Quantum Mechanics: from fundamental problems to applications

2006

Bertinoro

7 Dicembre 2006

# Degenerate quantum gases in periodic and disordered potentials

Francesco Minardi
CNR – INFM
LENS European Laboratory for Nonlinear Spectroscopy
Sesto Fiorentino – Firenze

http://quantumgases.lens.unifi.it

# Outline

**Bose-Einstein condensates in periodic and disordered potentials**

- Superfluid to Mott insulator transition

- Disordered potentials

**Quantum degenerate mixtures**

- Ultracold heteronuclear molecules

- Attractive condensates for Quantum Measurements

# Outline

**Bose-Einstein condensates in periodic and disordered potentials**

- Superfluid to Mott insulator transition

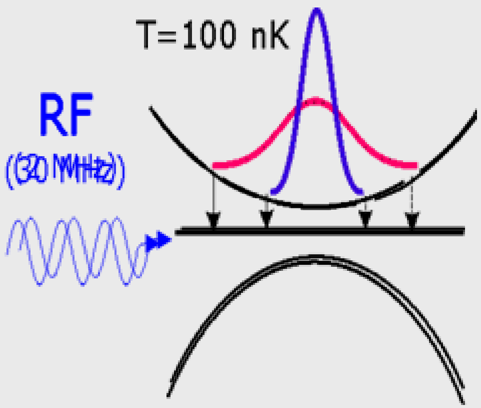
- Disordered potentials

**Quantum degenerate mixtures**

- Ultracold heteronuclear molecules

- Attractive condensates for Quantum Measurements

# Bose-Einstein condensation of alkali atoms

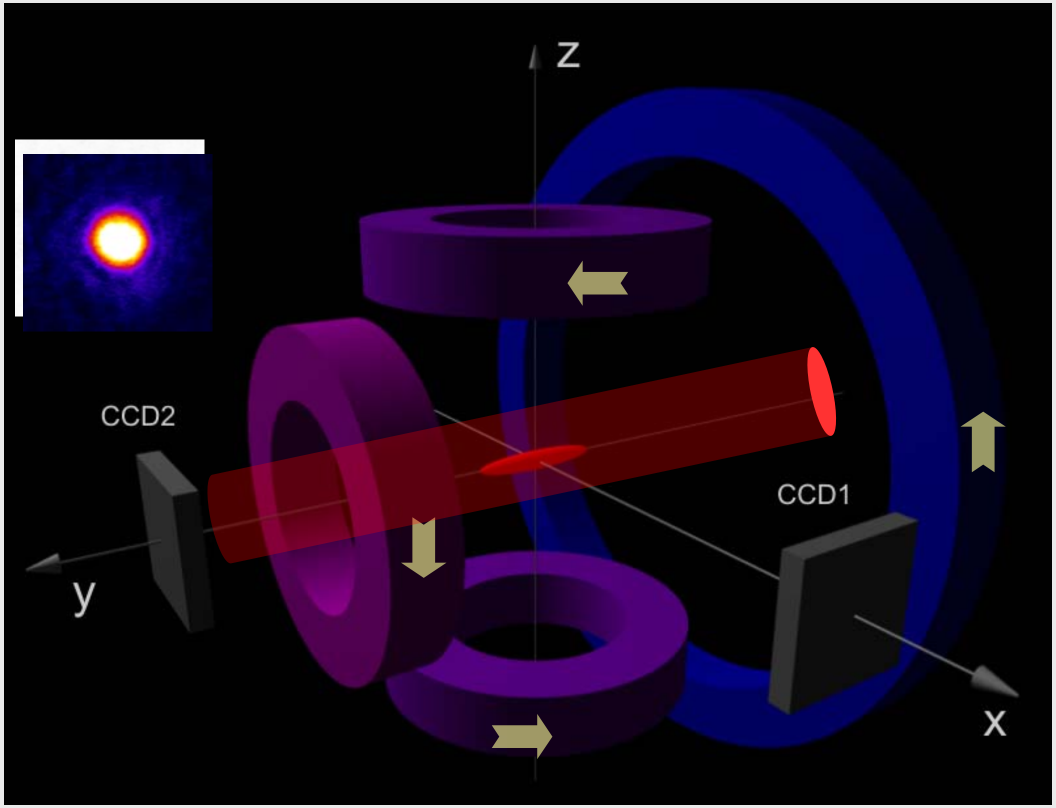



“Magneto-optical trap”, i.e. laser + weak magnetic quadrupole:
Natoms ~ $10^9$, Temperature ~ 100μK, log(PSD) → −7

Purely magnetic trap, i.e. high magnetic fields confine the atoms in harmonic potential

Forced evaporative cooling to BEC:
Natoms ~ $10^5$, Temperature ~ 100 nK

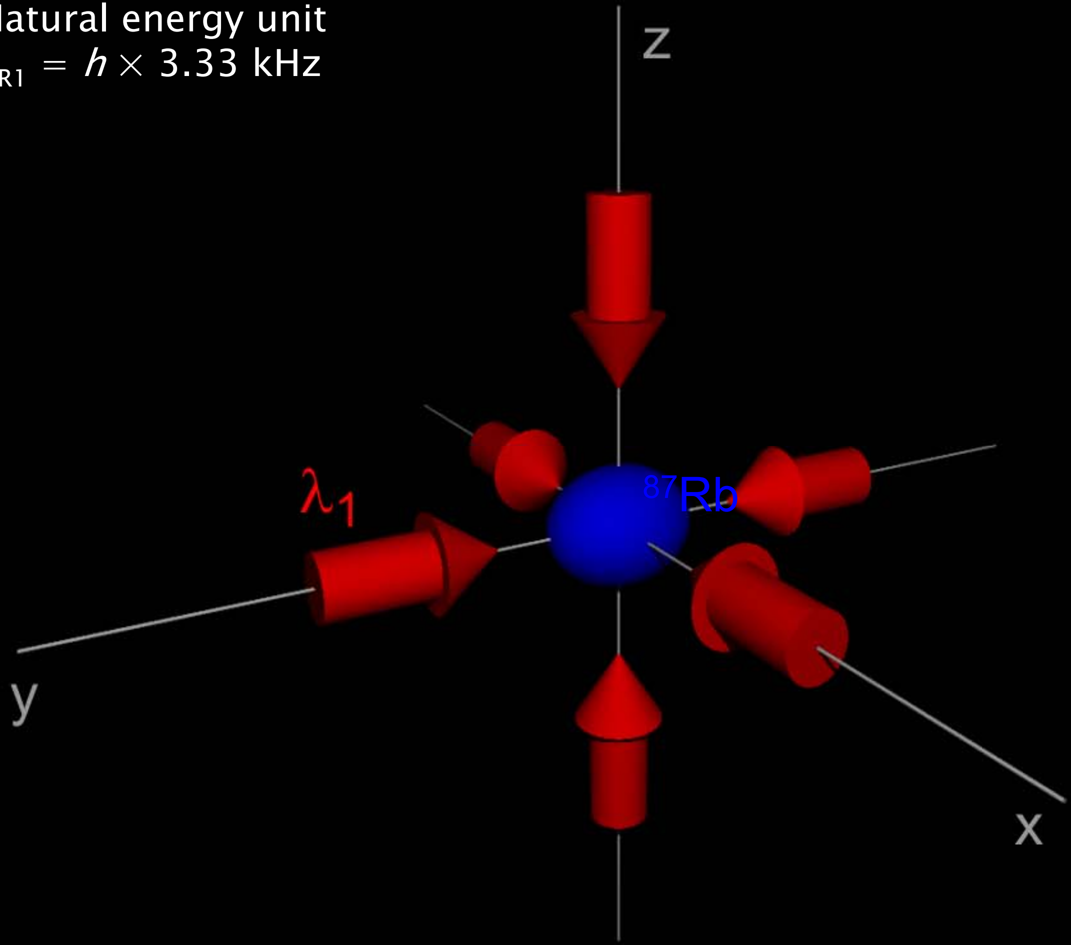
Distructive detection:
release the atoms from trap followed by absorption imaging, i.e. CCD detection of the shadow cast on resonant light beams

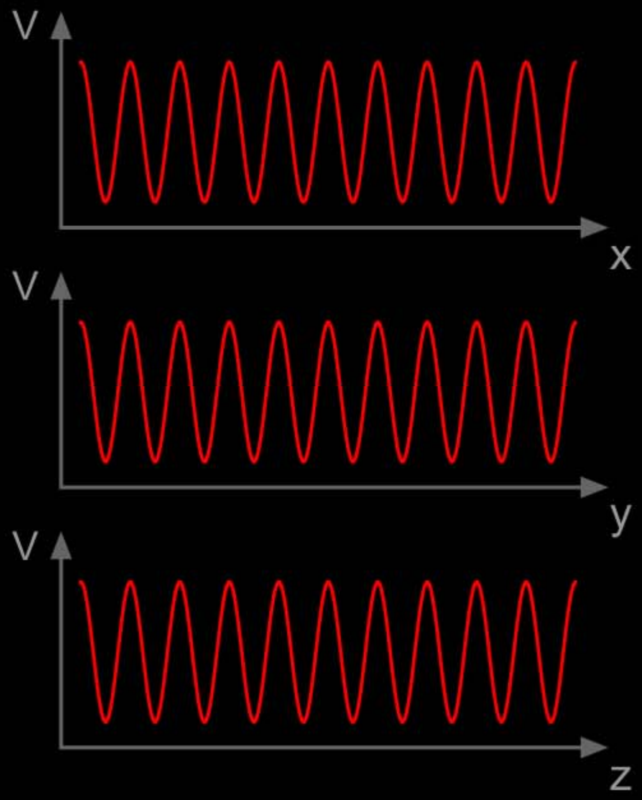


# Optical potentials

3 counterpropagating beams, far off-resonant:
conservative potential proportional to intensity, standing wave → perfect sine potential

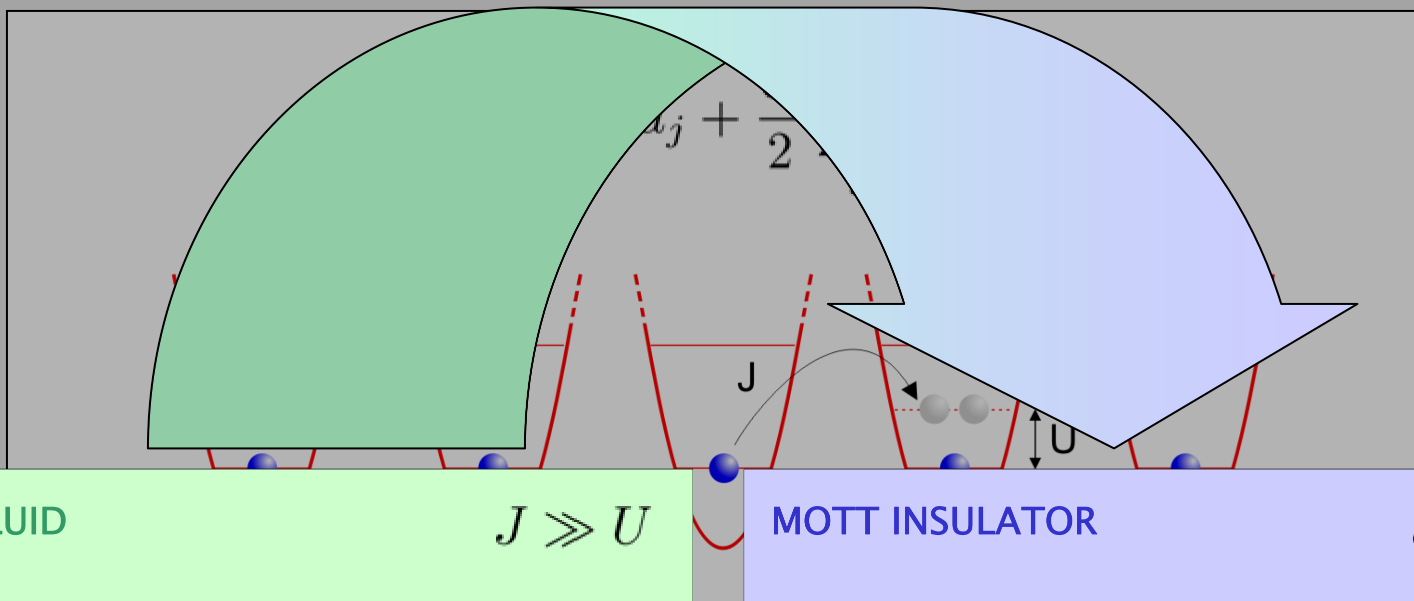
Natural energy unit
$E_{R1} = h \times 3.33$ kHz



# Interacting bosons in a lattice

Bose–Hubbard model for interacting bosons in a lattice:




**SUPERFLUID** $J \gg U$

- ✓ Long-range phase coherence
- ✓ High number fluctuations
- ✓ Gapless excitation spectrum

**MOTT INSULATOR** $J \ll U$

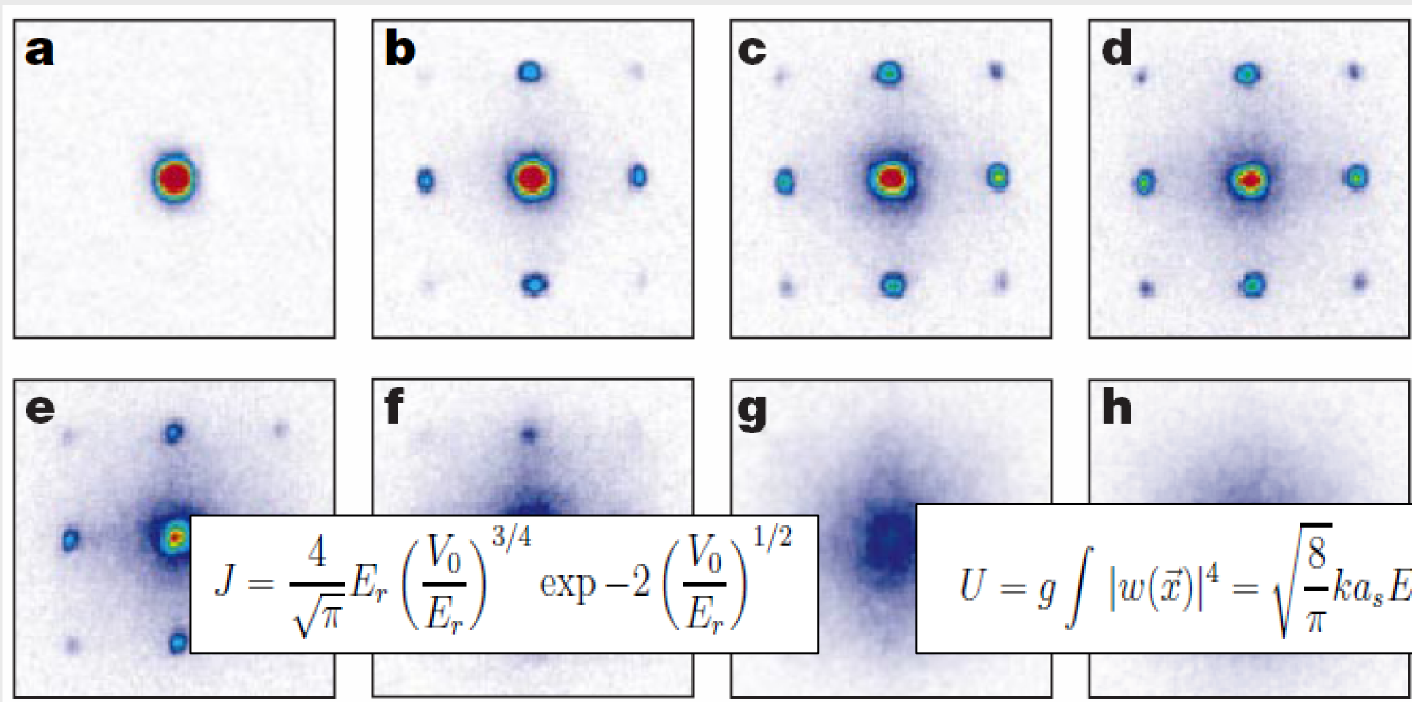
- ✓ No phase coherence
- ✓ Zero number fluctuations (Fock states)
- ✓ Gap in the excitation spectrum

| hopping energy | interaction energy |
|---|---|
| **J** | **U** |

# First observation of Superfluid to Mott Insulator transition
Greiner et al. Nature 415, 39 (2002)

## Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms

Markus Greiner*, Olaf Mandel*, Tilman Esslinger†, Theodor W. Hänsch* & Immanuel Bloch*




$$J = \frac{4}{\sqrt{\pi}} E_r \left(\frac{V_0}{E_r}\right)^{3/4} \exp -2 \left(\frac{V_0}{E_r}\right)^{1/2}$$

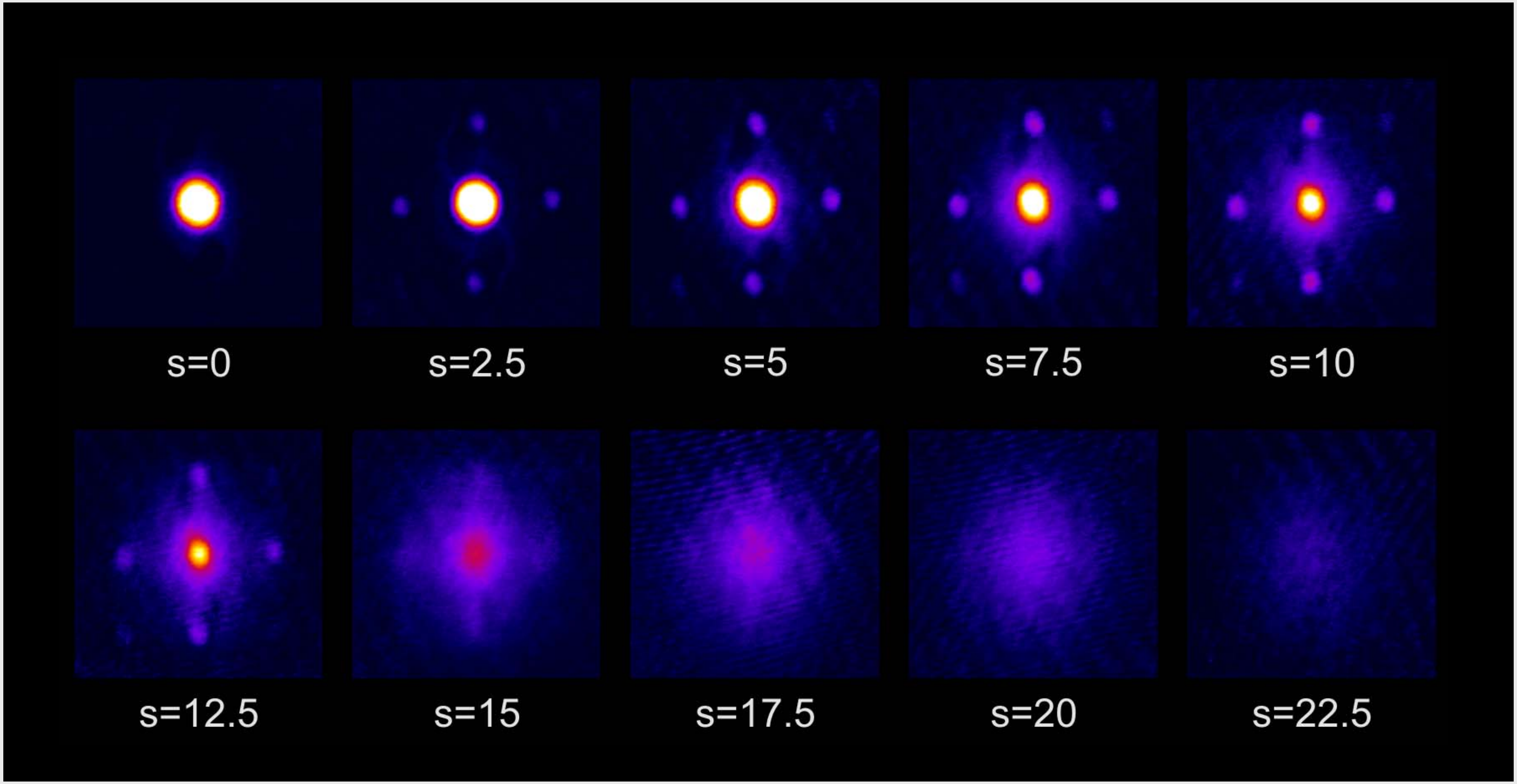
$$U = g \int |w(\vec{x})|^4 = \sqrt{\frac{8}{\pi}} k a_s E_r \left(\frac{V_0}{E_r}\right)^{3/4}$$

Vanishing interference pattern $\longrightarrow$ loss of long range coherence, phase fluctuations

Increasing the lattice height $V_0$ $\longrightarrow$ $J$ decreases, $U$ increases $\longrightarrow$ $U/J$ increases

# Superfluid to Mott Insulator transition

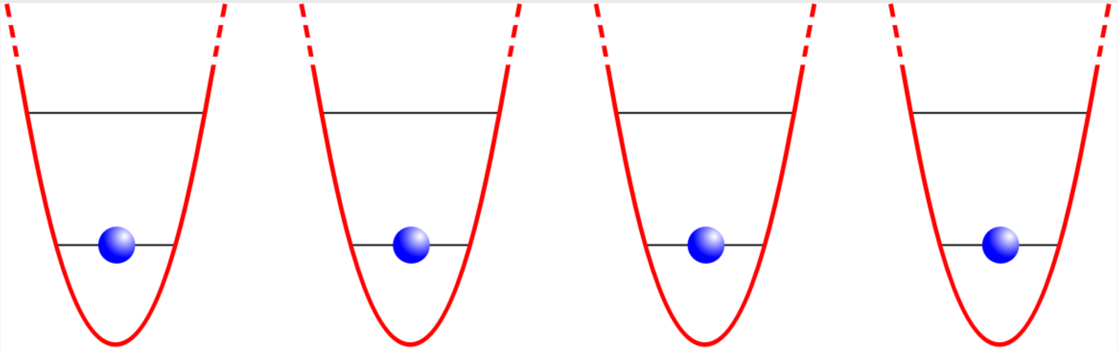
Fallani et al. cond-mat/0603655



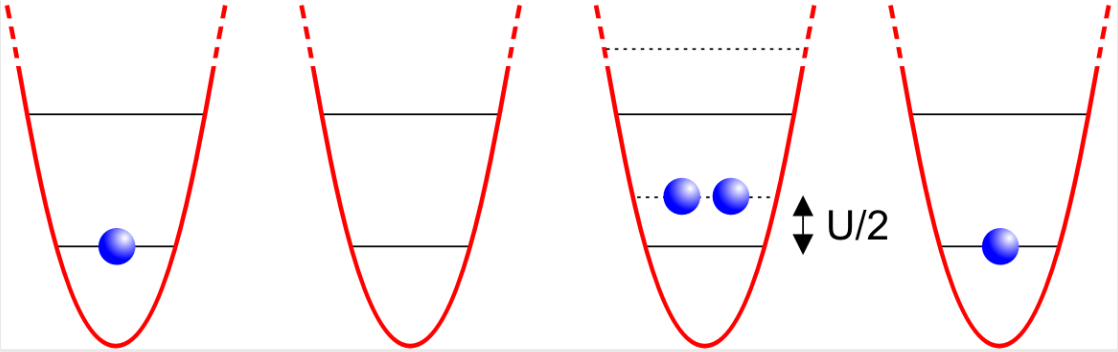
# Excitation of a Mott Insulator

The elementary excitation of a Mott Insulator consists in the tunnelling of one atom from a lattice site to a neighboring one, thereby increasing the total energy of the system:

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



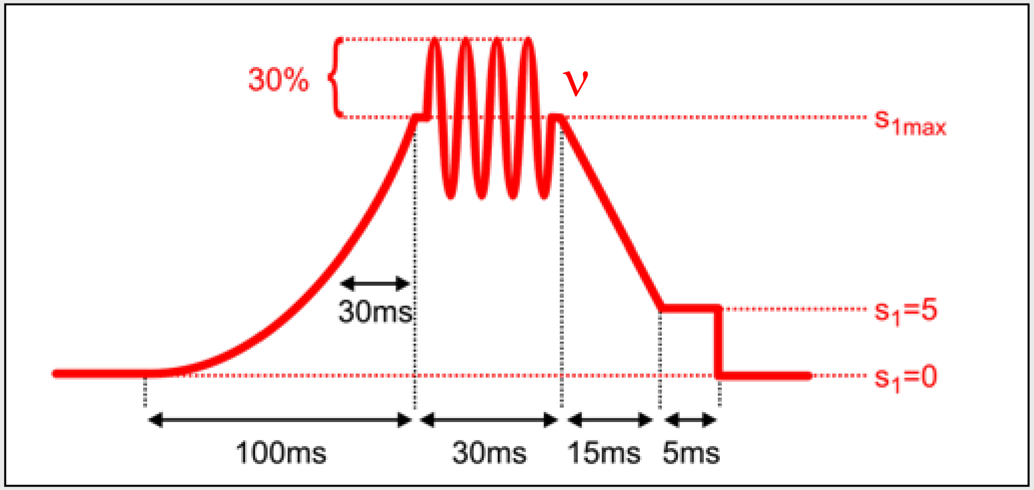
$E = E_0$




$E = E_0 + U$

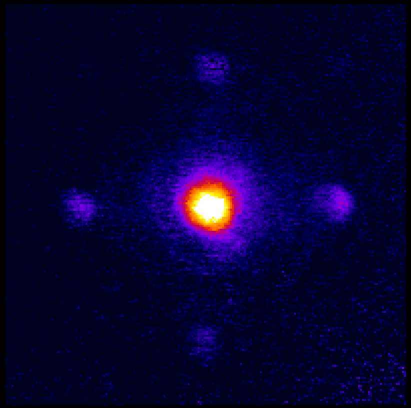
# Measuring the excitation spectrum

Excitation of the system with an amplitude modulation of the lattice potential along *y* at frequency ν:

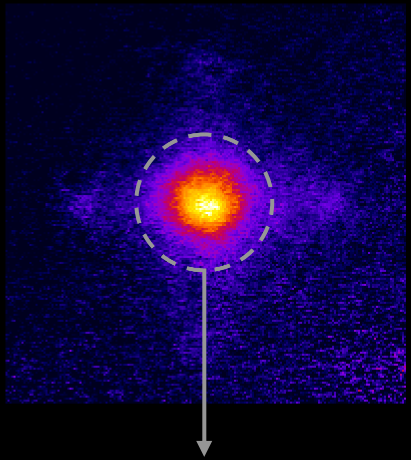



Resonant production of (particle-hole) excitations along *y* direction at energy *h*ν

without modulation:



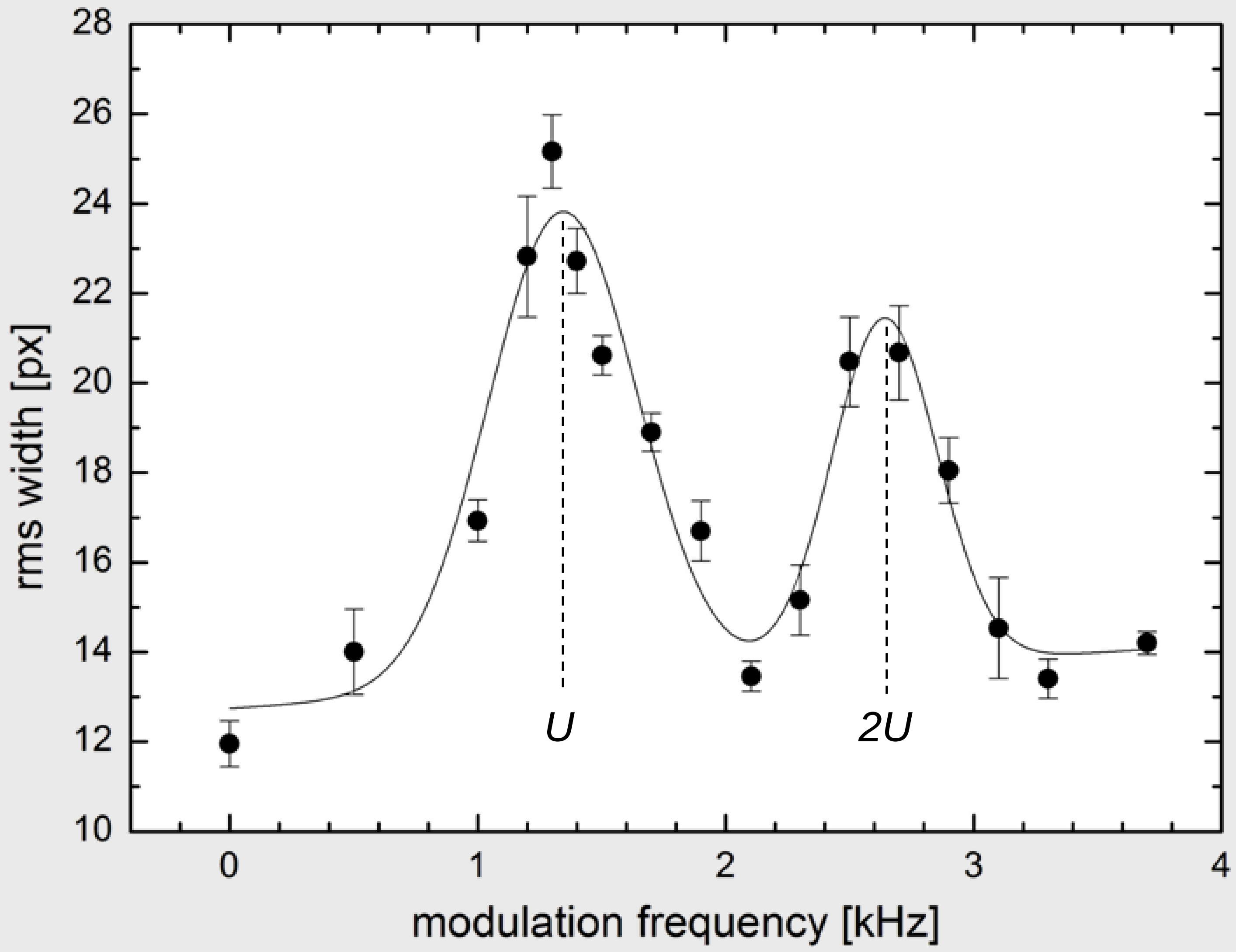
with modulation:



measurement of the width of the central density peak (energy transfer)

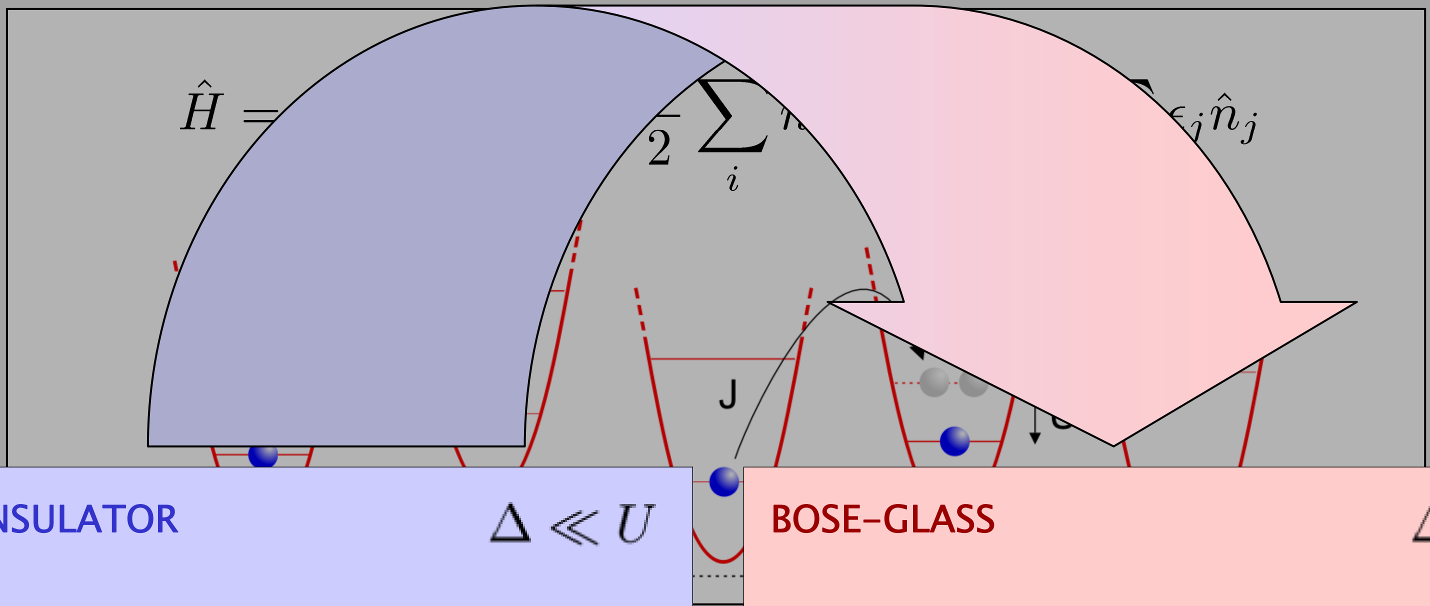
experimental technique introduced in
T. Stöferle et al., *PRL* **92**, 130403 (2004)

# Excitation spectrum of the Mott Insulator



# Adding disorder

Bose-Hubbard model with bounded disorder in the external potential $\epsilon_j \in [-\Delta/2, \Delta/2]$




**MOTT INSULATOR** $\Delta \ll U$

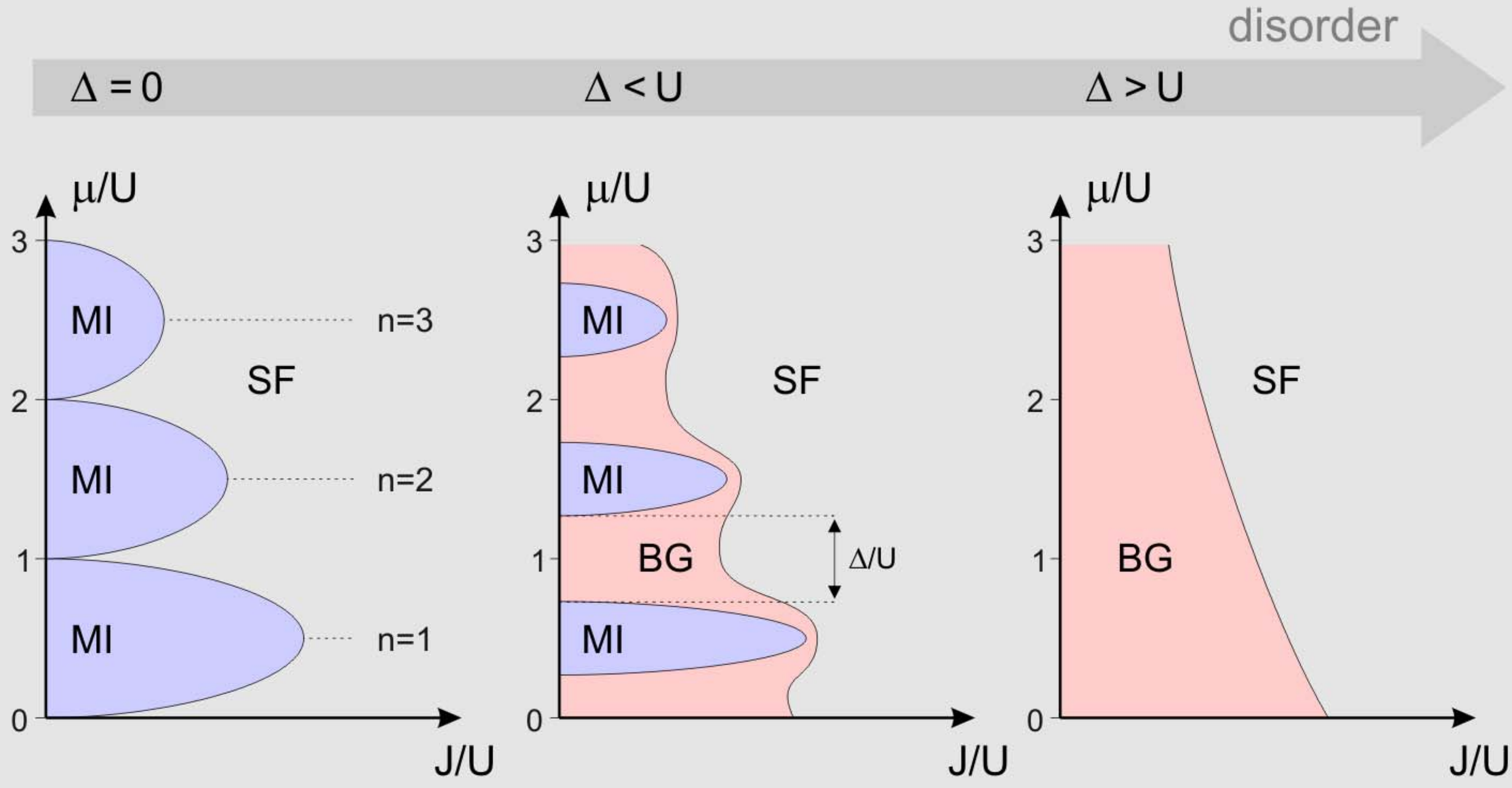
- ✓ No long-range phase coherence
- ✓ Zero number fluctuations
- ✓ Gap in the excitation spectrum

**BOSE-GLASS** $\Delta > U$

- ✓ No long-range phase coherence
- ✓ Small number fluctuations
- ✓ Gapless excitation spectrum

| hopping energy | interaction energy | disorder |
|---|---|---|
| **J** | **U** | $\Delta$ |

Qualitative phase-diagram for an interacting bosons in a disordered lattice:

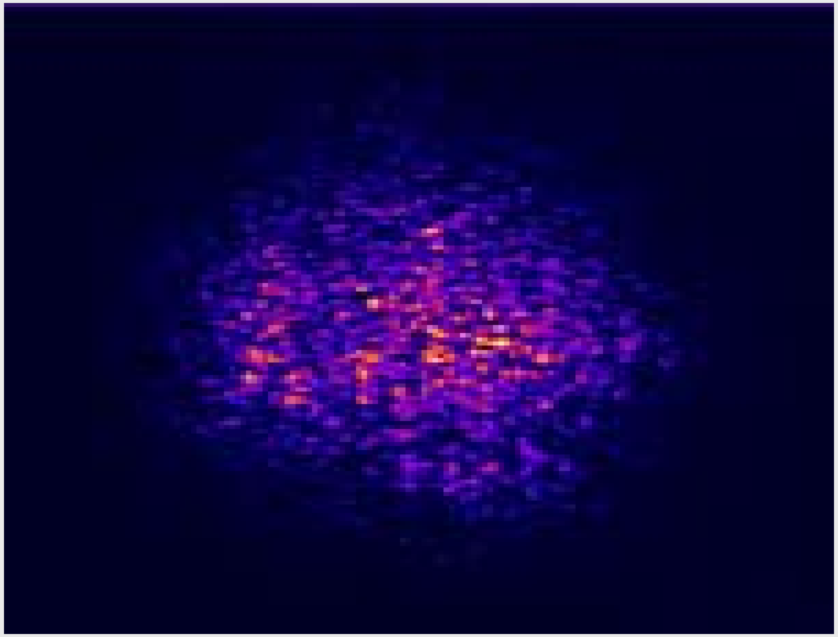



see M. P. A. Fisher et al., *PRB* **40** 546 (1989).

# Adding disorder in a controlled manner

For ultracold atoms in optical lattices one can add optical disorder in two ways:

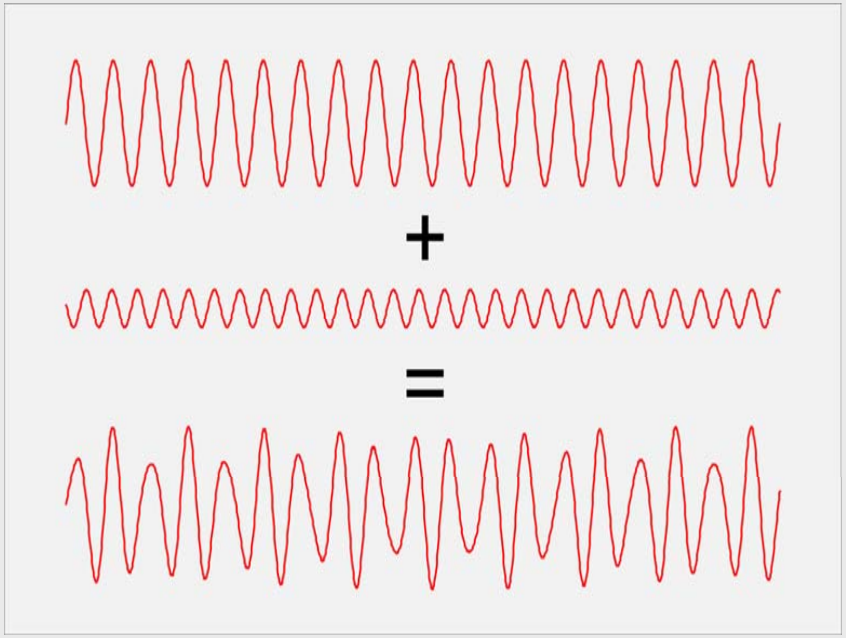
**speckle pattern**



✓ random potential

✗ large length scale (several mm)

**bichromatic lattice**



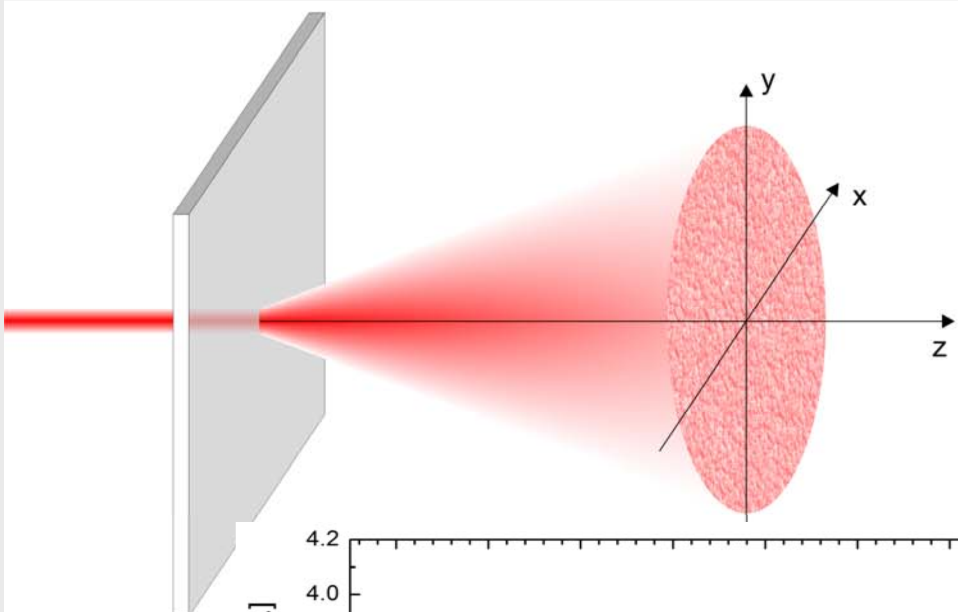

✓ quasiperiodic potential

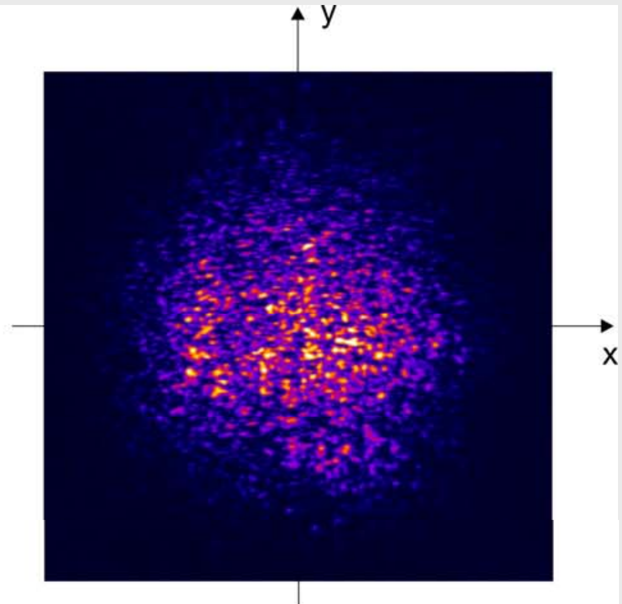
✓ smaller length scale (1 μm or less)

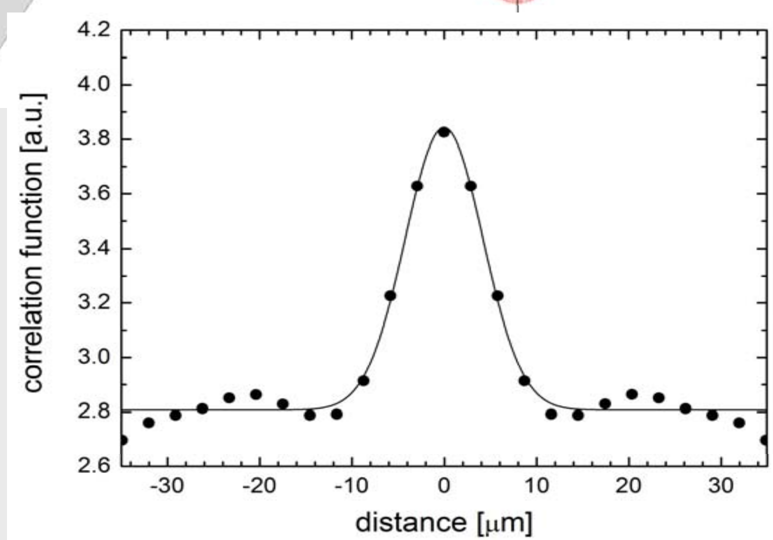
# Speckle optical potential

Lye et al., Phys. Rev. Lett. 95, 070401 (2005)
Fort et al., Phys. Rev. Lett. 95, 170410 (2005)

The random potential is produced by shining an off-resonant laser beam onto a diffusive plate and imaging the resulting speckle pattern on the BEC.



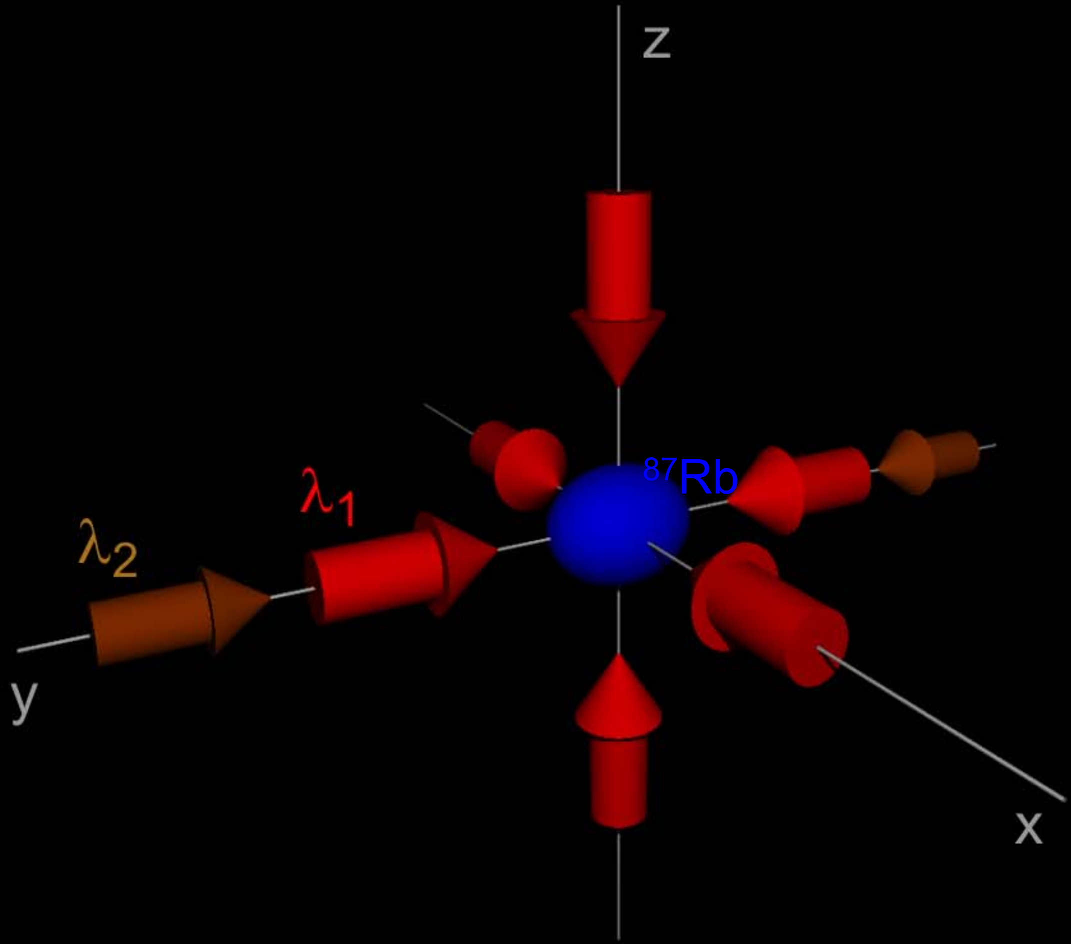



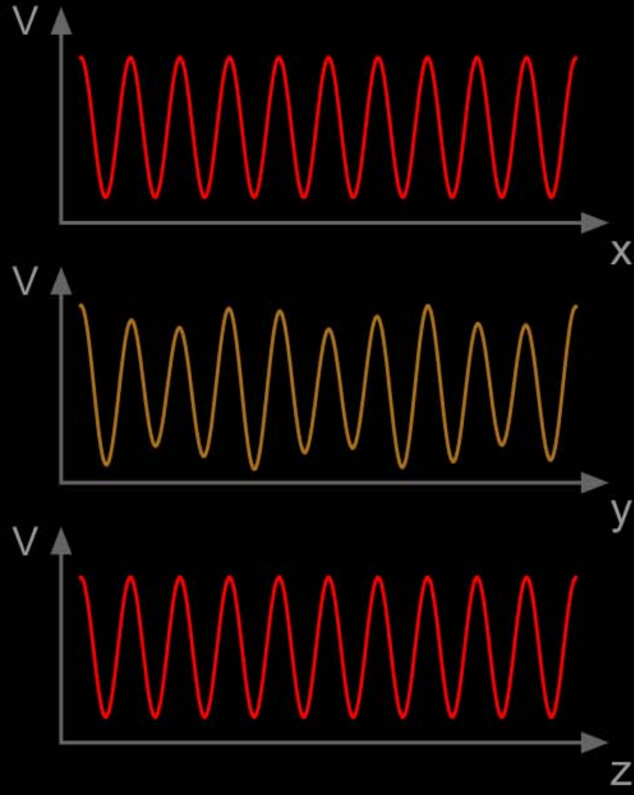

stationary in time
randomly varying in space

Width of speckle peaks diffraction limited to ~ 10 μm

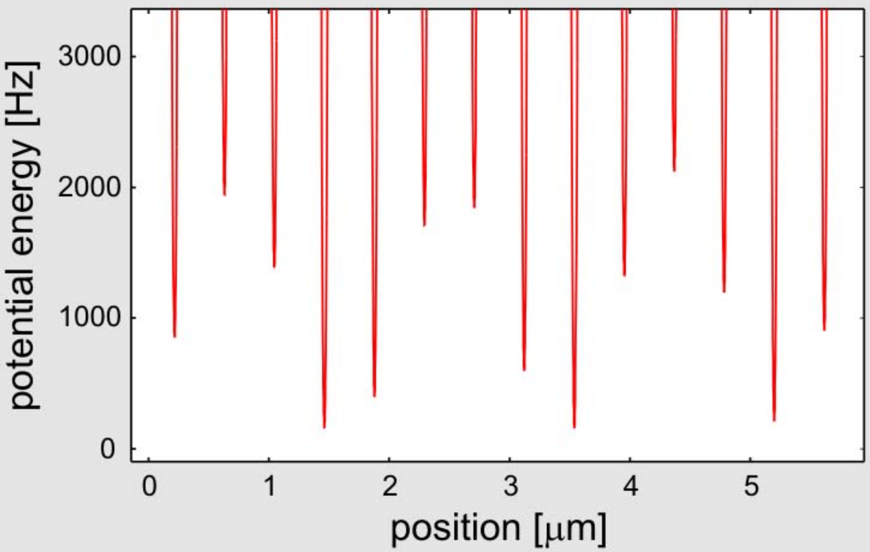
# Bichromatic optical lattice: experimental scheme

| | | | | |
|---|---|---|---|---|
| main lattice | $\lambda_1$ = 830 nm | $s_1$ = 25 | $E_{R1}$ = 3.33 kHz | 3D: x, y, z |
| disordering lattice | $\lambda_2$ = 1076 nm | $s_2$ = 0...3 | $E_{R2}$ = 1.98 kHz | 1D: y |



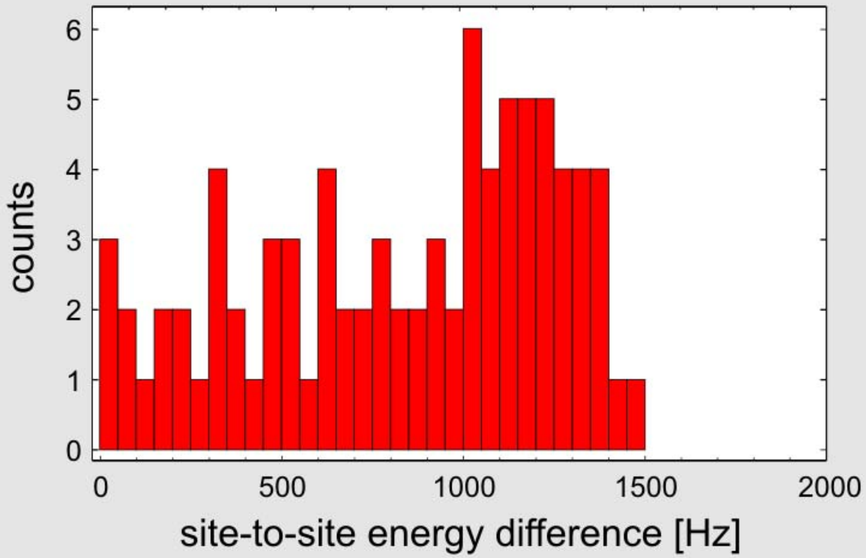
# The “disordered” lattice




Energy minima of the lattice potential along *y* direction

Small variations induced by disordering lattice:

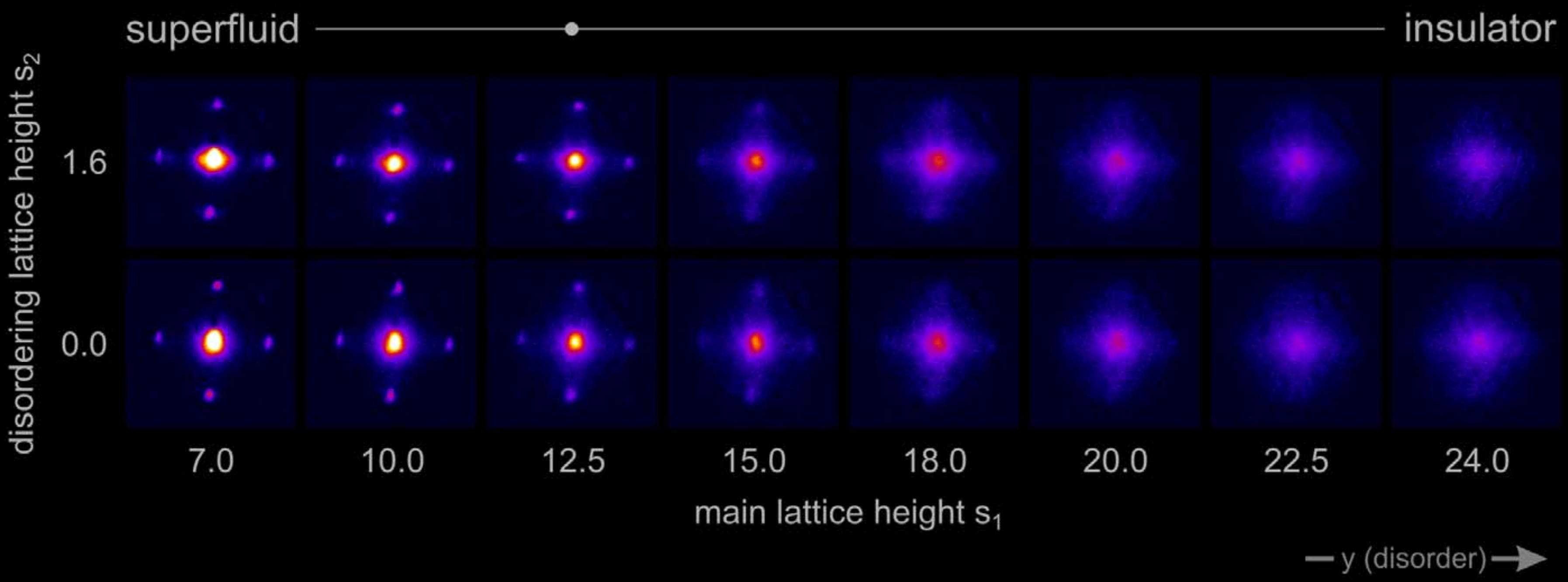
J constant within 5%
U constant within 1%




Distribution of the energy minima along *y* direction

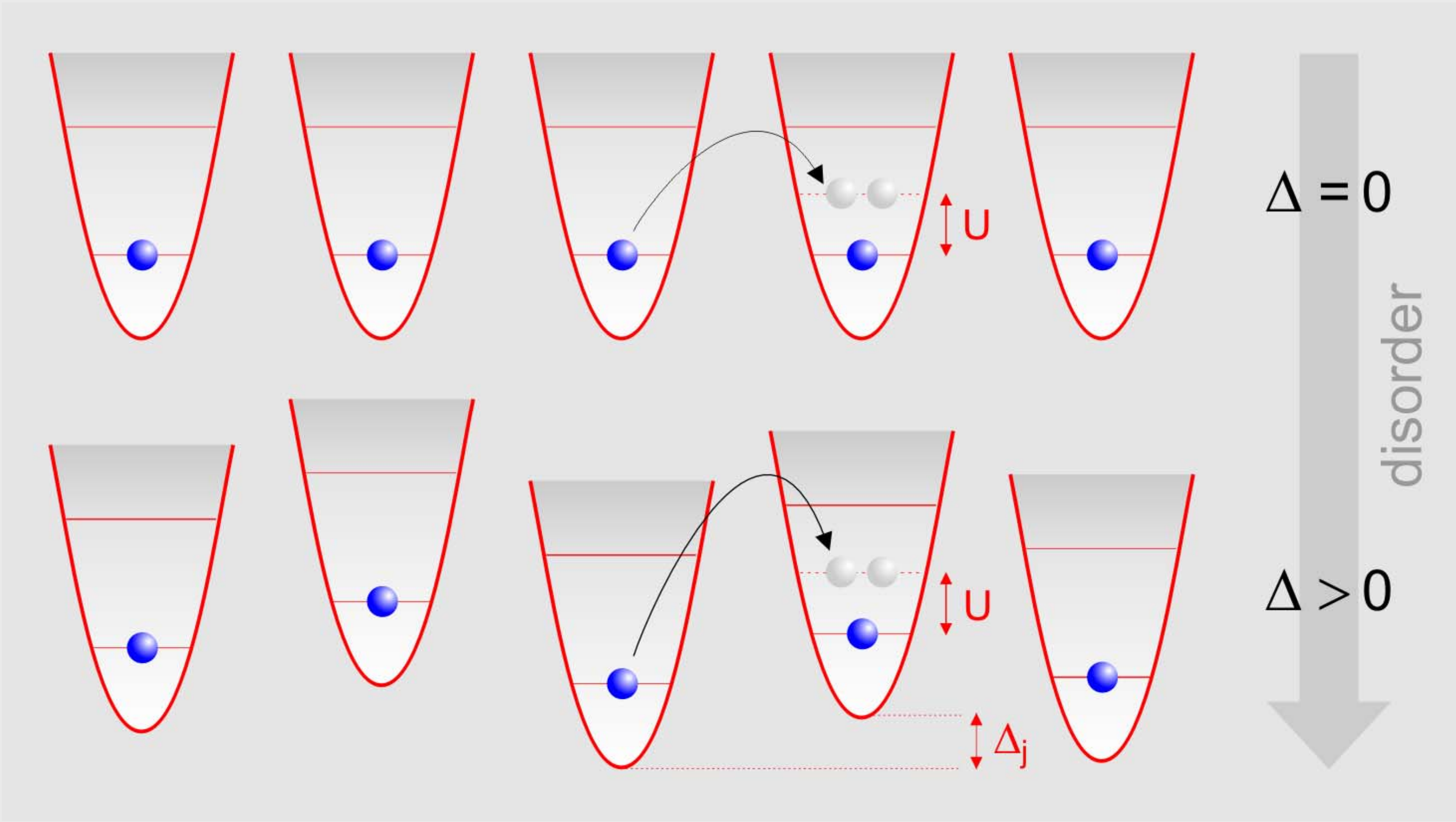
Size of BEC 35 μm

# Entering the insulating states



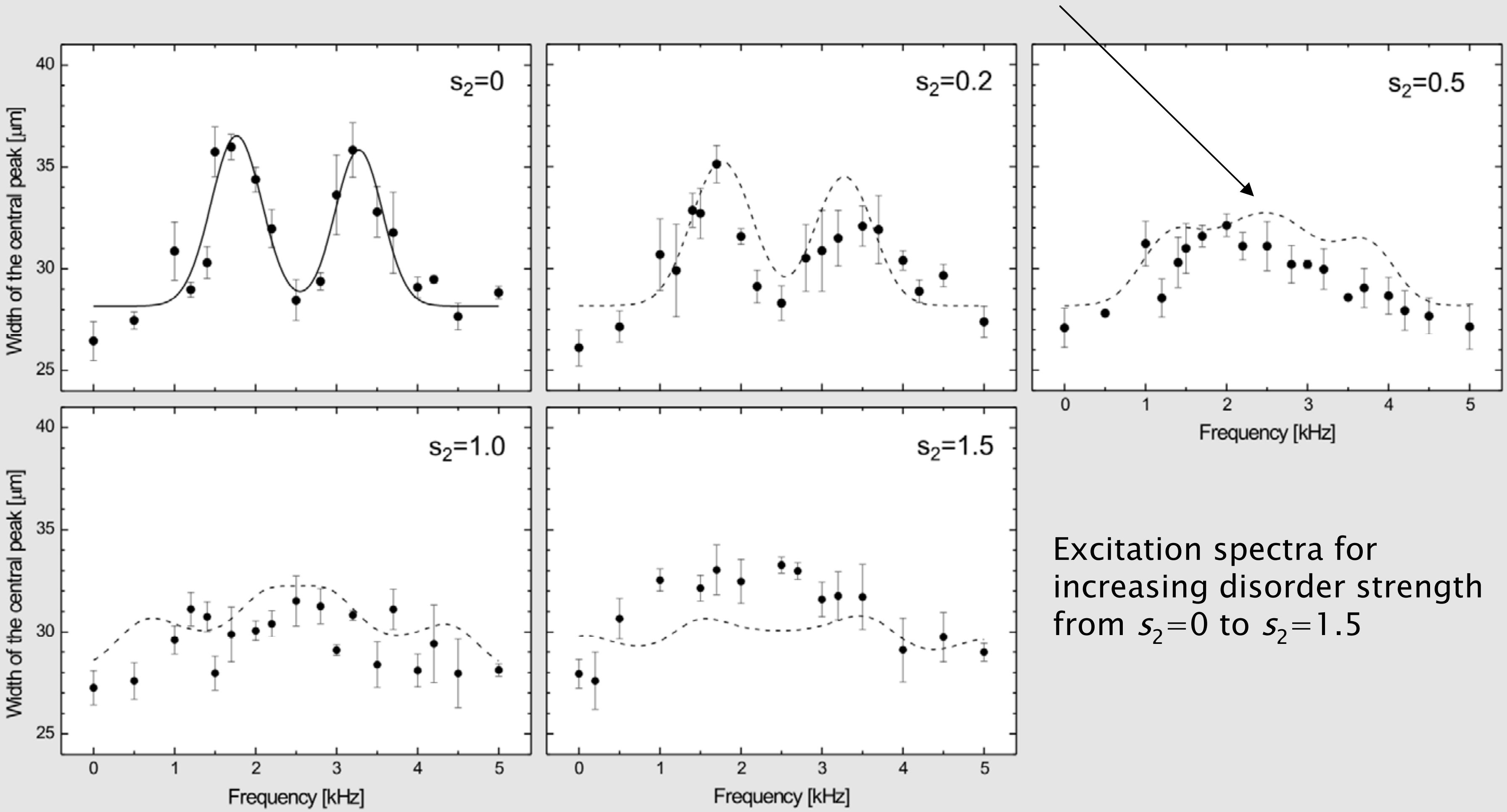

No clear effect due to presence of disorder on interference patterns

Starting from a Mott Insulator and adding disorder, the energy required for the hopping of a boson from a site to a neighboring one becomes a function of position



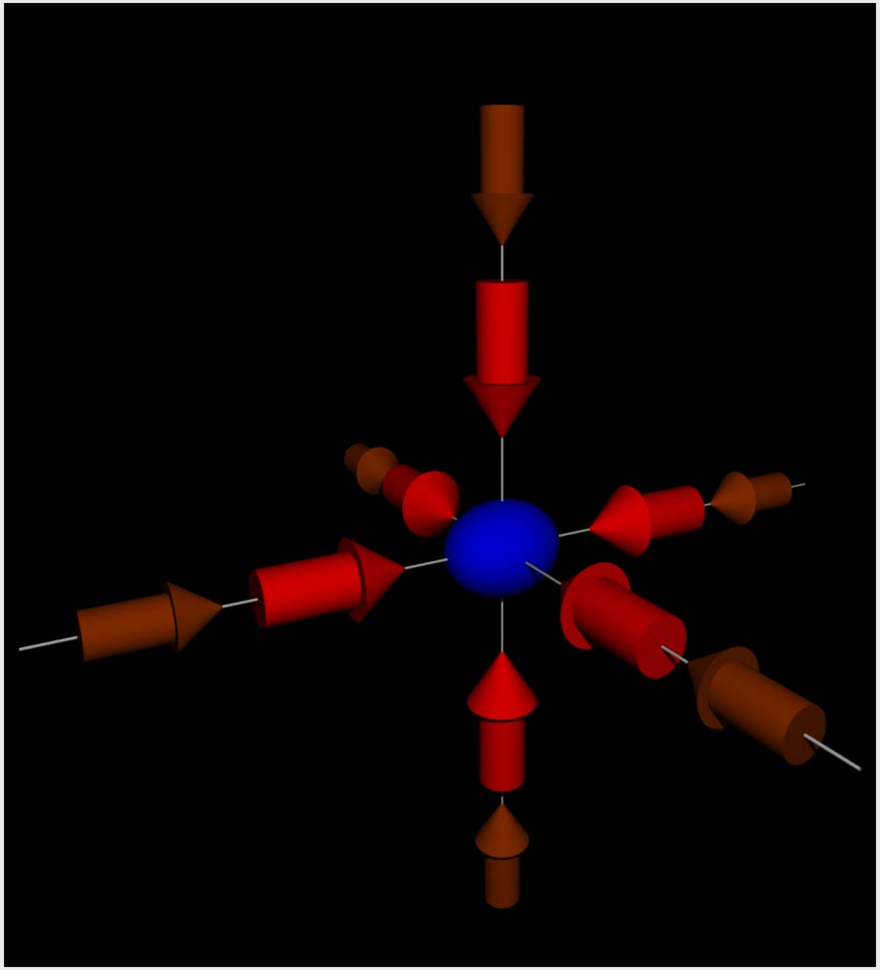
# Excitation spectra

Convolution of the MI spectrum at $s_2=0$ with the distribution of site-to-site energy shifts

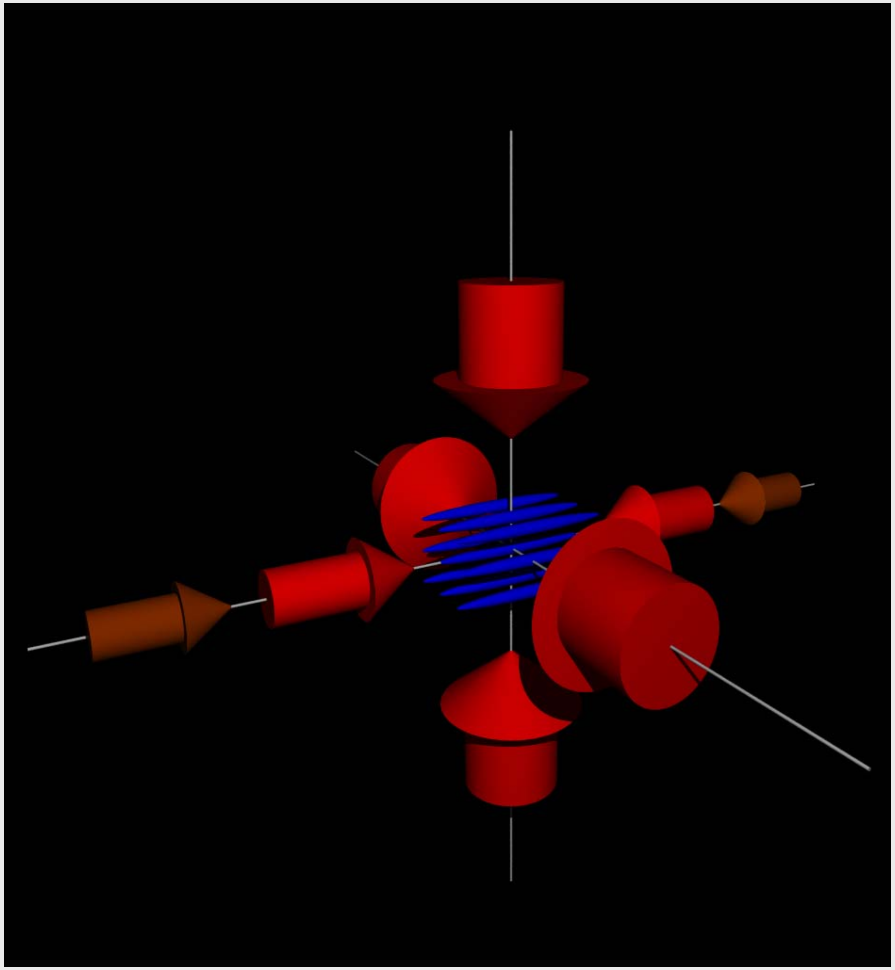



Excitation spectra for increasing disorder strength from $s_2=0$ to $s_2=1.5$

# Further geometries



3D system + 3D disorder



1D systems (“tubes”) + 1D disorder

# Outline

Bose-Einstein condensates in periodic and disordered potentials

- Superfluid to Mott insulator transition
- Disordered potentials

**Quantum degenerate mixtures**

- Ultracold heteronuclear molecules
- Attractive condensates for Quantum Measurements

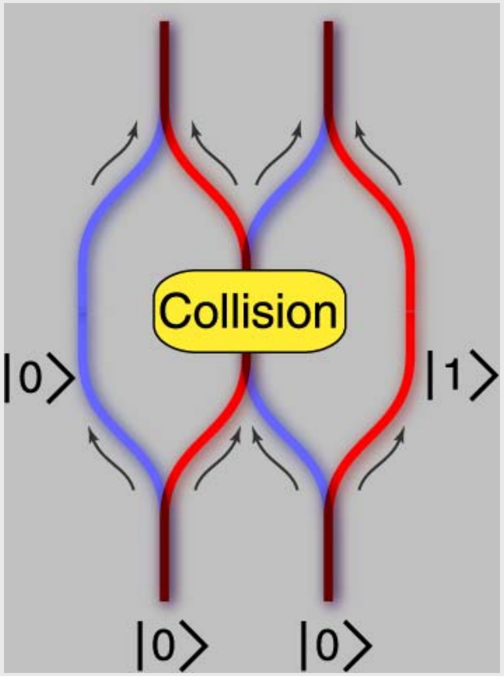
# Why ultracold heteronuclear molecules

**Conditional dynamics with neutral atoms**

- Only short range interactions, need to bring atoms in the same lattice site

- Weak interactions, slow gate, time τ~ ms

- To date only massive entanglement, no 2-qubits gate on specific sites




**Ultracold collisions with Quantum degenerate mixtures**

- Heteronuclear molecules can have electric dipole moments d ~ 1 D

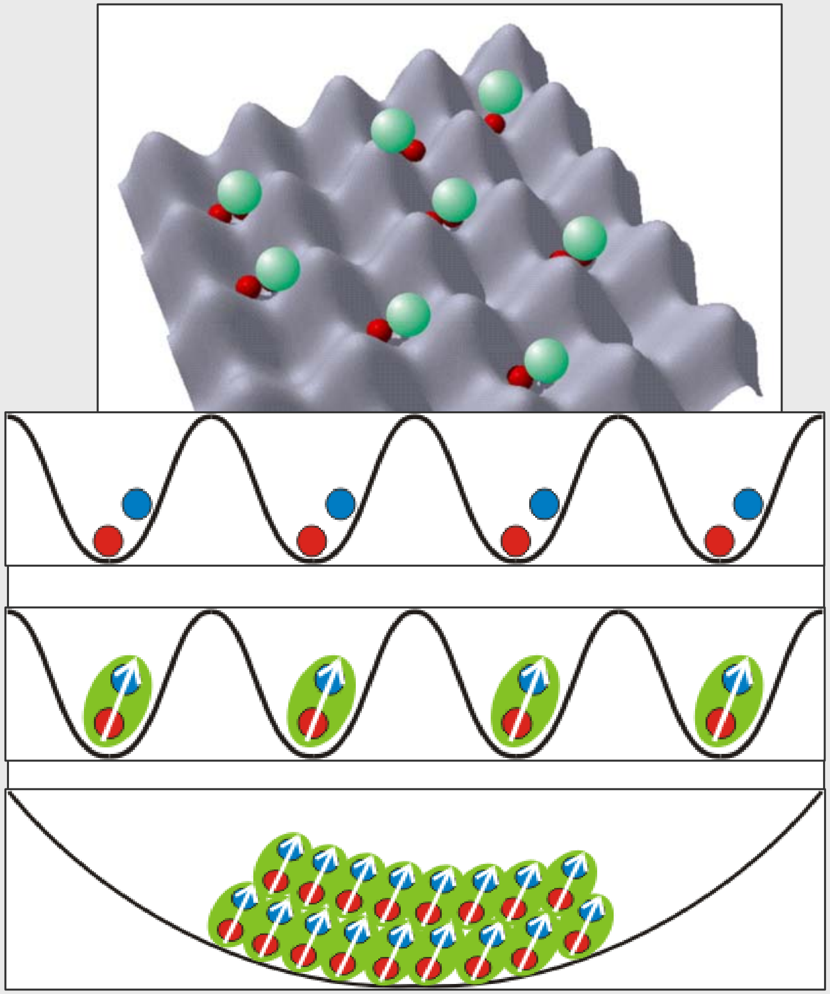
- Dipole-dipole interactions long-range ($1/R^3$)

- Several proposals to use molecules as addressable qubits

De Mille, Phys. Rev. Lett. 88 067901 (2002)

# Feshbach-associated heteronuclear bosonic molecules

Double Mott-insulator phase:
one atom per specie in each lattice site
a12 << a11, a22



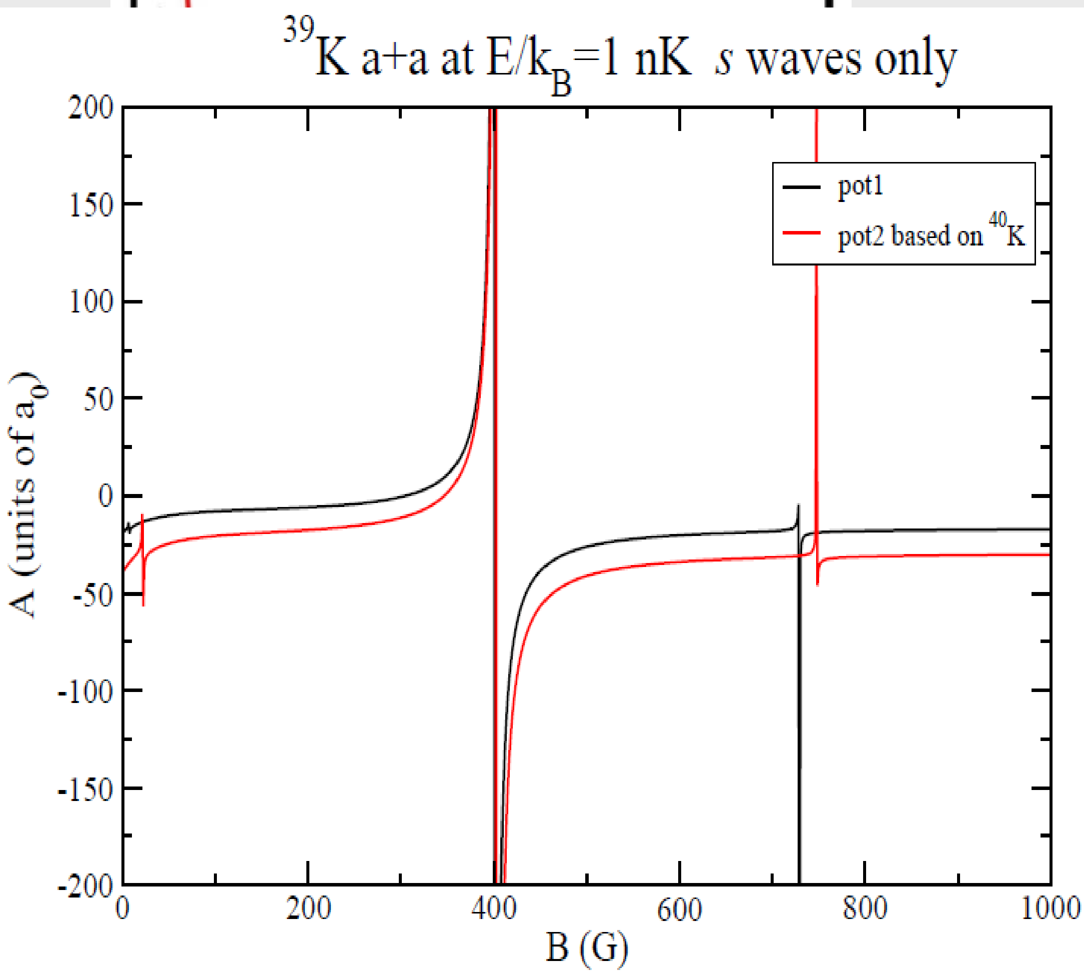
- Feshbach association of heteronuclear bosonic molecules

- no 3-body losses, shortening molecules lifetime

- Difficulty:
transfer to ground vibration state where d ~ 0.25 D

B. Damski et al., PRL. 90, 110401 (2003)
M. G. Moore et al., PRA 67, 041603 (2003)

**Scattering resonances** due to input state energy nearly coincident with bound level in a different scattering channel. Energy coincidence driven by applied magnetic field.


Enhancement of the scattering length, displaying a dispersive behavior vs magnetic field

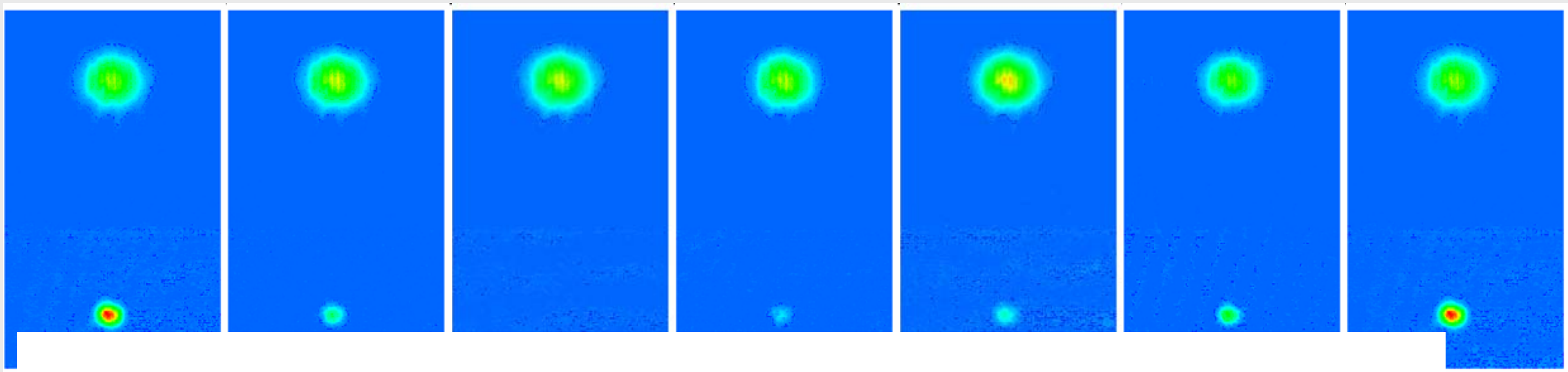
On the side of a>0 the molecular state is lower in energy than the input state → Feshbach assisted molecular association

(unpublished, courtesy of A. Simoni)

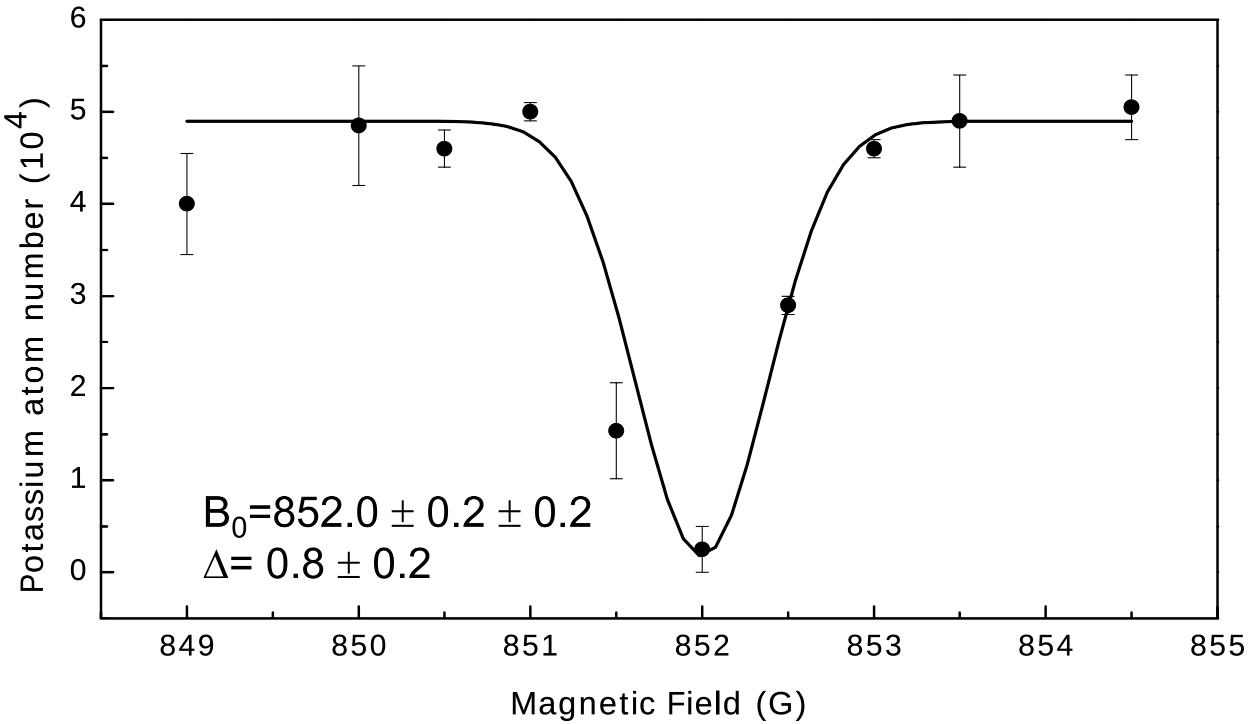
# Fano-Feshbach spectroscopy via atom losses

Rb

K



B (G) 854



# LENS results and identification

- Some 14 resonances observed at LENS in the range 300 – 850 G

  F. Ferlaino et al., Phys. Rev. A 73 040702(R) (2006)
  Erratum, Phys Rev A 74 039903 (2006)

- Fit with numerical calculations (A. Simoni) → scattering lengths for 40K–87R

- Mass scaling to predict scattering lengths and FF resonances for other isotopes combinations

TABLE II: Calculated singlet and triplet $s$-wave scattering lengths for collisions between K and Rb isotopes. Sensitivity parameters $\beta_{s,t}$ to the number of bound states (Eq. 1 in Ref. [1]) are also shown, with power of ten displayed in parenthesis.

| K-Rb | $\bar{a}_s$ ($a_0$) | $\beta_s$ | $\bar{a}_t$ ($a_0$) | $\beta_t$ |
|---|---|---|---|---|
| 39-85 | $26.5 \pm 0.9$ | -2.8(-2) | $63.0 \pm 0.5$ | -1.3(-2) |
| 39-87 | $824^{+90}_{-70}$ | -1.5(-2) | $35.9 \pm 0.7$ | -1.6(-2) |
| 40-85 | $64.5 \pm 0.6$ | -3.9(-3) | $-28.4 \pm 1.6$ | -1.8(-2) |
| 40-87 | $-111 \pm 5$ | | $-215 \pm 10$ | |
| 41-85 | $106.0 \pm 0.8$ | 3.6(-3) | $348 \pm 10$ | 6.5(-3) |
| 41-87 | $14.0 \pm 1.1$ | 2.6(-2) | $163.7 \pm 1.6$ | 7.7(-3) |

TABLE III: Predicted zero-field $s$-wave scattering lengths for the absolute ground state of K-Rb isotopes. Feshbach resonance positions and widths are also provided for three selected isotopic pairs. The quoted uncertainties do not include the uncertainty on the number of bound states.

| K-Rb | $a$ ($a_0$) | $B_{th}$ (G) | $\Delta_{th}$ (G) |
|---|---|---|---|
| 39-85 | $56.6 \pm 0.4$ | | |
| 39-87 | $27.9 \pm 0.9$ | $248.8 \pm 1.6$ | 0.26 |
| | | $320.1 \pm 1.6$ | 7.9 |
| | | $531.9 \pm 1.2$ | 2.7 |
| | | $616.2 \pm 1.5$ | 0.10 |
| 40-85 | $-21.3 \pm 1.6$ | | |
| 40-87 | $-185 \pm 7$ | | |
| 41-85 | $283 \pm 6$ | $132.5 \pm 0.6$ | 0.19 |
| | | $141.2 \pm 1.1$ | $2\ 10^{-4}$ |
| | | $147 \pm 2$ | 0.025 |
| | | $184.6 \pm 1.0$ | 2.9 |
| | | $191.4 \pm 1.0$ | 0.81 |
| | | $660 \pm 3$ | 3.4 |
| | | $687 \pm 2$ | 16 |
| 41-87 | $1667^{+790}_{-406}$ | $17 \pm 5$ | 45 |
| | | $67 \pm 3$ | 8.9 |
| | | $516 \pm 7$ | 82 |
| | | $688 \pm 8$ | 0.059 |

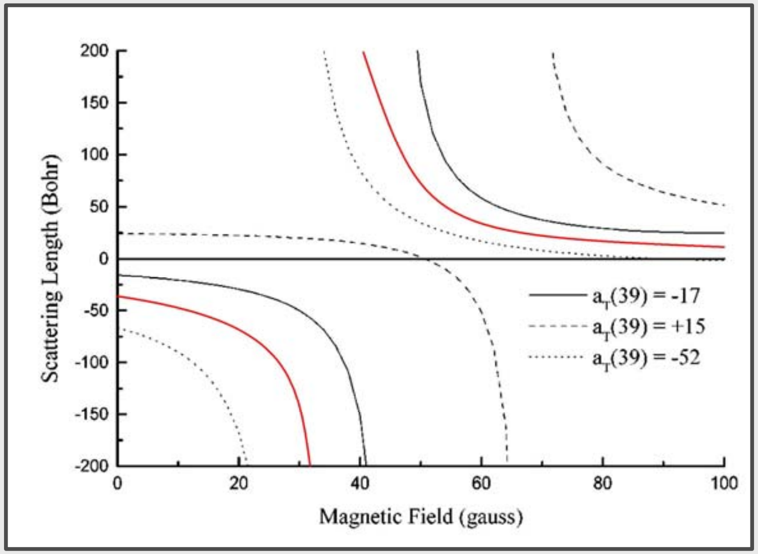
# K-Rb mixture for attractive condensates

Explore new single species:

- Bose condensate of K39 for tunable interactions

  attractive interactions: $a_t = -(33 \pm 5)a_0$, $a_s = -(45 \pm 15)a_0$
  H.Wang et al., Phys. Rev. A 62, 052704 (2000)

  wide Fano-Feshbach resonance predicted around 40 G
  J. Bohn et al, Phys. Rev. A 58 3660 (1999)



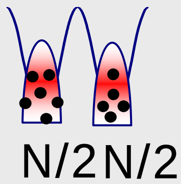

J. Bohn et al, Phys. Rev. A 58 3660 (1999)

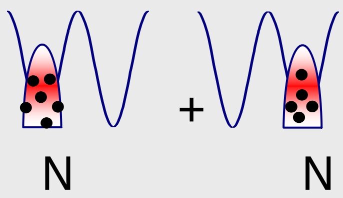
# Maximally entangled states with attractive condensates

Bose-Hubbard hamiltonian

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

- J >> U — coherent state
- |U|>>J, U>0 — Mott insulator
- |U|>>J, U<0 — superposition of localized states, Schroedinger cats



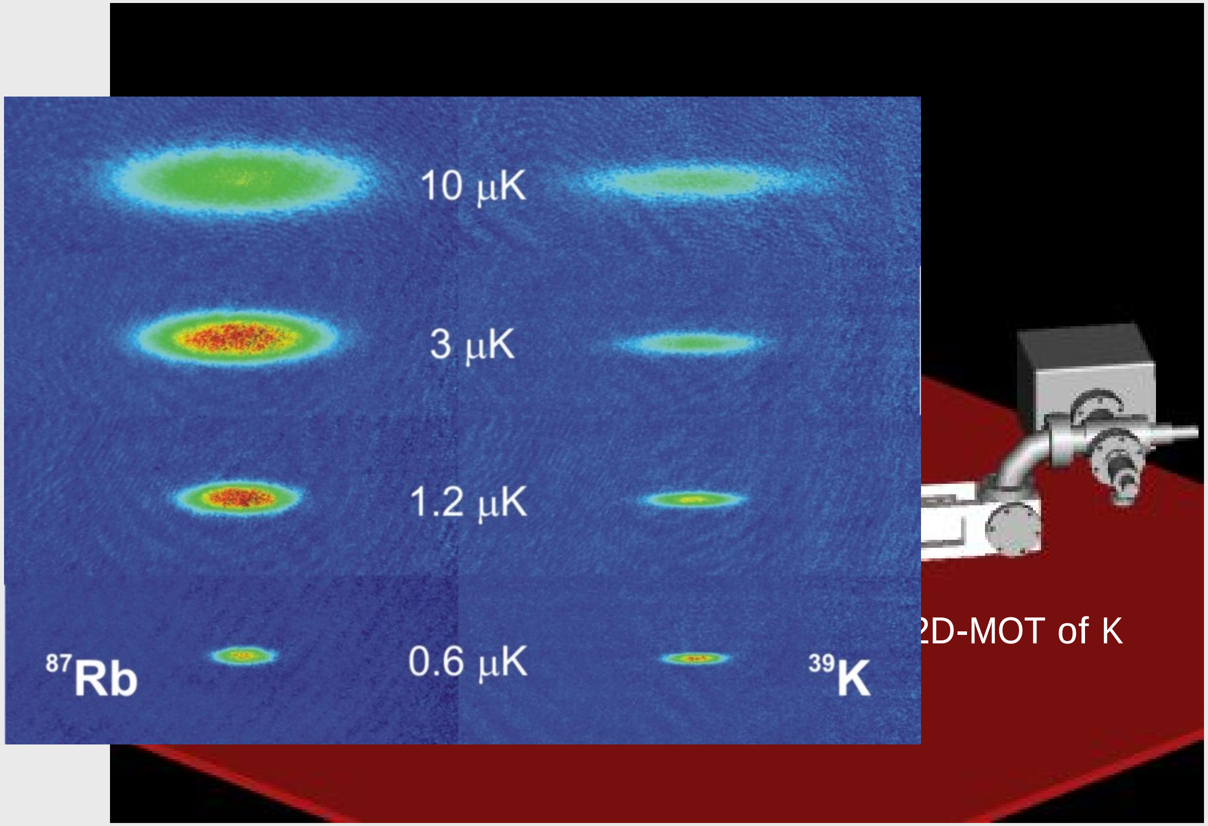



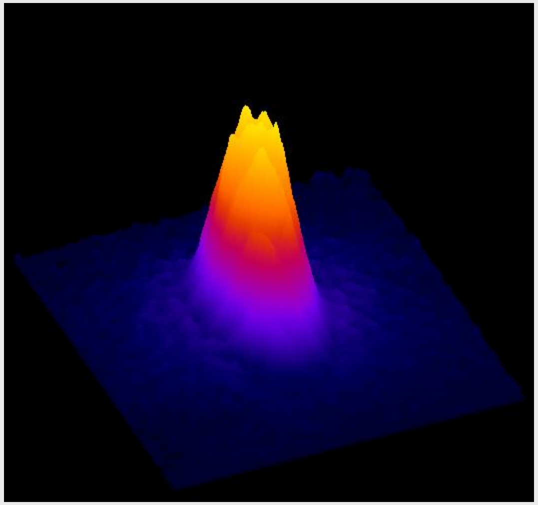

$$|\psi\rangle = \frac{1}{\sqrt{MN!}} \sum_{j=1}^{M} e^{i\phi_j} \hat{b}_j^{\dagger N} |\mathrm{vac}\rangle$$

P. Buonsante et al., Phys. Rev. A 72, 043620 (2005)

Interferometry with S-cats overcomes Standard Quantum Limit $\Delta G/G \sim 1/\mathrm{sqrt}(N)$

Decoherence & detection open issues



- ☑ 2 dimensional MOT of Rubidium
- ☑ 2 dimensional MOT of Potassium
- ☑ Dual 3D–MOT
- ☑ Magnetic trapping and evaporation

- ☑ BEC of Rb
- ☑ Sympathetic cooling of K39, K41
- ✖ Double BEC of Rb–K
- ✖ Optical trap and lattice @ 1060 nm
- ✖ Fano–Feshbach resonances

## Conclusions

- Onset of Bose-glass phase on 3D optical lattice disordered along 1D
- Fano-Feshbach resonances observed for Rb87-K40, precise determination of scattering lengths
- New Bose-Bose experiment: already single BEC, close to double BEC

## Perspectives (Bose-Bose experiment)

- Fano-Feshbach resonances in K-Rb and in K-K
- Superfluid to Mott insulator phase transition with two species

# Quantum Degenerate Gases team at LENS - Florence


Permanent members:
C. Fort, FM, G. Modugno
Massimo Inguscio

Post-docs and researchers:
L. Fallani, F. Ferlaino, J. Lye, M. Modugno, G. Roati, *P.Maioli*

PhDs:
J. Catani, L. De Sarlo, V. Guerrera, M. Zaccanti, C. D'Errico

The end

Thanks

http://quantumgases.lens.unifi.it

(coming soon)