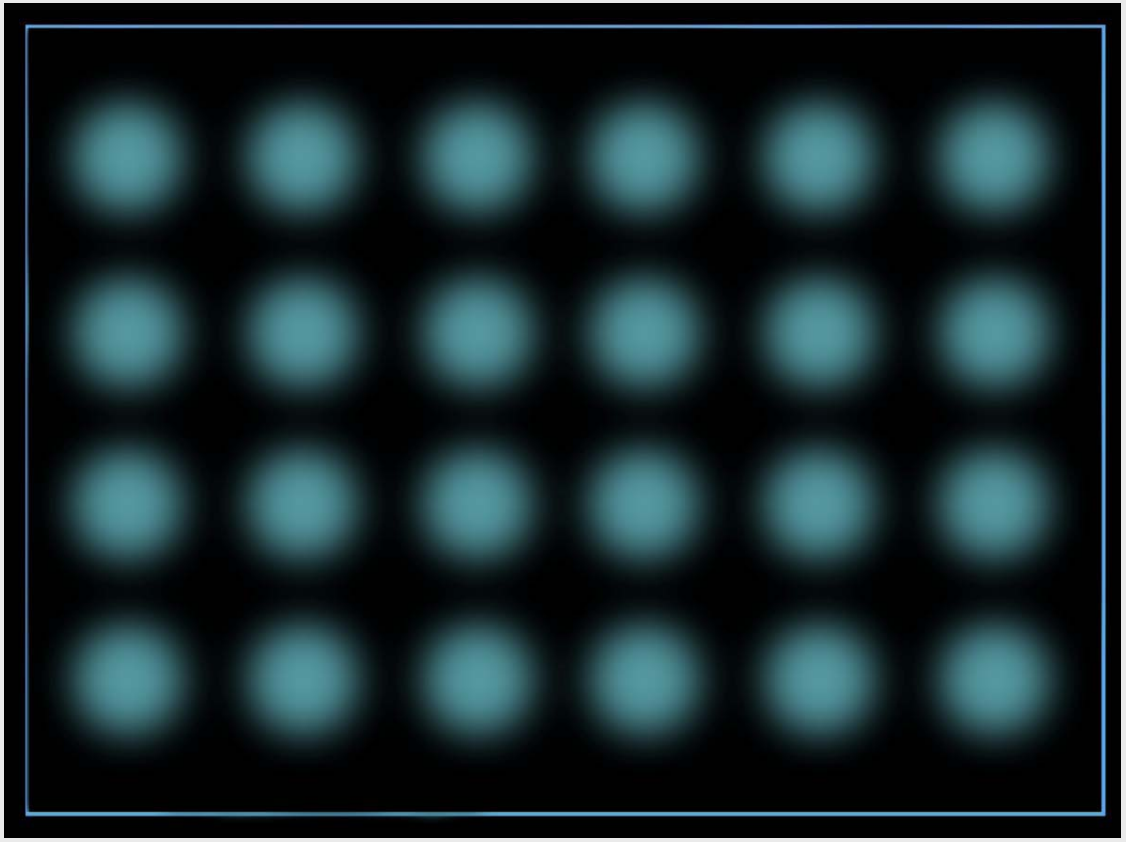


$T \approx 20nK < T_F$

$\lambda_{db} \sim d$

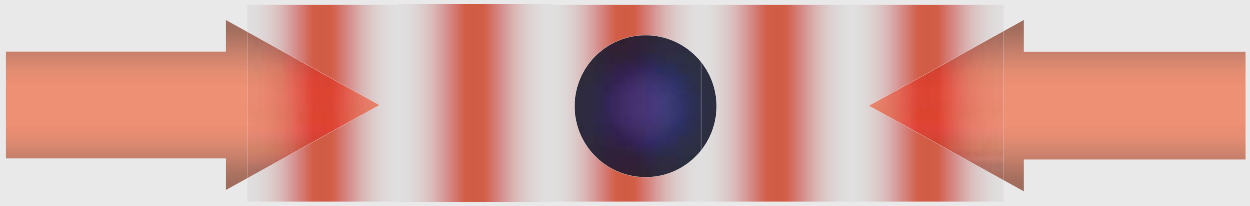
Ultracold fermions in a crystal structure

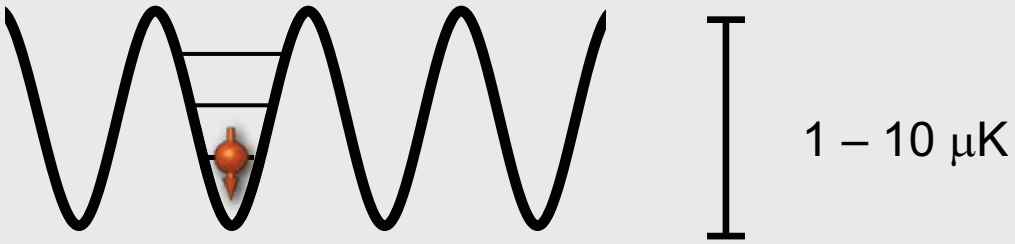
ETH



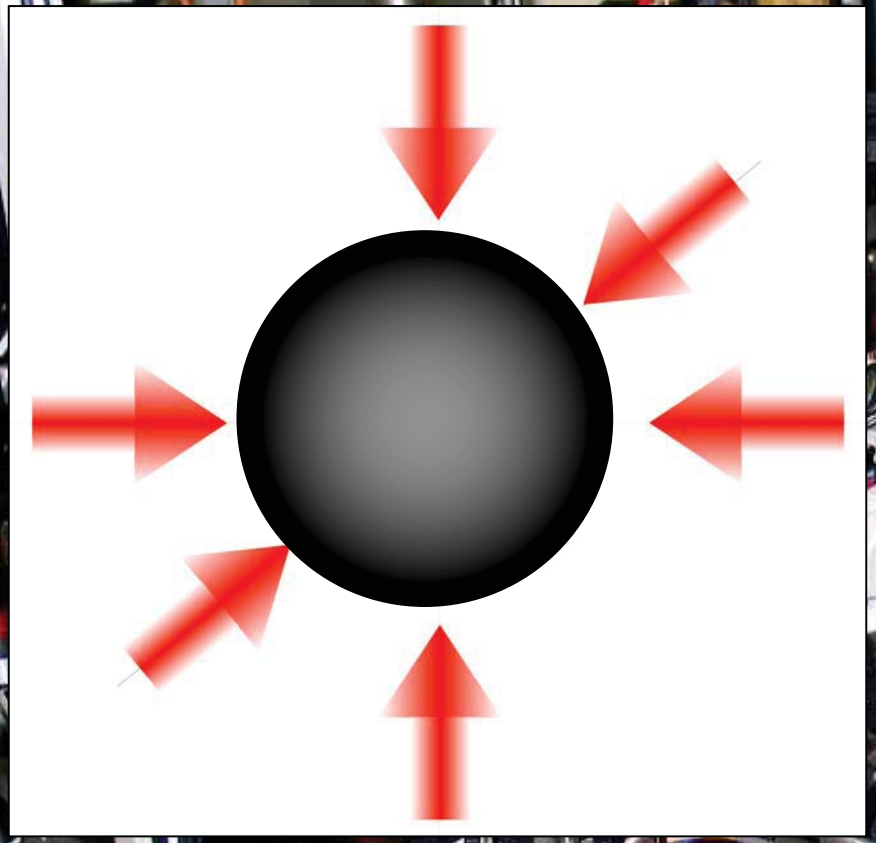
Trapping atoms in a standing wave

ETH





3D Optical Lattice



Fermions ~0K (typically ~10^{-9})

Lattice period 532nm

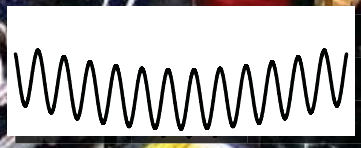
No more than 100 000 sites occupied

0-2 atoms per site

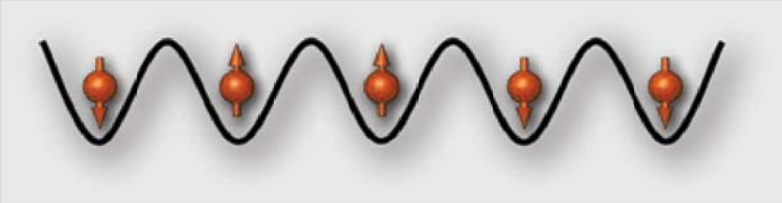
Size of HO ground state ~30nm

3D lattices with fermions: ETH, Hamburg, MIT, Mainz

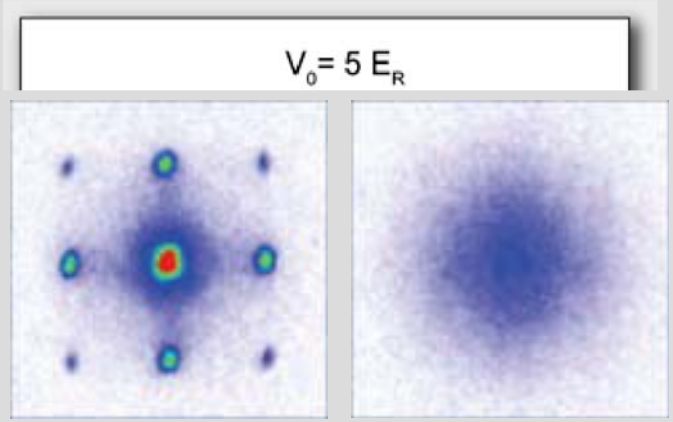
•Potential = simple cubic lattice + confining potential =



Strong correlations



With bosons



M. Greiner et al., Nature 415, 39 (2002) .

Sir Nevill Mott

Fermi-Hubbard model

ETH

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

- Interaction U; U=const. • scattering length
- Tunneling J
- Dimensionality
- Filling

D. Jaksch et al., PRL 81, 3108 (1998) .
W. Hofstetter et al., PRL 89, 220407 (2002).

Outline

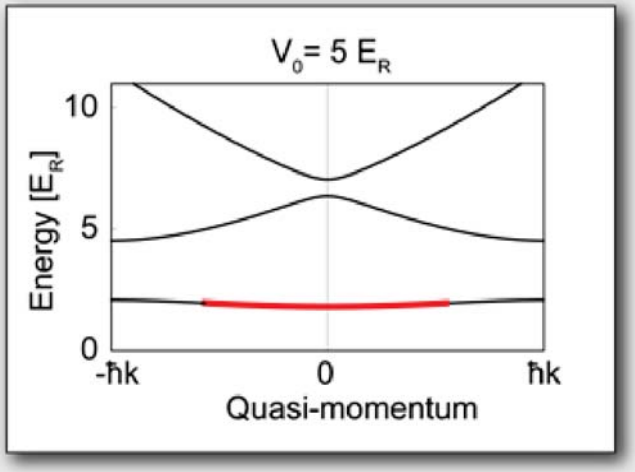
ETH

Ideal Fermi gas in a 3D lattice

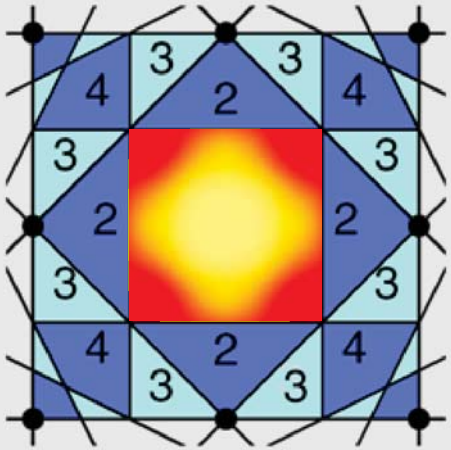
Strong interactions

A Mott insulating state of fermions

Filling the lattice



Brillouin zones
of a square lattice

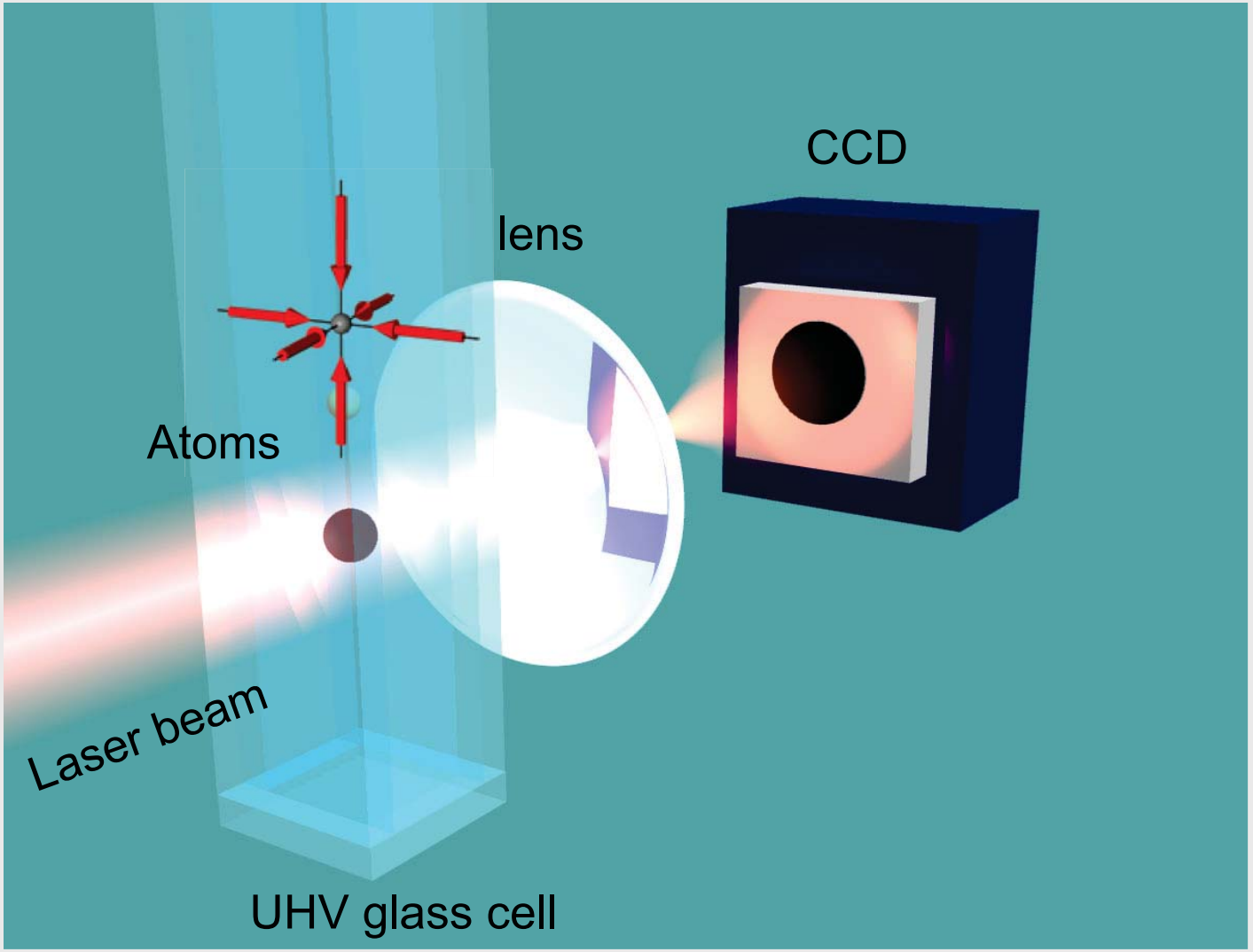


quasi momentum

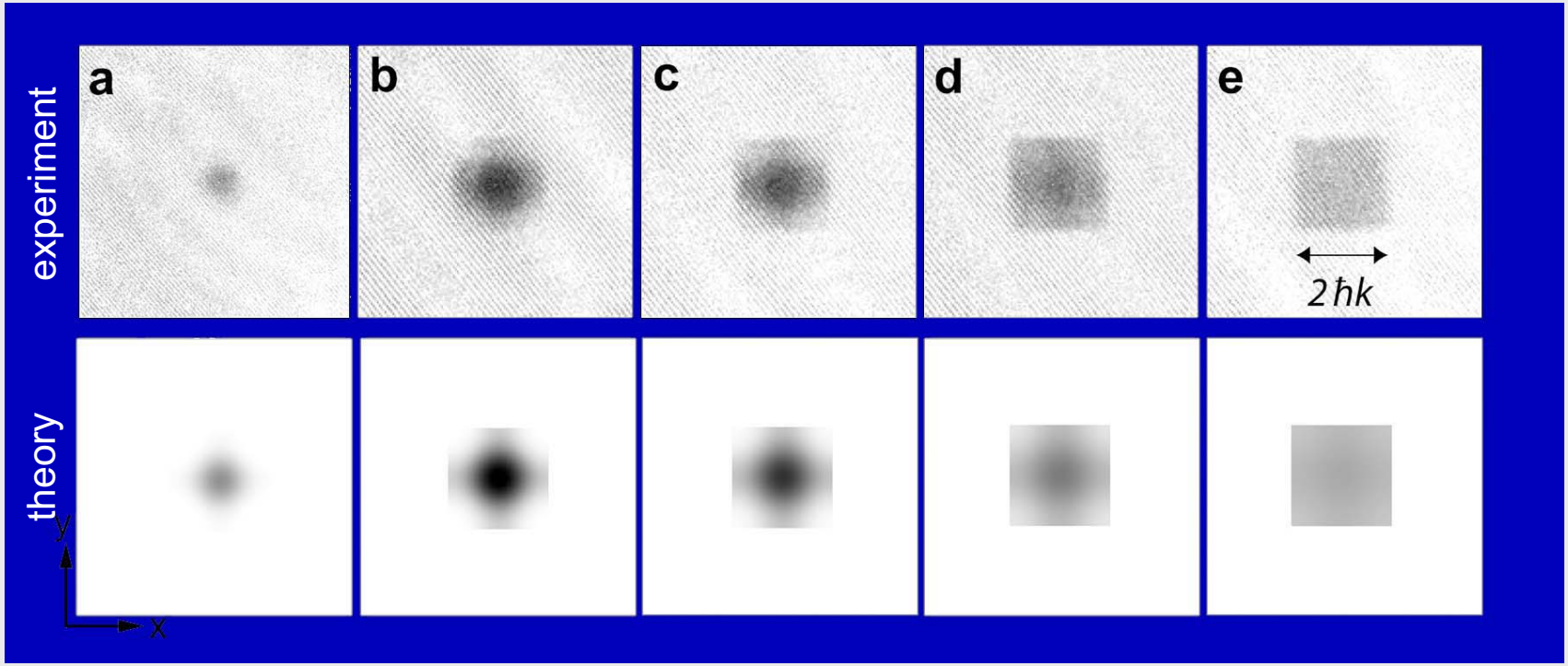
$2\ \hbar k$

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

Absorption Imaging



Observed Fermi surfaces



"conductive state" → "band insulator"

characteristic filling

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

Outline

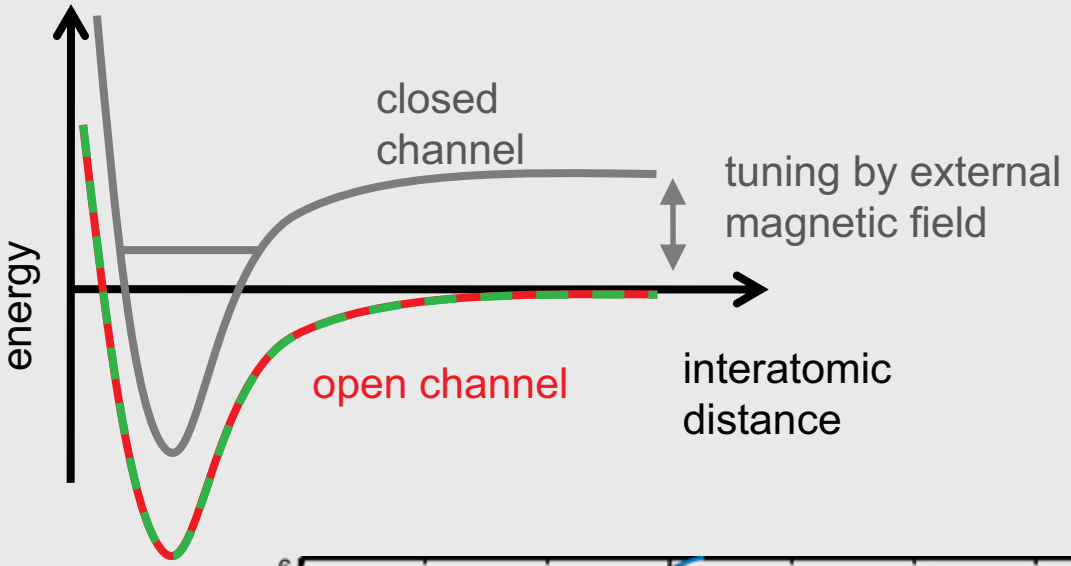
ETH

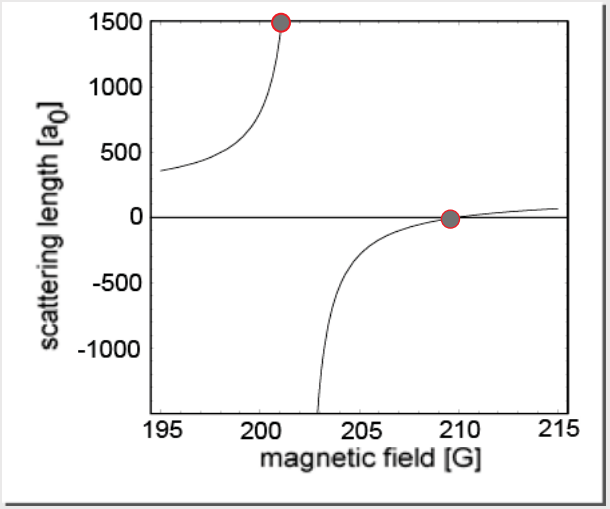
Ideal Fermi gas in a 3D lattice

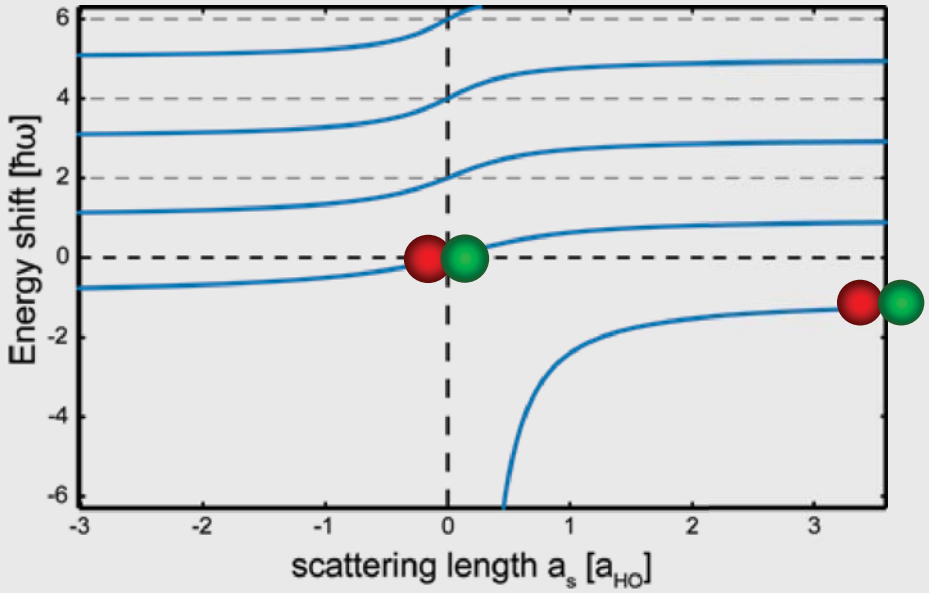
Strong interactions

A Mott insulating state of fermions

Tuning interactions: Feshbach Resonance

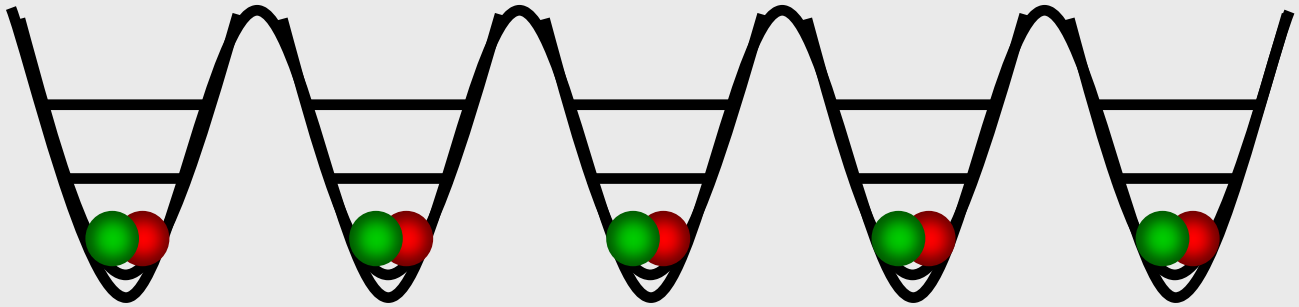






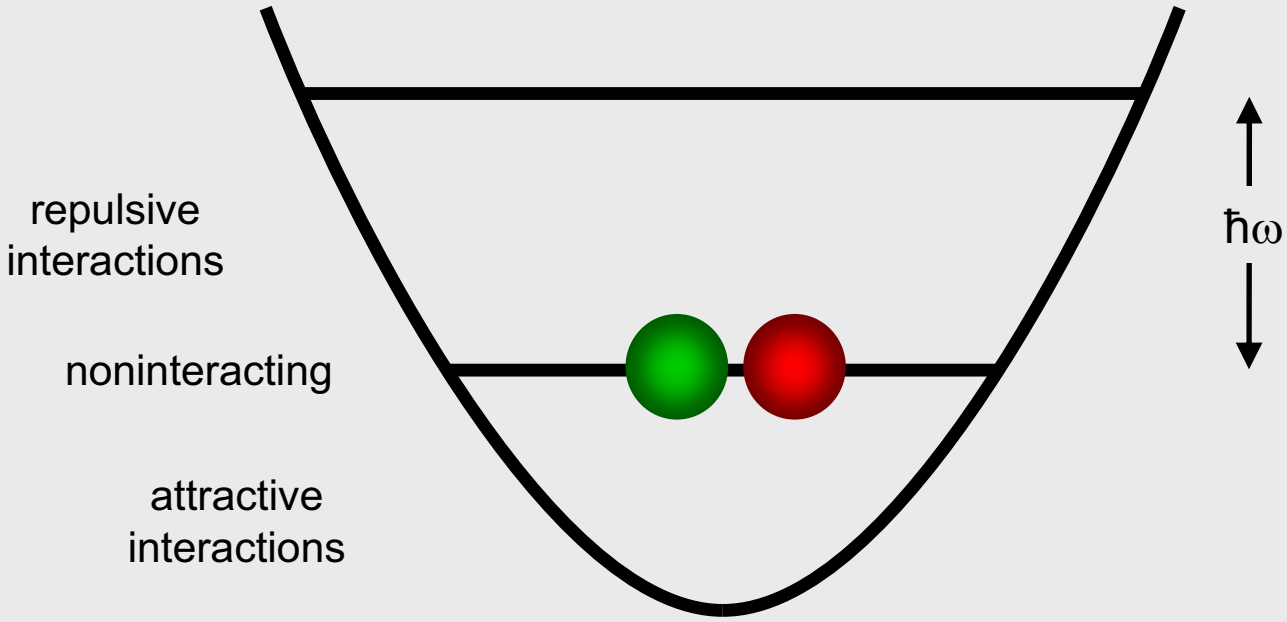
T. Busch et al.
Found. Phys. 28, 549 (1998)

Interactions in the lattice

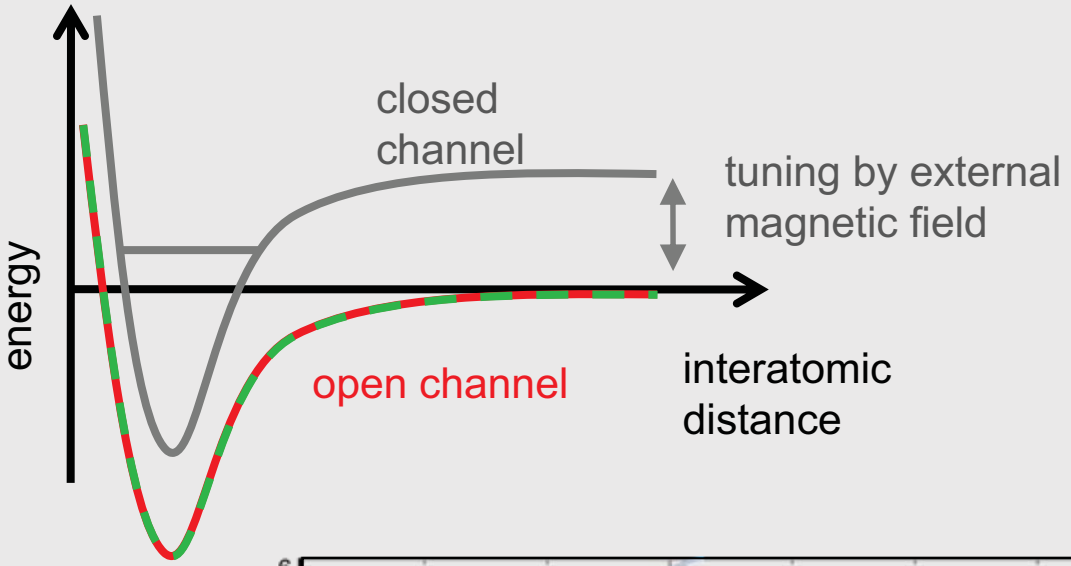


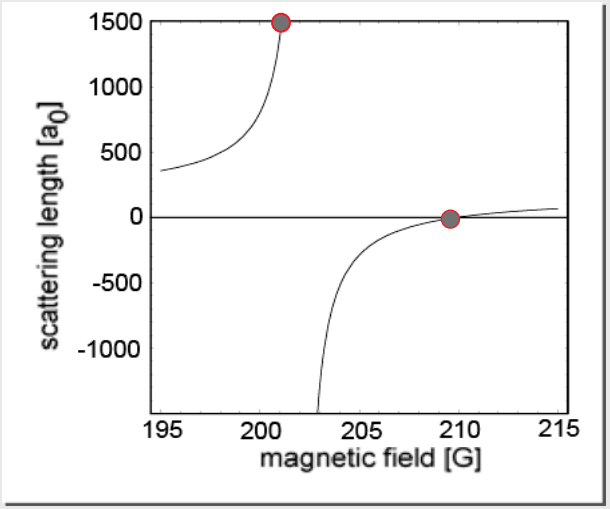
deep lattice = array of harmonic oscillators

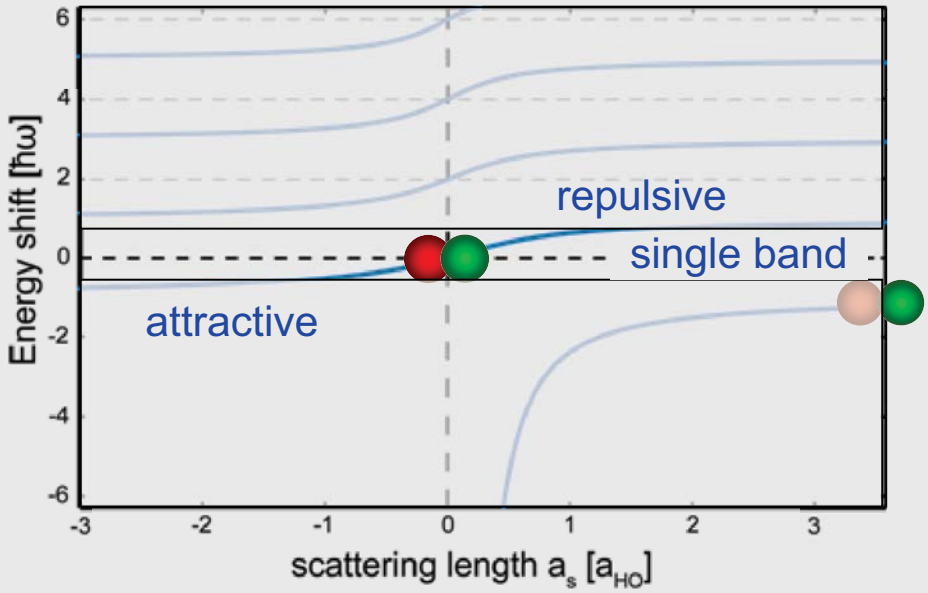
Interacting harmonic oscillator



Tuning interactions: Feshbach Resonance



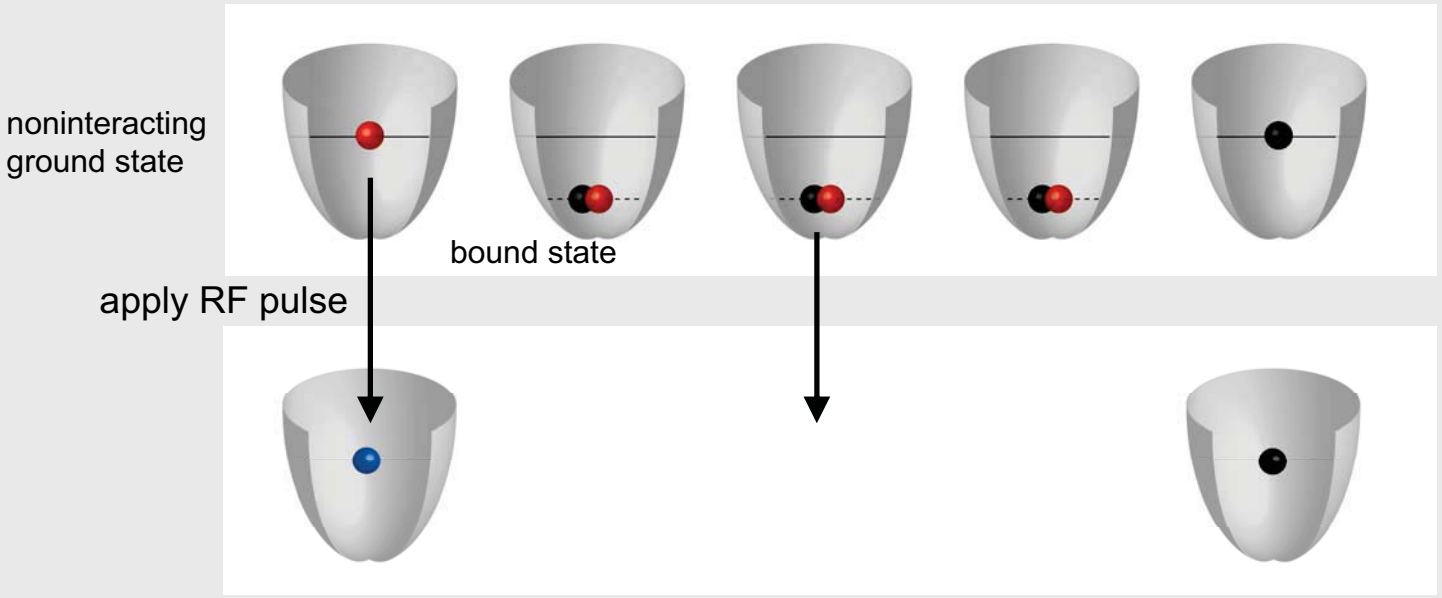


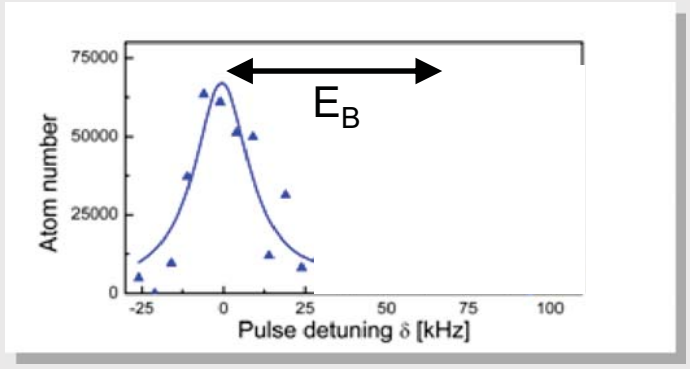


Hubbard model

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

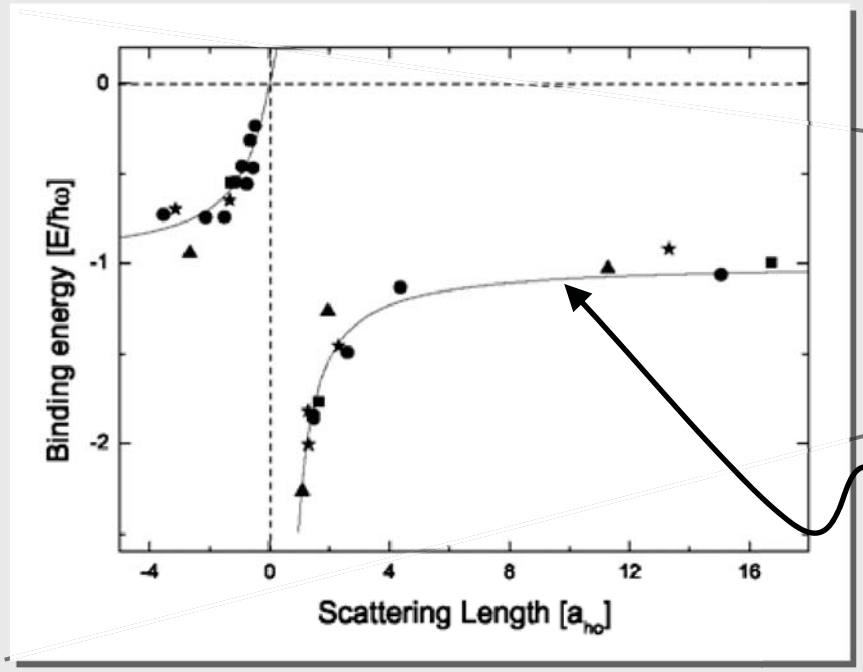
Radio-frequency spectroscopy

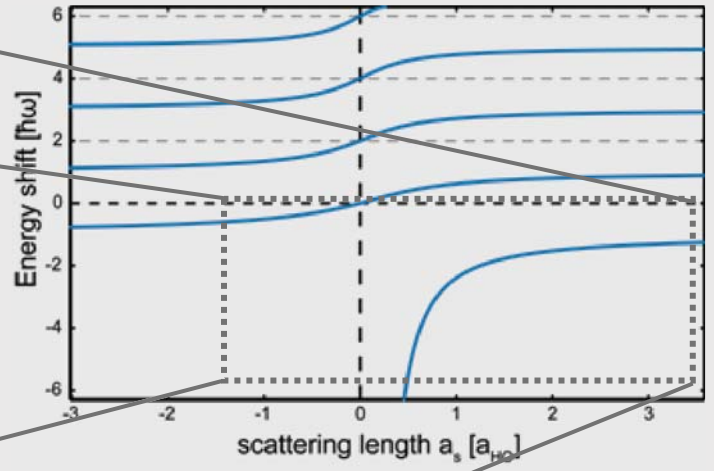




bound-bound
spectroscopy

Measuring the binding energy





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

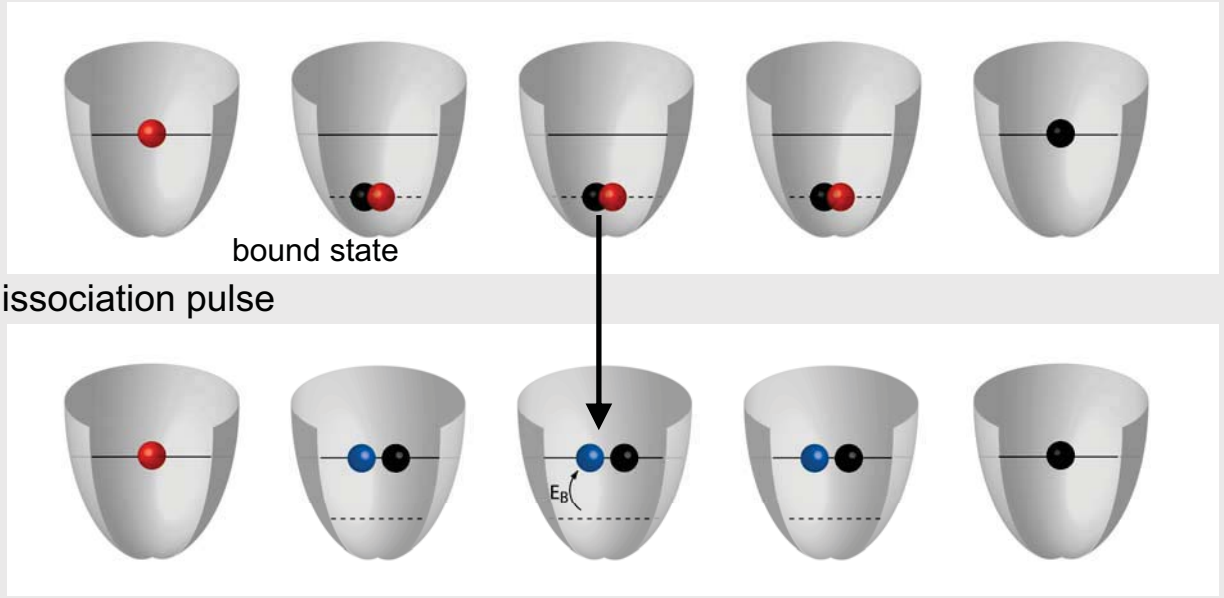
Exact theory
(no free parameters)

Fermionic atoms transform into bosonic molecules!

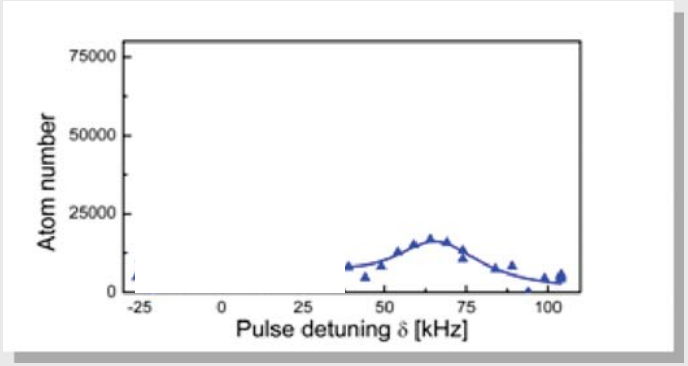
T Stöferle, H. M., K. Günter, M. Köhl, T. Esslinger, Phys. Rev. Lett. 96, 040301 (2006)

Measuring double occupancy

Interacting occupation



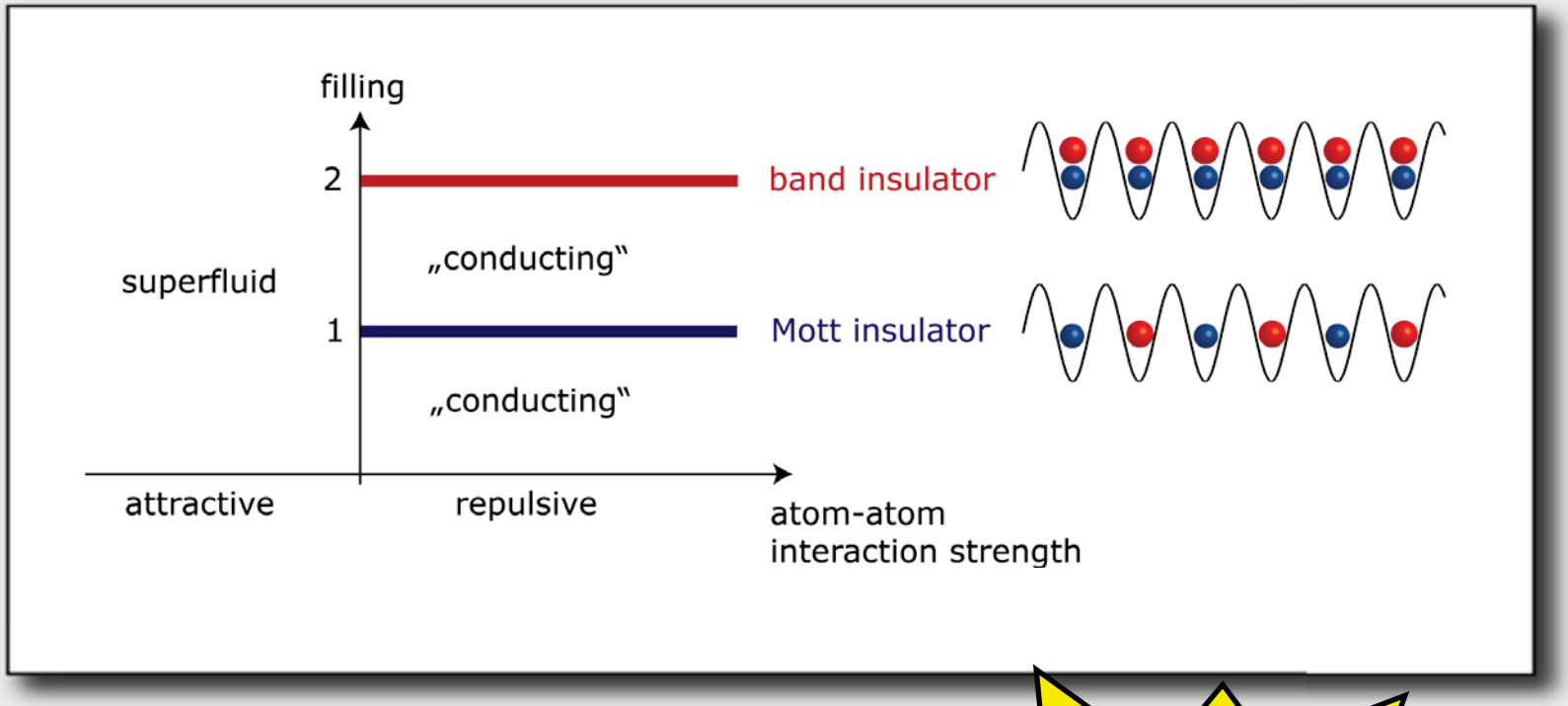
m_F
- -9/2
- -7/2
- -5/2



Blue atoms=

# of doubly occupied sites

T=0 Phase diagram



band insulator $\langle n_\uparrow n_\downarrow \rangle = 1$

Mott insulator $\langle n_\uparrow n_\downarrow \rangle = 0$

„conducting" state $0 < \langle n_\uparrow n_\downarrow \rangle < 1$

Probe for Mott insulator

Outline

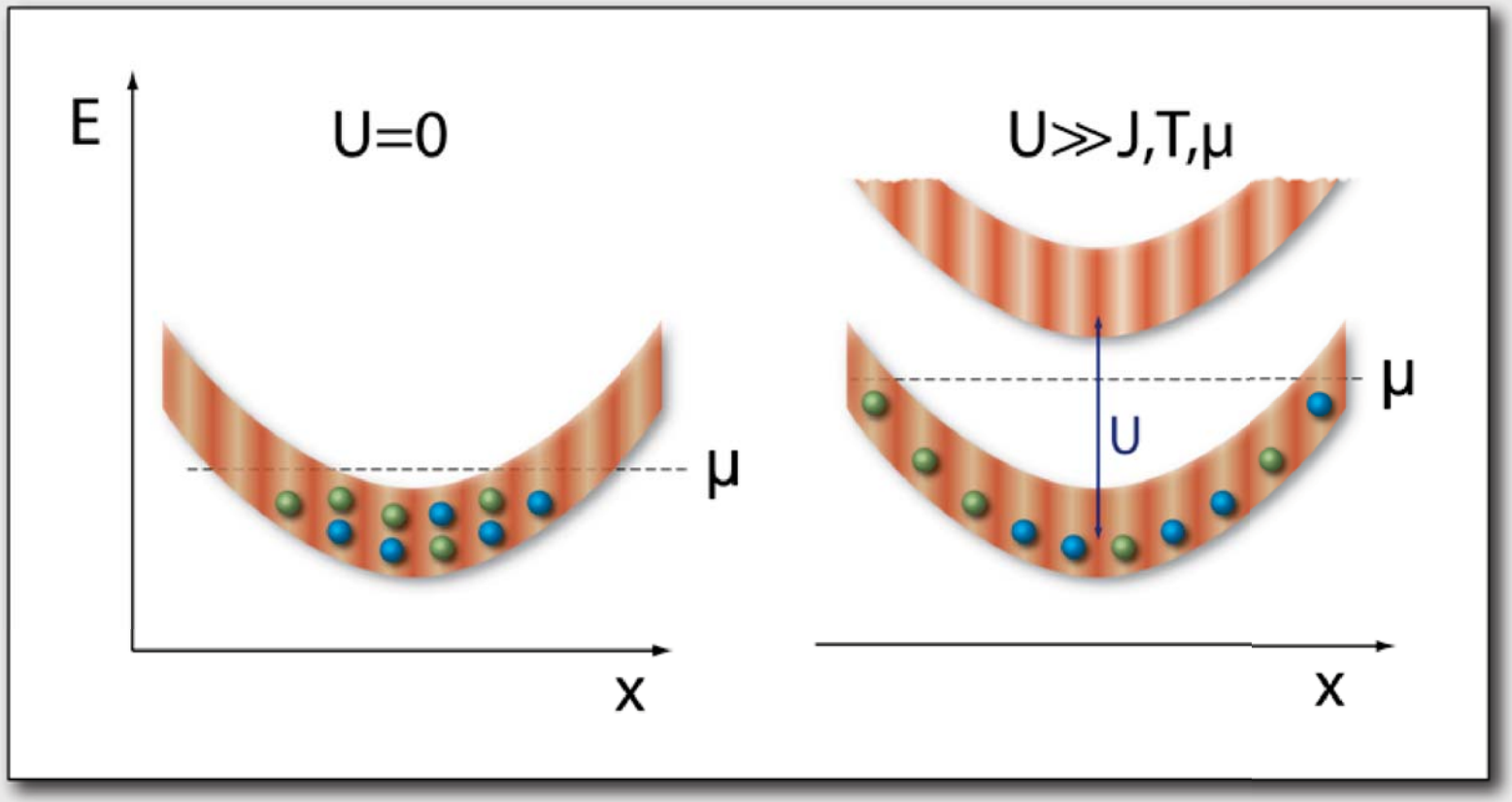
ETH

Ideal Fermi gas in a 3D lattice

Strong interactions

A Mott insulating state of fermions

Simplified energy spectrum

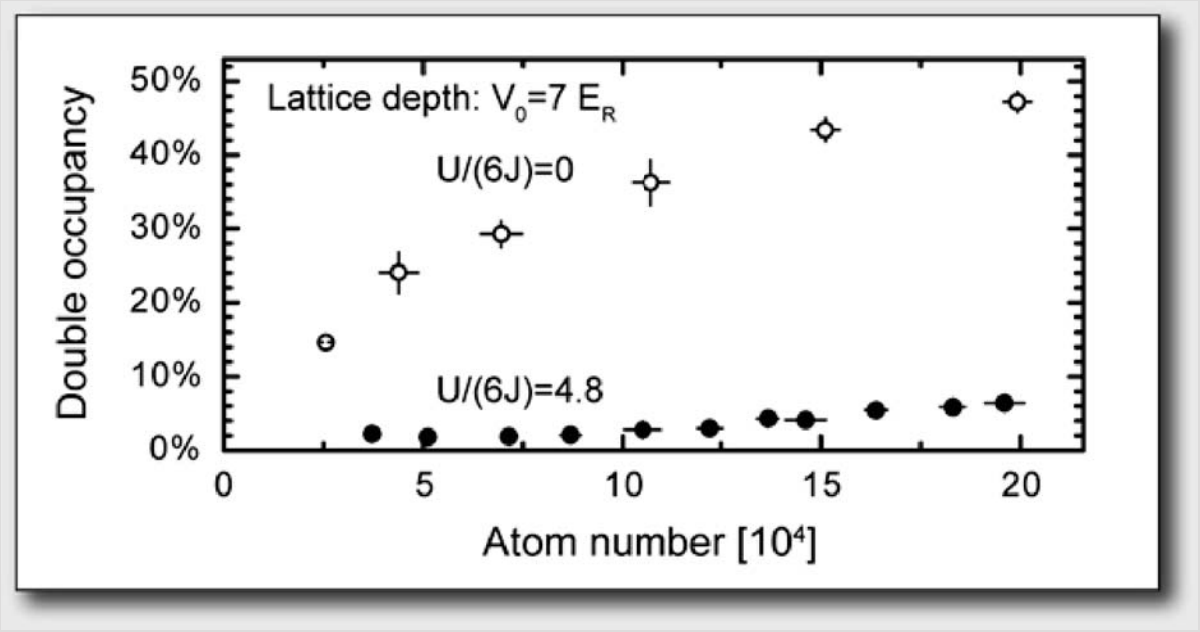


Double occupancy $D := \frac{\text{atoms on doubly occupied sites}}{\text{all atoms}}$

D = 80%

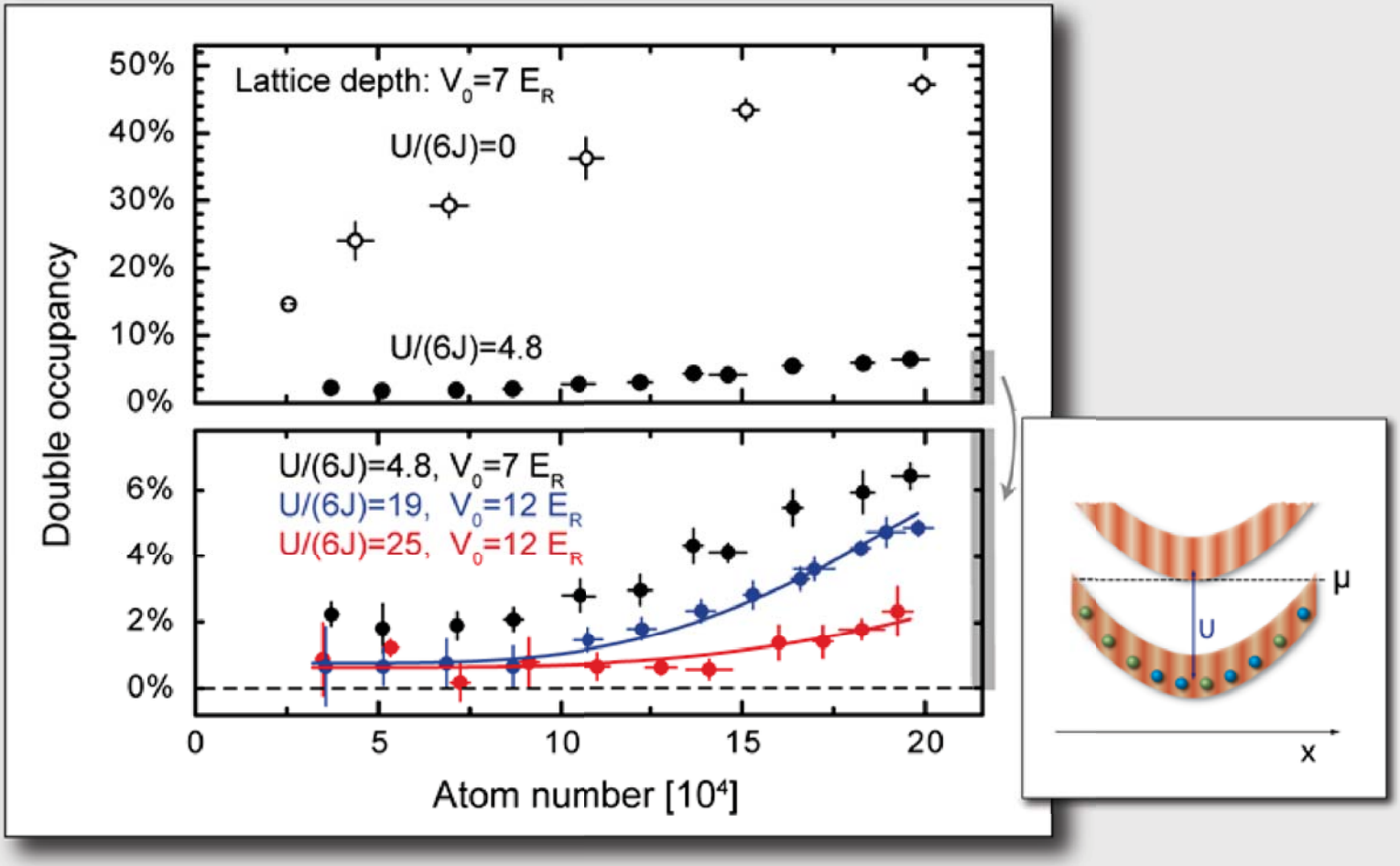
D = 0%

Noninteracting vs. Mott insulating regime



R. Jördens, N. Strohmaier, K. Günter, H.M., T. Esslinger, arXiv/0804.4009 and Nature in press (2008).

Occupation of upper Hubbard band

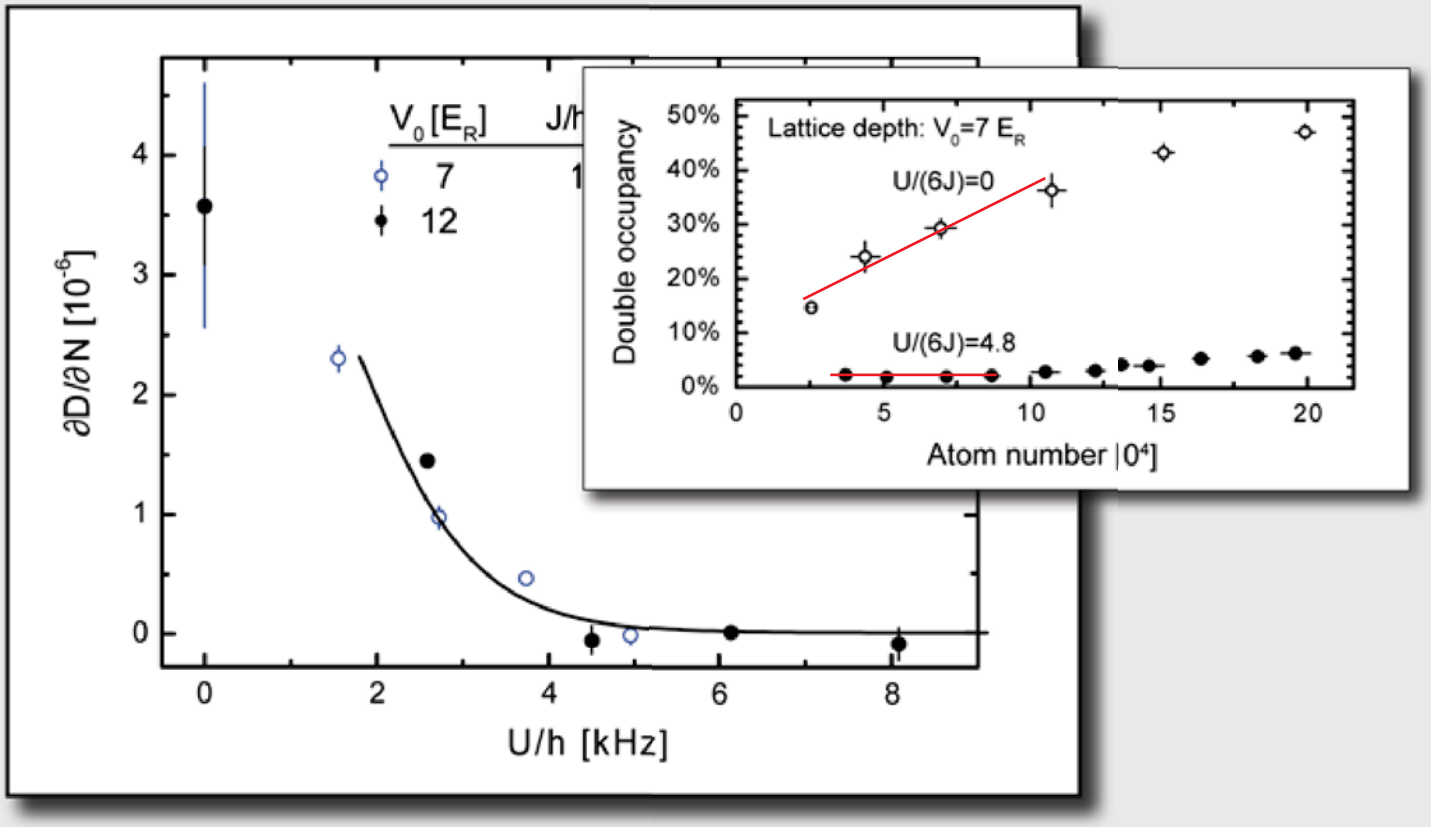


Theory: Hubbard model with J:=0, including confinement

$\Rightarrow T \cong 0.2 \pm 0.1\ T_F \cong 0.1\ U$

From entropy in dipole trap: $T/T_F \sim 0.28 \cong 0.1U$

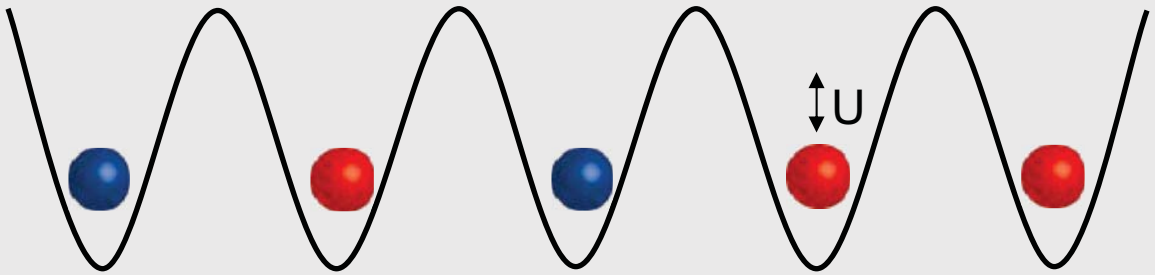
Compressibility with respect to D



$$\kappa \equiv \frac{\partial n}{\partial \mu}$$

Theory: Atomic limit (J=0) at $T/T_F \sim 0.28$

Modulation spectroscopy

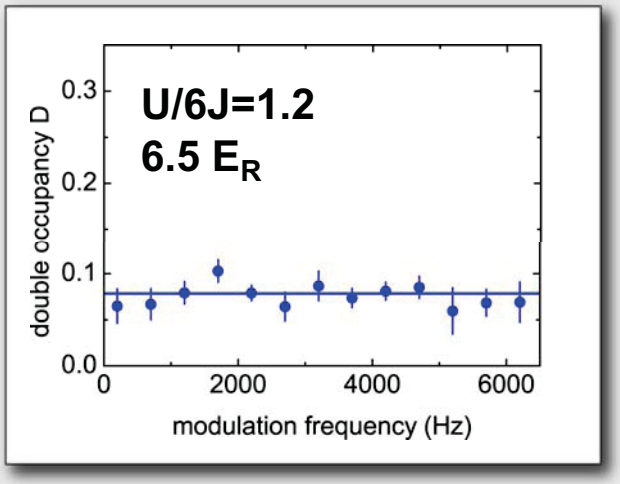


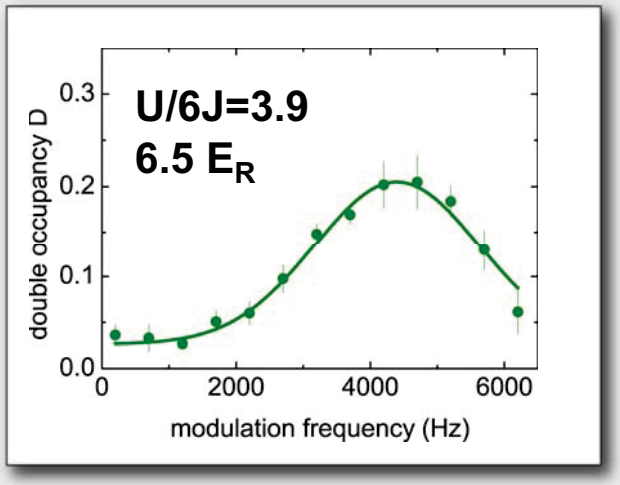
Modulation of the lattice amplitude with frequency U/h: Particle-hole excitation

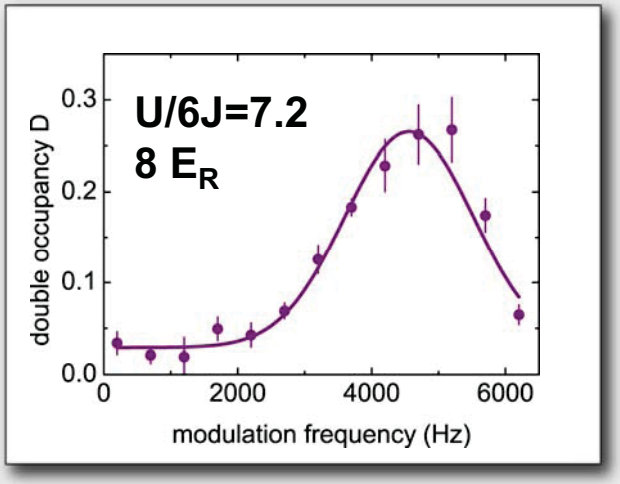
C. Kollath et.al, Phys.Rev.A., 74, 041604 (2006)

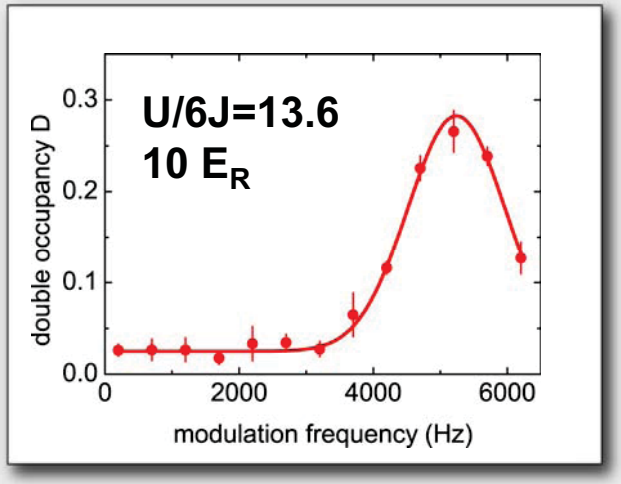
T. Stöferle et.al., Phys.Rev.Lett. 92, 130403 (2004)

Modulation spectroscopy

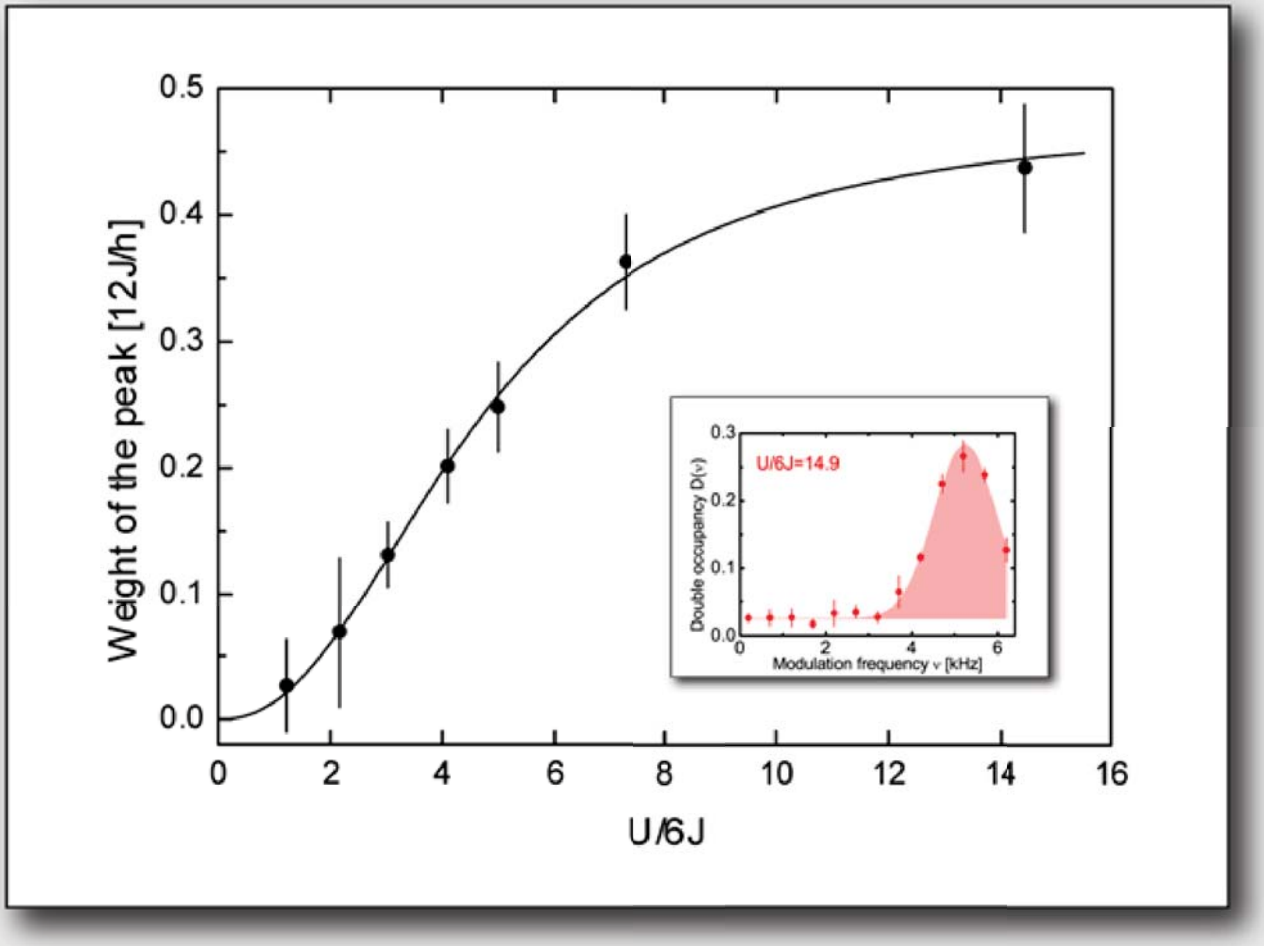






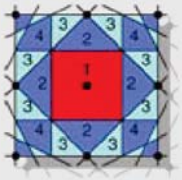


Spectral Weight

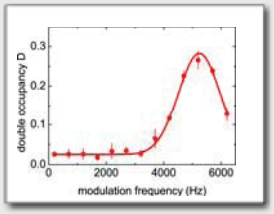


The black line is a guide to the eye

Conclusion

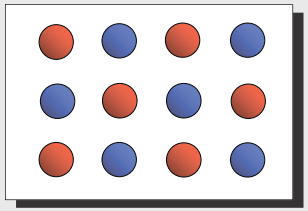


Noninteracting Fermi gas

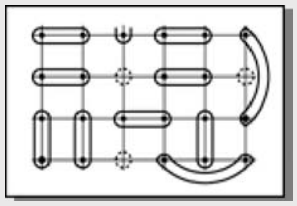


Evidence for Mott insulating state

Roadmap for simulation of the Hubbard model



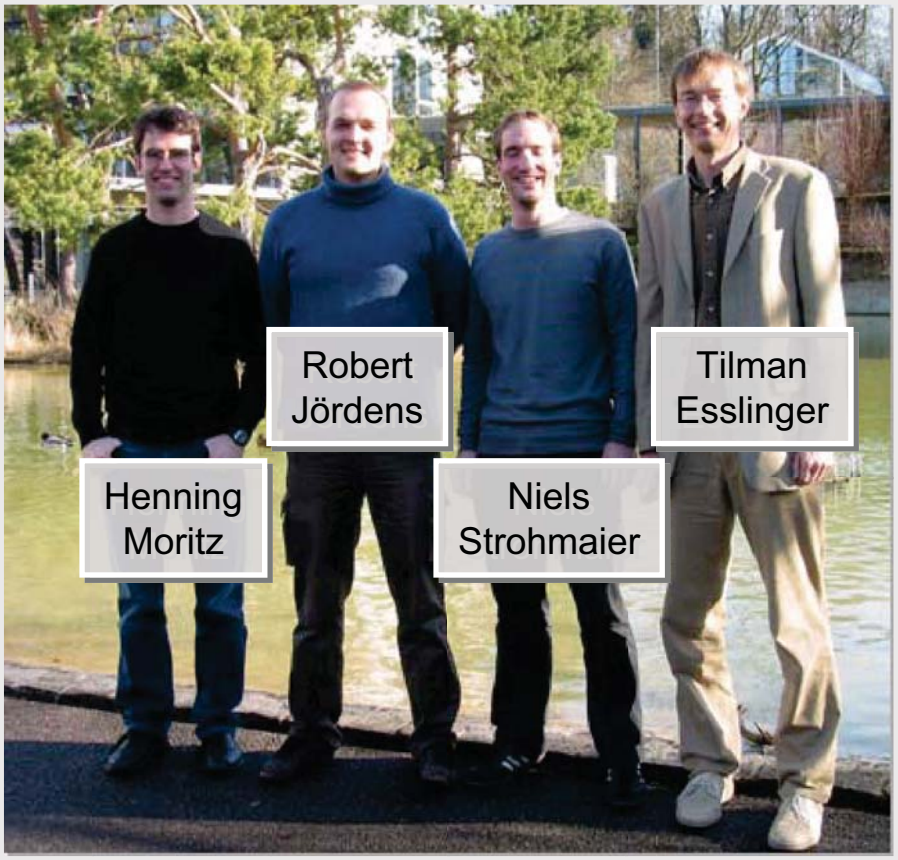
Antiferromagnetic ordering



Test for RVB superfluidity in 2D

- *Trebst et al., PRL 96, 250402 (2006)*

Thanks



+ Daniel Greif
+ Letitia Tarruell
+ Kenneth Günter (LKB Paris)
+ Yosuke Takasu (U. Kyoto)
+ Michael Köhl (U. Cambridge)