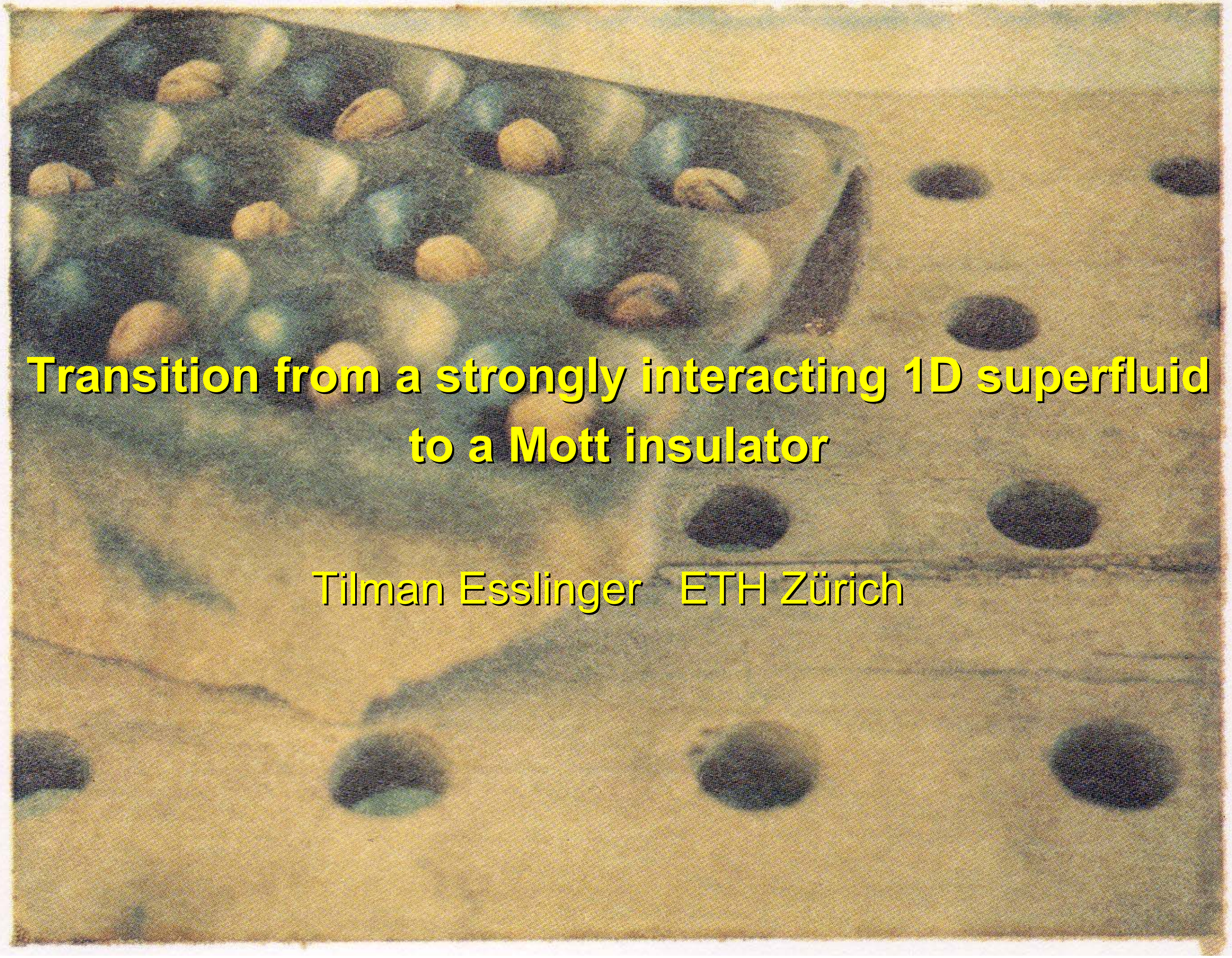


# Transition from a strongly interacting 1D superfluid to a Mott insulator

Tilman Esslinger ETH Zürich

# Optical Lattices and Hubbard models

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

- tunneling
- dimensionality
- geometry
- disorder
- interactions
- atom number
- time dependency
- change the statistics
- multi- component

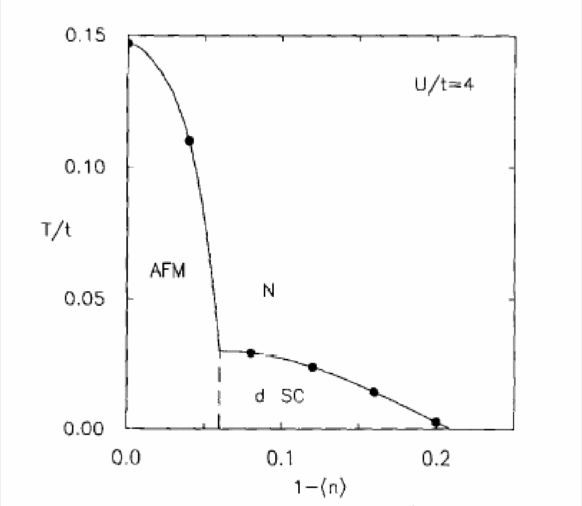

D. Jaksch, C. Bruder, J.I. Cirac, C.W. Gardiner, and P. Zoller, Phys. Rev. Lett. 81, 3108 (1998).

M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, und I. Bloch, Nature 415, 39-44 (2002).

# Fermions in Optical Lattices

$$H = -J \sum_{\{i,j\},\sigma} \hat{c}^{\dagger}_{i,\sigma}\hat{c}_{j,\sigma} + \sum_i \varepsilon_i \hat{n}_i + U \sum_i \hat{n}_{i,\uparrow}\hat{n}_{i,\downarrow}$$

- BEC-BCS cross-over
- d-wave pairing in 2D



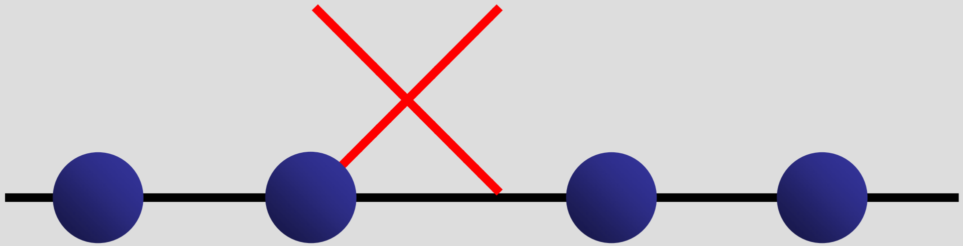

From: D.J. Scalapino, Phys. Rep. 250, 329 (1995).

See also W. Hofstetter, et al., Phys. Rev. Lett. 89, 220407 (2002).

# Outline

- 1D Atom Gas
- Superfluid Mott Insulator Transition in 1D
- From weak to strong interactions in an optical lattice
- Fermions

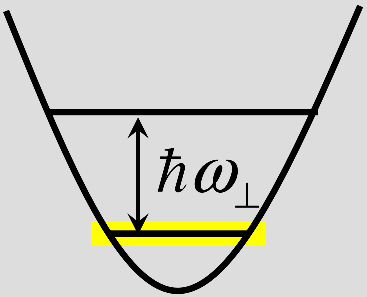
# A Gas in One Dimension



- Increased quantum fluctuations of the phase
- In the homogeneous system: no BEC
- Interactions more important
- Theoretically understood: exactly known ground state and excitation spectrum from weak to strong interactions (Lieb and Lininger, 1963)

# First Experimental Realization of 1D Atomic Gas

H. Moritz, T. Stöferle, M. Köhl and T. Esslinger, Phys. Rev. Lett. **91**, 250402 (2003)




## Conditions for 1D:

$$k_B T << \hbar\omega_\perp$$

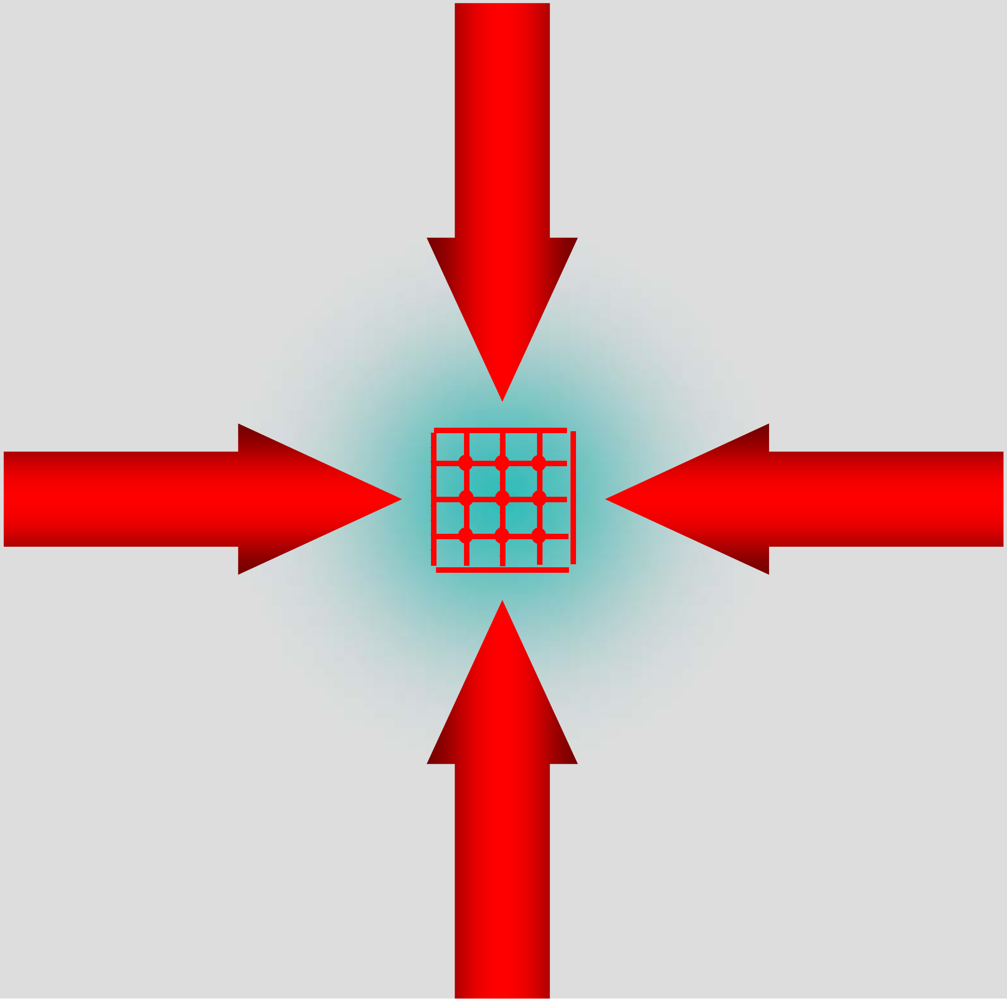
$$\mu << \hbar\omega_\perp$$

Suppressed tunnel coupling between the tubes

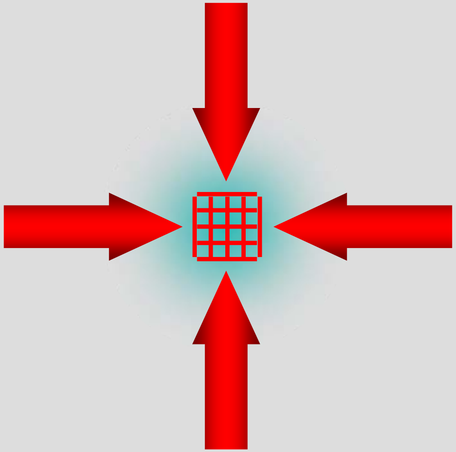
Elongated traps: MIT, ENS, Texas, Hannover, Orsay, Amsterdam, Microtraps…

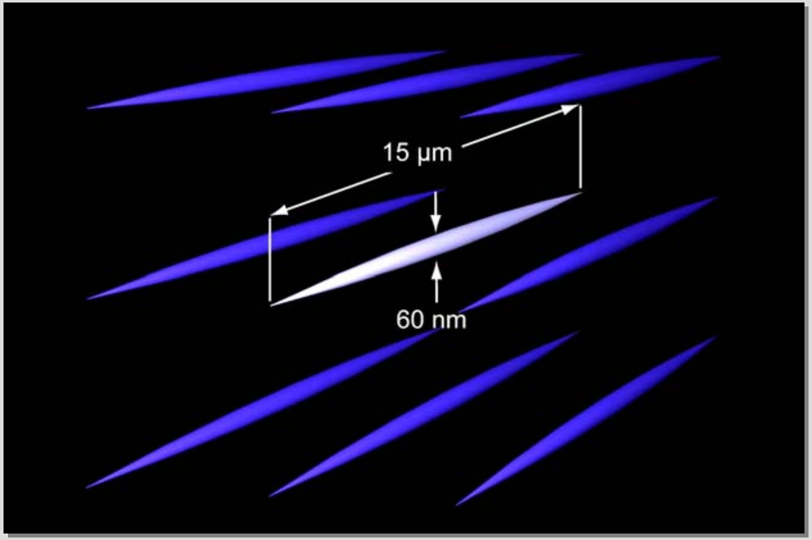
Optical Lattices: Zurich, Munich, NIST…

# Optical Lattices



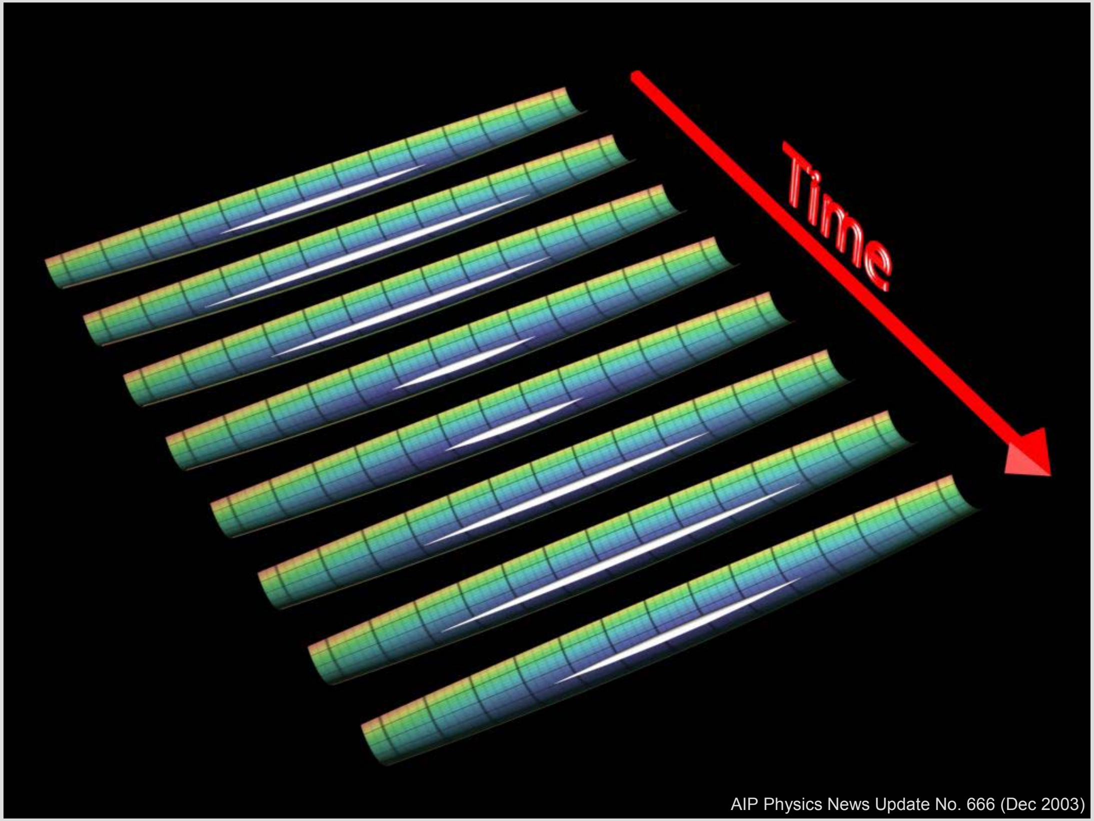
# An array of quantum gases





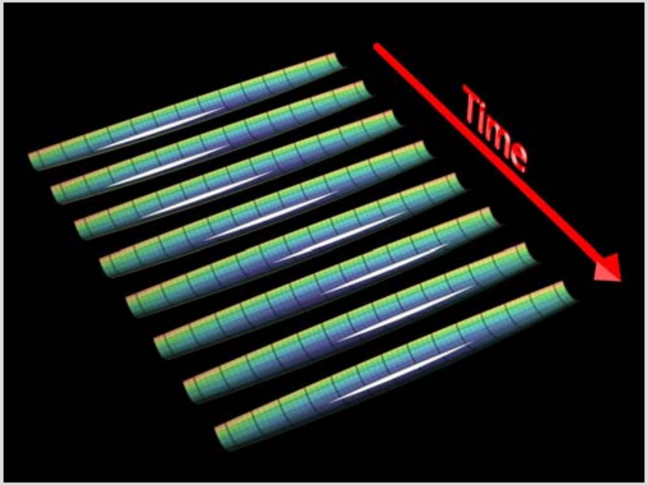

- Anisotropic harmonic confinement: $\omega_\perp >> \omega_z$
- 20-100 atoms per tube

# Lowest lying collective modes



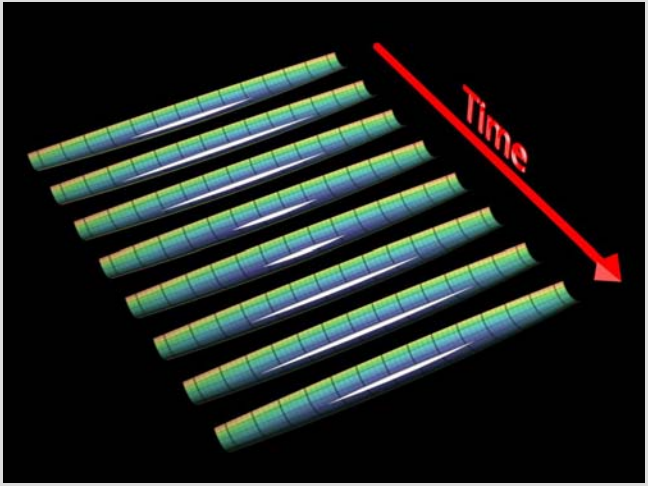

„Breathing“ mode
(axial compressional oscillation)

# Lowest lying collective modes




Dipol mode
(center-of-mass oscillation)

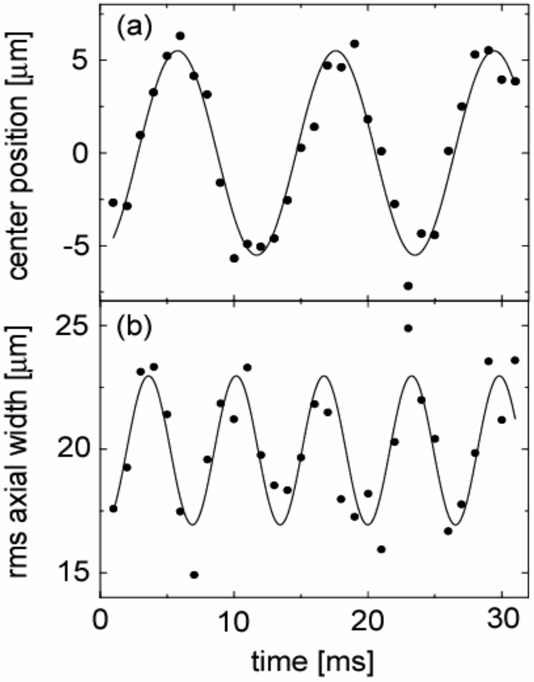
„Breathing“ mode
(axial compressional oscillation)



# Excitations in a 1D Gas

Dipole oscillation

Breathing oscillation




Measured ratio of frequencies:

Bose condensate

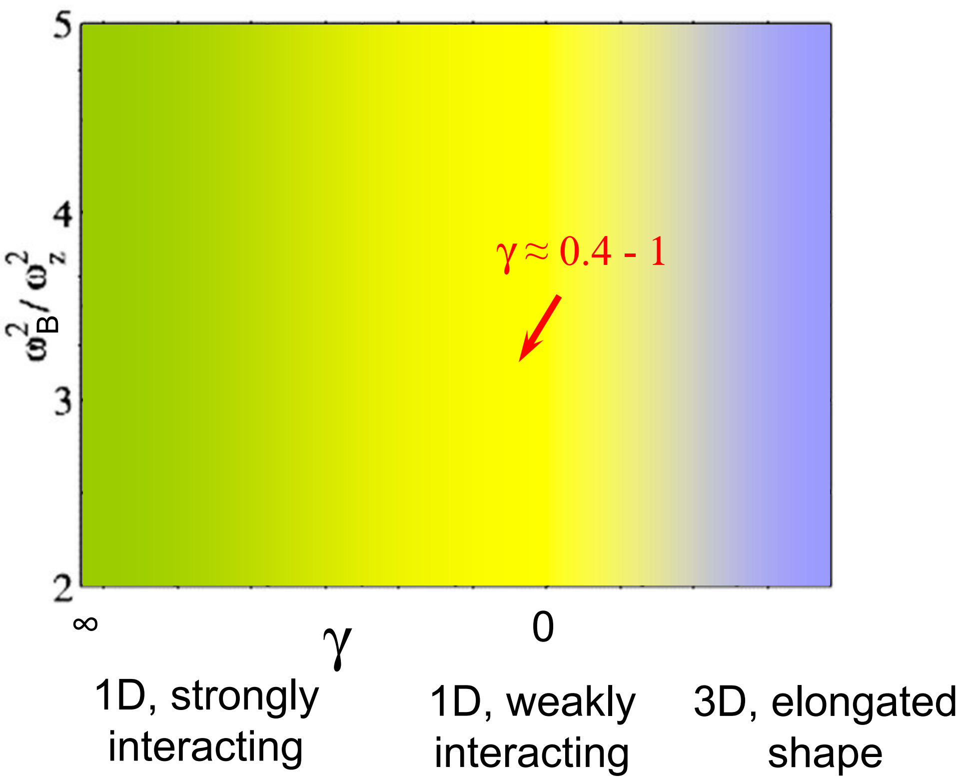
$$\left(\frac{\omega_B}{\omega_D}\right)^2 = 3.1$$

Thermal gas

$$\left(\frac{\omega_B}{\omega_D}\right)^2 = 4$$

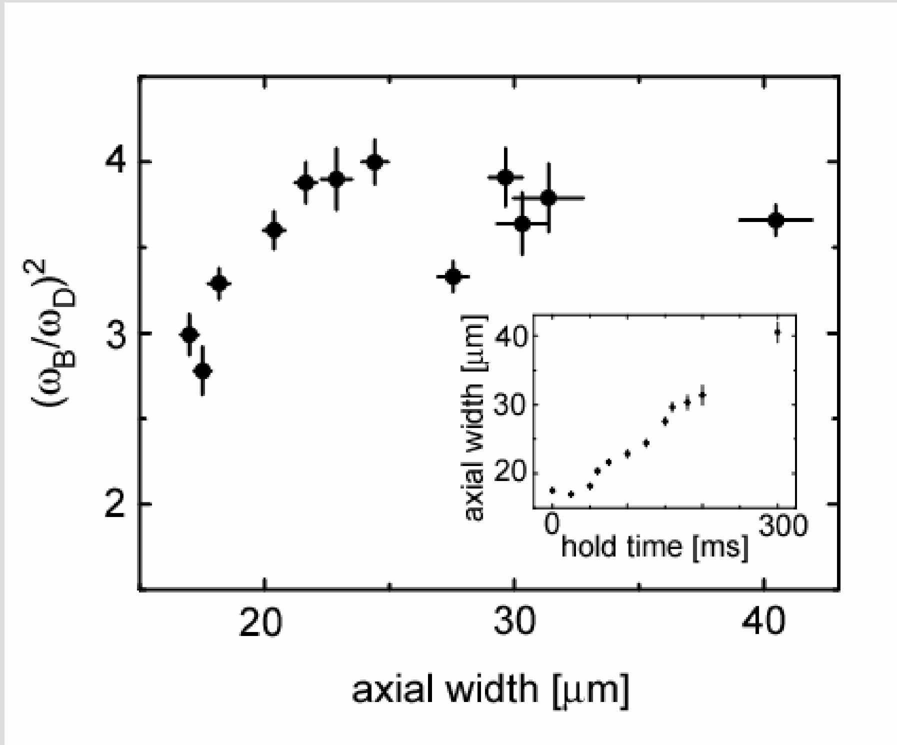
H. Moritz, T. Stöferle, M. Köhl and T. Esslinger, Phys. Rev. Lett. **91**, 250402 (2003)

# Excitations in a trapped 1D Gas at T=0

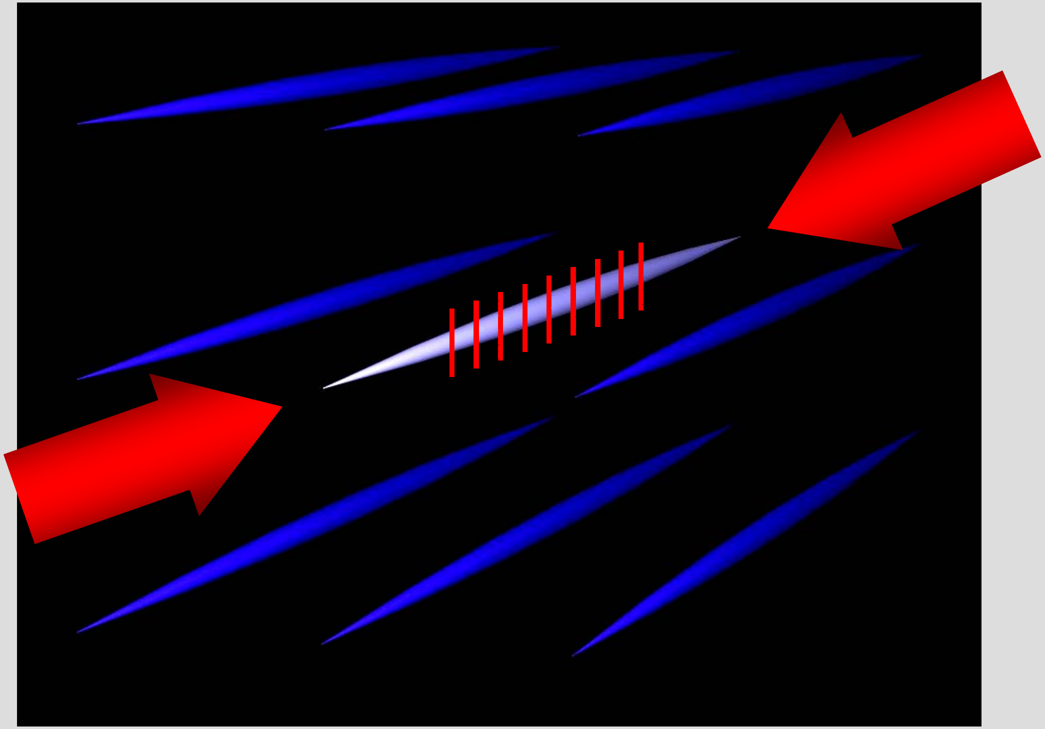



C. Menotti and S. Stringari, Phys. Rev. A **66**, 043610 (2002)

# Temperature dependence

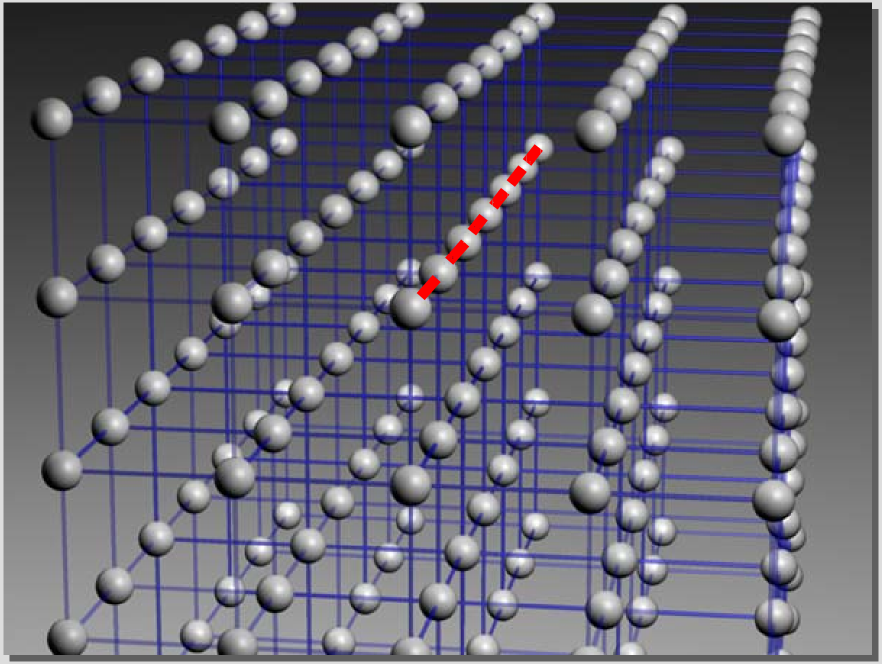


# Creating a strongly interacting 1D Gas



T. Stöferle, H. Moritz, C. Schori, M. Köhl, and T. Esslinger, accepted for publication in Phys. Rev. Lett. (cond mat/0312440).

# Bose-Hubbard Model in 1D



Stronger quantum fluctuations → mean-field theory fails

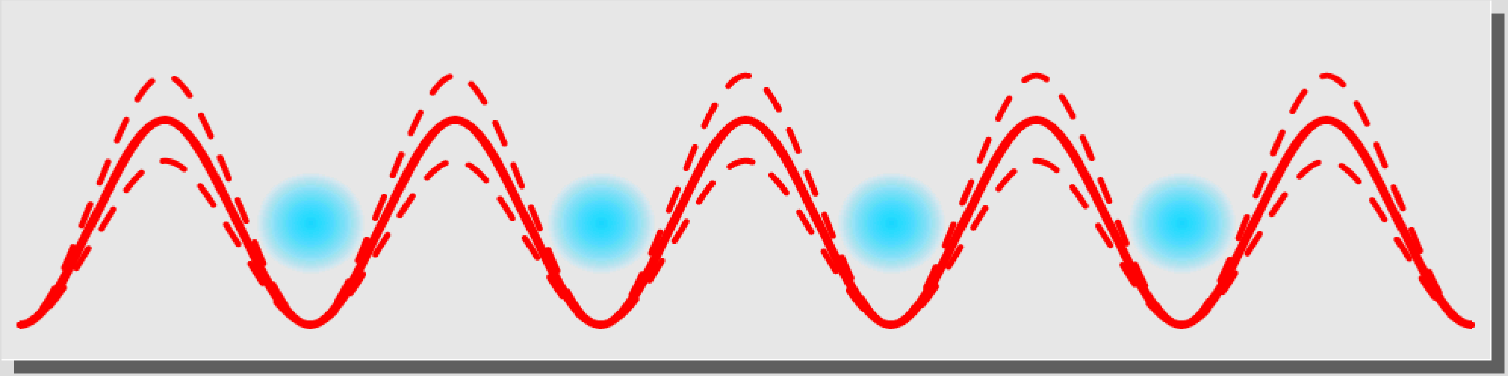
Theory 1D: J:K. Freericks and H. Monien, Europhys. Lett. 26, 545 (1994).

Atomic gases: H.P. Büchler, G. Blatter and W. Zwerger, PRL 90, 130401 (2003)

QMC: GG. Batrouni, M. Troyer et al. PRL 89, 117203 (2002).

3D: proposed: Fisher et al. (1989), Jaksch, Bruder, Cirac, Gardiner and Zoller (1998)

# Bragg Spectroscopy in an Optical Lattice



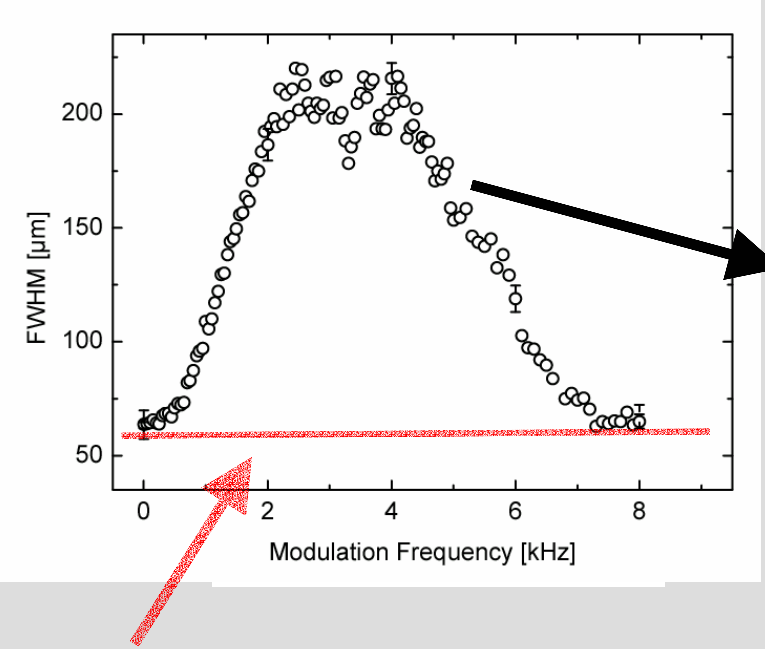
$$V_{ax}(y, t) = V_{ax,0}(1 + A_{mod} \sin(2\pi\nu_{mod}t)) \sin^2(ky)$$

Frequency sidebands at $\pm\nu_{mod}$

Energy transfer: $\Delta E = \hbar(2\pi\nu_{mod})$

Momentum transfer: $\Delta \boldsymbol{p} = 2\hbar\boldsymbol{k}$ = reciprocal lattice vector

# Excitation spectrum of a 1D superfluid



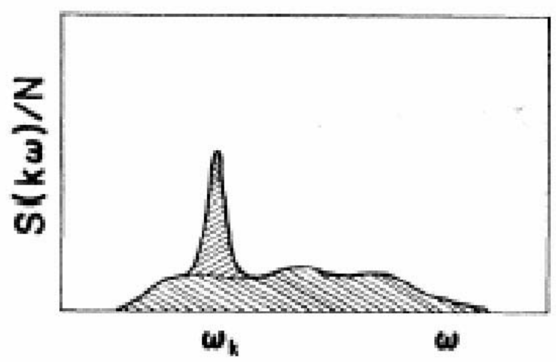

Signature for a strongly interacting superfluid?

Prediction for a weakly interacting superfluid in an optical lattice:
no excitation possible
(C. Menotti et al.)

# Excitation spectrum in liquid He

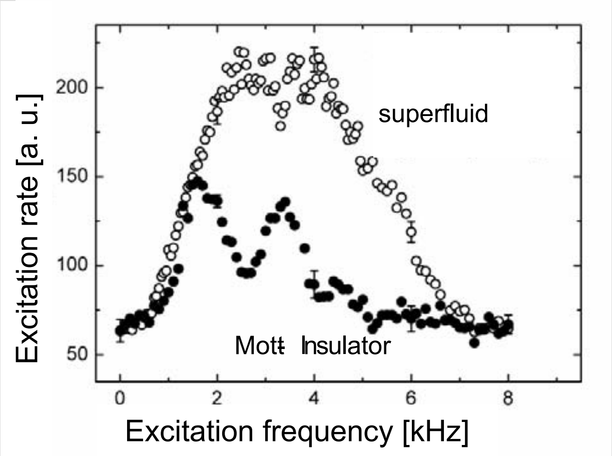
Dynamic structure factor shows two features:

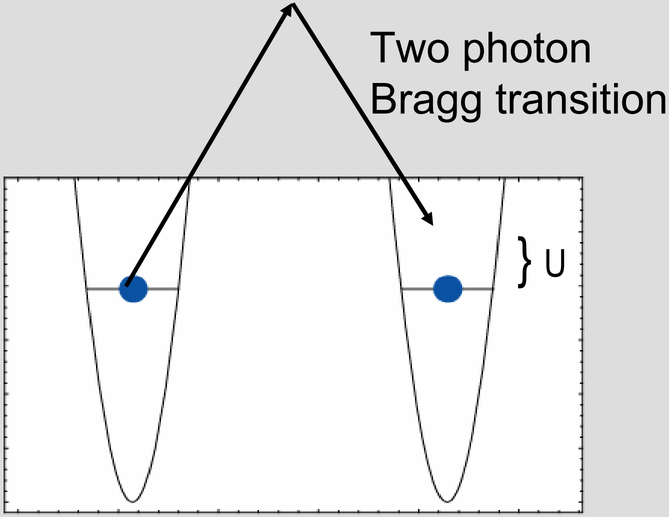
- Collective mode
- Broad background due to multiphonon excitations




A. Miller, D. Pines and P. Nozieres, PR 127, 1452 (1962)

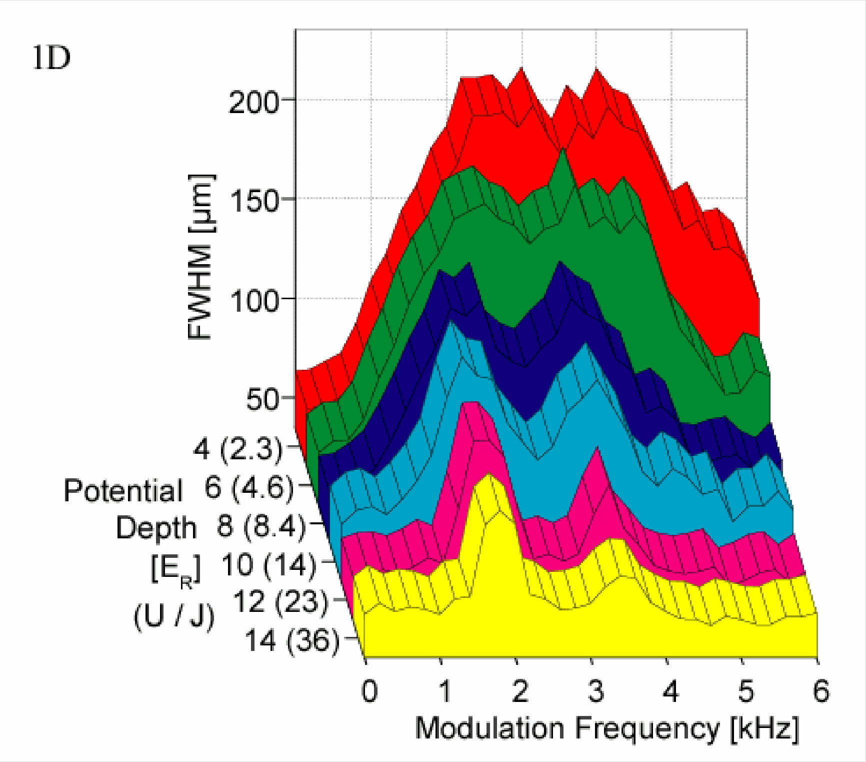
# 1D Mott-Insulator: Excitation Spectrum



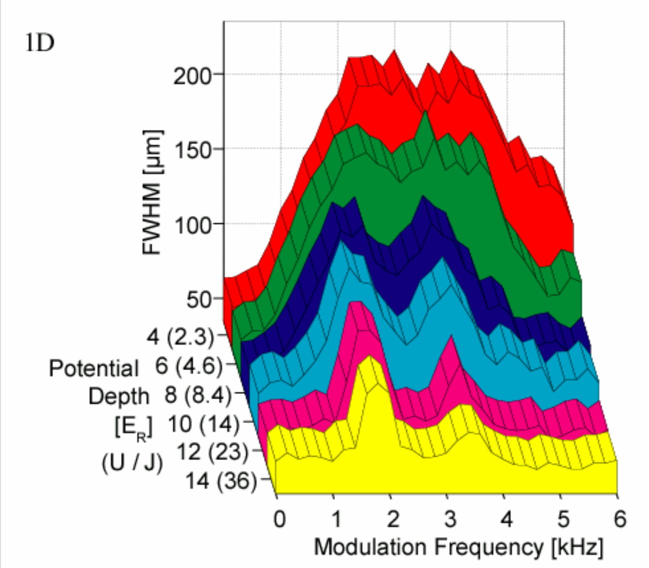



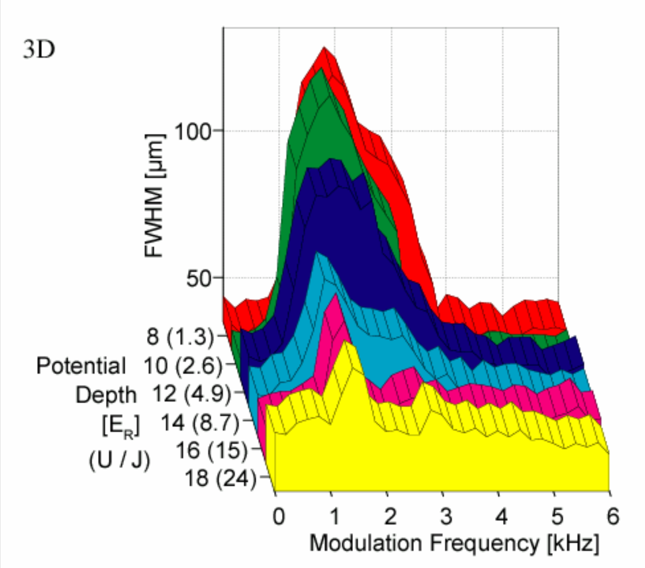

Observed Peaks: U, 1.91*U, 2.60*U

# Transition from a superfluid to a Mott insulator in 1D



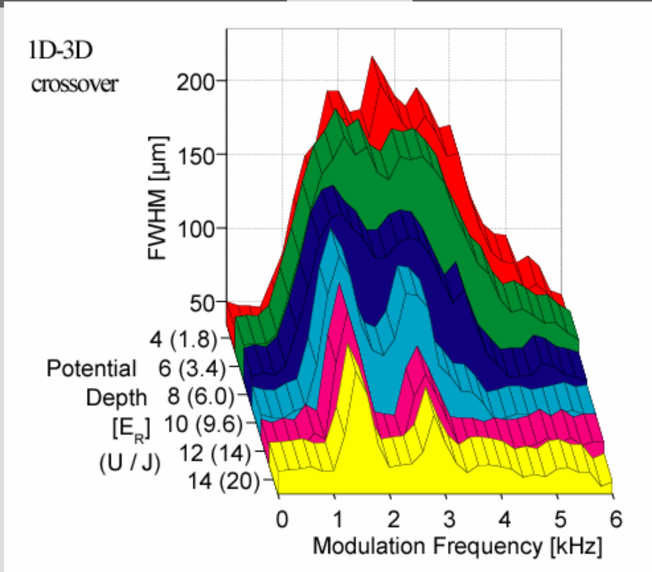

T. Stöferle, H. Moritz, C. Schori, M. Köhl, and T. Esslinger, accepted for publication in Phys. Rev. Lett. (cond mat/0312440).



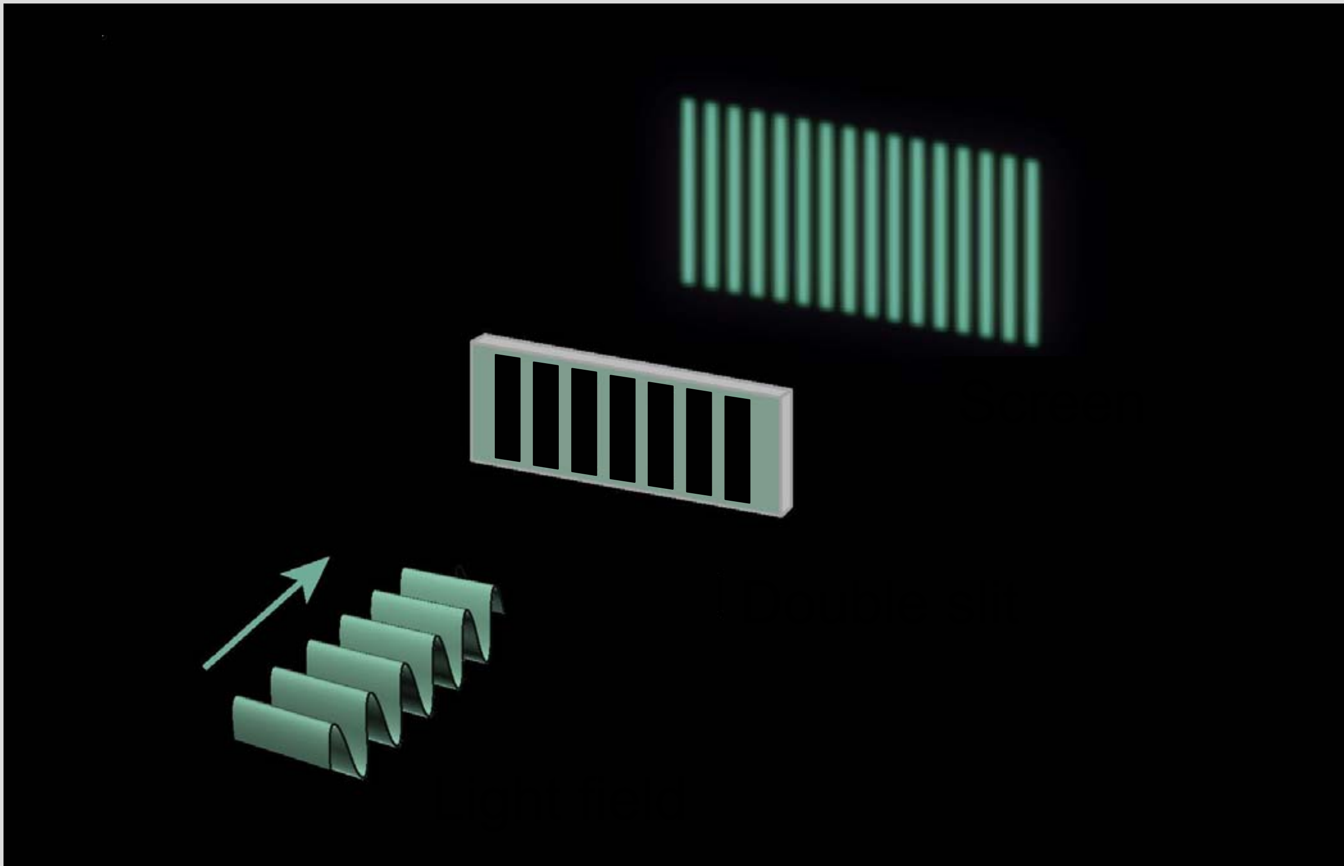




Strong 2nd peak

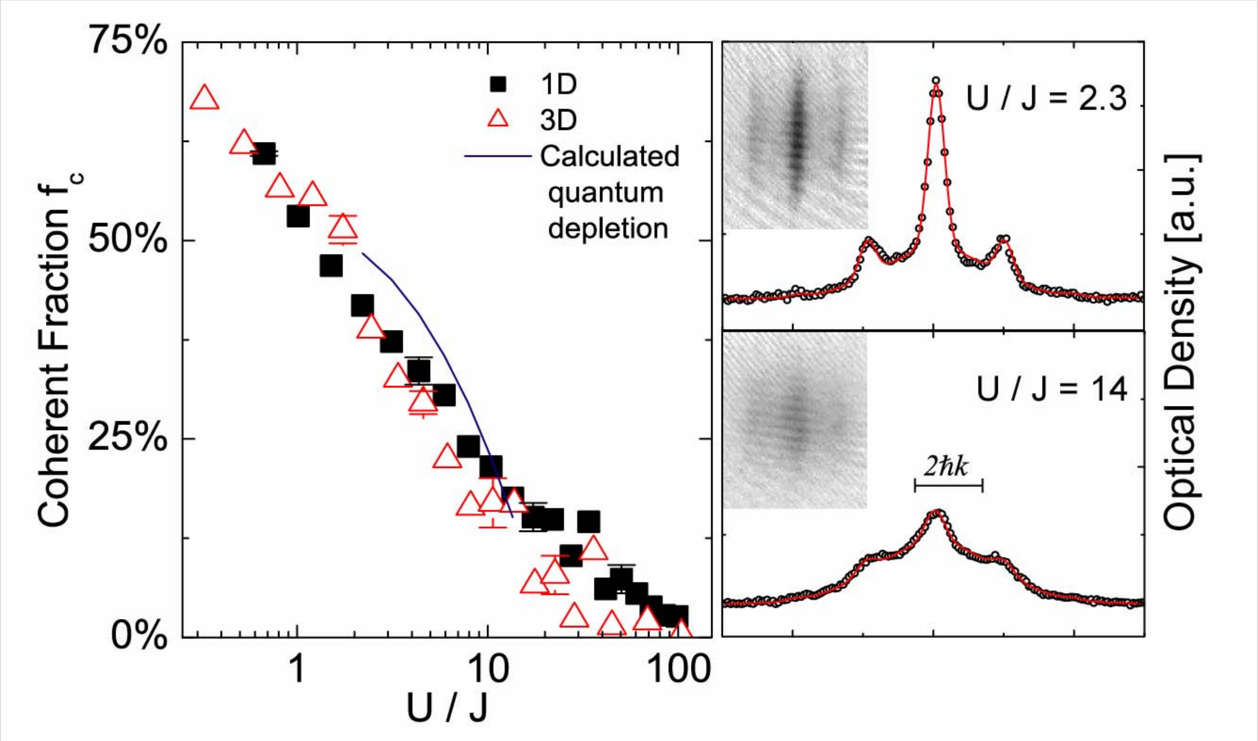
Broad Spectrum



# Coherence in Optics

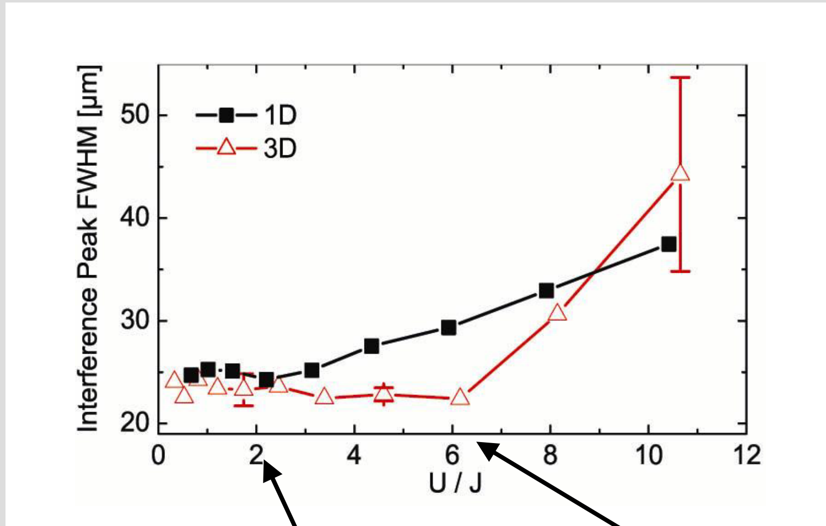


# Coherent Fraction



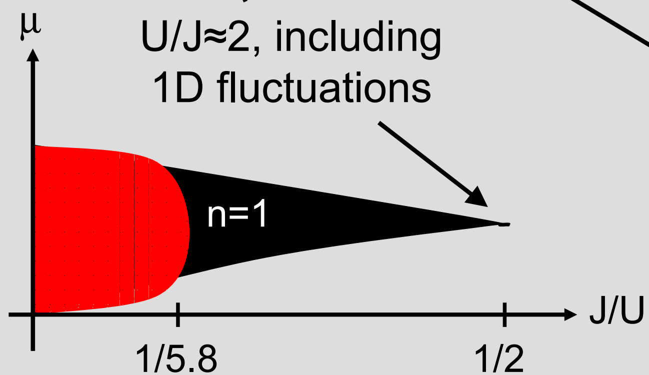

T. Stöferle, H. Moritz, C. Schori, M. Köhl, and T. Esslinger, accepted for publication in Phys. Rev. Lett. (cond mat/0312440).

# Coherence length at the transition



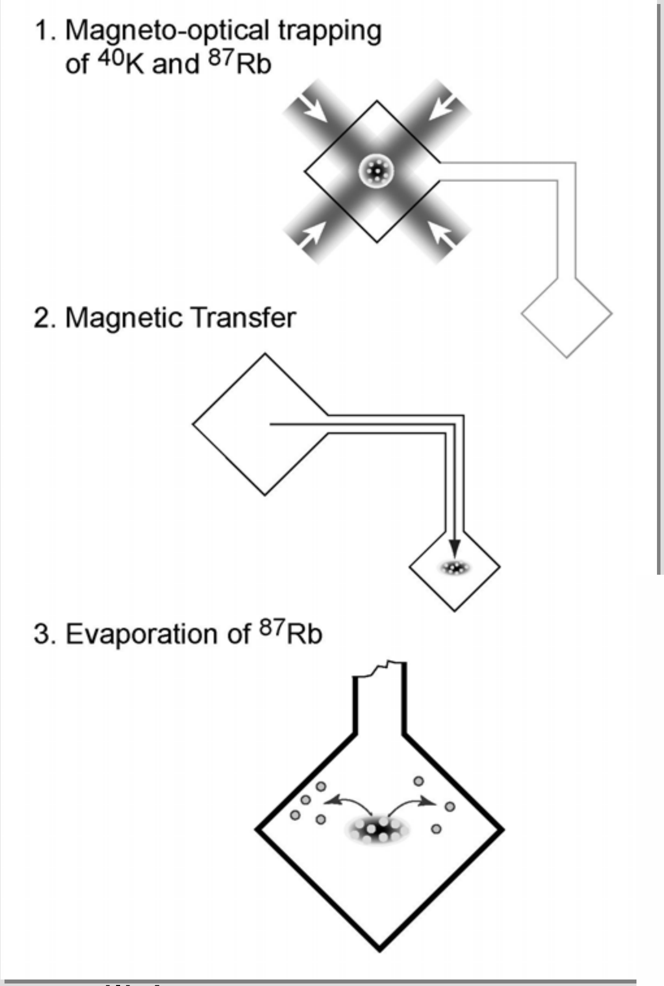

U/J≈2, including 1D fluctuations

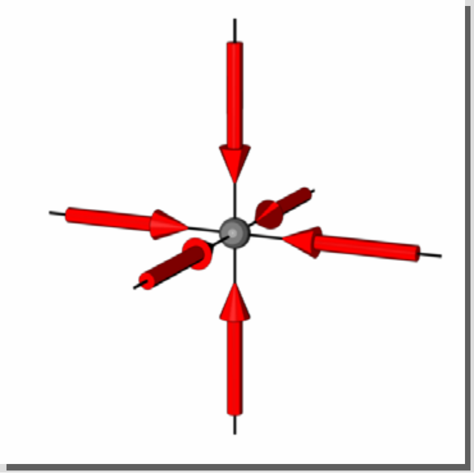
U/J=5.8, according to mean-field theory




- Experiment: T. Stöferle, H. Moritz, C. Schori, M. Köhl, and T. Esslinger, cond-mat/0312440.
- Theory: C. Kollath, U. Schollwöck, J. von Delft, W. Zwerger, preprint cond-mat/0310388.

# Fermions in Optical Lattices

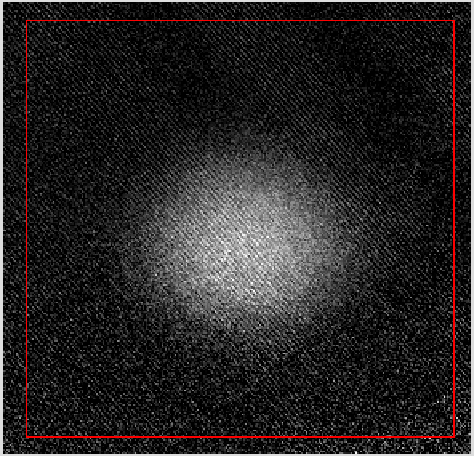


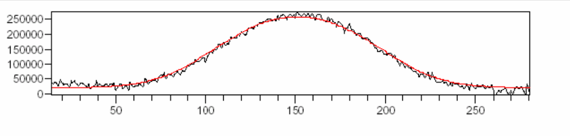



See: Florence, JILA

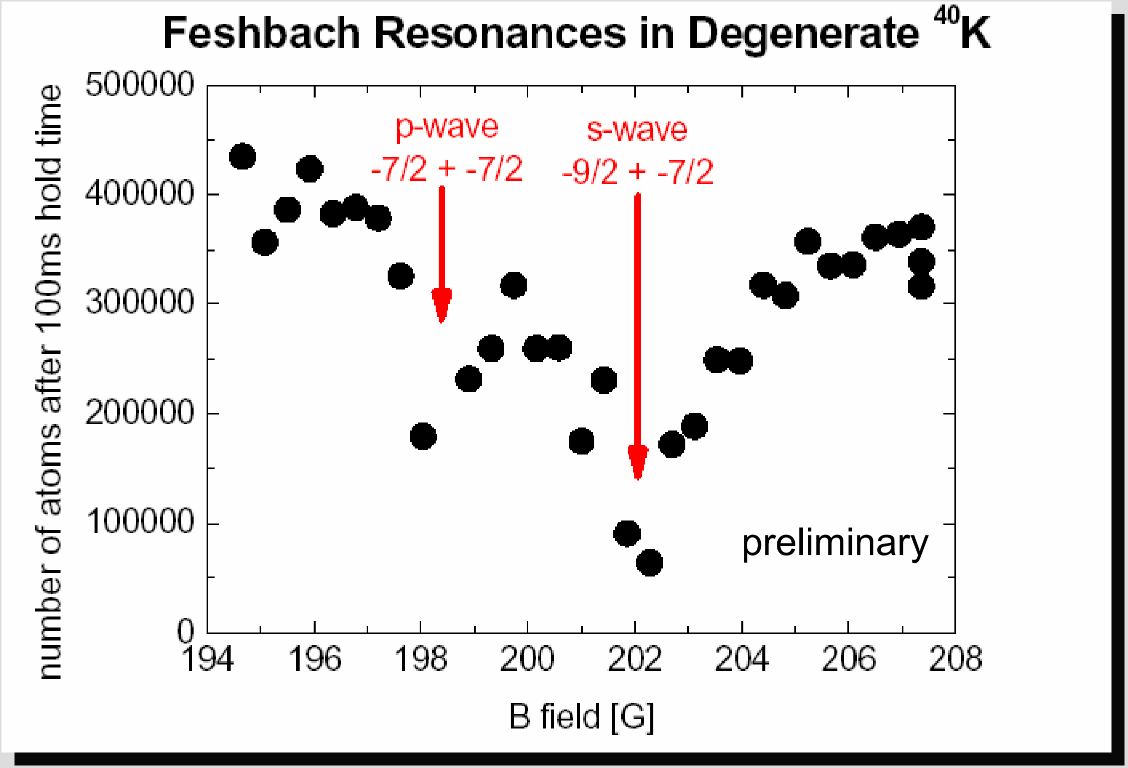
# Ultracold Fermions

- 300.000 $^{40}K$ atoms in magnetic trap
- $T$=0.27 $T_F$





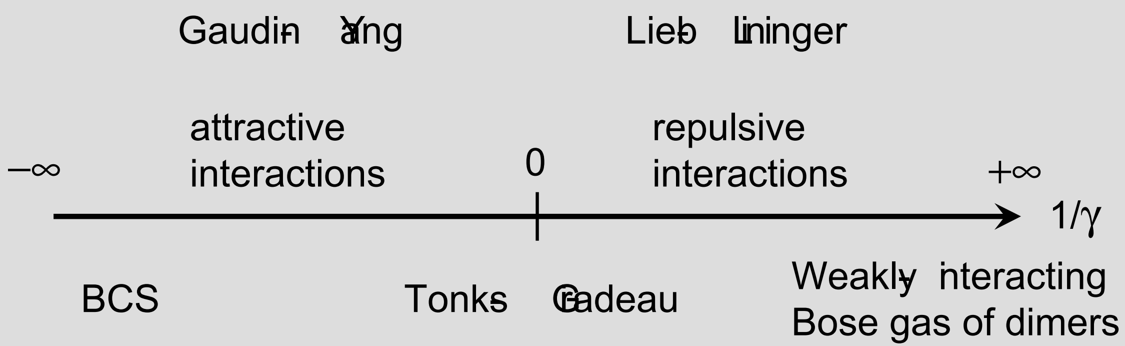
# Spin mixtures in a crossed dipole trap




See: JILA

# Fermions in Optical Lattices

- 1D two component Fermi gases in potassium 40




Use Feshbach resonance at 202.1 Gauss


G.E. Astrakharchik, D. Blume, S. Giorgini, and L.P. Pitaevskii, cond-mat/0312538 (2003).
I. V. Tokatly, cond-mat/0402276 (2004).
J.N. Fuchs, A. Recati, W. Zwerger, cond-mat/0402448 (2004).

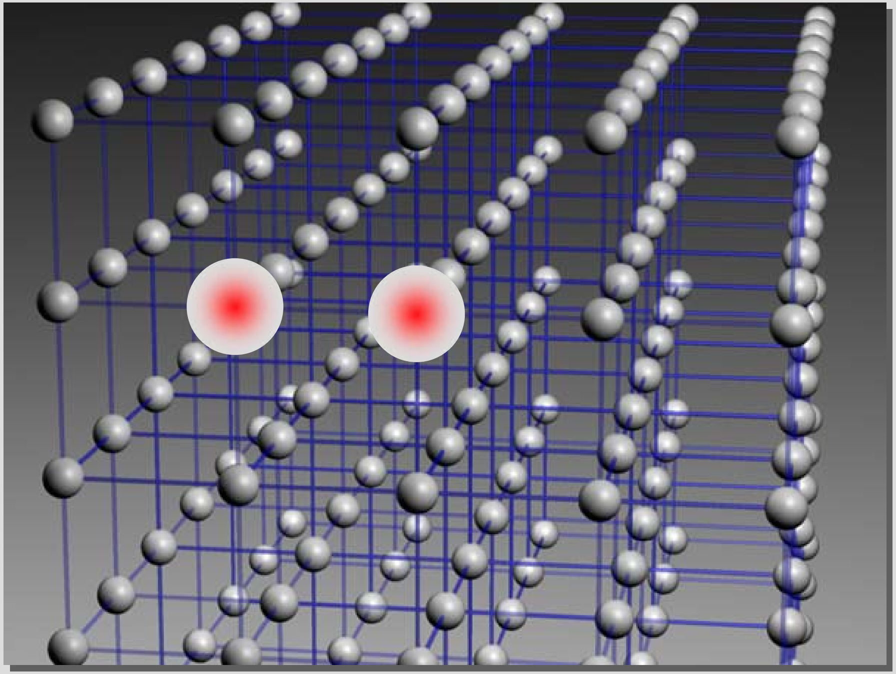
# Fermions in Optical Lattices

- Hubbard model

$$H = -J \sum_{\{i,j\},\sigma} \hat{c}^{\dagger}_{i,\sigma} \hat{c}_{j,\sigma} + \sum_i \varepsilon_i \hat{n}_i + U \sum_i \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow}$$

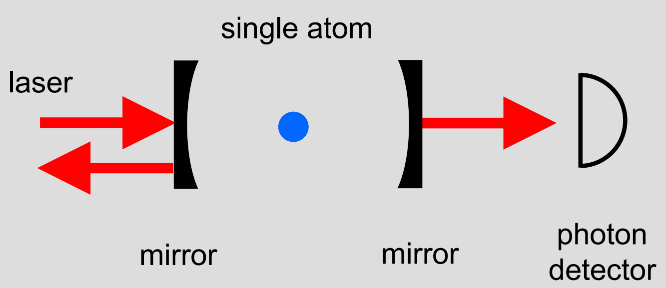
- BEC-BCS cross-over
- d-wave pairing in 2D

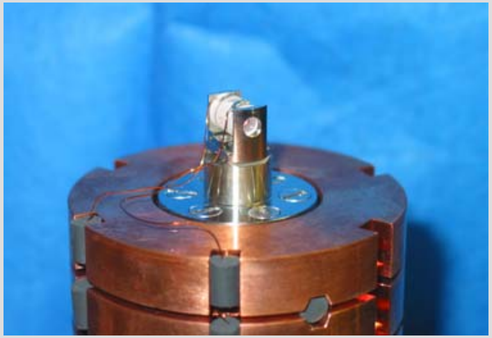
# Quantum Computing

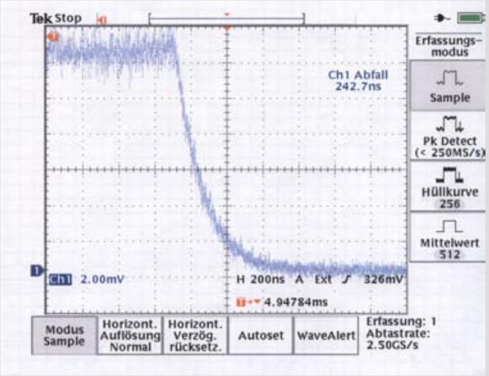


# Single Atom Detection

Ultra-high-finesse optical cavity






Finesse: 500.000

Length: 180 μm

Q-Factor: ≈ $10^9$

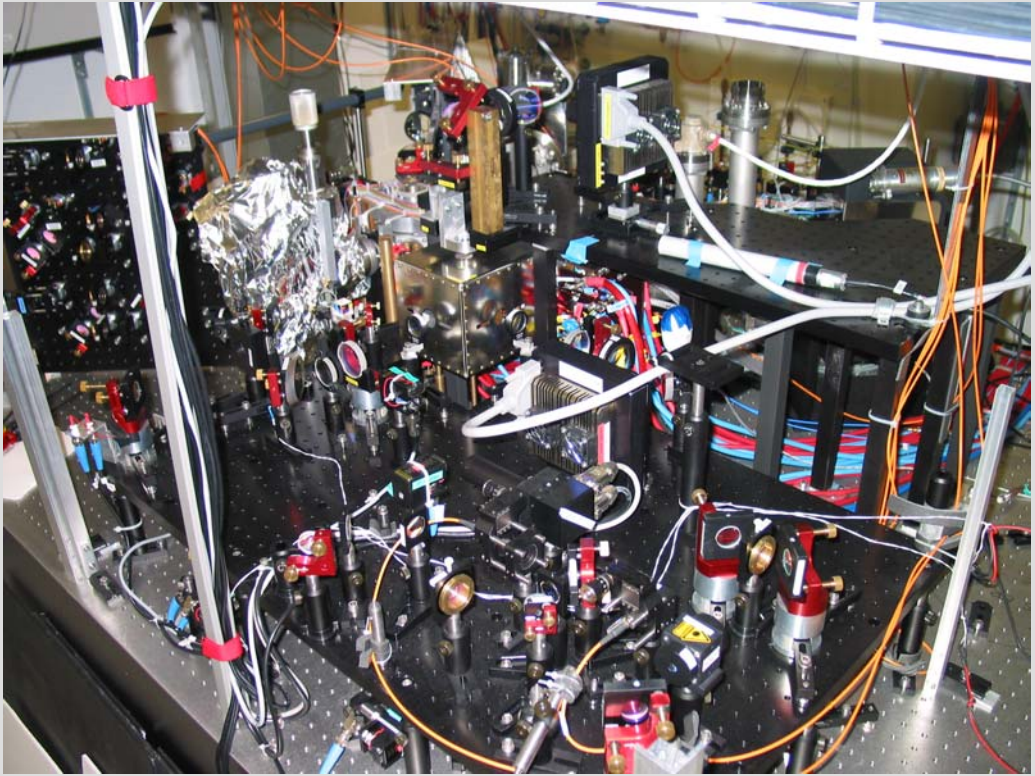
# Experimental setup

12 stabilized lasers

> 500 optical elements

> 100 m optical fiber

# Experimental setup

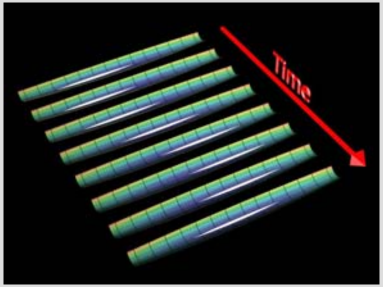


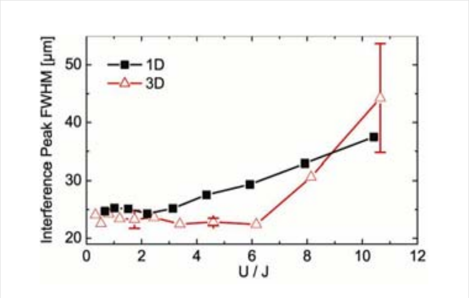
Ultra high vacuum

Magnetic field fluctuations <1 mG

# Conclusions

• Creating quantum systems with optical lattices, e.g. 1D




• From weak to strong interactions

• Towards counting and Fermi-Hubbard systems


Anton Öttl, Michael Köhl, Martin Schultze, Christian Schori, Henning Moritz Patrick Maletinsky, Stephan Ritter, Thilo Stöferle, Veronica Bürgisser, Alexander Frank

ETH, SNF, ESF, QSIT