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

27 August - 7 September, 2007

Quantum degenerate mixtures and disorder in optical lattices.

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Quantum Degenerate Mixtures and Disorder in Optical Lattices

(Disorder Induced Quantum Phases in Ultracold Atoms)

TRIESTE – Novel Quantum Phases … 3 September 2007

Ultracold atoms in disordered potentials

✓ *Why disorder?*

- Disorder is a key ingredient of the microscopic (and macroscopic) world
- Fundamental element for the physics of **conduction**
- **Superfluid-insulator transition** in condensed-matter systems

✓ *Why cold atoms?*

- Ultracold atoms are a versatile tool to study disorder-related phenomena
- **Precise control** on the kind and amount of disorder in the system
- Quantum simulation

✓ *Localization effects*

- **Bose glasses**, spin glasses (strongly interacting systems)

- **Anderson localization** (weakly interacting systems)

Different ways to produce disorder

Several proposal for the production of a disordered potential:

✓ ***Optical potentials***

B. Damski et al., PRL **91**, 080403 (2003).
R. Roth & K. Burnett, PRA **68**, 023604 2003).

- Speckle fields
- Multi-chromatic lattices

✓ ***Collisionally-induced disorder***

U. Gavish & Y. Castin, PRL **95**, 020401 (2005).
P.Massignan & Y. Castin, cond mat 0604232v2

- Interaction with a different randomly-distributed species

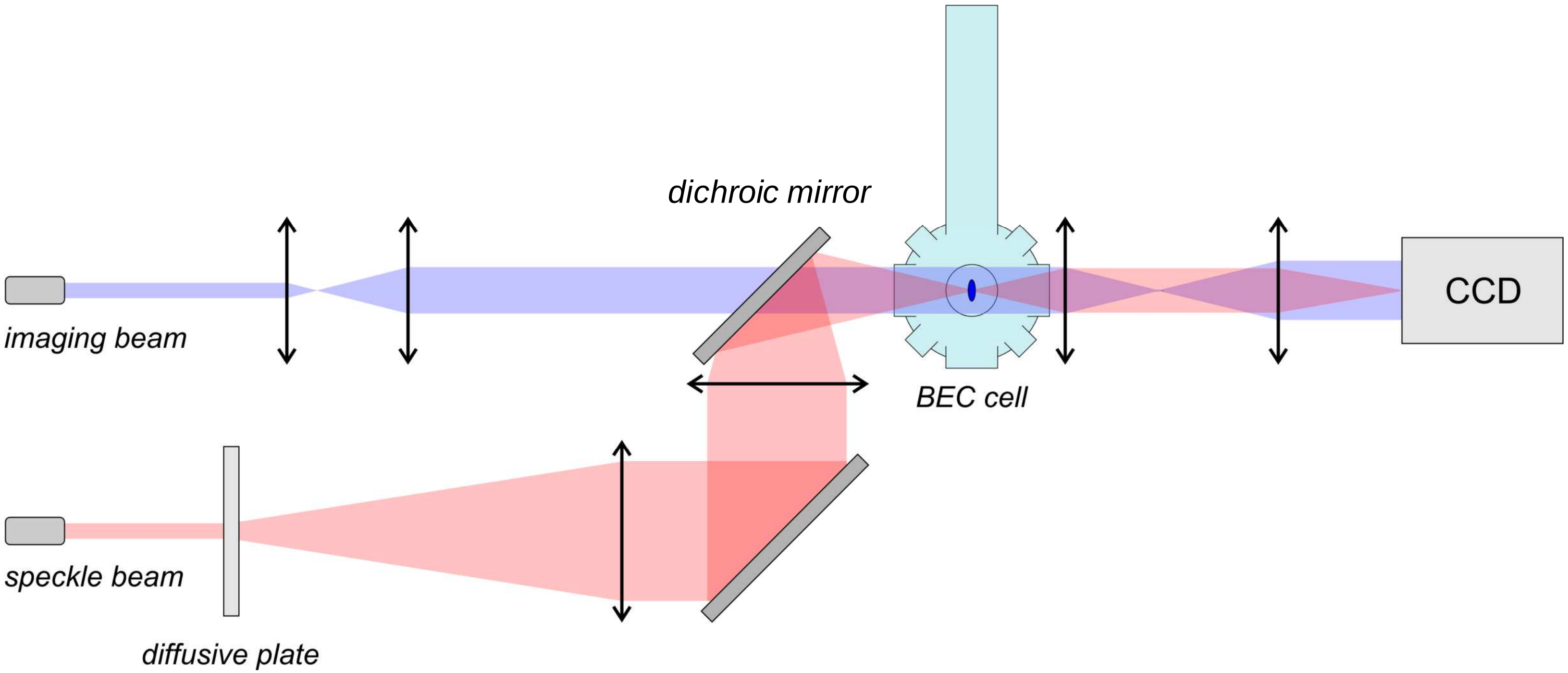
✓ ***Magnetic potentials***

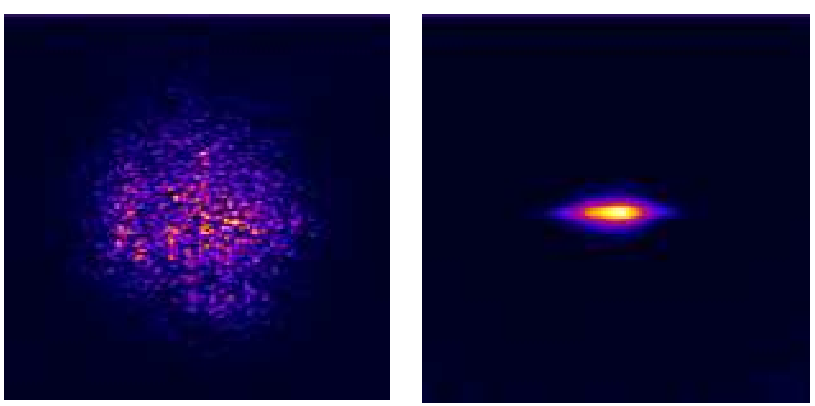
H. Gimperlein et al., PRL **95**, 170401 (2005).

- Magnetic field inhomogeneity near an atom chip

Production of the random potential

J.E.Lye, L.Fallani, M.Modugno,D.S.Wiersma, C.Fort, M.I.
Phys.Rev.Lett. 95 070401 (2005)

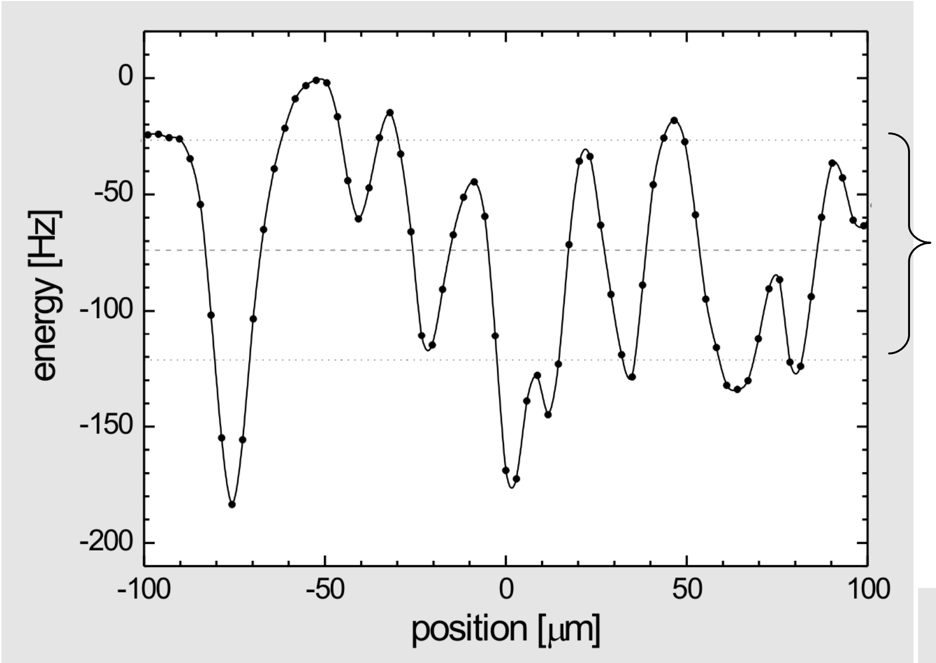




The BEC is illuminated by the speckle beam in the same direction as the imaging beam.

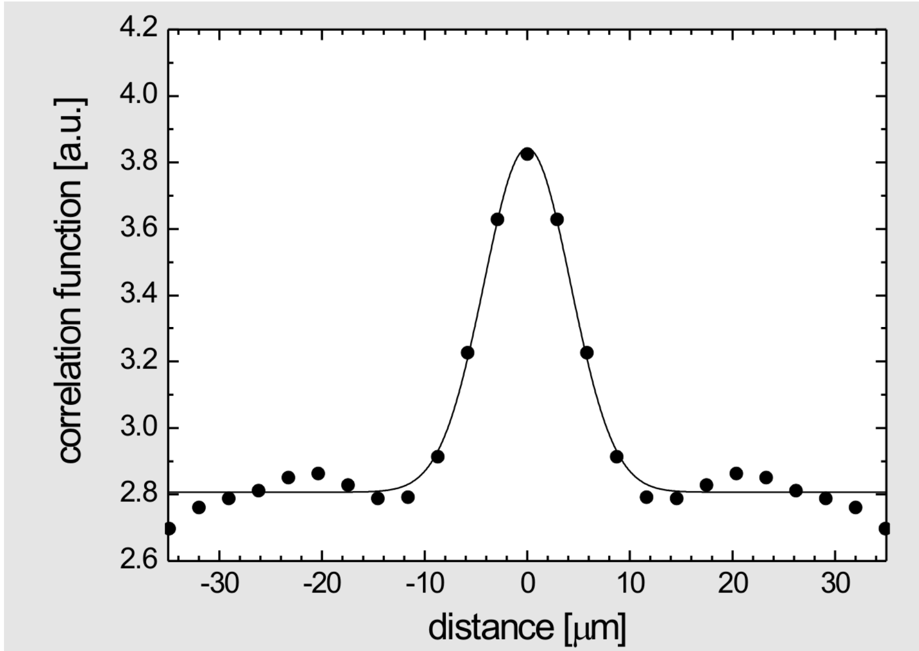
With the same imaging setup we can detect both the BEC and the speckle pattern.

Speckle potential



average speckle height:

$$V_S = 2\sigma_V = 2\sqrt{\frac{1}{2L}\int_{-L}^{+L}\left[V(x)-\bar{V}\right]^2 \mathrm{d}x}$$



speckle autocorrelation function:

$$f(d) = \frac{1}{2L\sigma_V^2}\int_{-L}^{+L}\left[V(x+d)-\bar{V}\right]\left[V(x)-\bar{V}\right]\mathrm{d}x$$

$$\approx \exp\left[-\frac{d^2}{2\sigma^2}\right] \qquad \sigma \simeq 4.2\ \mu\mathrm{m}$$

Bose-Einstein condensates in speckle fields

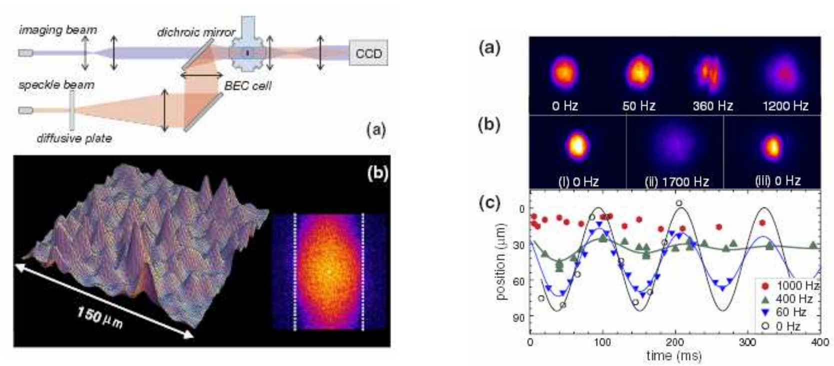
PRL 95, 070401 (2005) PHYSICAL REVIEW LETTERS week ending 12 AUGUST 2005

Bose-Einstein Condensate in a Random Potential

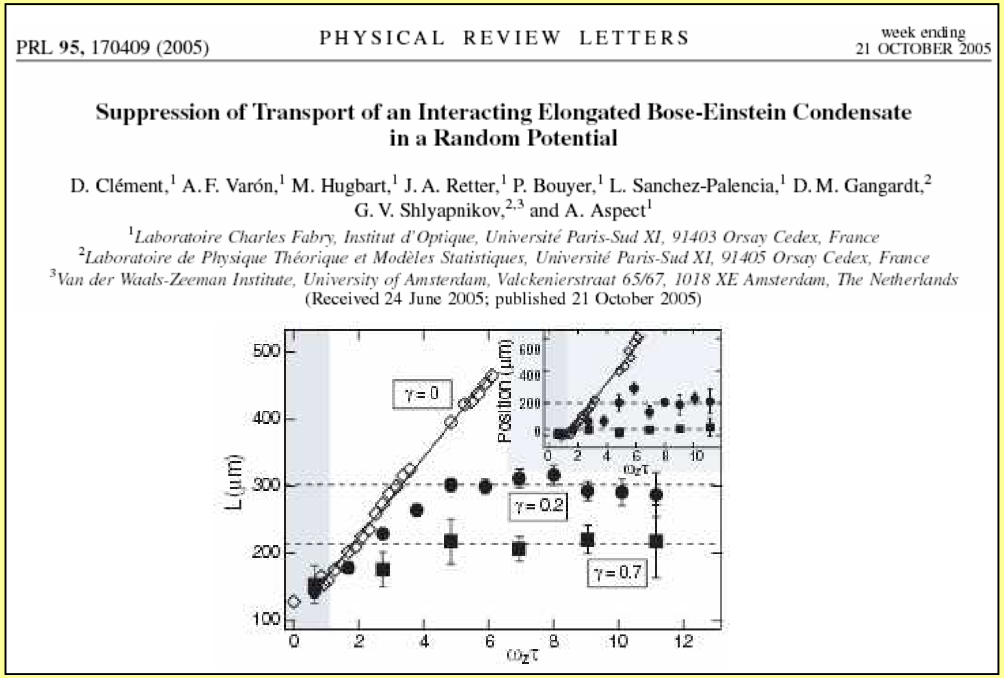
J. E. Lye,[1,*] L. Fallani,[1] M. Modugno,[1,2] D. S. Wiersma,[1,3] C. Fort,[1] and M. Inguscio[1]

[1]*LENS, Dipartimento di Fisica, and INFM Università di Firenze, via Nello Carrara 1, I-50019 Sesto Fiorentino (FI), Italy*
[2]*BEC-INFM Center, Università di Trento, I-38050 Povo (TN), Italy*
[3]*INFM-MATIS, Catania, Italy*

(Received 7 December 2004; published 9 August 2005)



Bose-Einstein condensates in speckle fields



PRL 95, 170409 (2005) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2005

Suppression of Transport of an Interacting Elongated Bose-Einstein Condensate in a Random Potential

D. Clément,[1] A. F. Varón,[1] M. Hugbart,[1] J. A. Retter,[1] P. Bouyer,[1] L. Sanchez-Palencia,[1] D. M. Gangardt,[2] G. V. Shlyapnikov,[2,3] and A. Aspect[1]

[1]*Laboratoire Charles Fabry, Institut d'Optique, Université Paris-Sud XI, 91403 Orsay Cedex, France*
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(Received 24 June 2005; published 21 October 2005)

Bose-Einstein condensates in speckle fields

PRL 95, 170410 (2005) PHYSICAL REVIEW LETTERS week ending 21 OCTOBER 2005

Effect of Optical Disorder and Single Defects on the Expansion of a Bose-Einstein Condensate in a One-Dimensional Waveguide

C. Fort,[1] L. Fallani,[1] V. Guarrera,[1] J. E. Lye,[1] M. Modugno,[2] D. S. Wiersma,[1,3] and M. Inguscio[1]
[1]*LENS, Dipartimento di Fisica and INFM, Università di Firenze, via Nello Carrara 1, I-50019 Sesto Fiorentino (FI), Italy*
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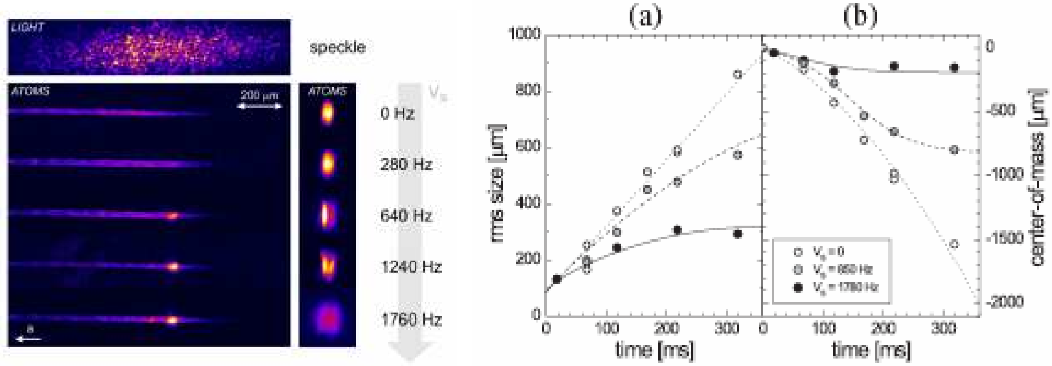
[3]*INFM-MATIS, Catania, Italy*

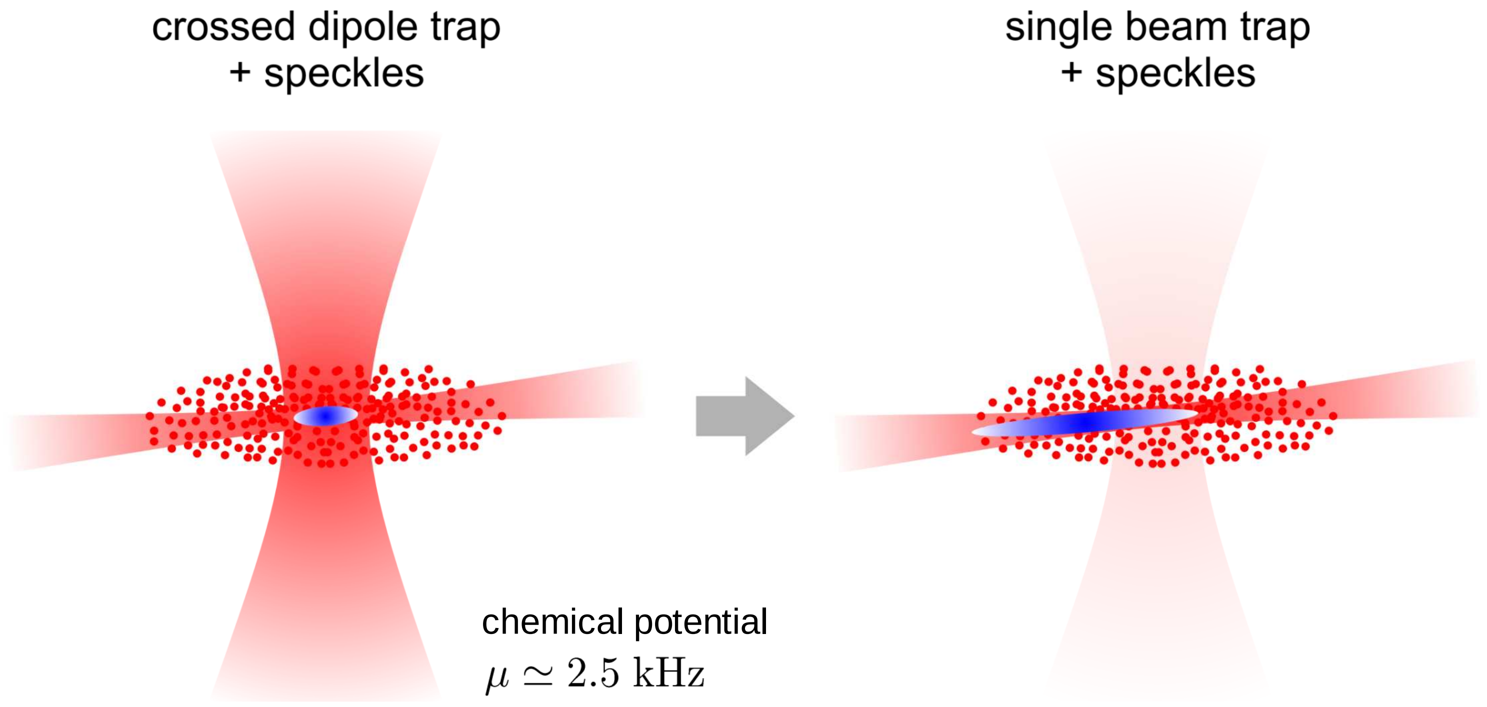
(Received 6 July 2005; published 21 October 2005)



BEC expansion in a disordered waveguide

Fort et al. P R L ***95****, 170410 (2005)*

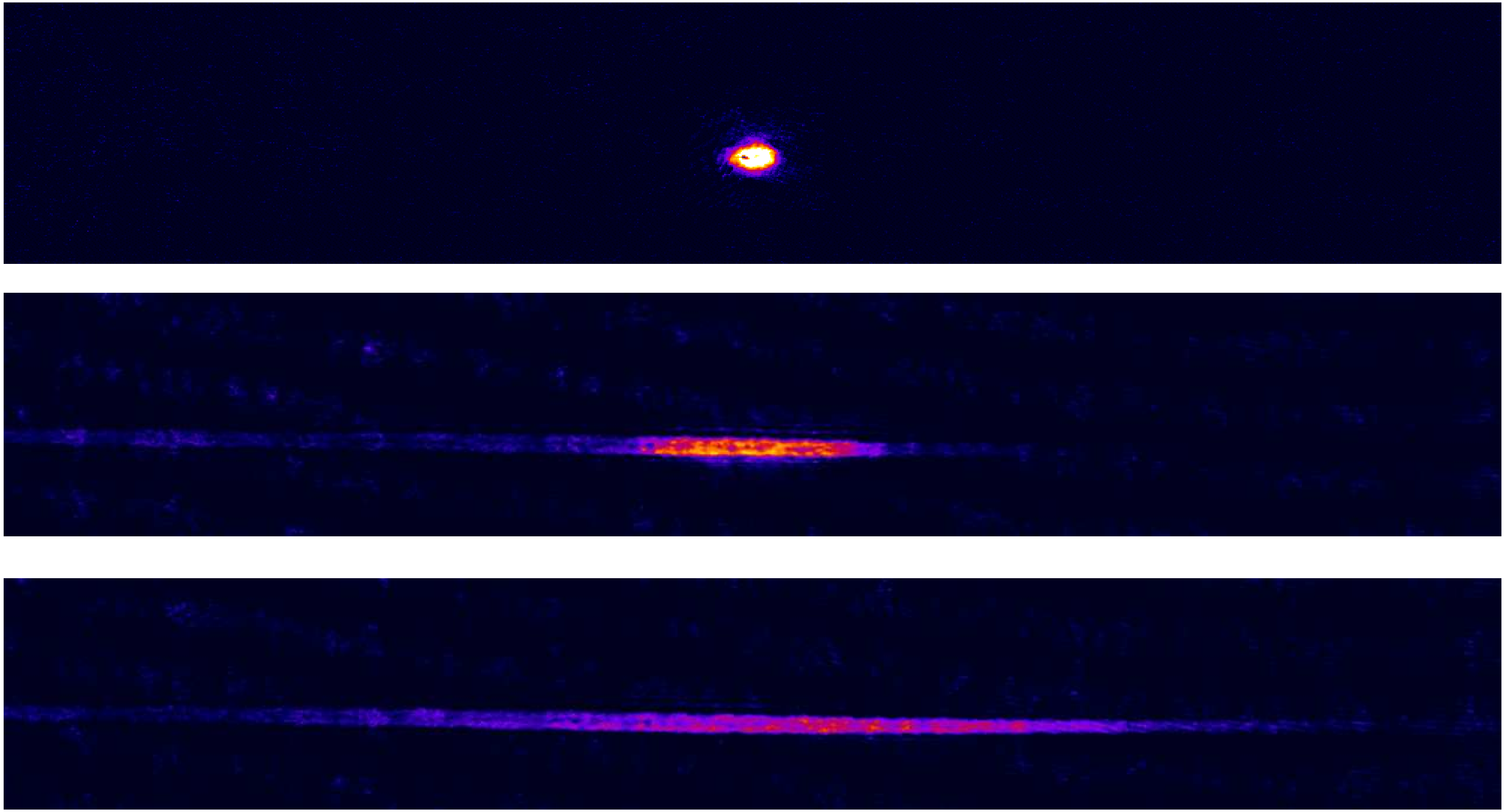
We transfer the BEC from the magnetic trap to a crossed dipole trap + speckle potential. After switching off the vertical beam we study the expansion of the BEC in the horizontal waveguide in the presence of disorder.



$$\begin{cases} \omega_z/2\pi = 25 \text{ Hz} \\ \omega_\perp/2\pi = 290 \text{ Hz} \end{cases}$$

$$\begin{cases} \omega_z/2\pi = 1 \text{ Hz} \\ \omega_\perp/2\pi = 290 \text{ Hz} \end{cases}$$

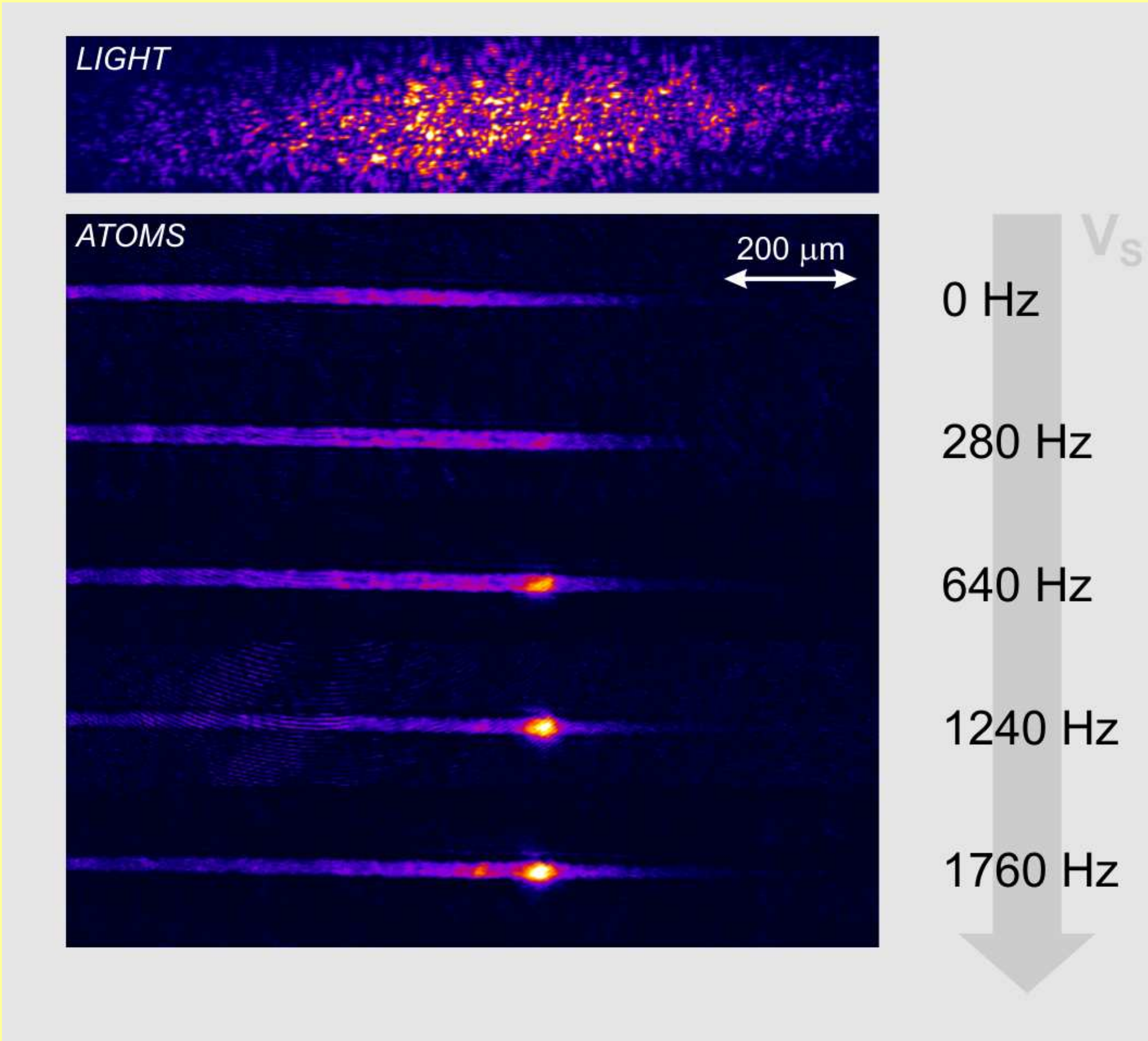
BEC expansion in a disordered waveguide



BEC expansion in a disordered waveguide

*C. Fort et al., PRL **95**, 070401 (2005)*

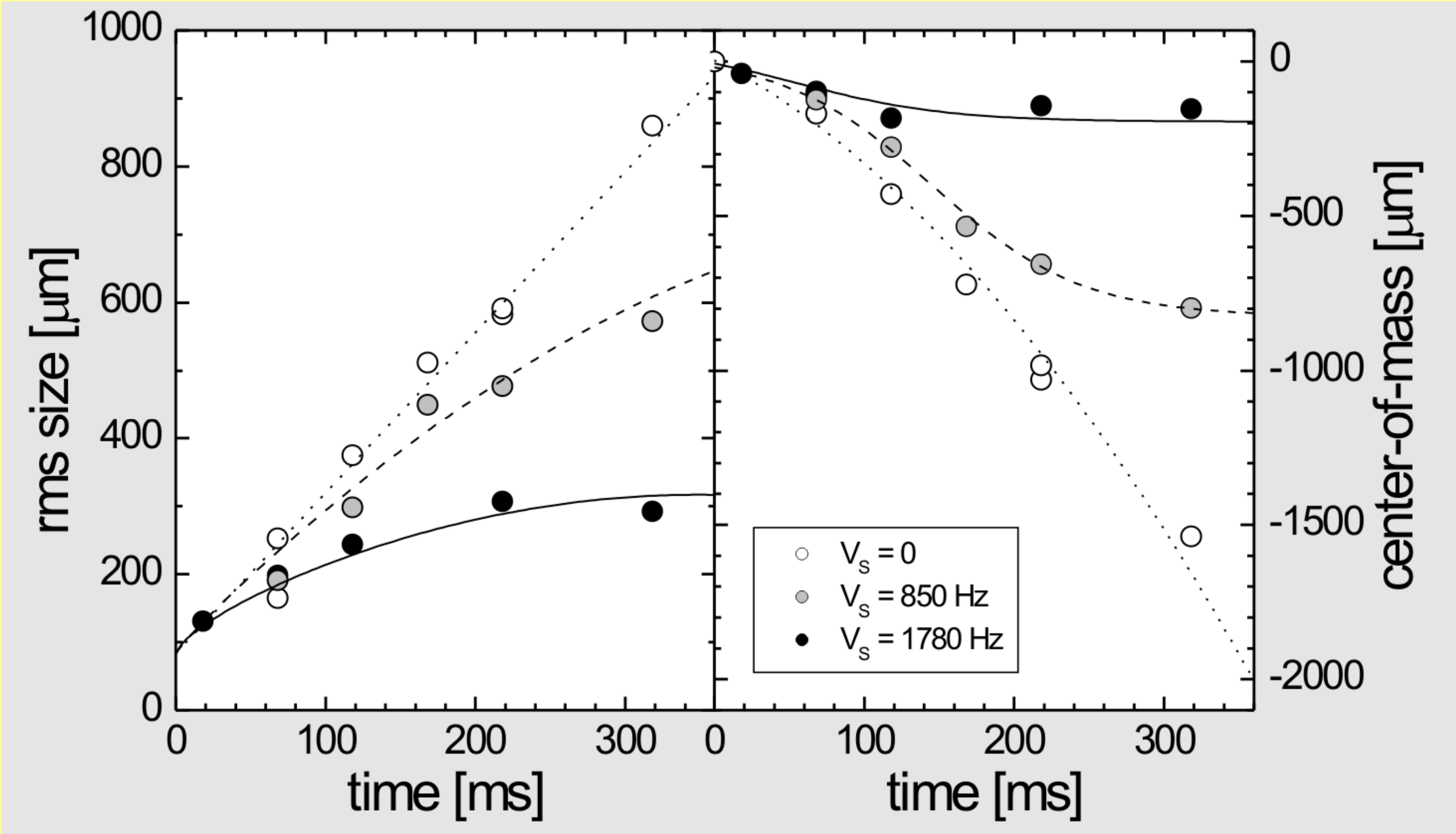
In-situ images of the BEC expanding in the disordered waveguide:



BEC expansion in a disordered waveguide

*C. Fort et al., PRL **95**, 070401 (2005)*

Axial size of the condensate and center of mass position of the BEC expanding in the optical waveguide in presence of the speckle potential:

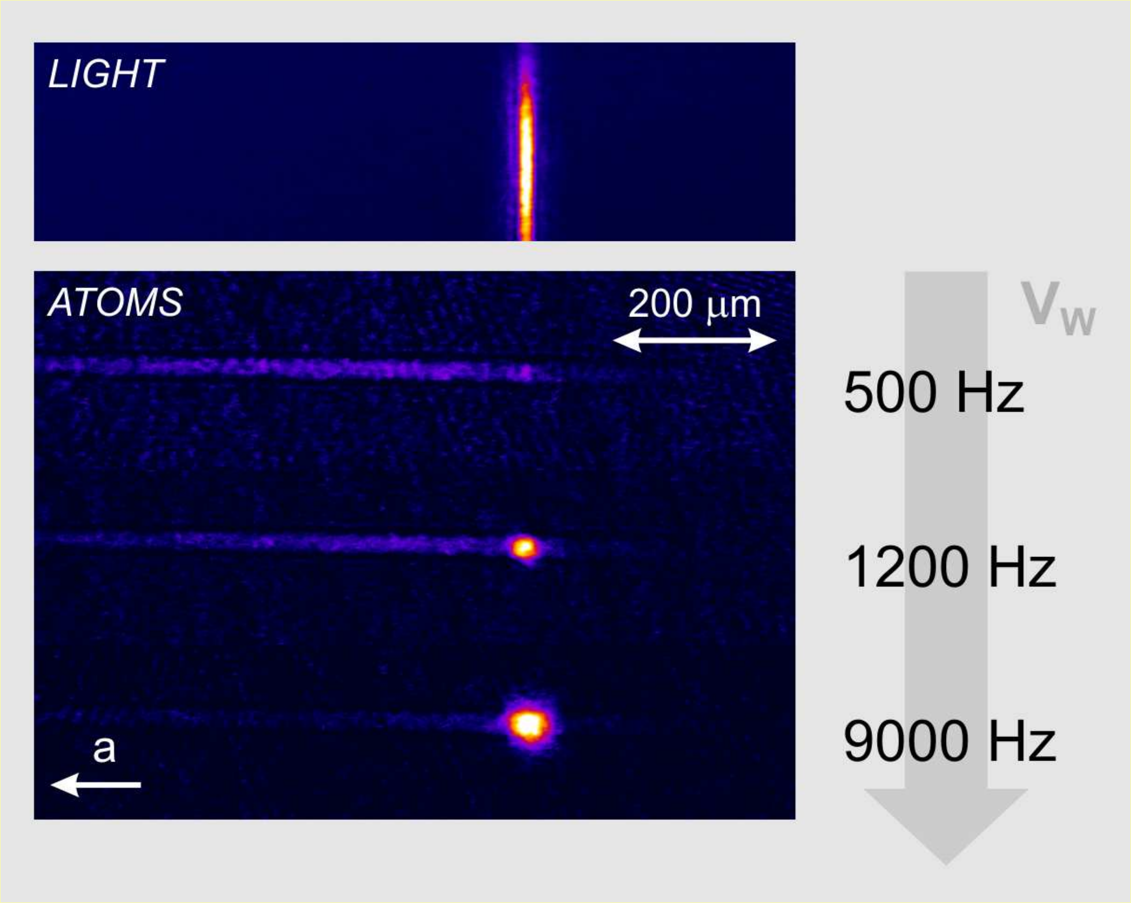


also A.Aspect, Orsay

Interaction of a BEC with an optical defect

*C. Fort et al., PRL **95**, 070401 (2005)*

With the single gaussian well we observe the same kind of behavior: while a low density component expands freely, a sharp peak appears due to slow atoms got trapped in the well.



Optical lattices

✓ ***Solid state physics with ultracold atoms***

- Study of quantum transport in periodic potentials (band structure)
- Role of atom-atom interactions (nonlinear systems $\rightarrow$ solitons, instabilities, ...)

✓ ***Strongly correlated systems***

- Superfluid to Mott insulator quantum phase transition
- Systems with low dimensionality (Tonks gases...)

✓ ***Atom optics***

- Tools for the implementation of mirrors, beam splitters, diffraction gratings, lenses

✓ ***Quantum computing***

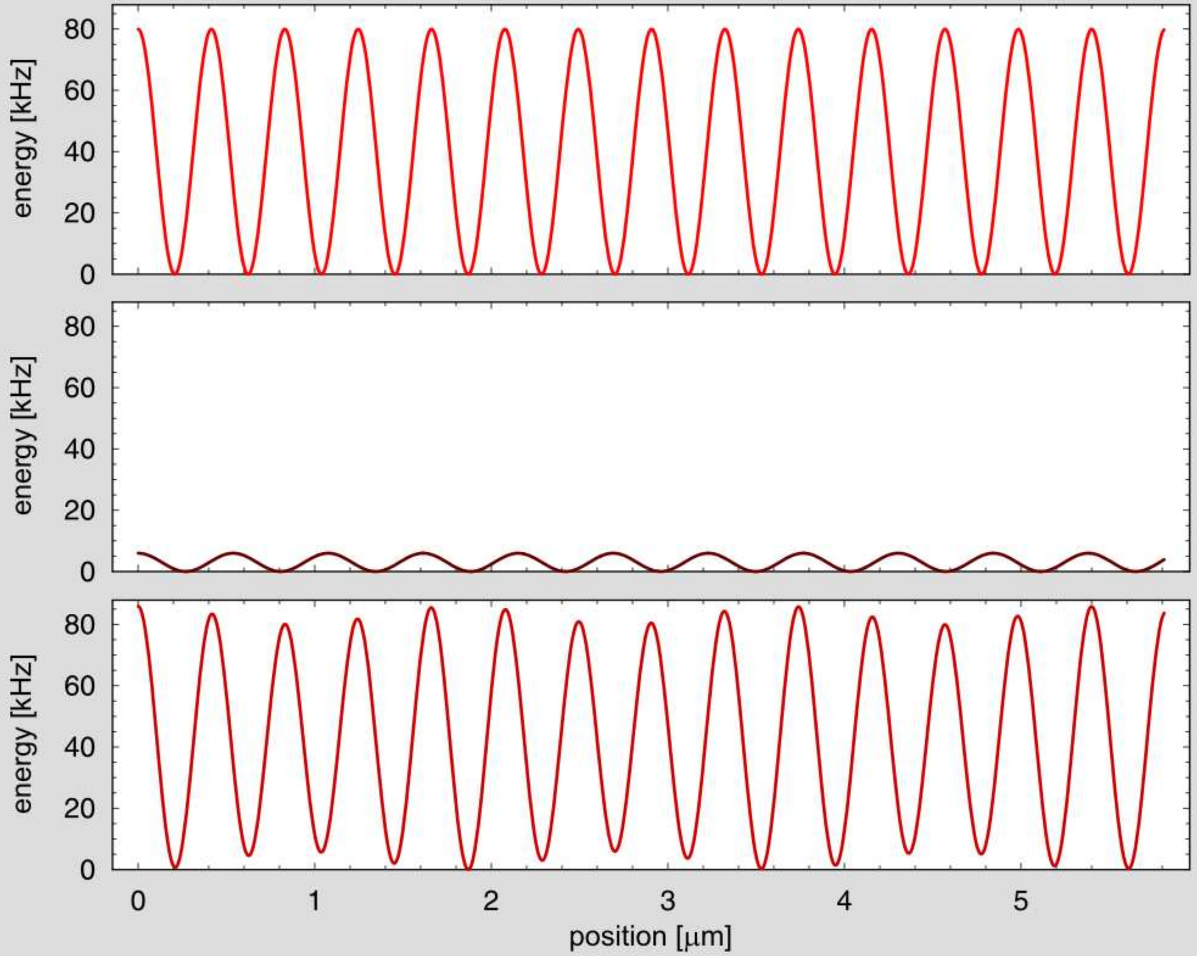
- Quantum registers

Disordered optical lattices

The bichromatic lattice

$$V(x) = s_1 E_{R1} \cos^2(k_1 x) + s_2 E_{R2} \cos^2(k_2 x)$$

bichromatic lattice



main lattice

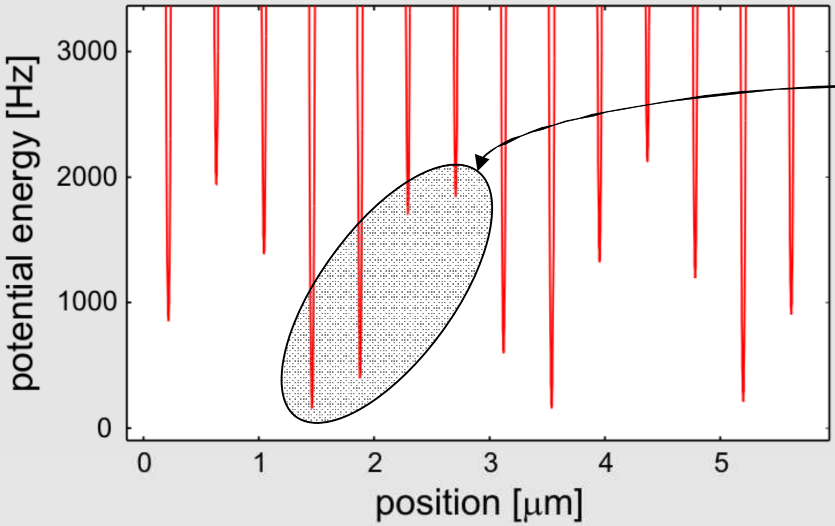
λ=830 nm

disordering lattice

λ=1076 nm

λ=830 nm
+
λ=1076 nm

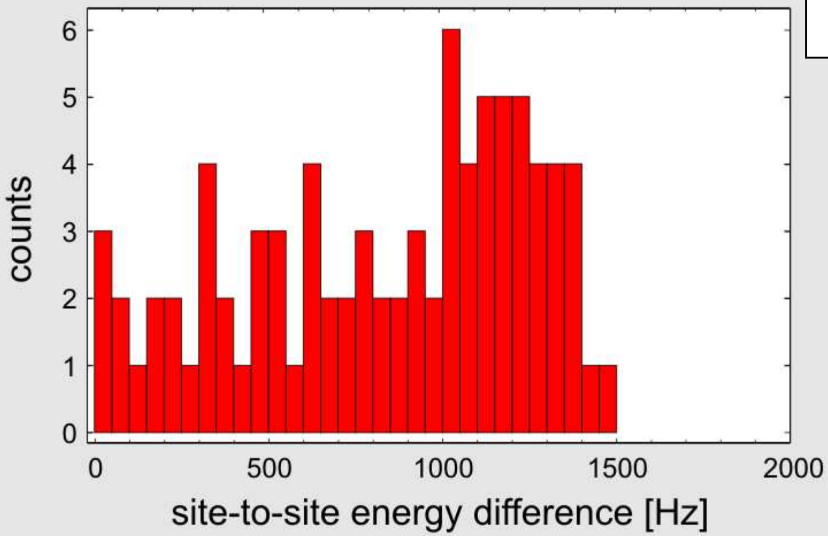
The bichromatic lattice



Energy minima of the lattice potential along *y* direction

Non-periodic modulation of the energy minima with length scale

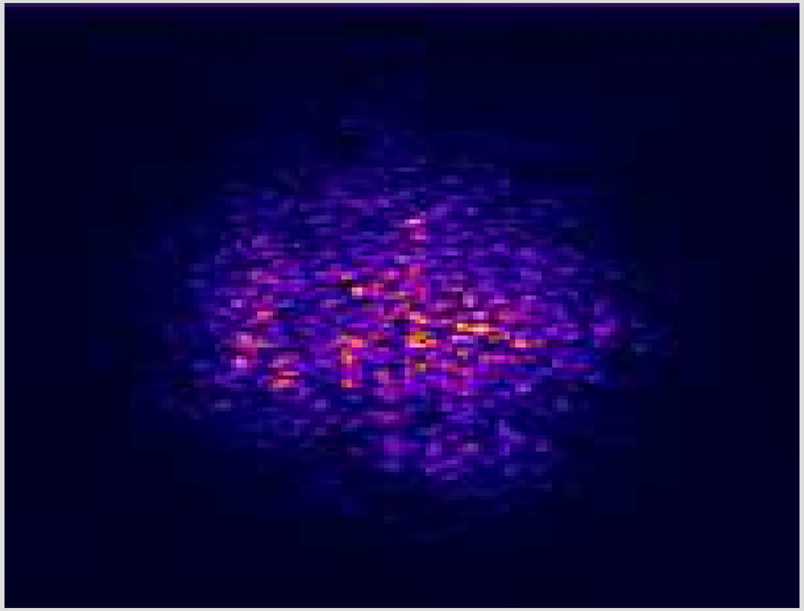
$$d = \left(\frac{2}{\lambda_1} - \frac{2}{\lambda_2}\right)^{-1} = 1.8\ \mu\mathrm{m} = 4.3$$ sites



Adding disorder

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

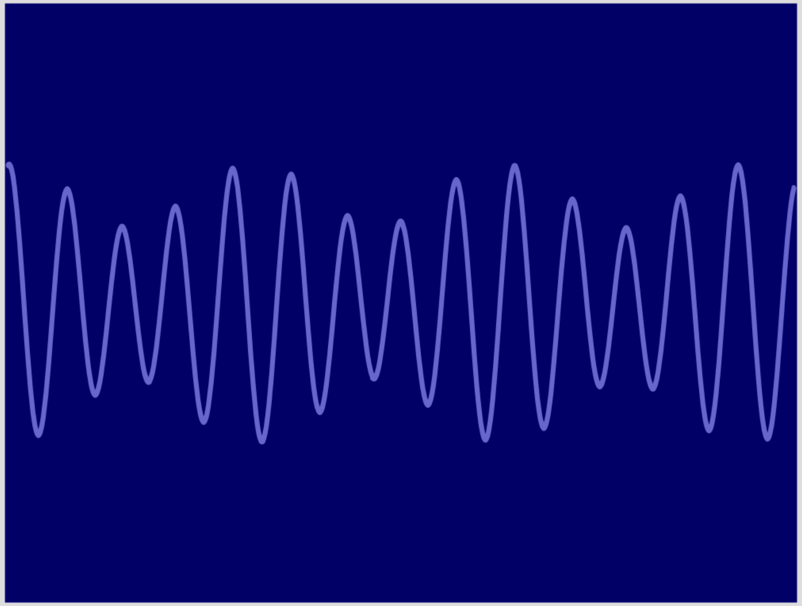
speckle pattern



✓ random potential

✗ large length scale (several μm)

bichromatic lattice



✓ quasiperiodic potential

✓ smaller length scale (1 μm or less)

Ultracold atoms in optical lattices

Adding disorder

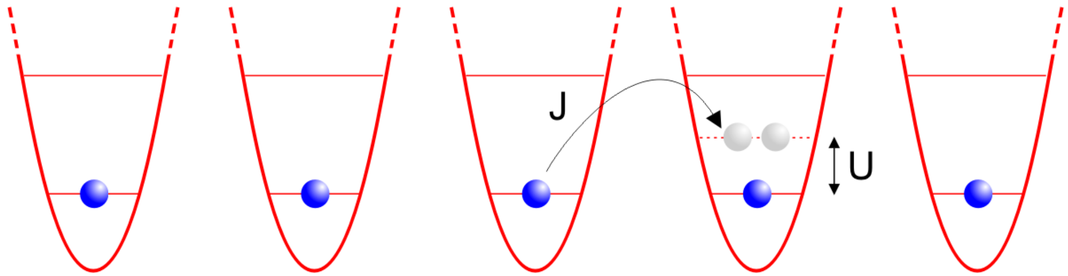
Strongly interacting bosons
in a disordered lattice

Weakly interacting bosons
in a disordered lattice

Interacting bosons in a lattice

Bose-Hubbard model for interacting bosons in a lattice:

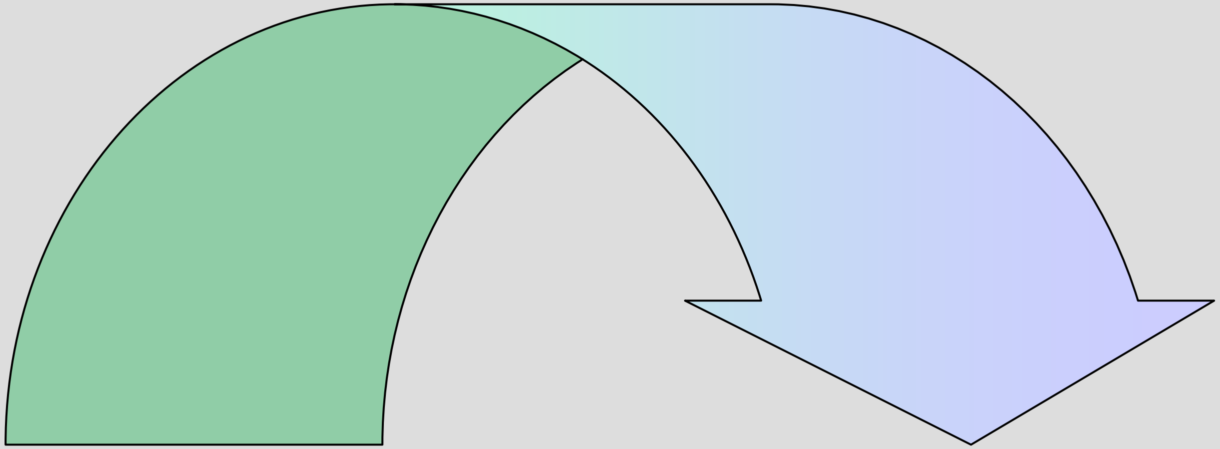
$$\hat{H} = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{U}{2} \sum_i \hat{n}_i \left(\hat{n}_i - 1 \right)$$



At zero temperature the state of the system is determined by the competition between two energy scales: the hopping energy *J* and the on-site interaction energy *U*

hopping energy **J**	interaction energy **U**

Interacting bosons in a lattice



SUPERFLUID $J \gg U$

- ✓ Long-range phase coherence
- ✓ High number fluctuation
- ✓ Gapless excitation spectrum
- ✓ Compressible

MOTT INSULATOR $J \ll U$

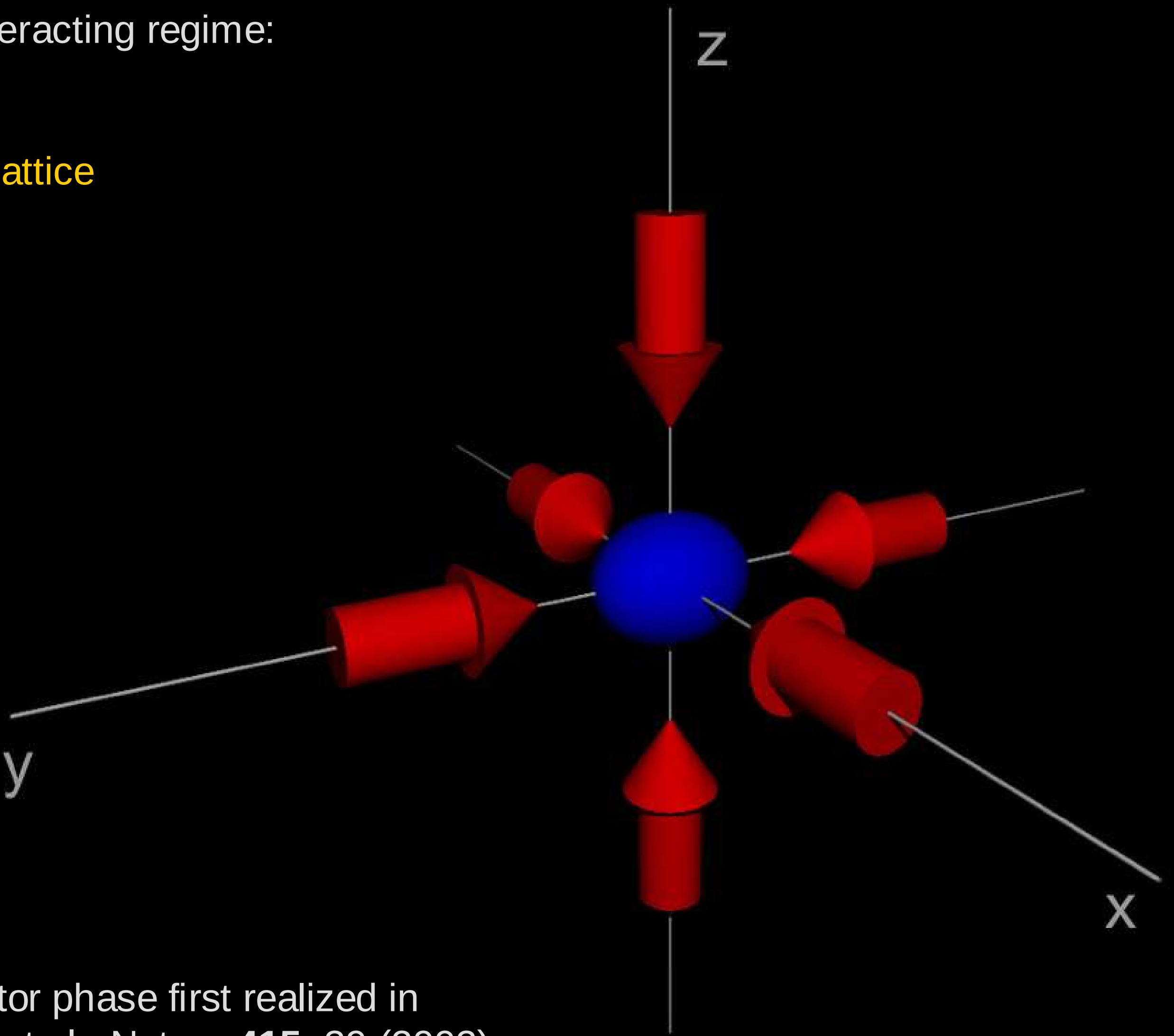
- ✓ No phase coherence
- ✓ Zero number fluctuation (Fock states)
- ✓ Gap in the excitation spectrum
- ✓ Not compressible

Experimental scheme

strongly interacting regime:

↓

3D optical lattice



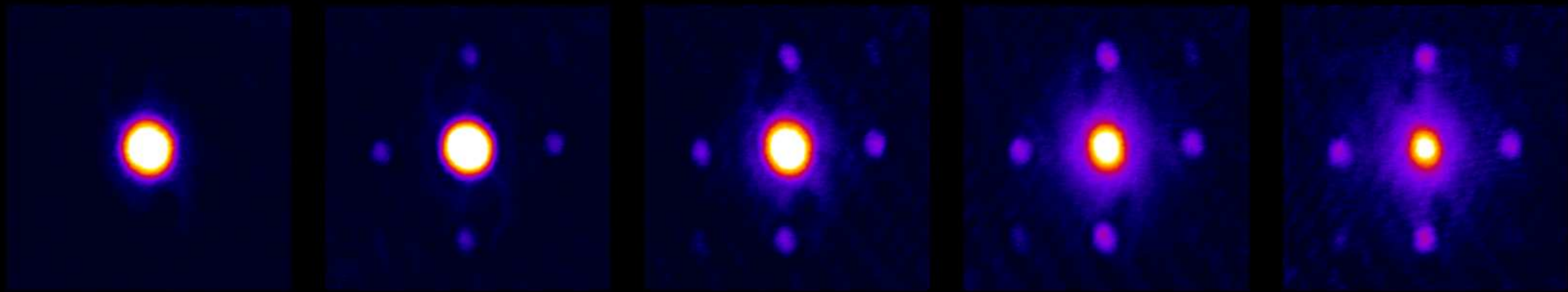
Mott insulator phase first realized in
M. Greiner et al., Nature **415**, 39 (2002).

Superfluid to Mott Insulator transition at LENS

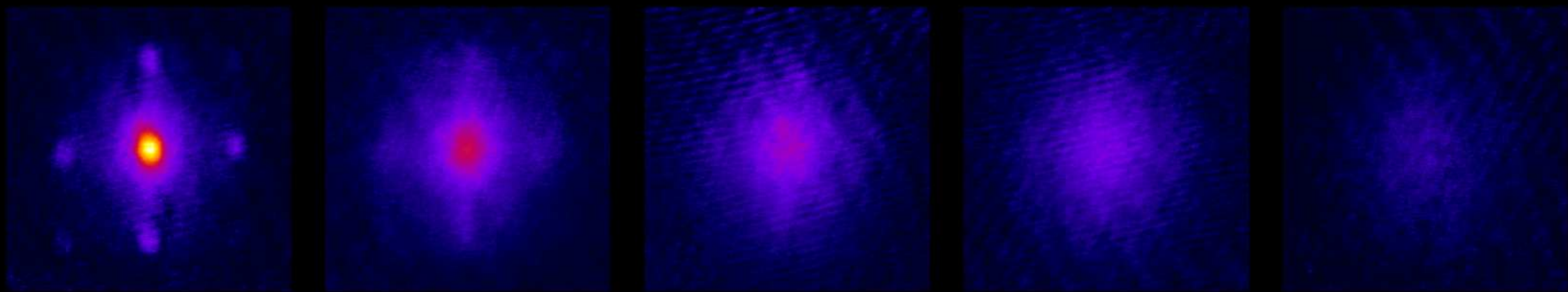
Fallani, Fort , Guarrera, Lye, M.I.

momentum distribution of the atomic sample after expansion

test of phase coherence



s=0 s=2.5 s=5 s=7.5 s=10



s=12.5 s=15 s=17.5 s=20 s=22.5

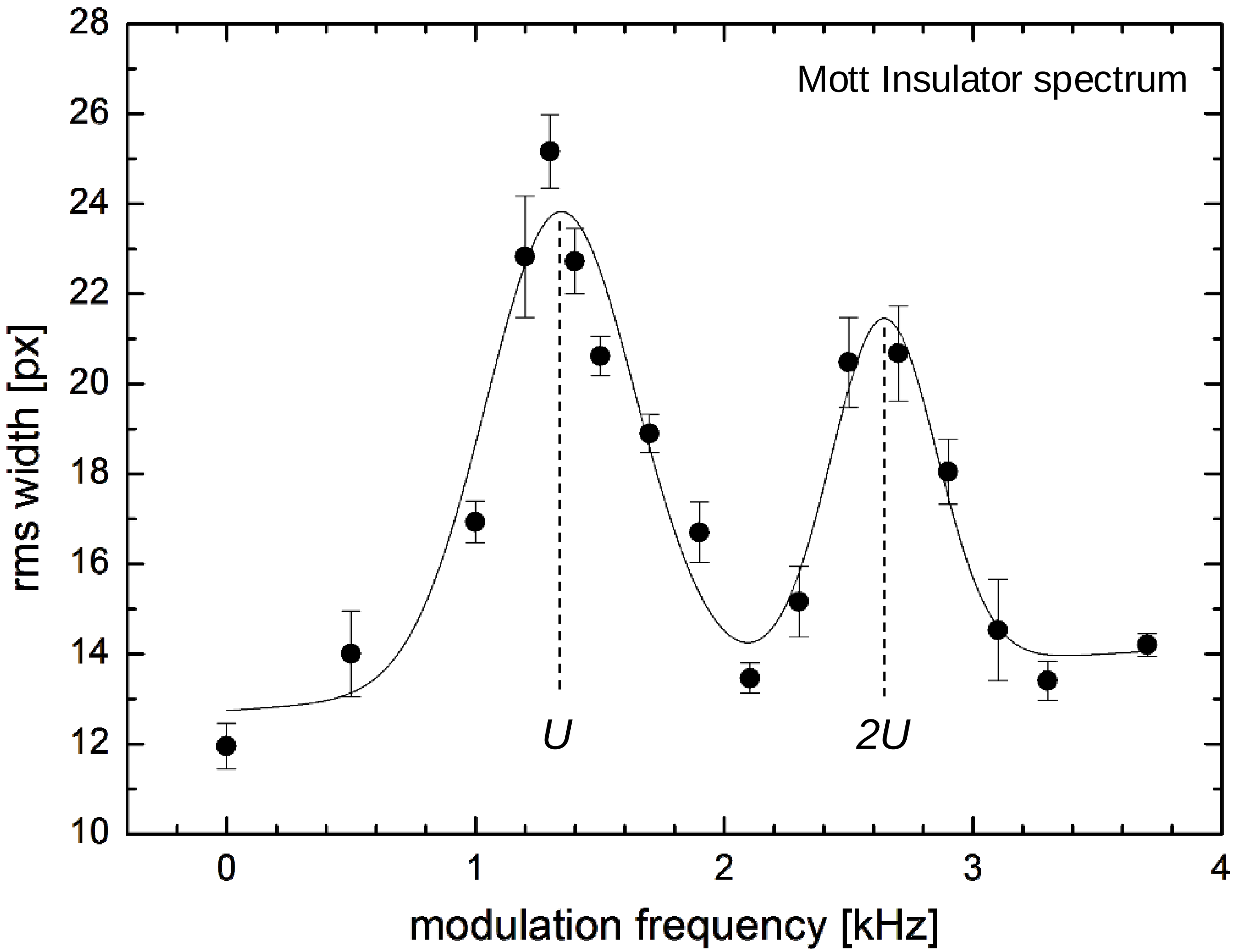
increasing the lattice height ⟶ *U/J* increases

Measuring the excitation spectrum

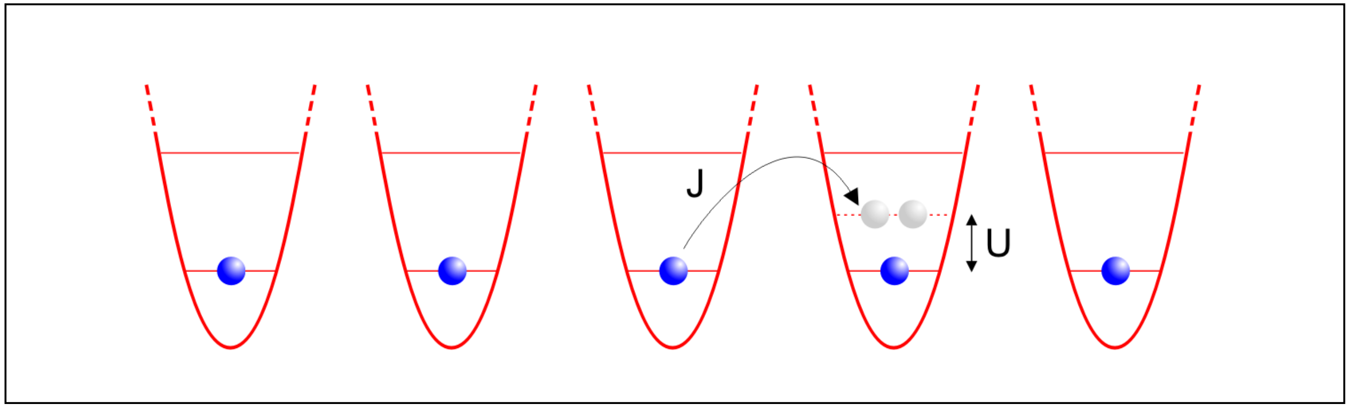
amplitude modulation of the lattice potential
resonant production of excitations (particle-hole pairs)

see also T. Stöferle et al., *PRL* **92**, 130403 (2004)

Measuring the excitation spectrum



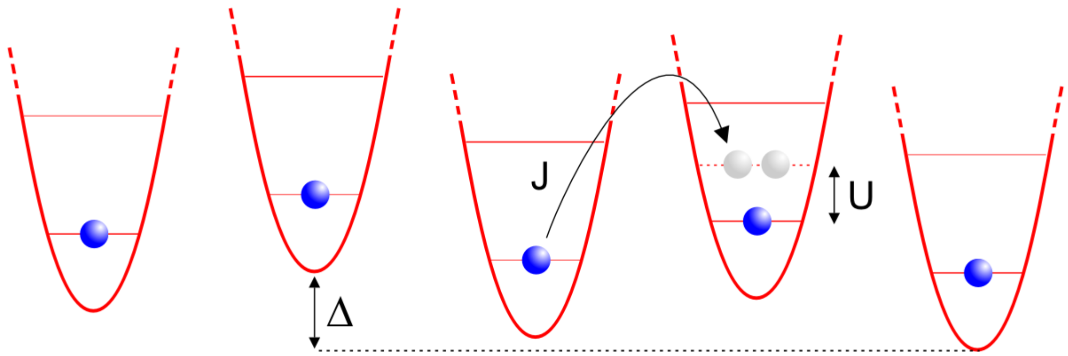
Measuring the excitation spectrum



Adding disorder — Towards a Bose Glass Quantum Phase

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

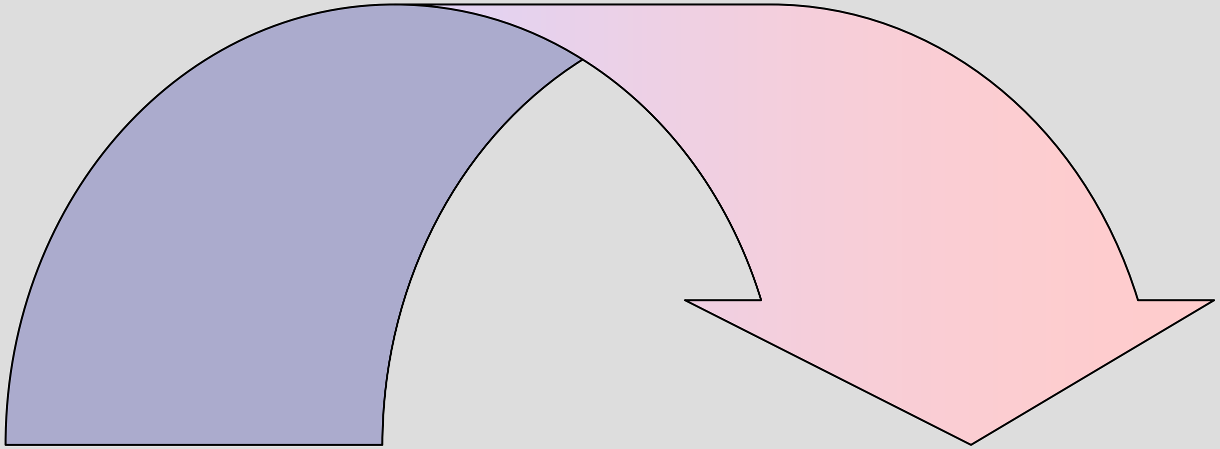
$$\hat{H} = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{U}{2} \sum_i \hat{n}_i \left(\hat{n}_i - 1 \right) + \sum_i \epsilon_j \hat{n}_j$$



In the presence of disorder an additional energy scale Δ enters the description of the system. The interplay between these energy terms may induce new quantum phase transitions

hopping energy	interaction energy	disorder
J	**U**	Δ

Towards a Bose Glass Quantum Phase



MOTT INSULATOR $\Delta \ll U$

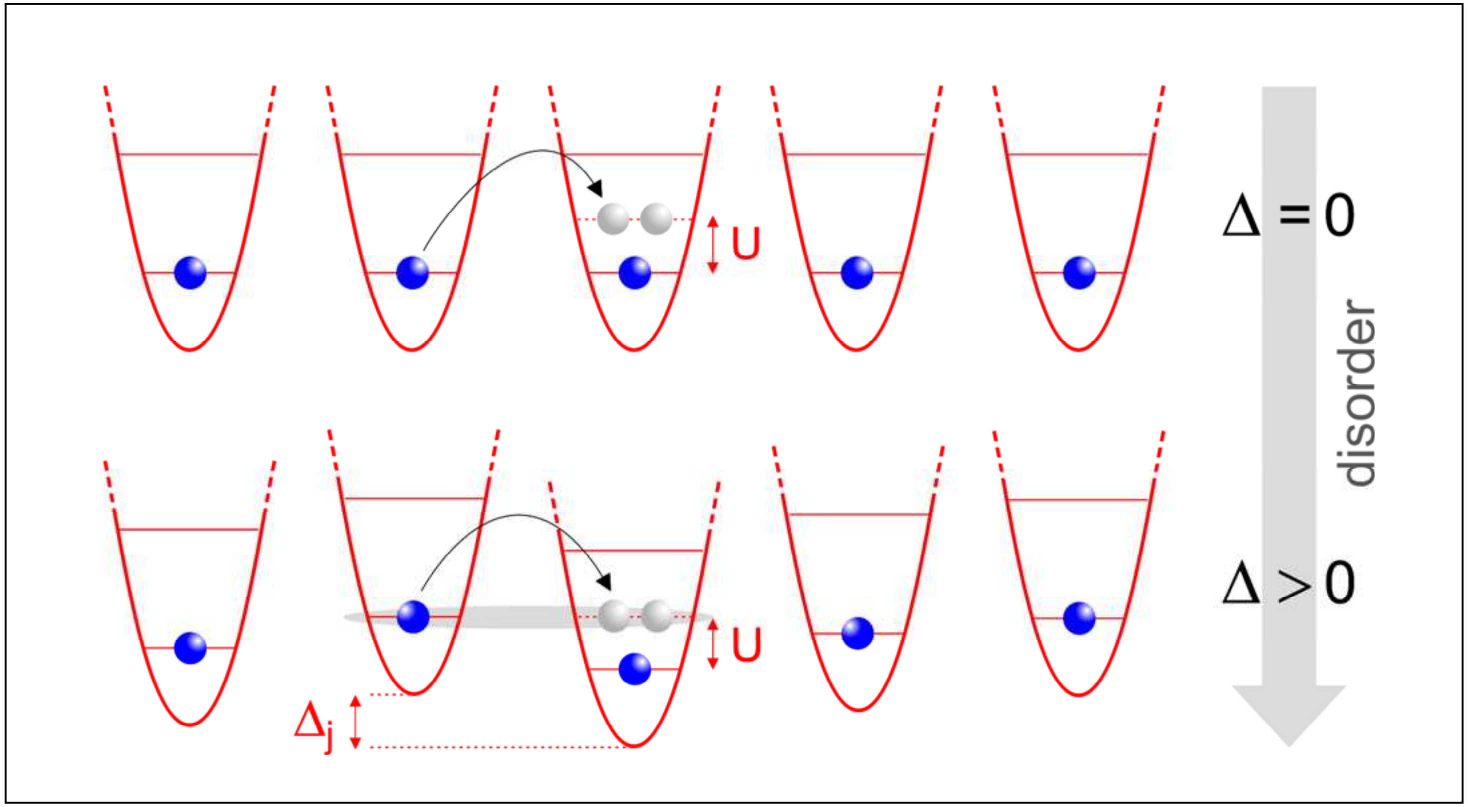
- ✓ No long-range phase coherence
- ✓ Gap in the excitation spectrum
- ✓ Not compressible

BOSE-GLASS $\Delta > U$

- ✓ No long-range phase coherence
- ✓ **Gapless excitation spectrum**
- ✓ **Finite compressibility**

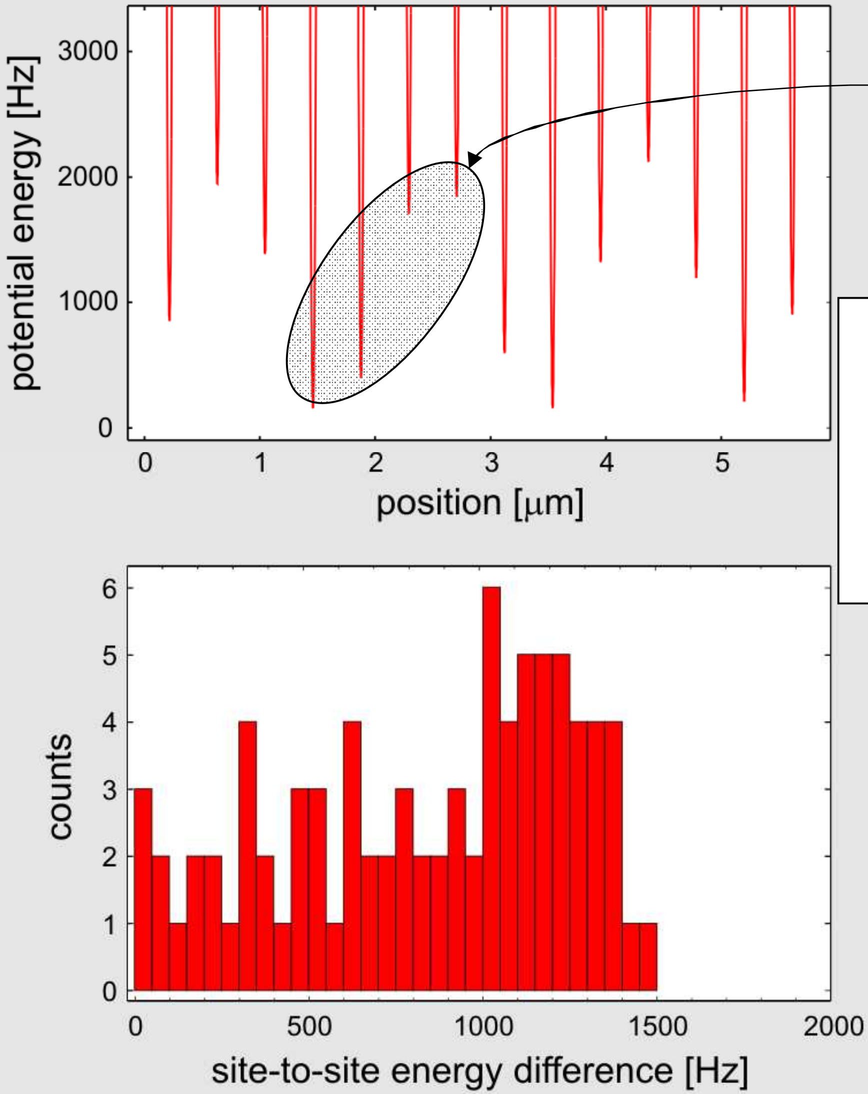
Broadening the MI spectrum

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



When $\Delta_j = U$ the excitation energy goes to zero and the gap disappears

The bichromatic lattice



Energy minima of the lattice potential along *y* direction

Non-periodic modulation of the energy minima with length scale

$$d = \left(\frac{2}{\lambda_1} - \frac{2}{\lambda_2}\right)^{-1} = 1.8\ \mu\text{m} = 4.3$$ sites

Inhomogeneous broadening

V. Guarrera et al., New J. Phys. ***9****, 107 (2007)*

Simple toy-model (from spectroscopy):

Mott Insulator resonance:

$$f(\nu) = Ae^{-\frac{(\nu-\nu_0)^2}{2\sigma^2}}$$

(fit to experimental data)

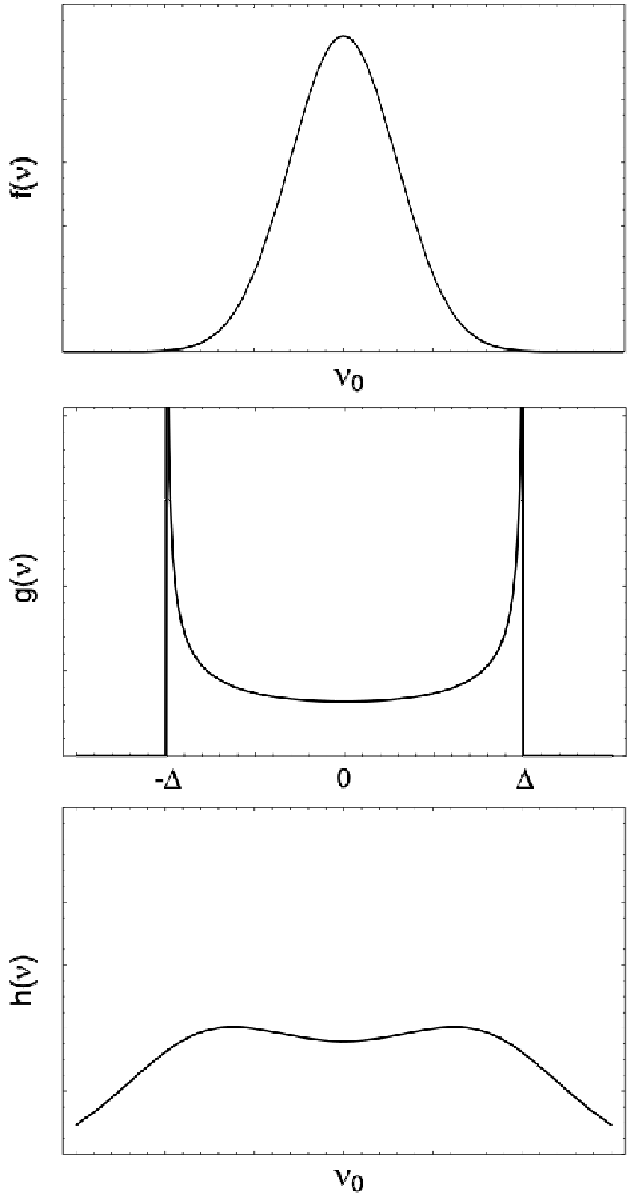
Distribution of energy shifts:

$$g(\nu) = \frac{1}{\pi\Delta}\frac{1}{\sqrt{1-\left(\frac{\nu}{\Delta}\right)^2}}\theta(\Delta+\nu)\theta(\Delta-\nu)$$

↓

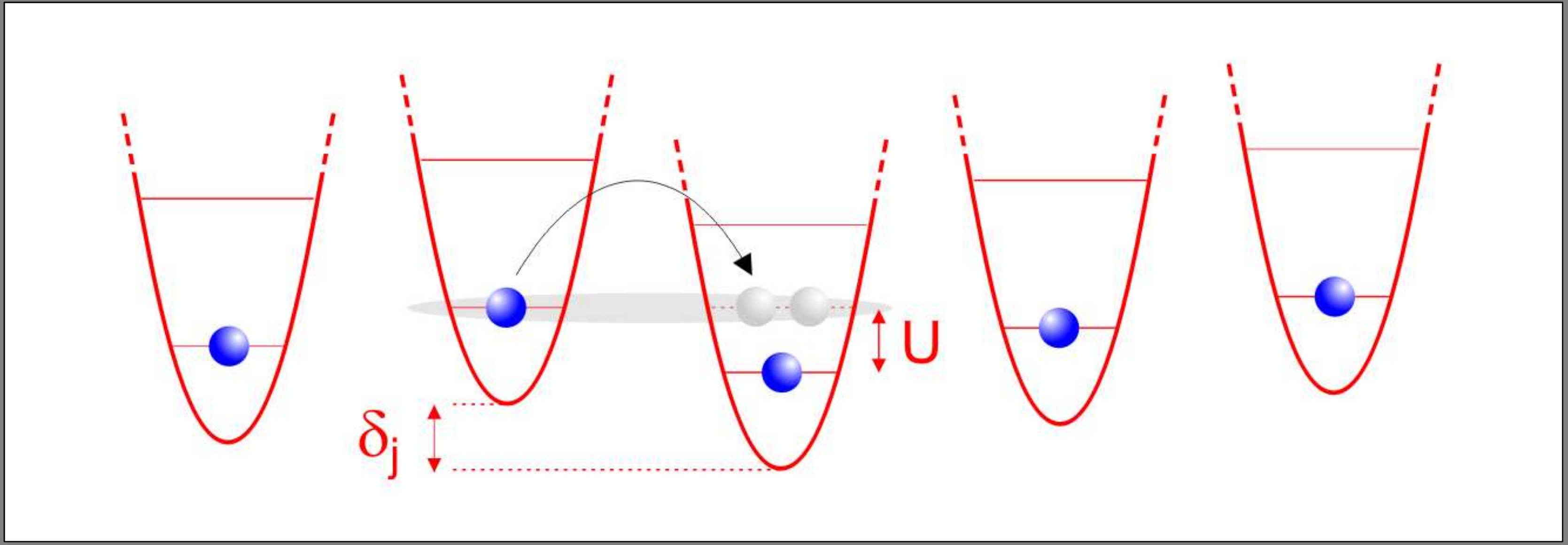
Convoluted spectrum:

$$h(\nu) = \int f(\nu-\bar{\nu})g(\bar{\nu})d\bar{\nu}$$



Vanishing gap for strong disorder

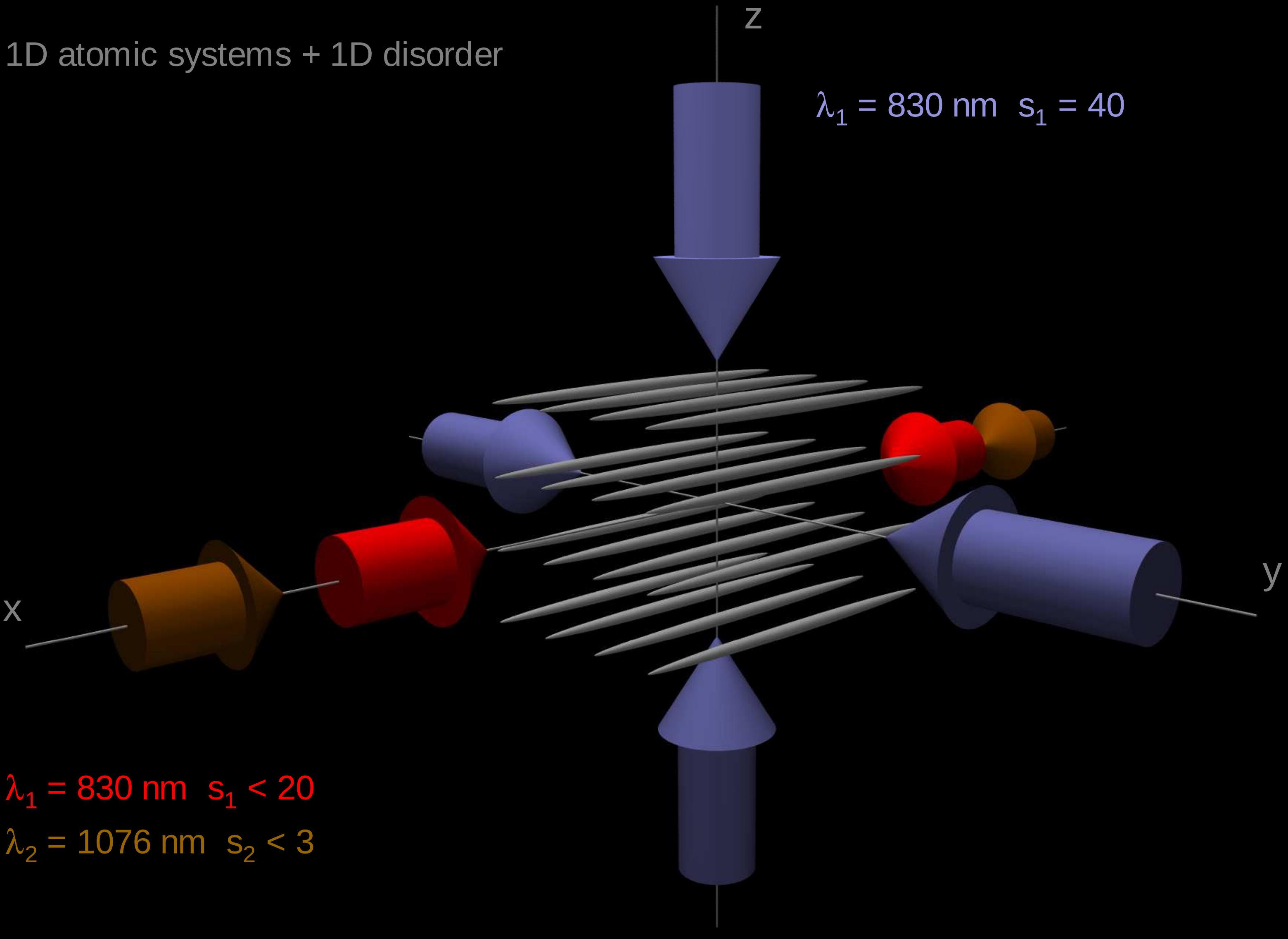
For strong disorder Δ>U the system can be excited at zero energy, the gap vanishes, and different filling configurations in neighboring sites become degenerate.



Experimental geometry

L.Fallani et al. Phys.Rev.Lett. 98, 130404 (2007)

1D atomic systems + 1D disorder



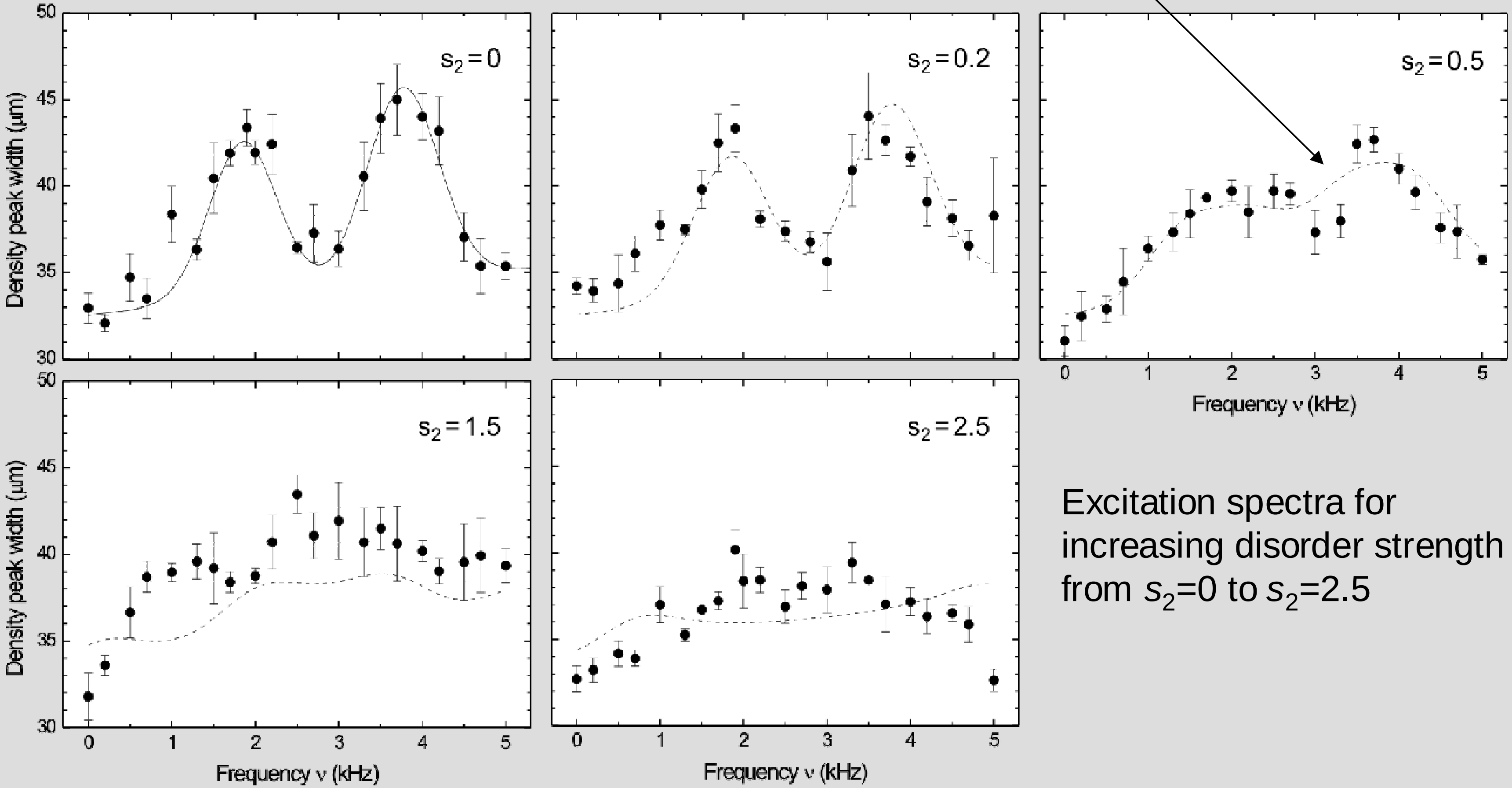
Measuring the excitation spectrum

amplitude modulation of the lattice potential
resonant production of excitations (particle-hole pairs)

see also T. Stöferle et al., *PRL* **92**, 130403 (2004)

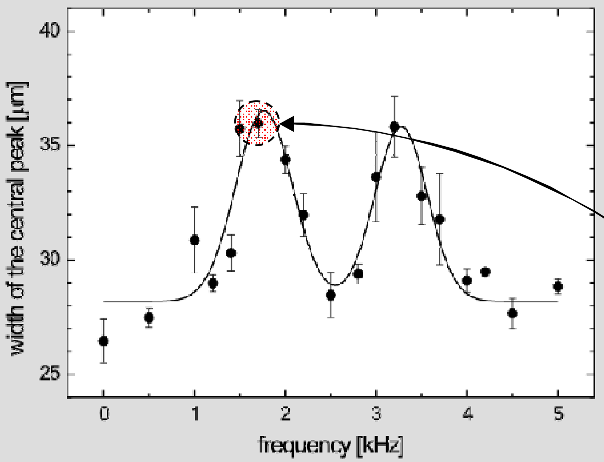
Excitation spectra

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

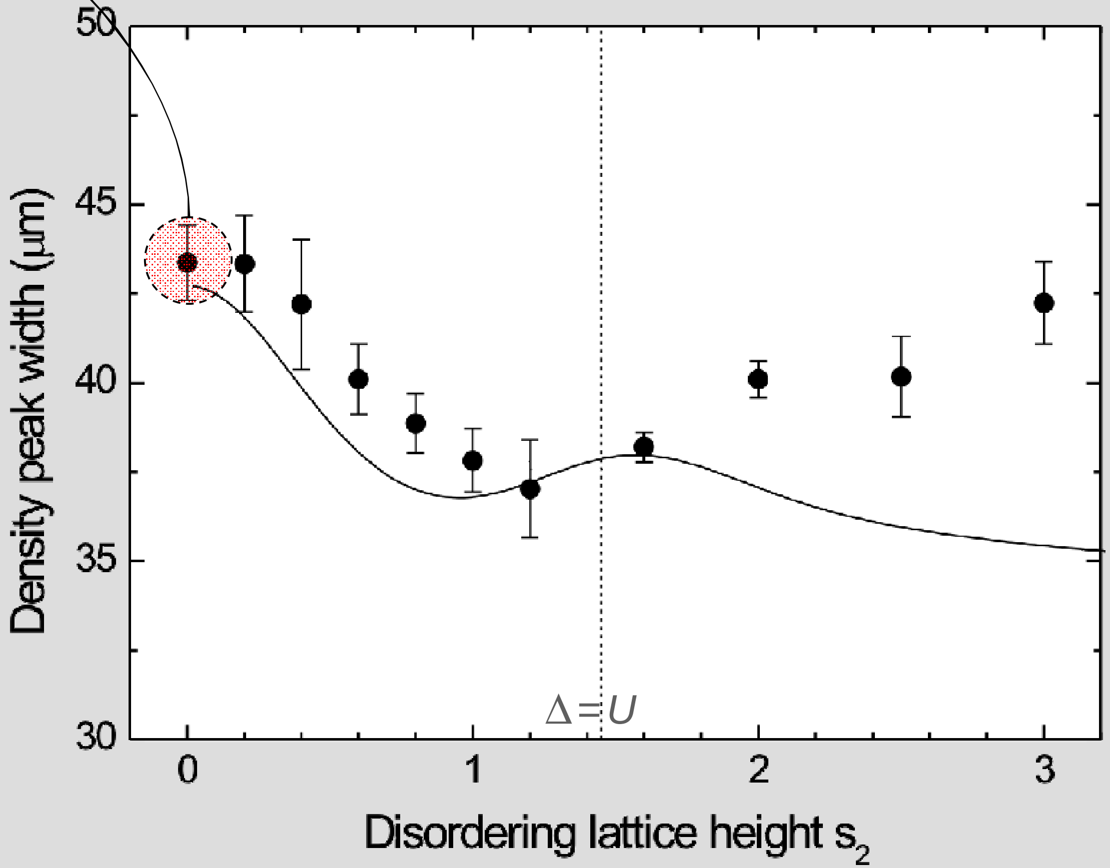


Excitation spectra for increasing disorder strength from s_2=0 to s_2=2.5

MI spectral brodening



Excitation maximum at *U*
as a function of disorder strength:

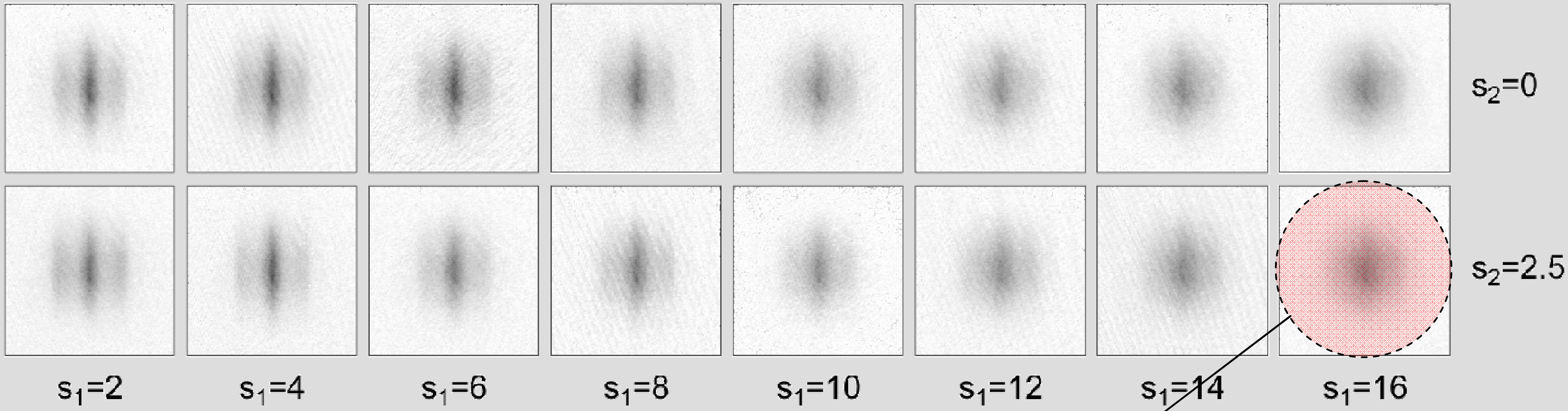


Good agreement with the MI broadening for weak disorder Δ<U

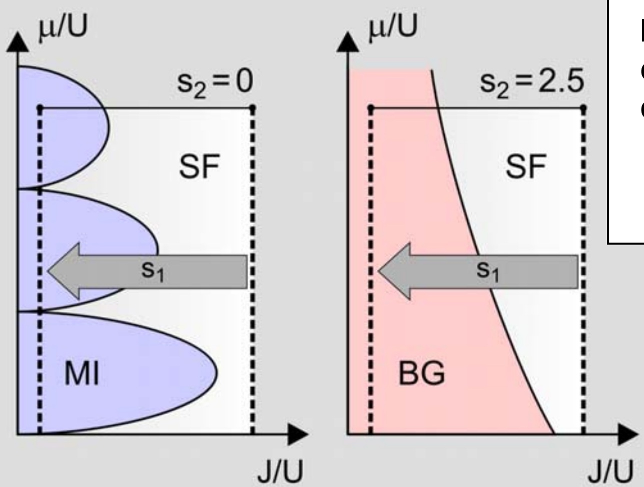
No agreement for strong disorder Δ>U when the gap goes to zero

Phase coherence

L.Fallani et al. Phys.Rev.Lett. 98, 130404 (2007)

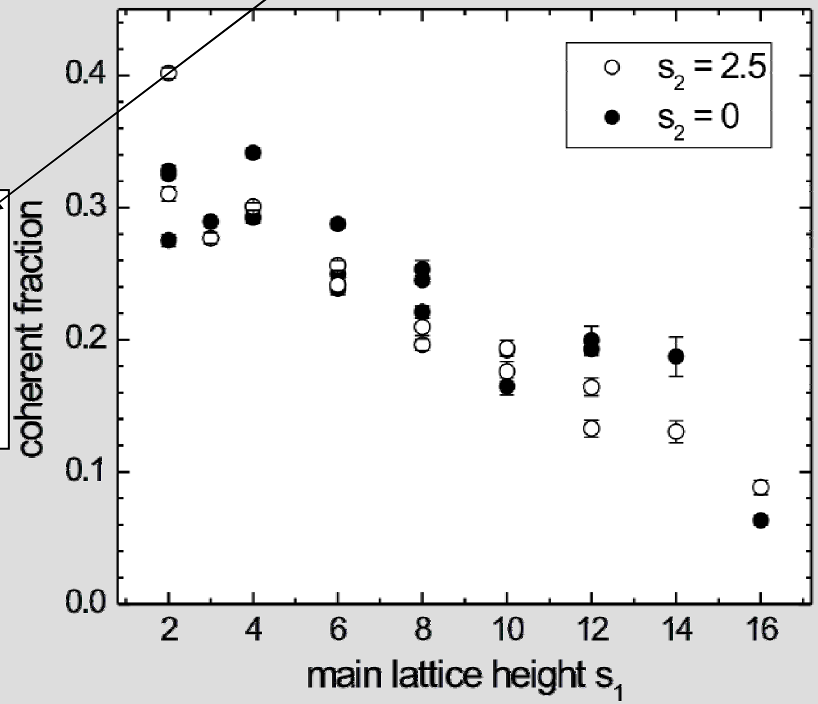


Measurement of the coherent fraction
(visibility of fringes in the TOF images):



Insulating state (no phase coherence) with vanishing energy gap

Bose-Glass



Need of new diagnostics!

Some ideas:

- ✓ ***Noise interferometry***

  Higher order correlations

- ✓ ***Bragg spectroscopy***

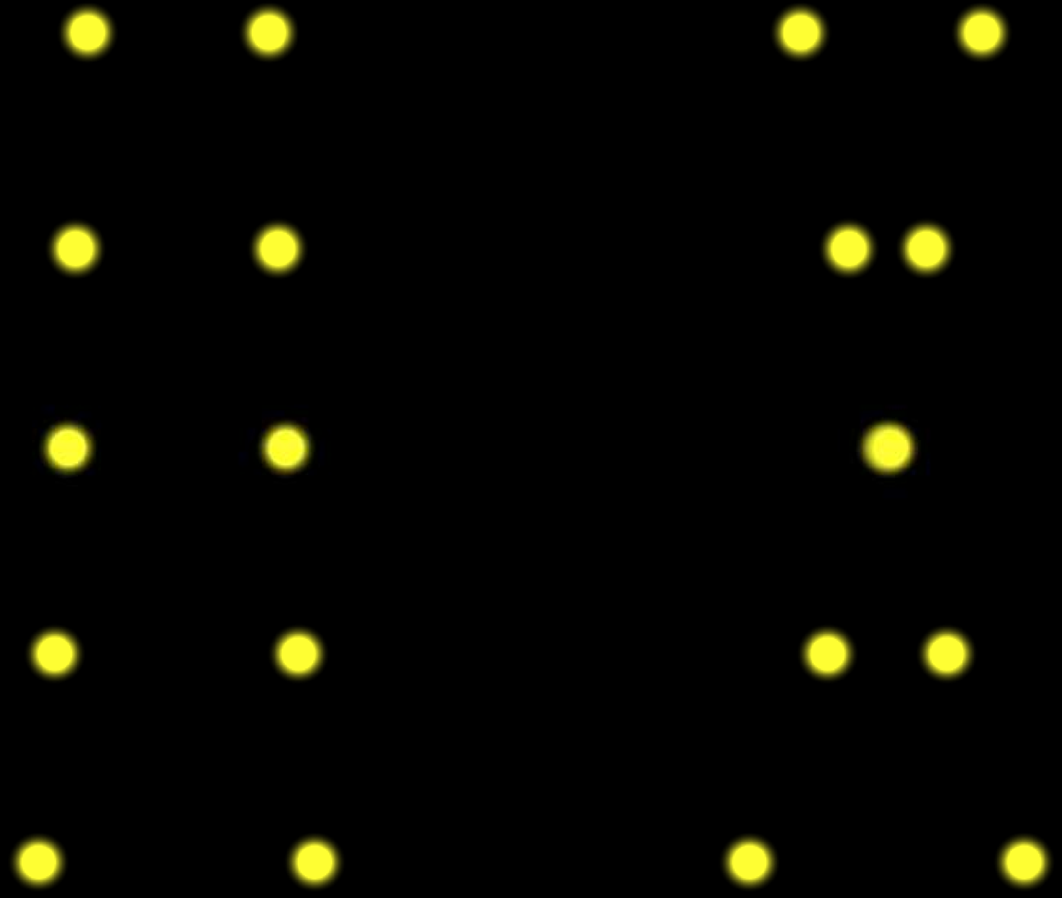
  Cleaner probe of excitation spectrum

- ✓ ***"In-situ" imaging***

  Clock transition collisional shift, spin-changing collisions, ...

Quantum interpretation of HBT effect

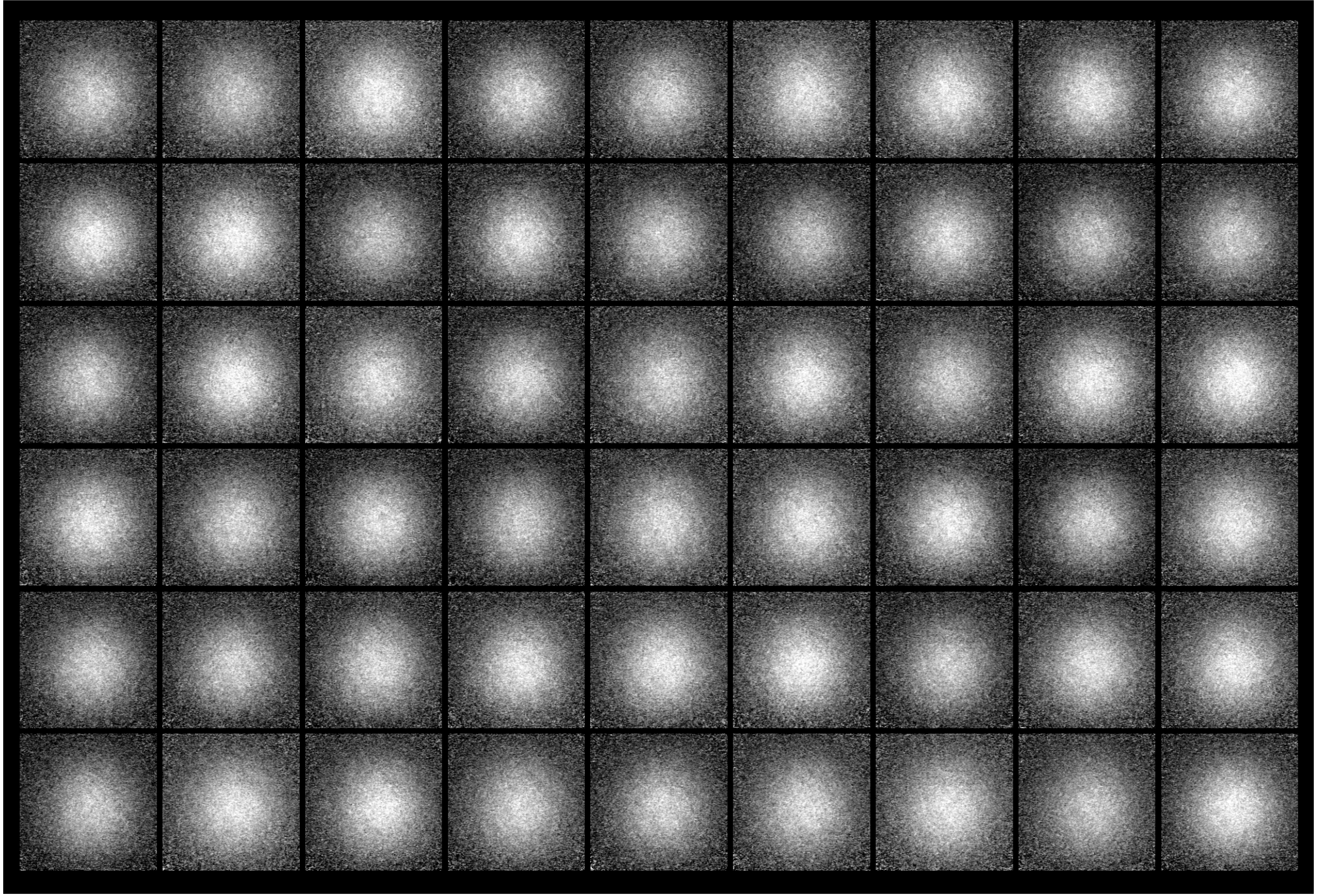
correlations between joint probability at detector positions



interference between quantum-mechanical paths of identical particles

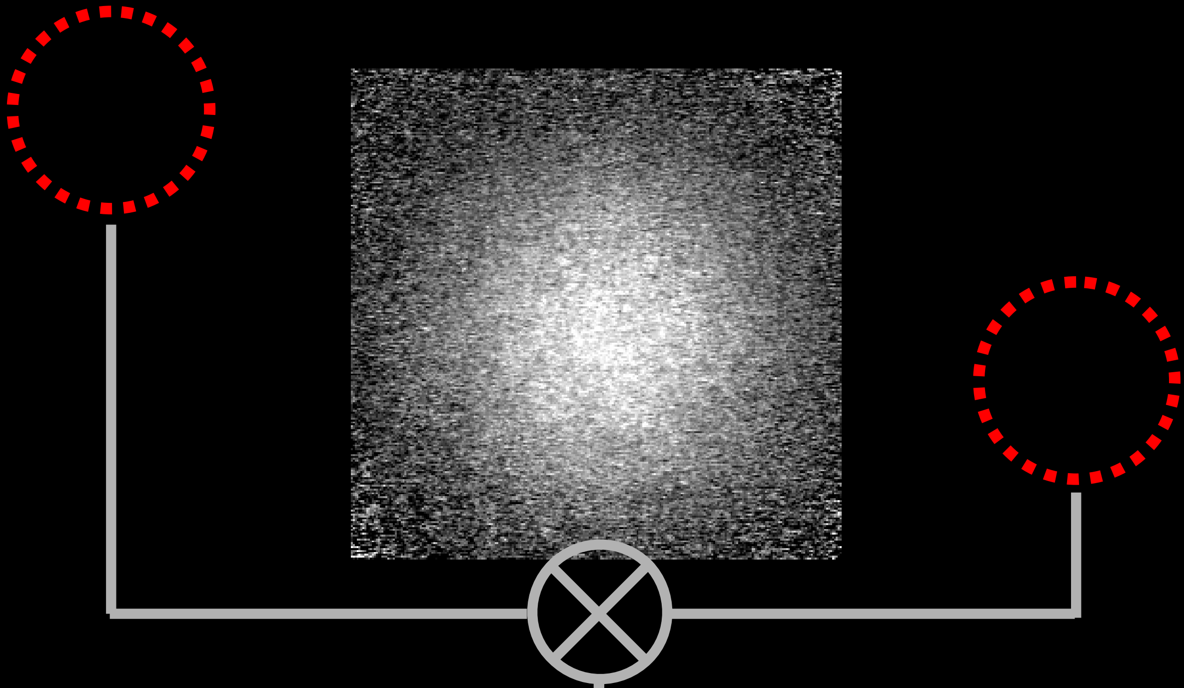
U. Fano, Am. J. Phys. **29**, 539 (1961)

Noise correlations – first results



HBT interferometry in quantum gases

absorption image of a Mott Insulator state

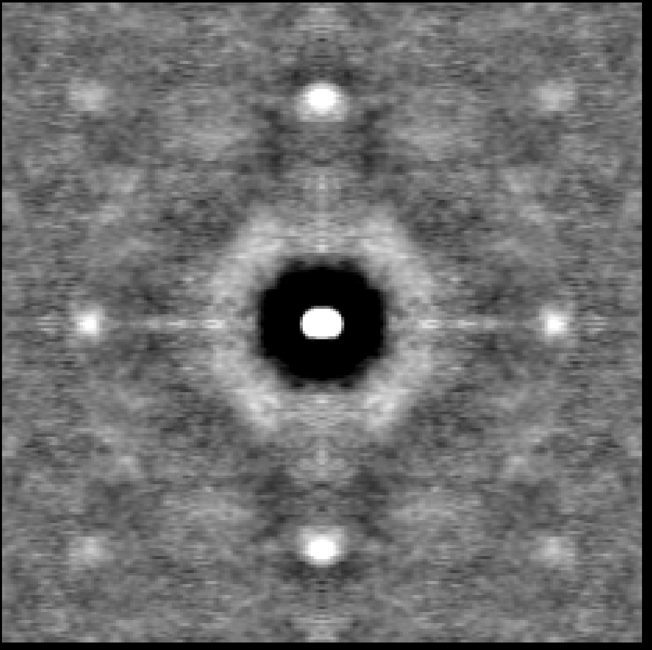


in a single image we have approx. 50000 detectors!

from the analysis of the atom shot noise (averaged on many images)
we can extract the joint detection probability at different pixels

Noise correlations in a Mott Insulator at LENS

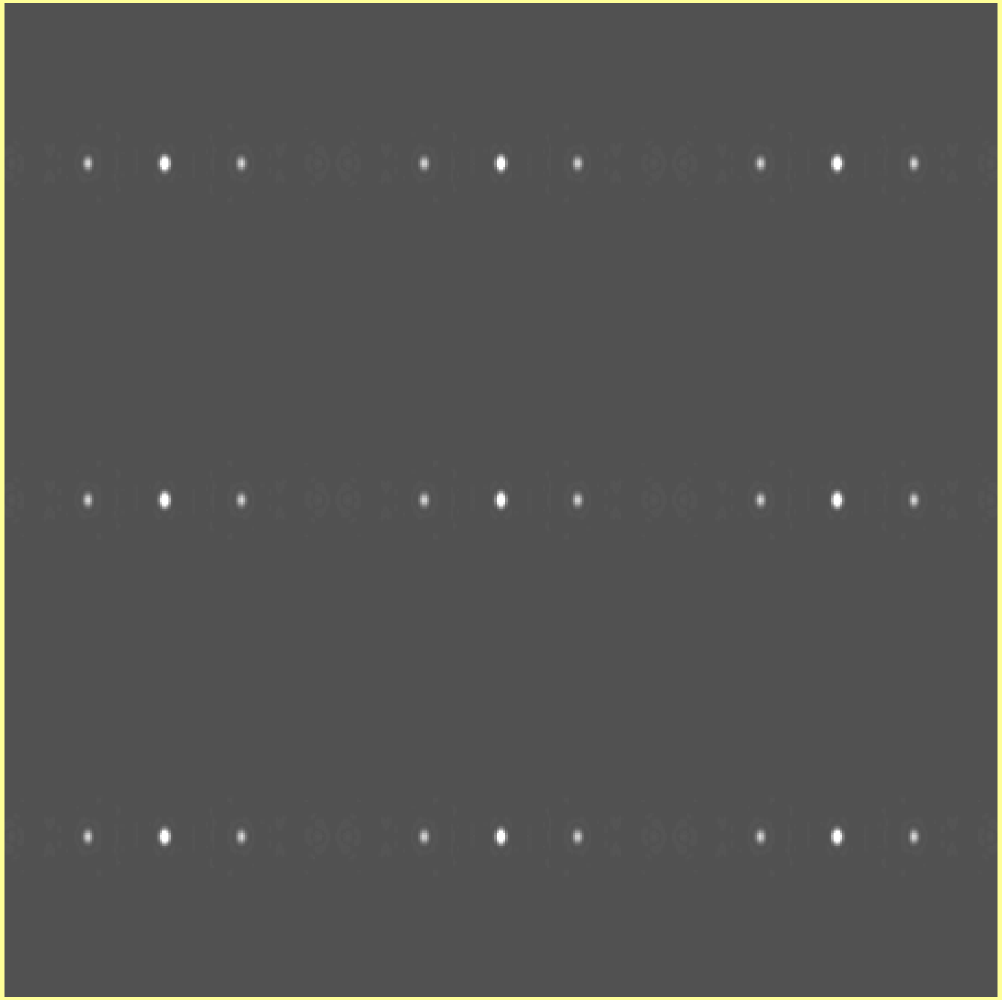
First Folling et al. Nature 434421 (2005)



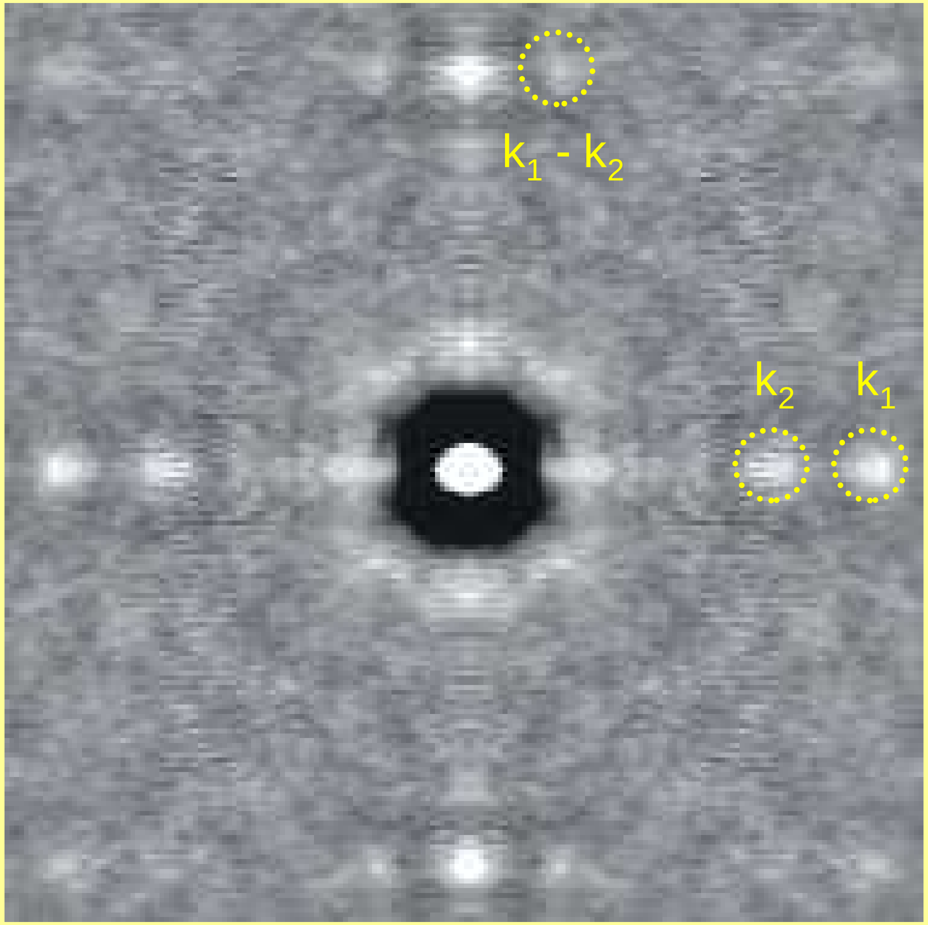
$$C(\mathbf{d}) = \frac{\int \langle n(\mathbf{x}+\mathbf{d}/2)\cdot n(\mathbf{x}-\mathbf{d}/2)\rangle \mathrm{d}^2\mathbf{x}}{\int \langle n(\mathbf{x}+\mathbf{d}/2)\rangle\langle n(\mathbf{x}-\mathbf{d}/2)\rangle \mathrm{d}^2\mathbf{x}}$$

correlation signal for a bichromatic lattice (disordered Mott Insulator)
(J=0 calculation, Fock states in each lattice well)

disorder



noise correlations in the bichromatic lattice



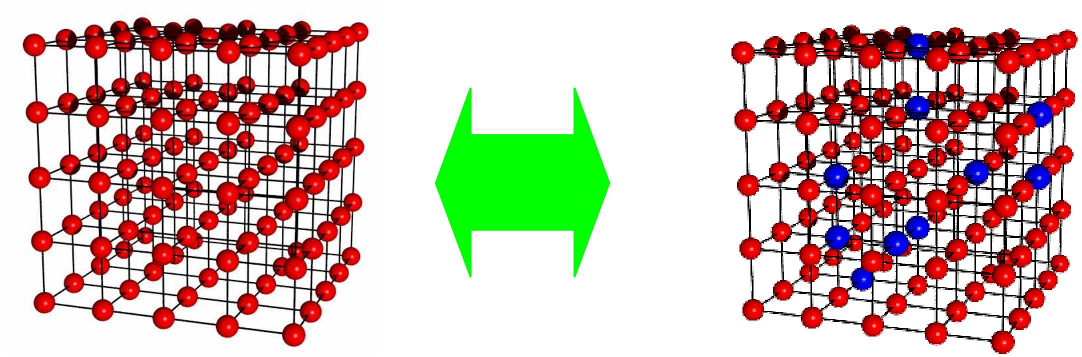
$s_2 = 9$

Adding disorder with another atomic species…

… à la Castin…

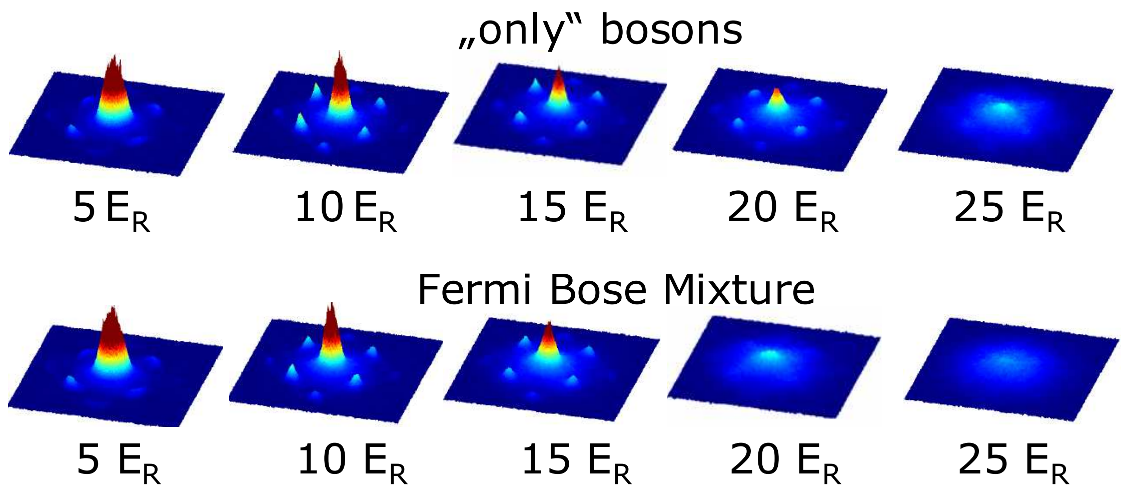
Hamburg, Zurich

Fermi-Bose quantum gas mixture in a 3d optical lattice.

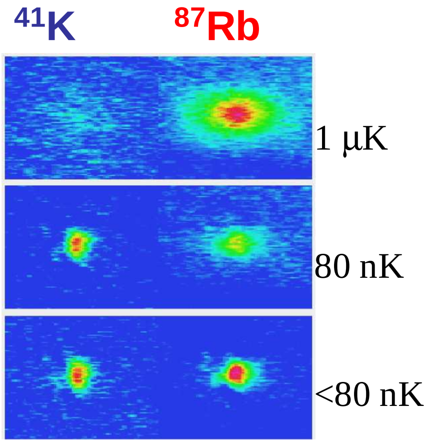


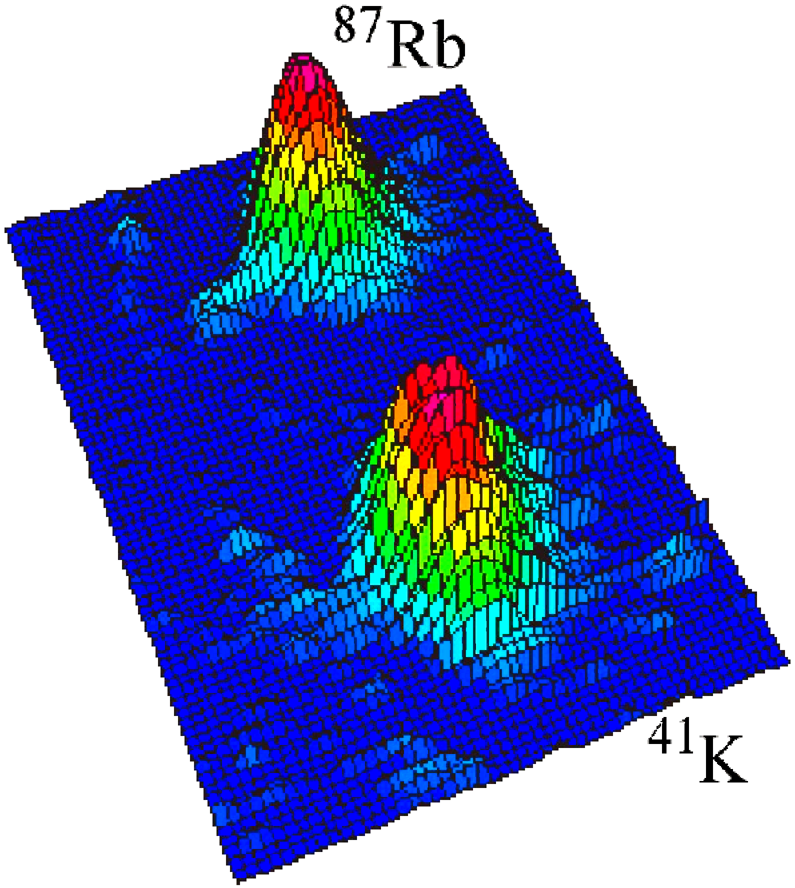
^{87}Rb $\quad$ ^{40}K/^{87}Rb mixture

Localization physics: Shift of the "Mott-insulator" transition.



A two-species BEC





$a_{KRb}=+163a_0$ $a_K=+60a_0$ $a_{Rb}=+90a_0$

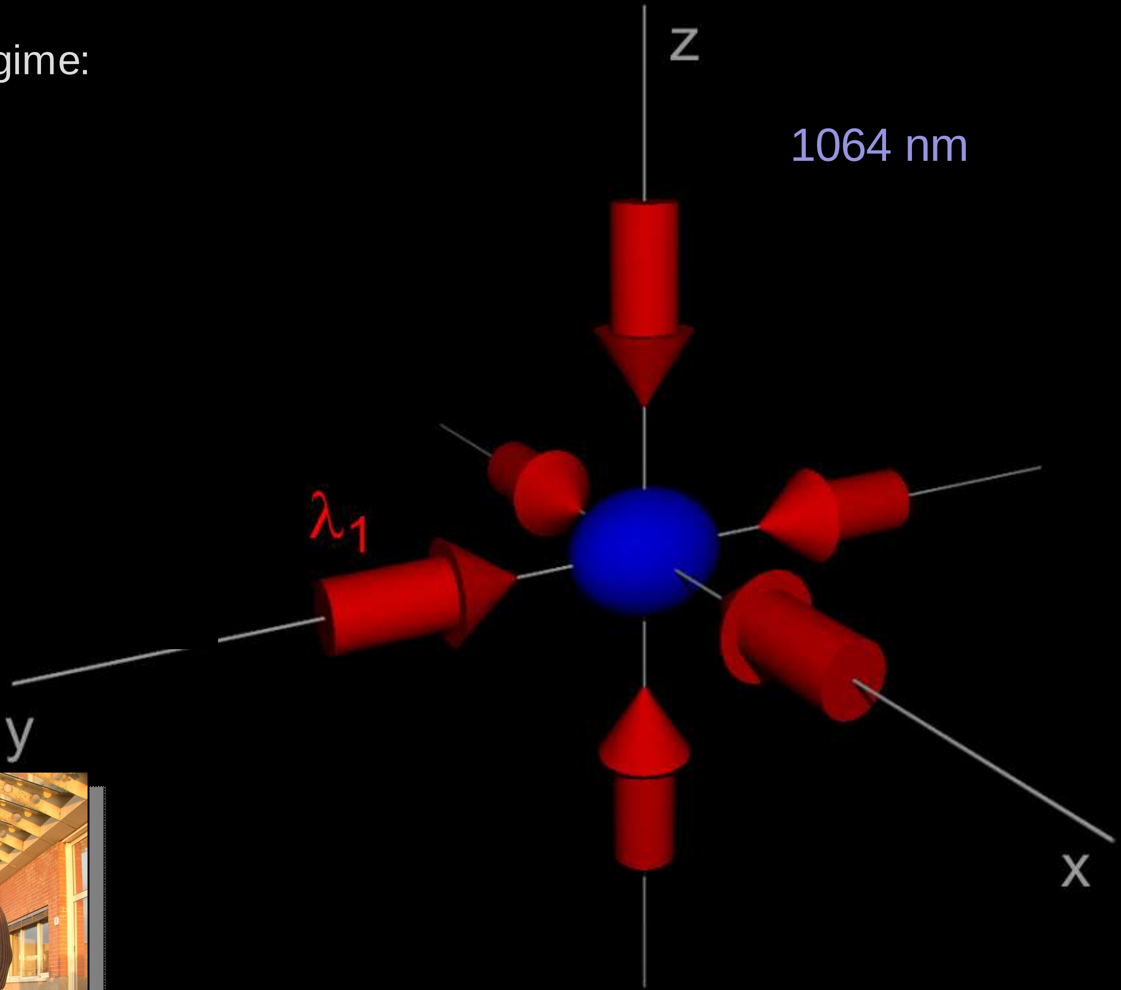
G. Modugno, M. Modugno, F, Riboli, G, Roati, M. Inguscio, Phys.Rev.Lett. 89, 190404 (2002)

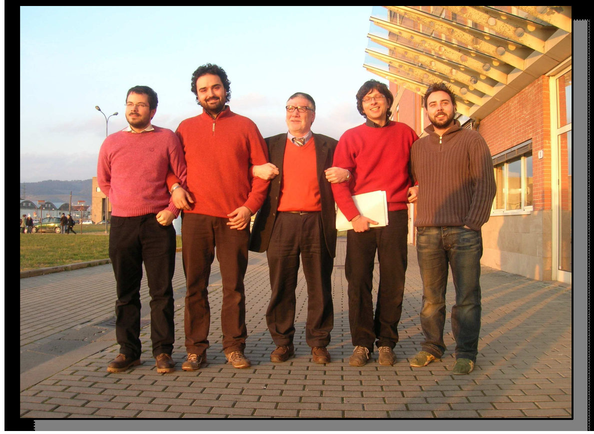
ADDING THE 3D OPTICAL LATTICE

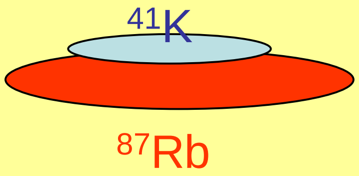
strongly interacting regime:

↓

3D optical lattice



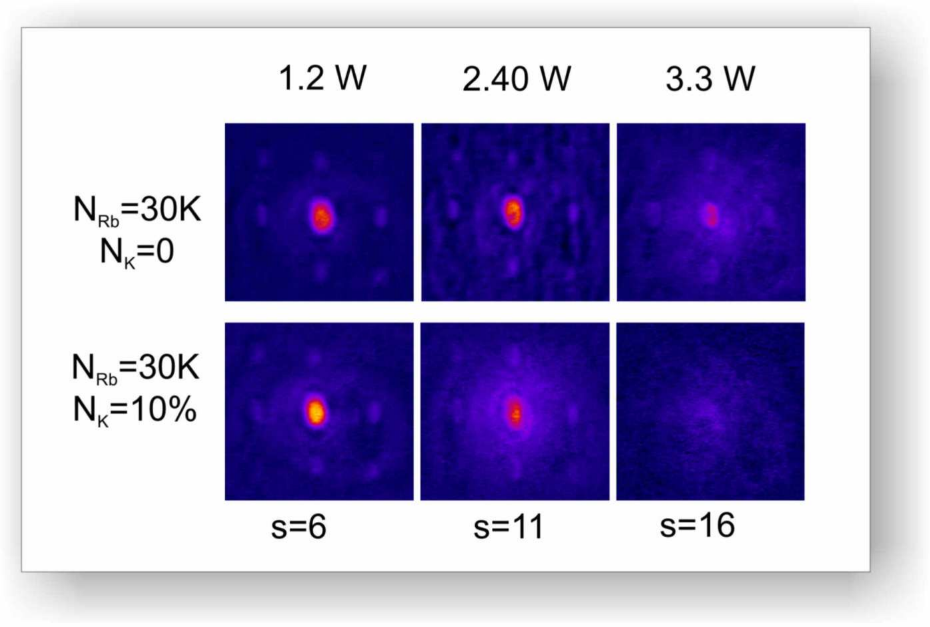


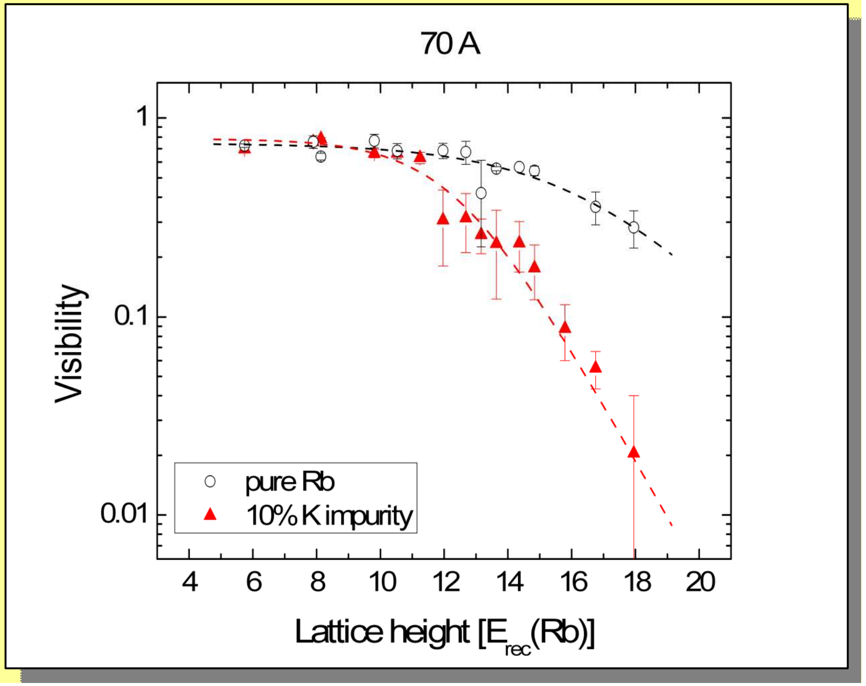


Degenerate Bose-Bose mixture in a 3D optical lattice

J. Catani, L. De Sarlo, G. Barontini, F. Minardi and M. Inguscio

cond.mat./ 0706.2781





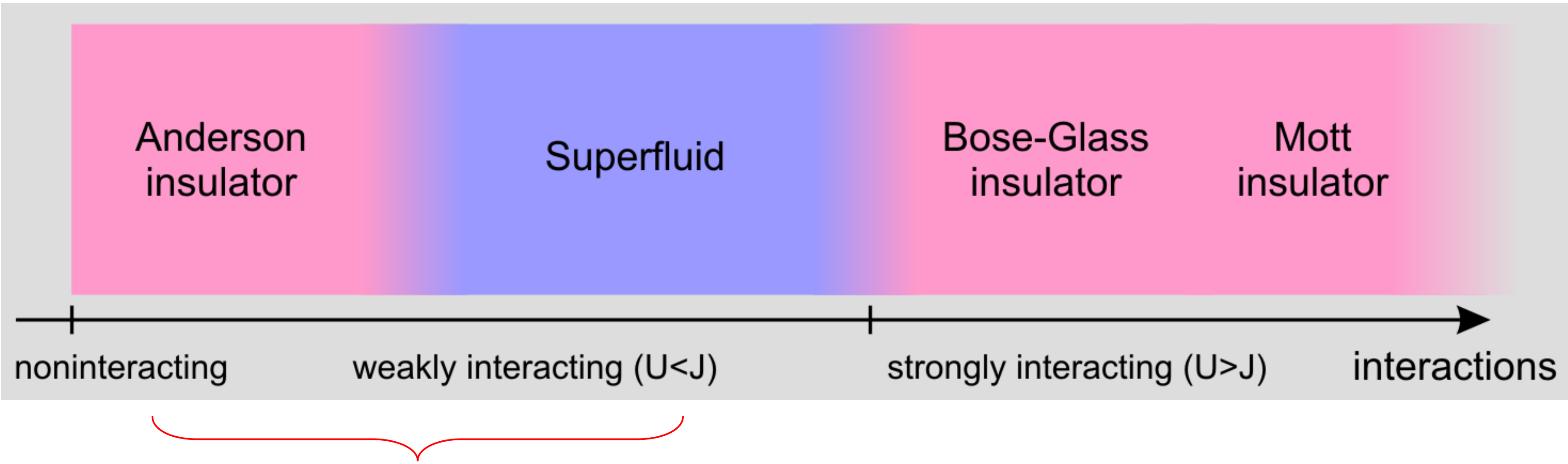
Ultracold atoms in optical lattices

Adding disorder

Strongly interacting bosons
in a disordered lattice

Weakly interacting bosons
in a disordered lattice

Disordered systems: Role of interactions

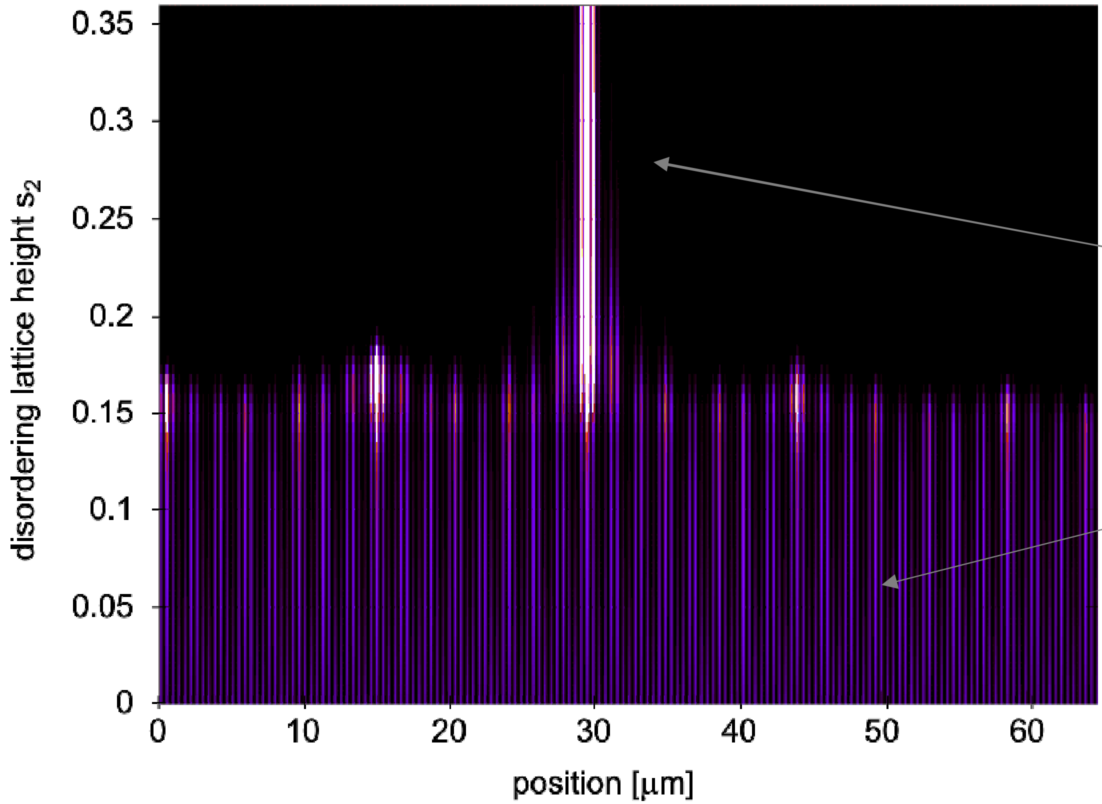


Effects of interaction in the Anderson localization

Localization in a quasi-periodic lattice

$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + s_1 E_{R1}\cos^2(k_1 x) + s_2 E_{R2}\cos^2(k_2 x)\right]\psi(x) = E\psi(x)$$

λ_1 = 830 nm s_1 = 10 / λ_2 = 1076 nm



square modulus of the ground state wavefunction

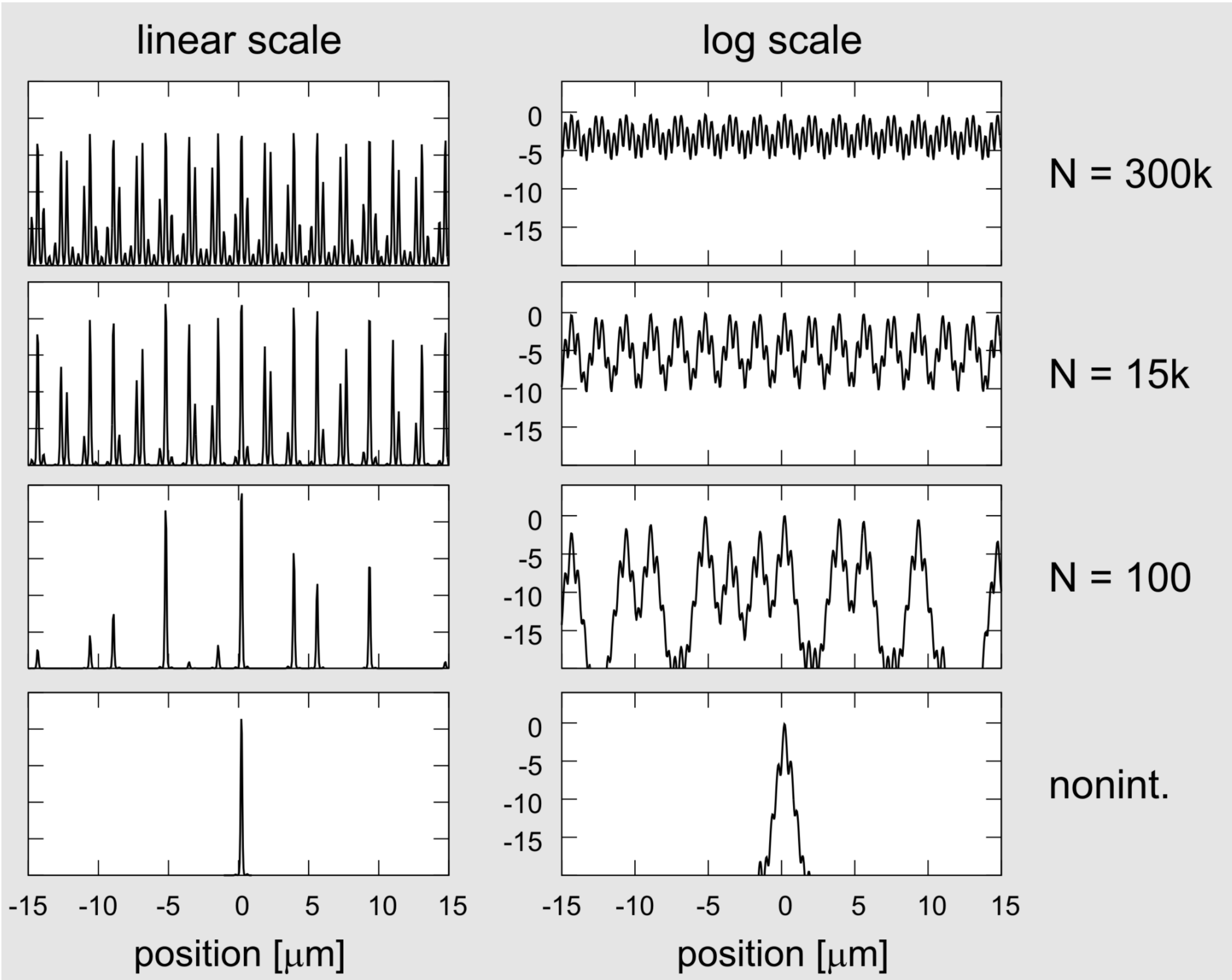
localized states

extended states

localization transition in 1D (Aubry-André)

Screening induced by interactions

$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + s_1 E_{R1}\cos^2(k_1 x) + s_2 E_{R2}\cos^2(k_2 x) + gN|\psi(x)|^2\right]\psi(x) = E\psi(x)$$



NPSE solution of the ground state for s_1=10 and s_2=1

see also:
T. Schulte et al.,
PRL **95**, 170411 (2005)

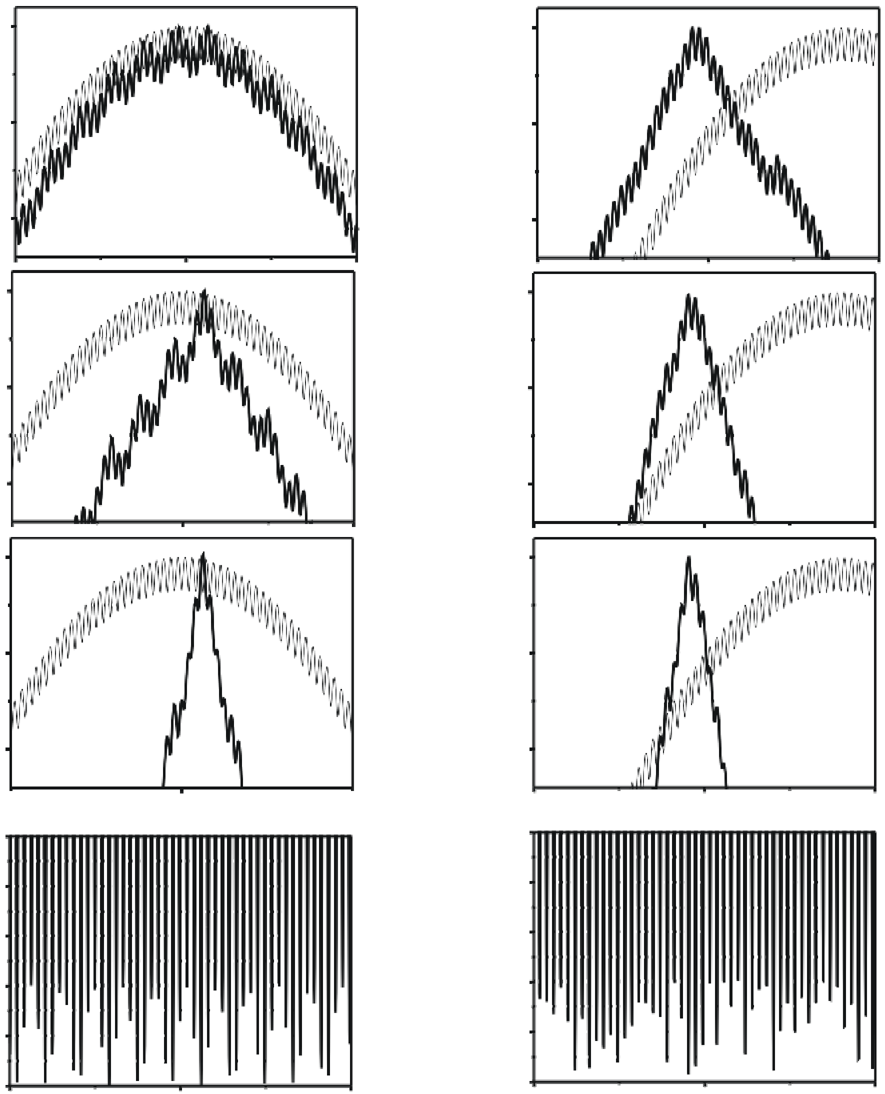
Localization in a quasi-periodic lattice + harmonic trap (no interactions)

quasi-periodic potential | random site to site energy

$s_1=10$ $s_2=0.1$

$s_2=0.25$

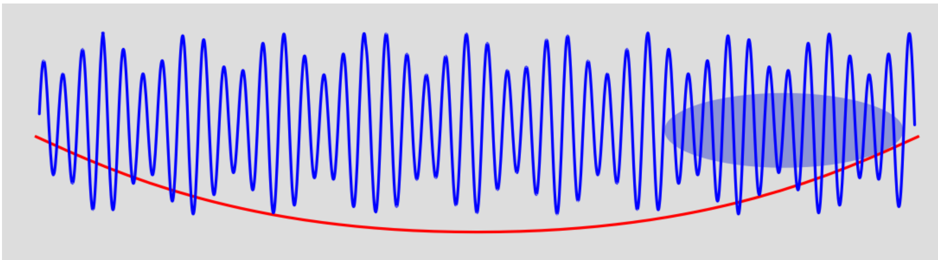
$s_2=1$

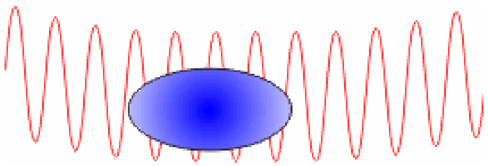


Oscillations in the bichromatic potential

J. Lye et al., PRA 75, 061603R (2007)

Localized states can be revealed by setting the system out of equilibrium and observing the following dynamics under the action of a harmonic driving force.



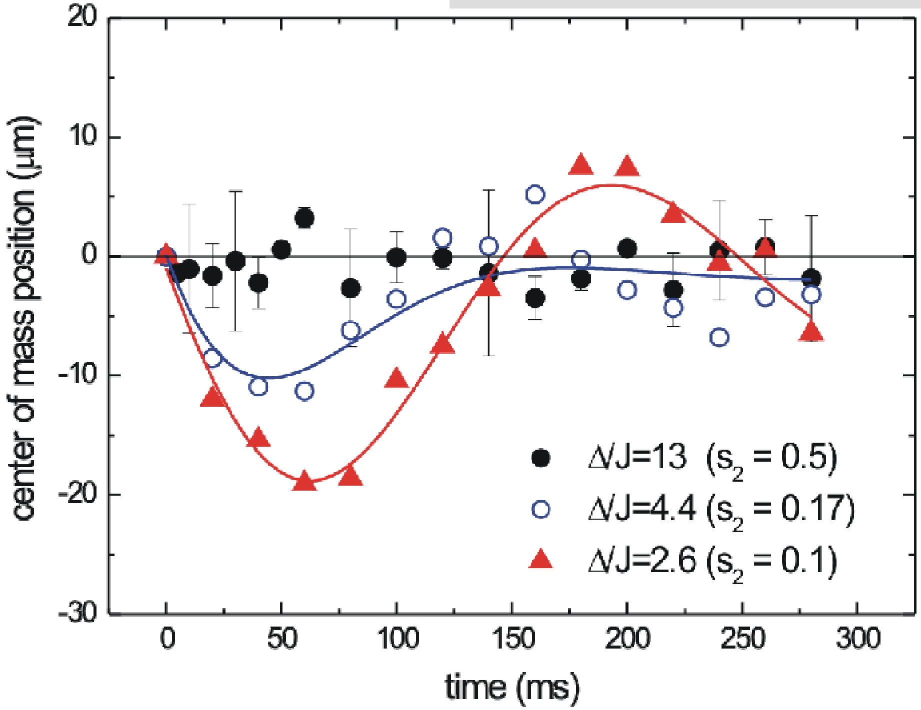


Oscillations in the bichromatic potential

J. Lye et al., PRA 75, 061603R (2007)

Center-of-mass as a function of time for s_1=10 and different heights of the disordering lattice.

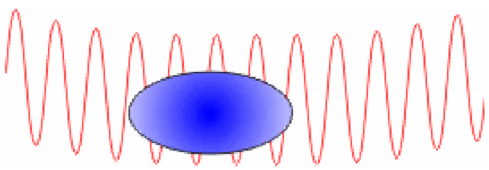
Localization effect increasing with increasing disorder



Oscillations in the bichromatic potential

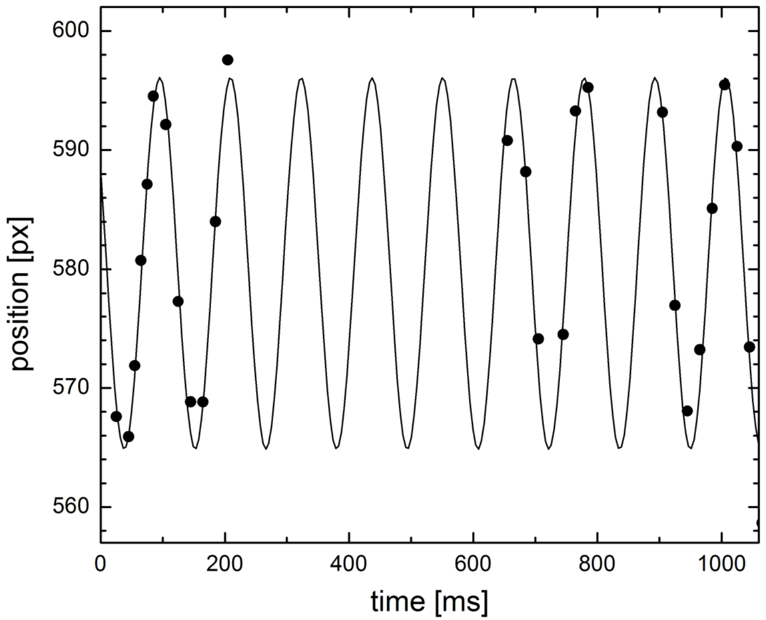
J. Lye et al., PRA 75, 061603R (2007)

Undamped oscillation of a Bose-Einstein condensate in a periodic optical lattice + harmonic potential (magnetic trap)



Oscillation frequency: $$\omega^* = \sqrt{\frac{m}{m^*}}\omega$$

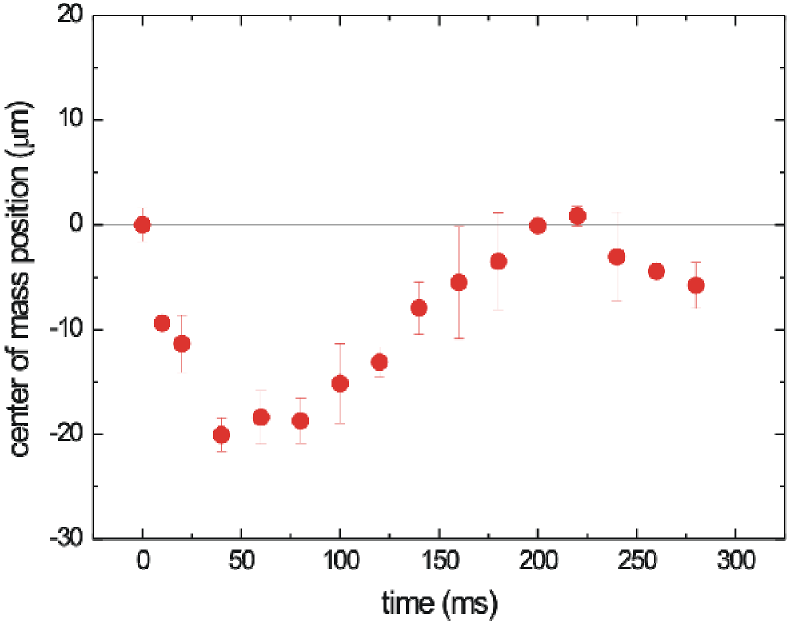
F. S. Cataliotti et al., *Science* **293**, 843 (2001)



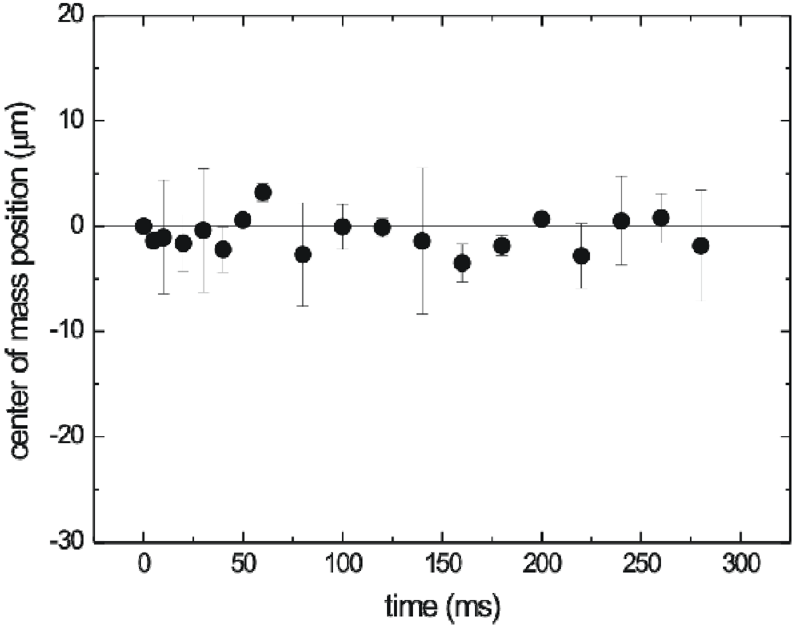
Oscillations in the bichromatic potential

Decreasing the number of atoms the “localization” effect increases

N = 300k

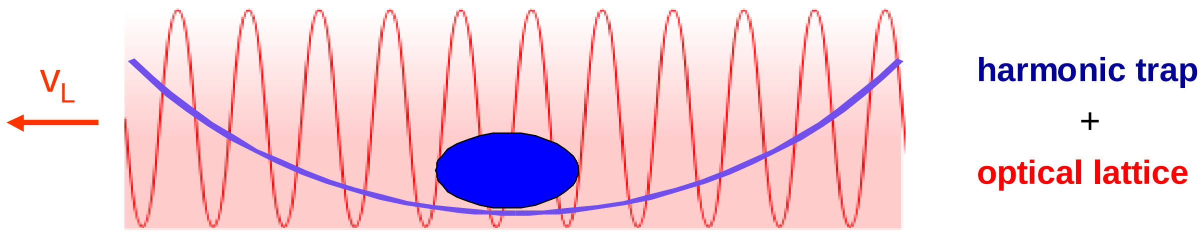


N = 15k



But disorder alone is not the only effect that can lead to localization...

Instabilities of a BEC in a moving optical lattice



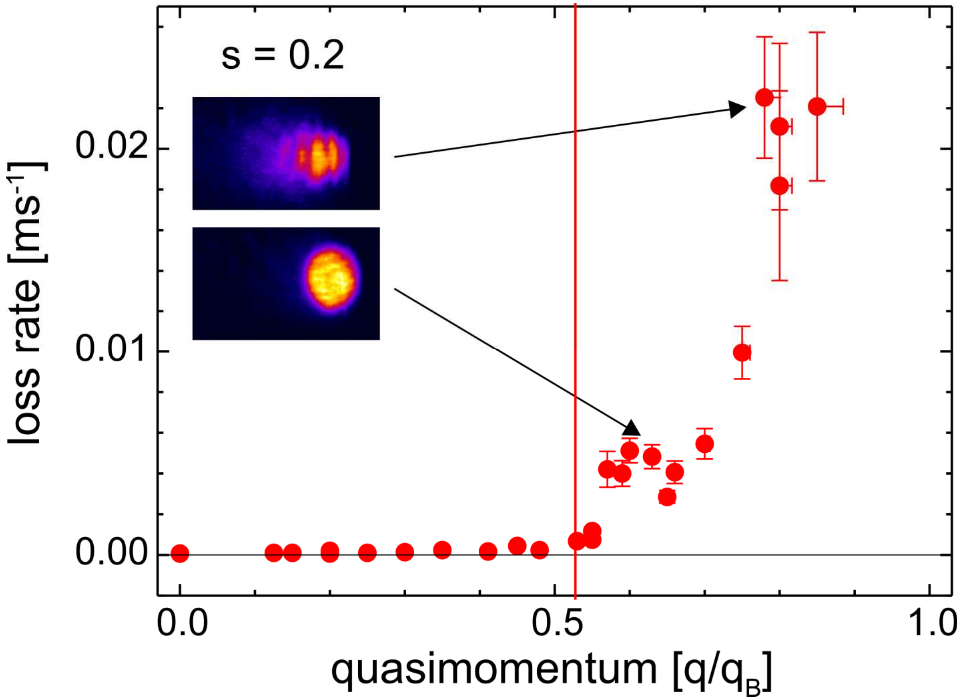
Nonlinear system; complex frequencies in the eigenspectrum of the excitations

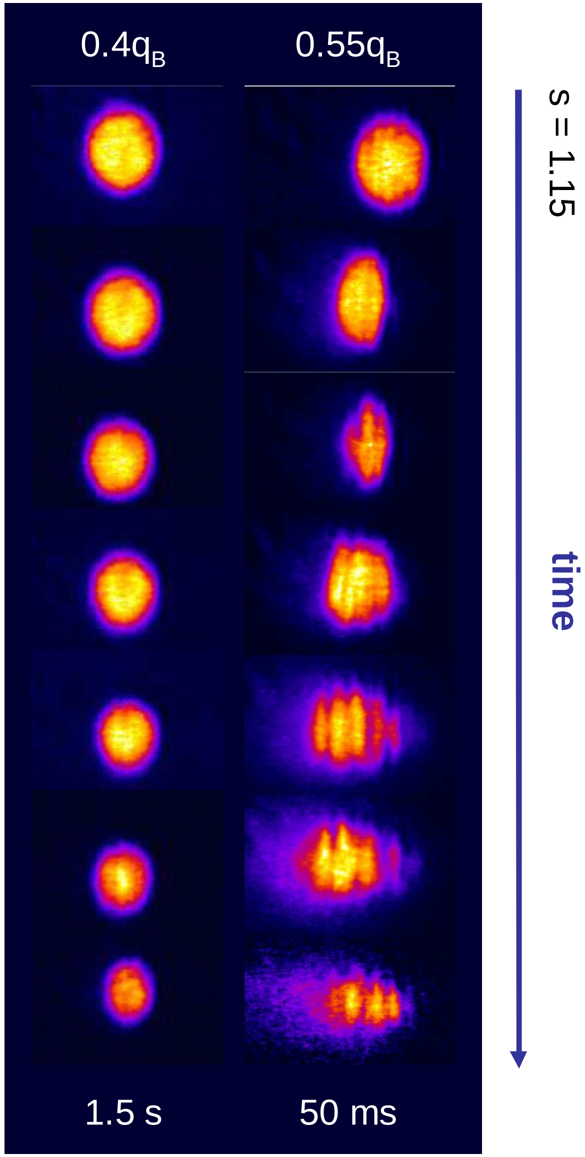
***Dynamical instability** – critical velocity*

$$i\hbar\frac{\partial\psi}{\partial t}=\left(-\frac{\hbar^2}{2m}\nabla^2+sE_R\cos^2(kx)+g\left|\psi\right|^2\right)\psi$$

Instabilities of a BEC in a moving optical lattice

L. Fallani et al., Phys. Rev. Lett. 93, 140406 (2004)

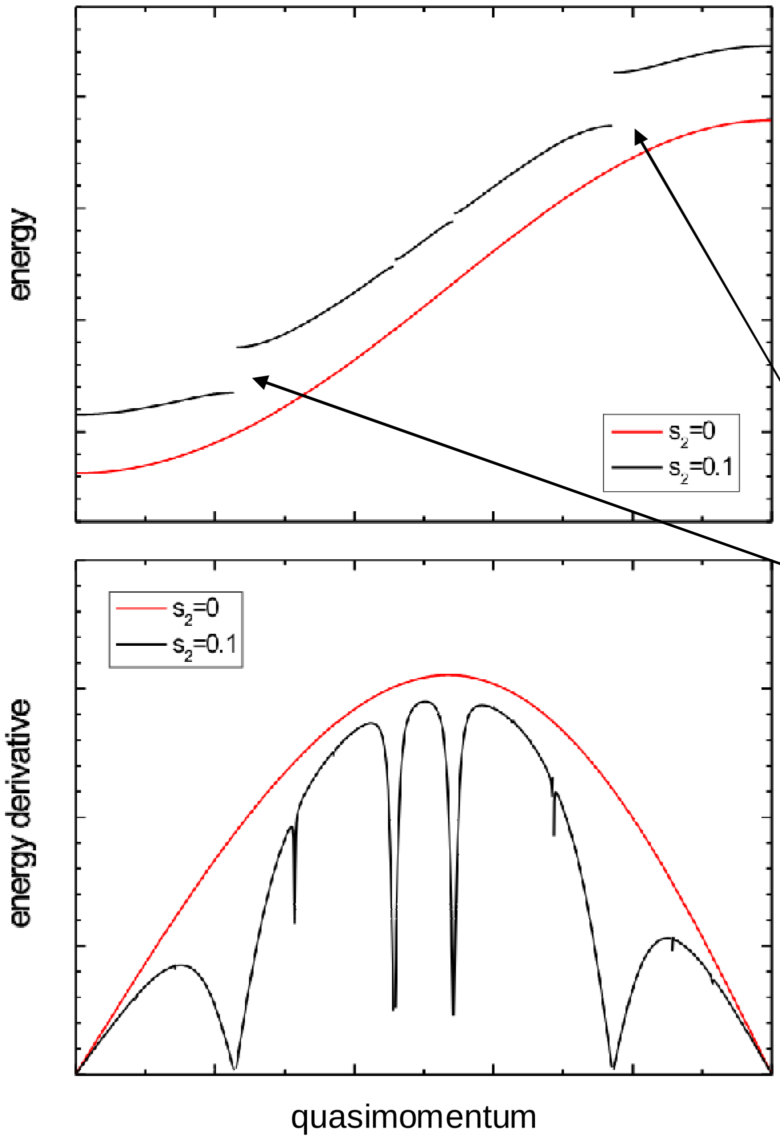




$$i\hbar\frac{\partial\psi}{\partial t} = \left(-\frac{\hbar^2}{2m}\nabla^2 + sE_R\cos^2(kx) + g|\psi|^2\right)\psi$$

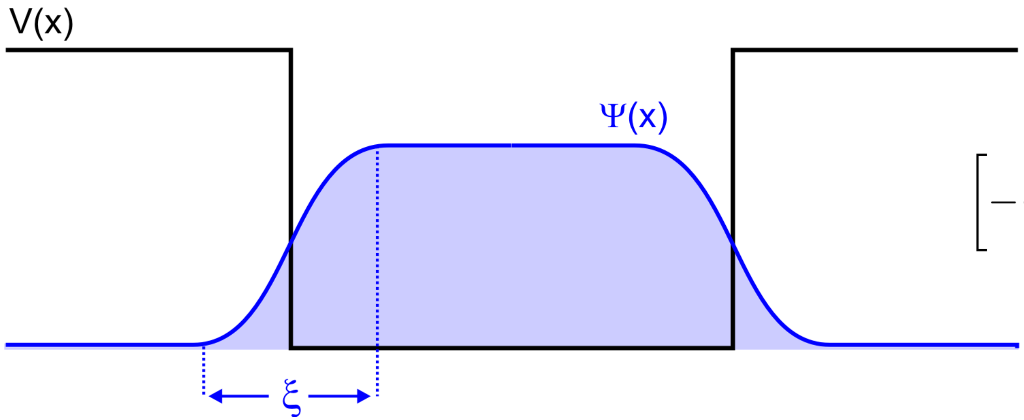
Nonlinearities induced by atom-atom interactions cause the Bloch waves to be **dynamically unstable**. An exponential growth of perturbations may start, eventually leading to the destruction of the Bloch state.

Localization in a quasi-periodic lattice



Suppression of center-of-mass motion may be caused also by dynamical instability occurring at small momenta

Extra gaps appearing in the energy spectrum due to quasi-periodicity on a longer length-scale interacting BEC in a box



$$\left[-\frac{h^2}{2m}\partial_x^2 + V(x) + \frac{4\pi\hbar^2 a}{m}|\Psi|^2\right]\Psi = \mu\Psi$$

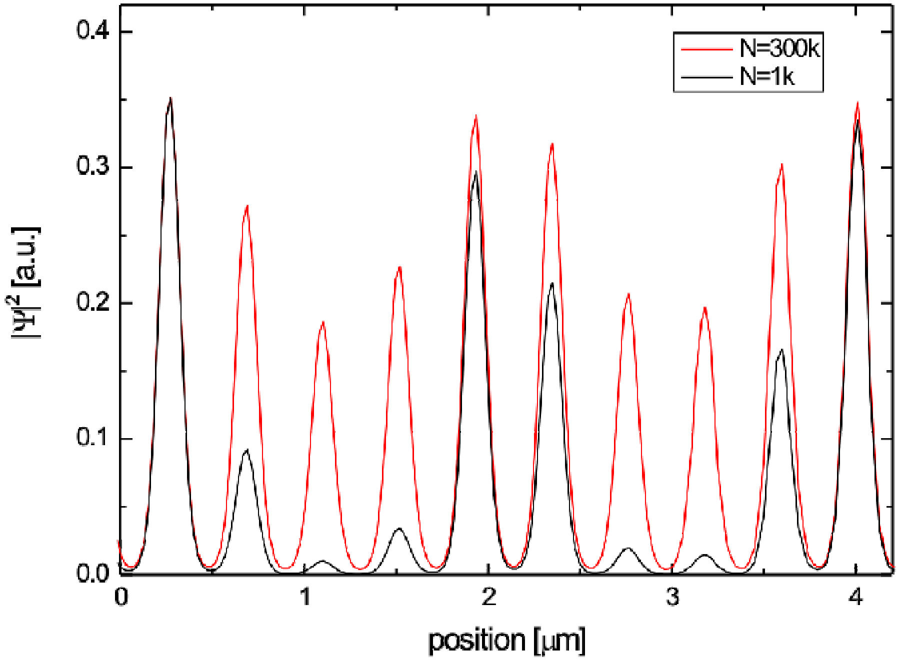
the wavefunction "adapts" to variations in the external potential
on a length scale set by the healing length ξ

healing length $\xi = \frac{1}{\sqrt{8\pi a n}}$

$\Delta x > \xi \rightarrow$ classical effects (Thomas-Fermi approx., ...)

$\Delta x < \xi \rightarrow$ quantum effects (tunnelling, barrier penetration, ...)

Screening induced by interactions



Interactions effectively screen the potential on the larger length scale of the beating

↓

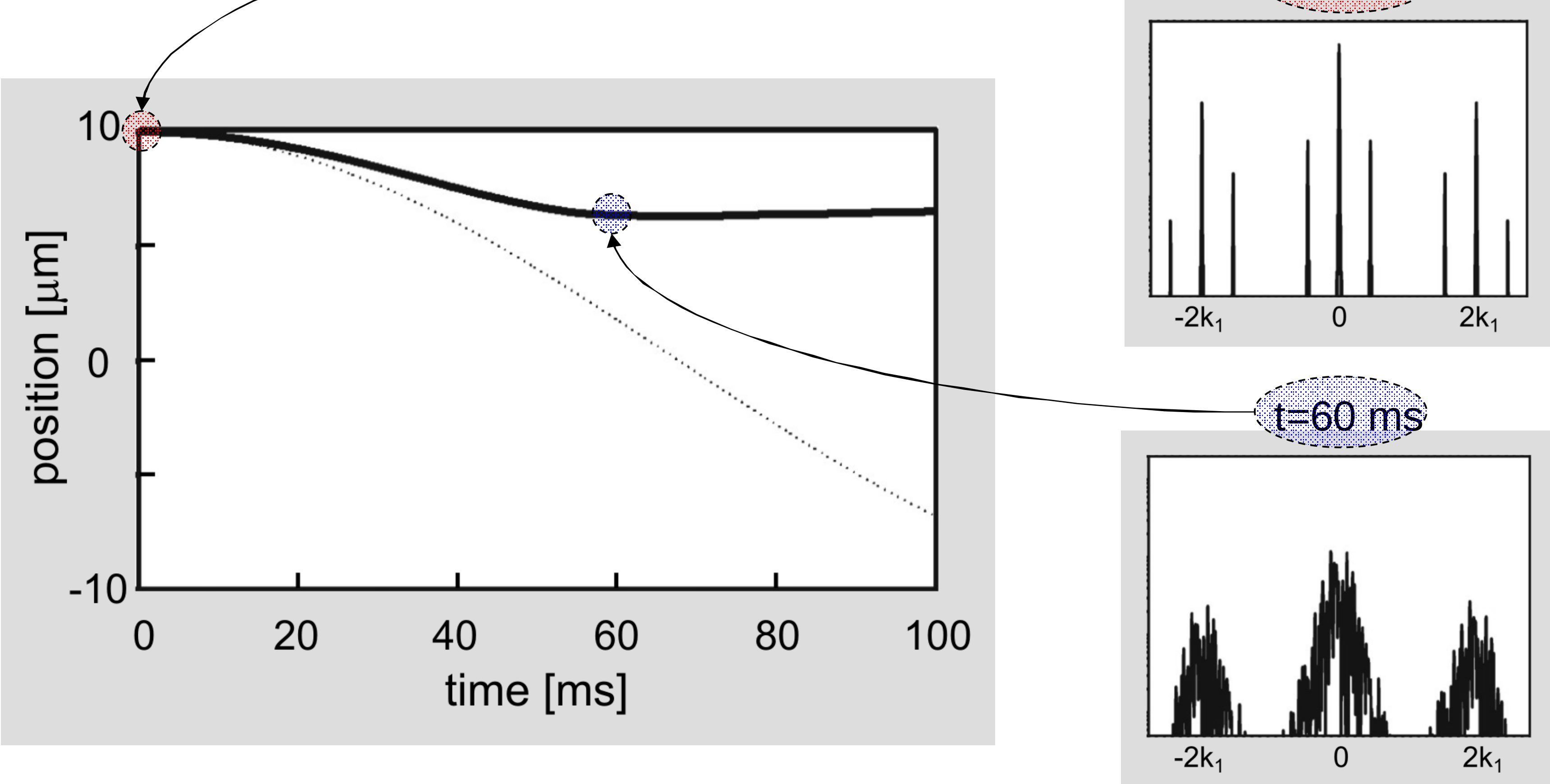
Decreasing *N* the wavefunction is more strongly modulated

Screening when disorder length scale >> healing length

$$\xi \simeq \frac{1}{\sqrt{n}}$$

$$\left[-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} + s_1 E_{R1}\cos^2(k_1 x) + s_2 E_{R2}\cos^2(k_2 x) + gN|\psi(x)|^2\right]\psi(x) = E\psi(x)$$

Numerical solution of the NPSE (effective 1D GPE model):

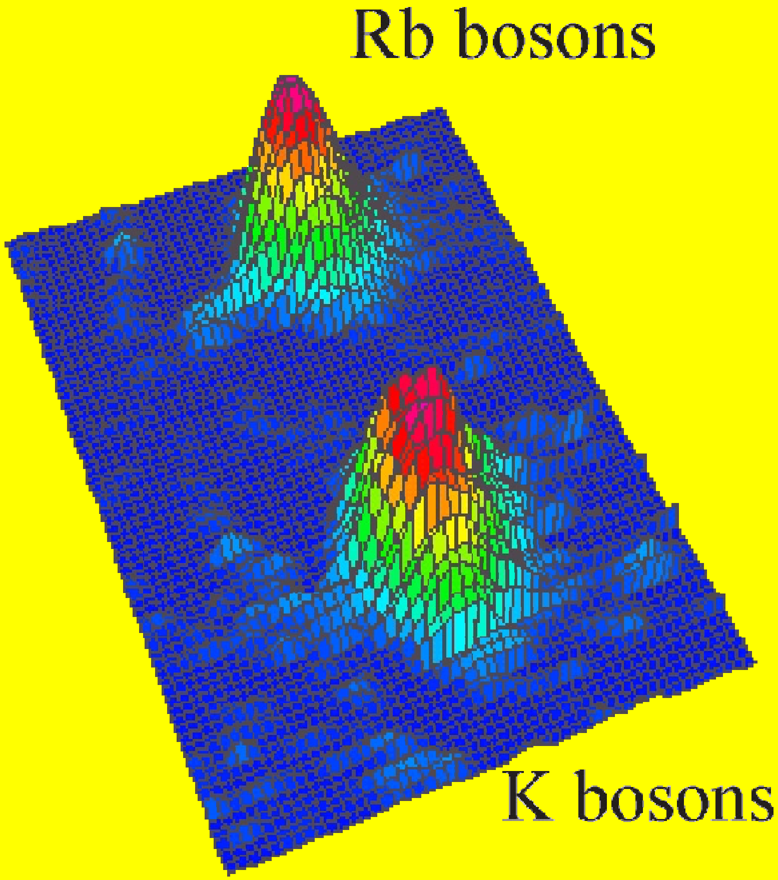


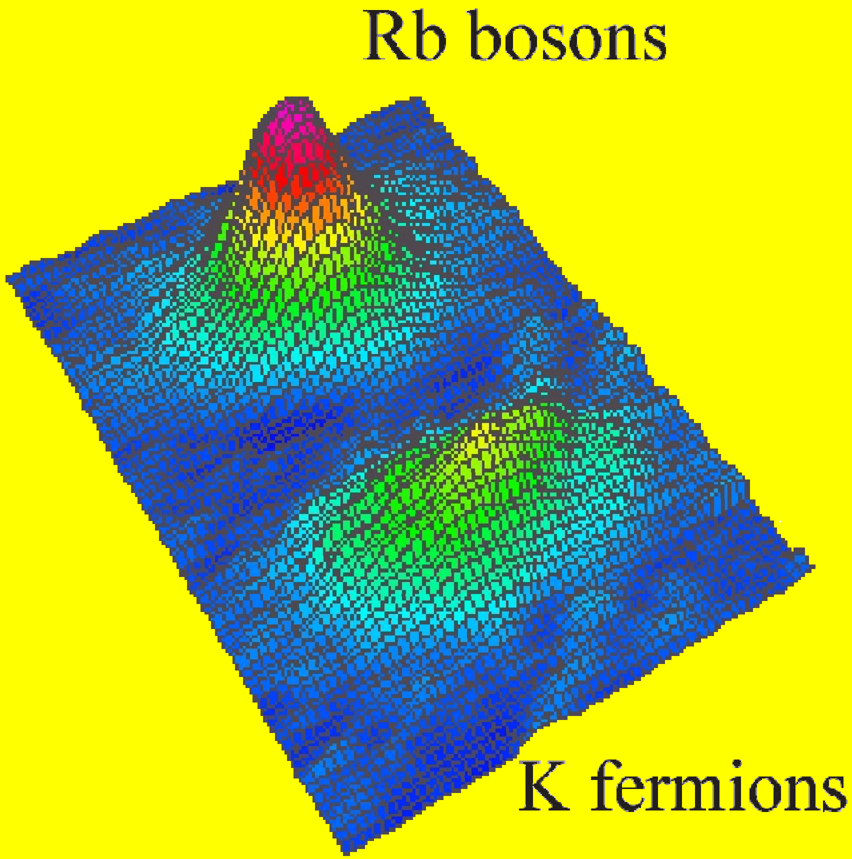
How to avoid interactions?

Fermions?

Tuning the interactions with Feshbach resonances?

Sympathetic cooling of Potassium 41 (boson) and 40 (fermion)

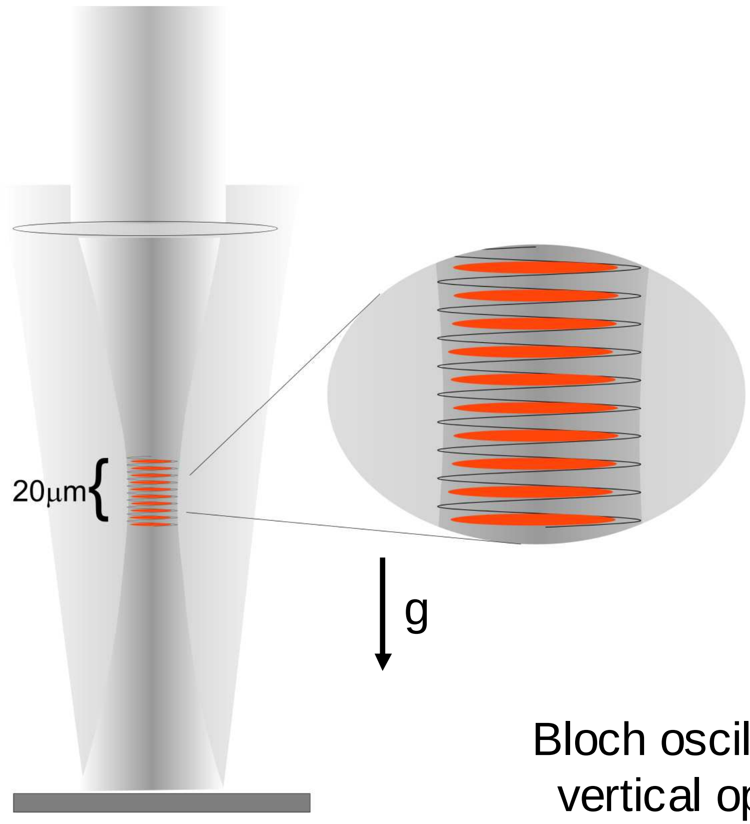


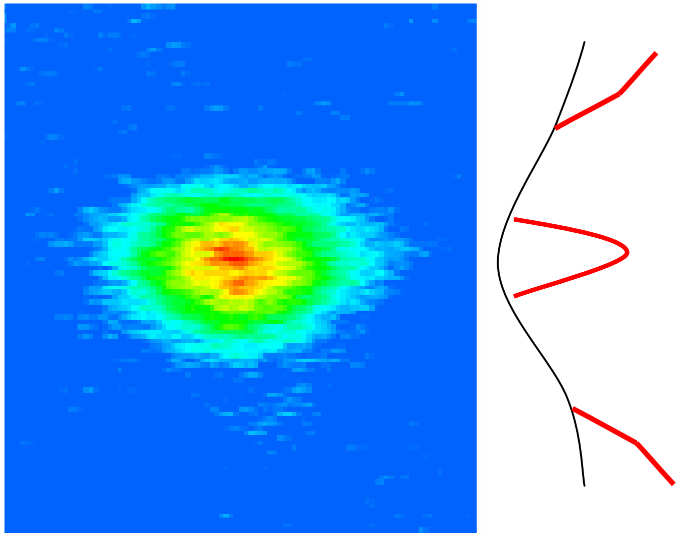


G. Modugno, G. Ferrari, G. Roati, R. Brecha, A. Simoni, M. I., *Science* 294, 1320 (2001)

G. Roati, F. Riboli, G.Modugno, M. I. Phys. Rev. Lett. 89, 150403 (2002).

Bloch oscillations with fermions

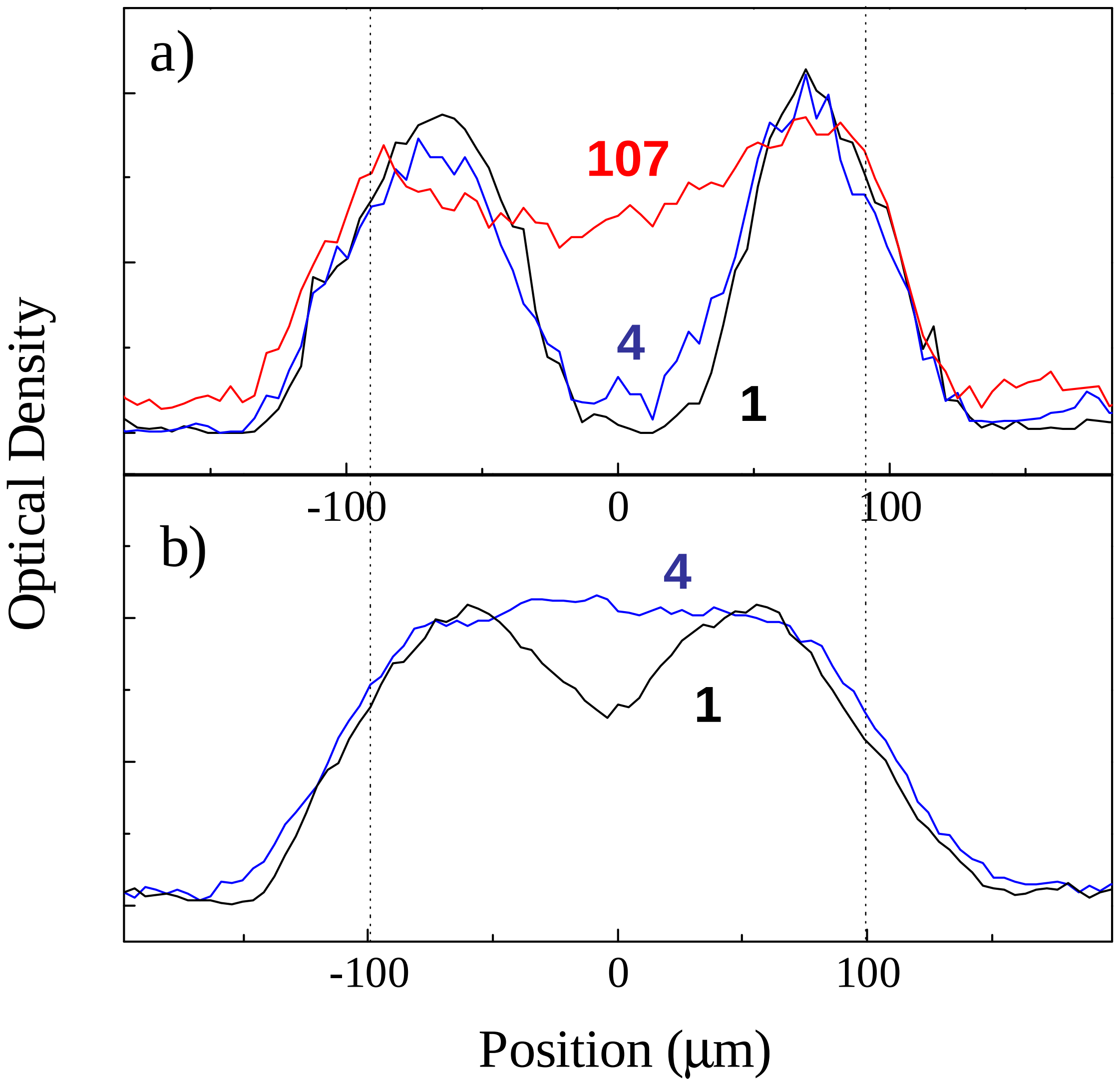




Bloch oscillations of ^{40}K fermions trapped in a vertical optical lattice in presence of gravity

G.Roati, E. De Mirandes, F.Ferlaino, H.Ott, G.Modugno, M.I. Phys.Rev.Lett. 92, 230402 (2004)

Effect of interactions: Fermi vs. Bose

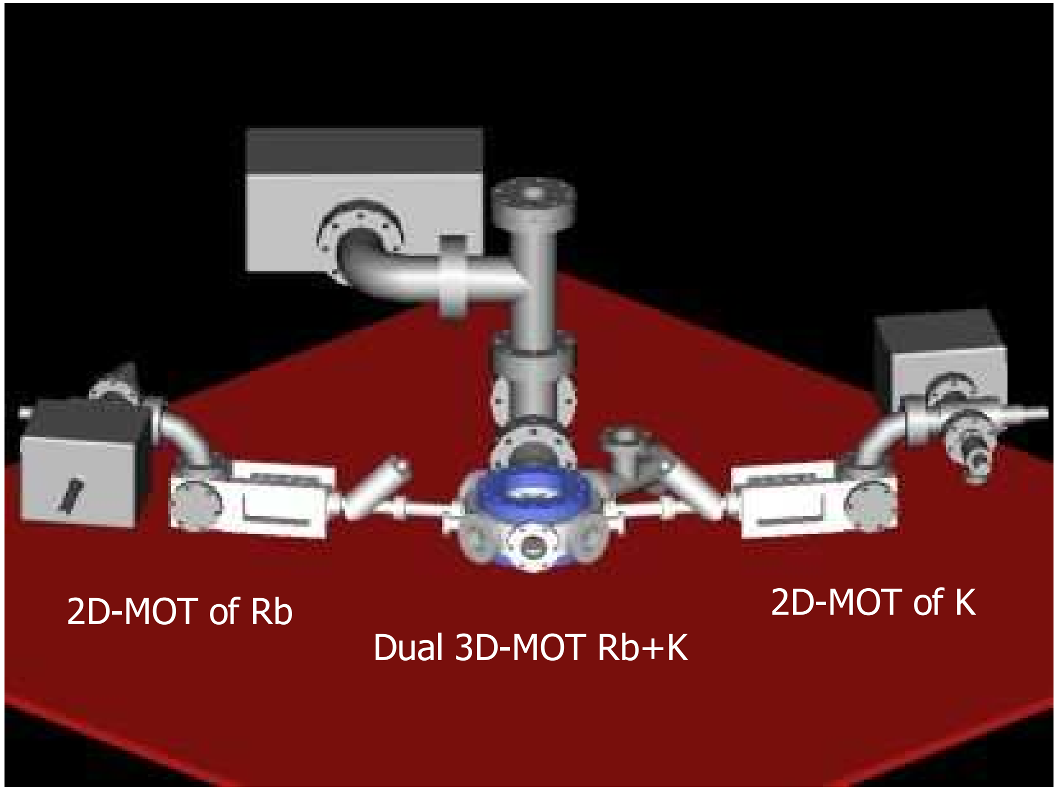


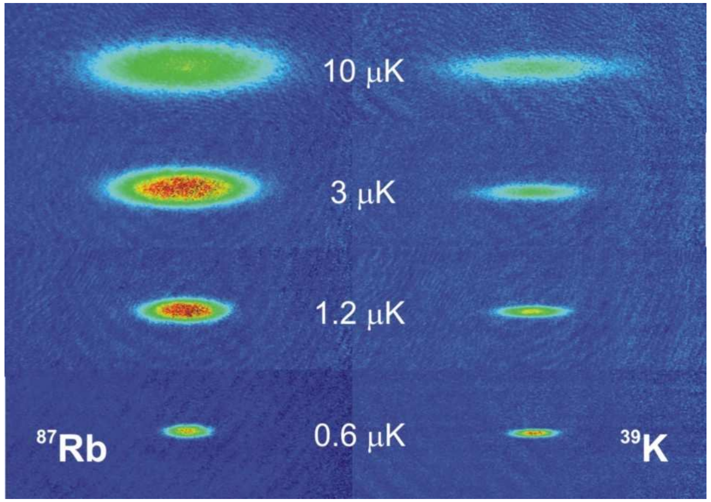
^{41}K boson

^{40}K fermion

^{39}K boson

A new K-Rb Bose-Bose mixture apparatus   **Bose – Bose (^{39}K)**





In spite of a low interspecies

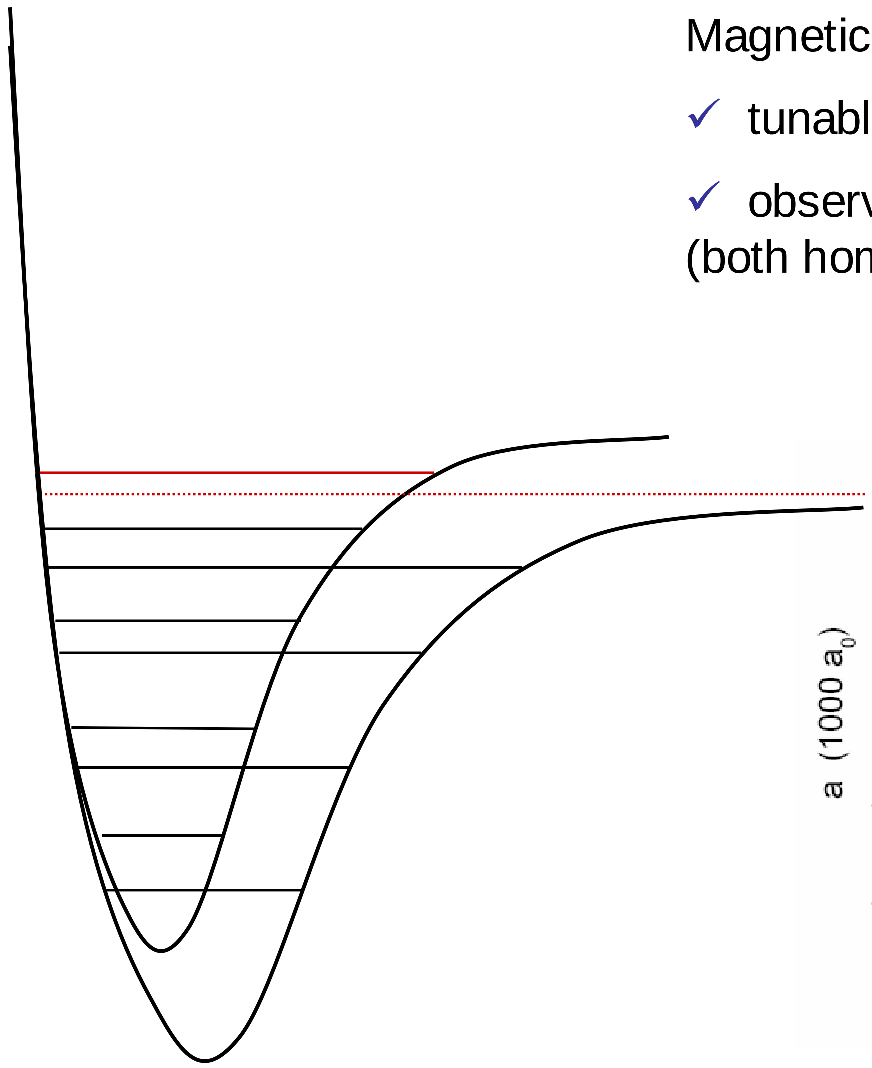
$a_{39\text{-}87} = +\,28\, a_0$

but $a_{39\text{-}39} = -\,33\, a_0$

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

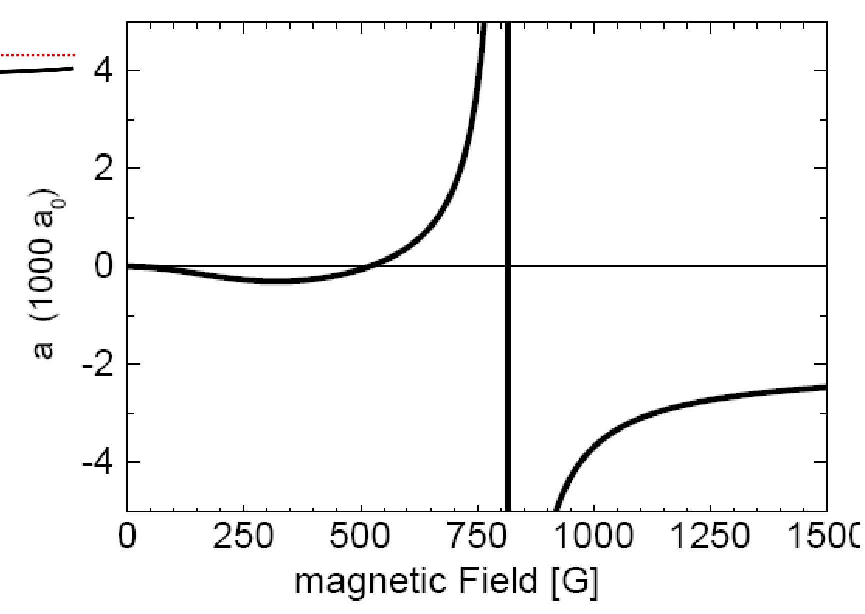
L.De Sarlo, P.Maioli, G.Barontini,J.Catani, F.Minardi, M.I.
Phys.Rev. A75, 022715 (2007)

Fano-Feshbach resonances: resonant control of the interactions



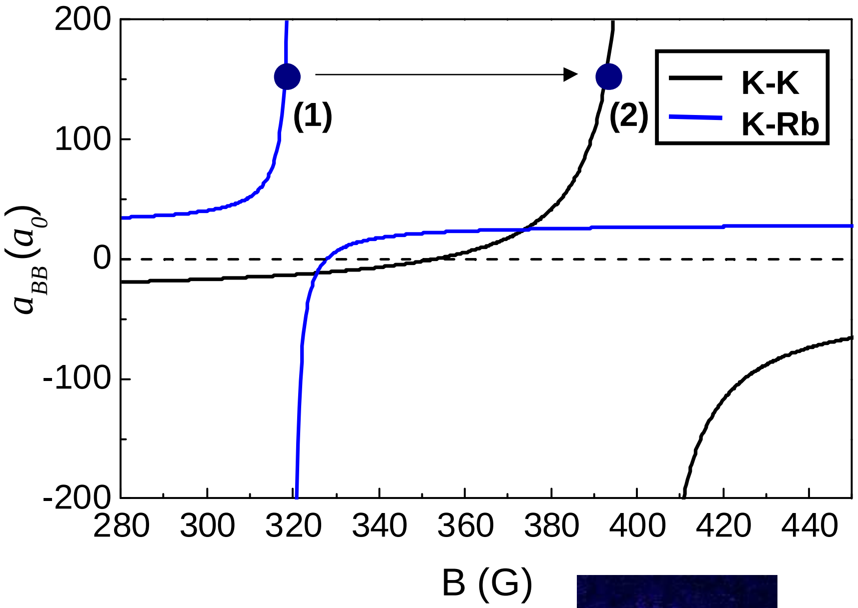
Magnetically tunable scattering resonances:

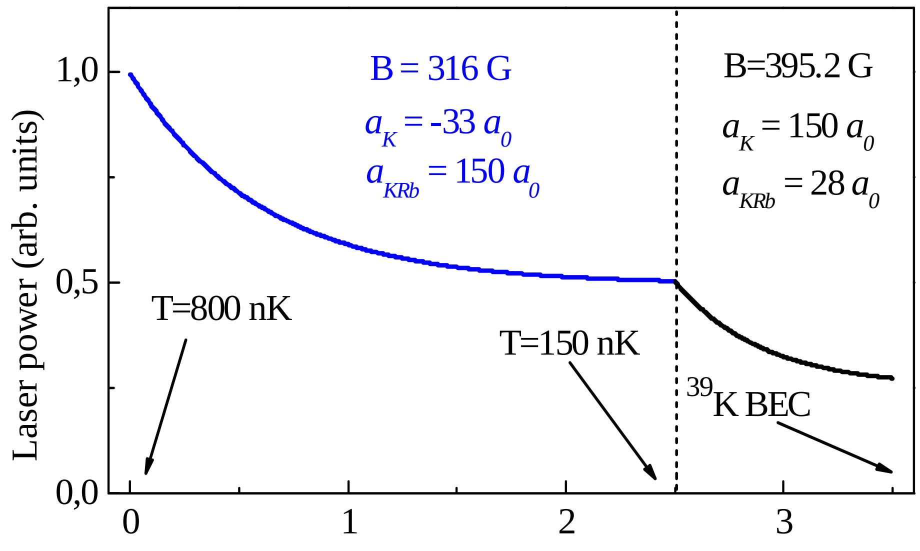
- ✓ tunable interaction in s, p, and other waves
- ✓ observed or expected for all alkali species (both homo- and hetero-nuclear)

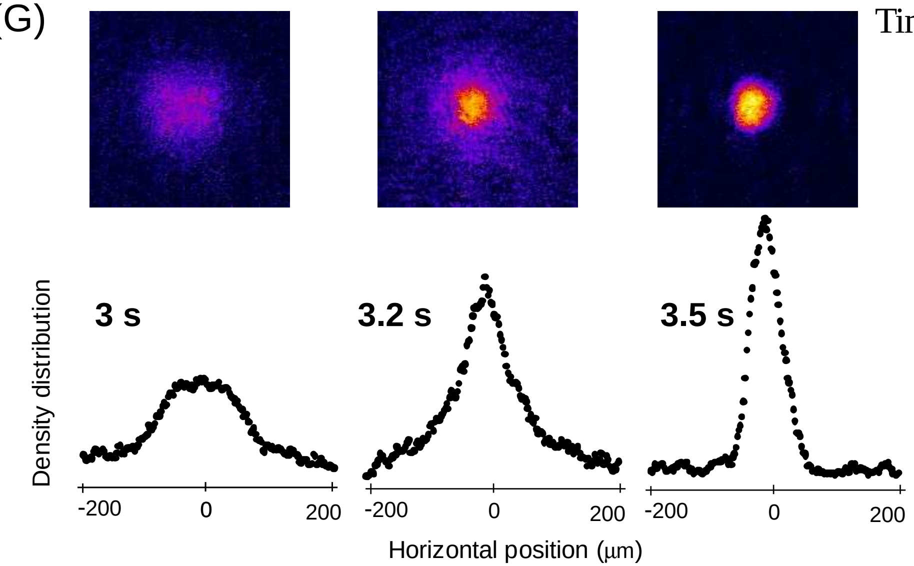


BEC of ^{39}K

Roati et al PRL 99, 010403 (2007)







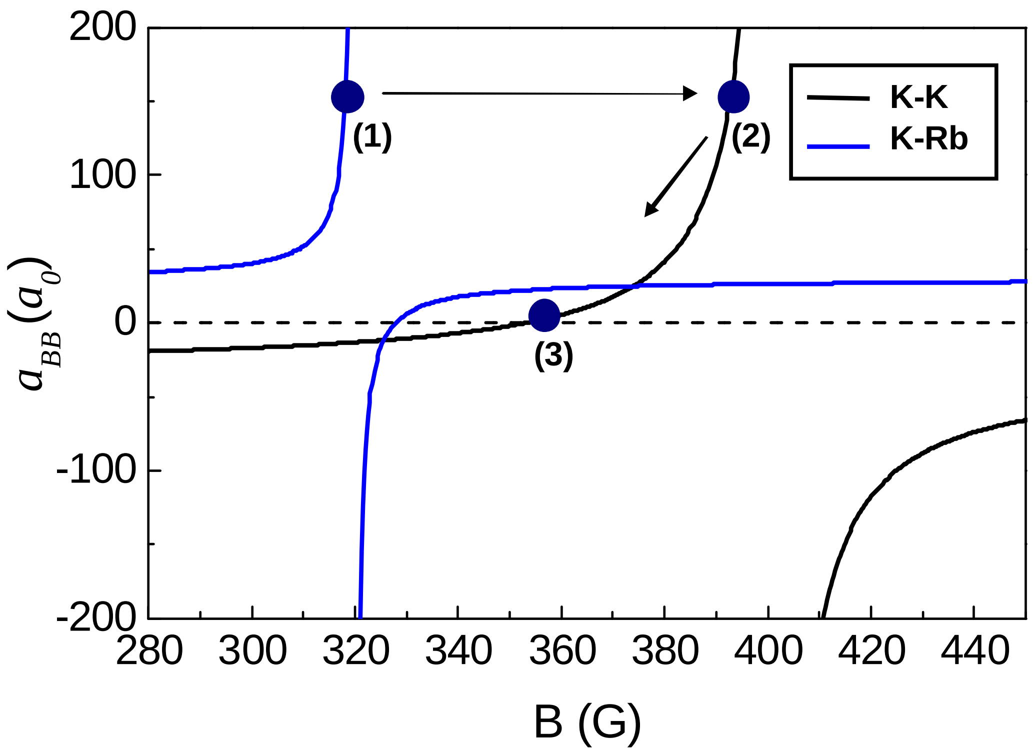
B_0 = 317.9 G

B_0 = 402.4 G

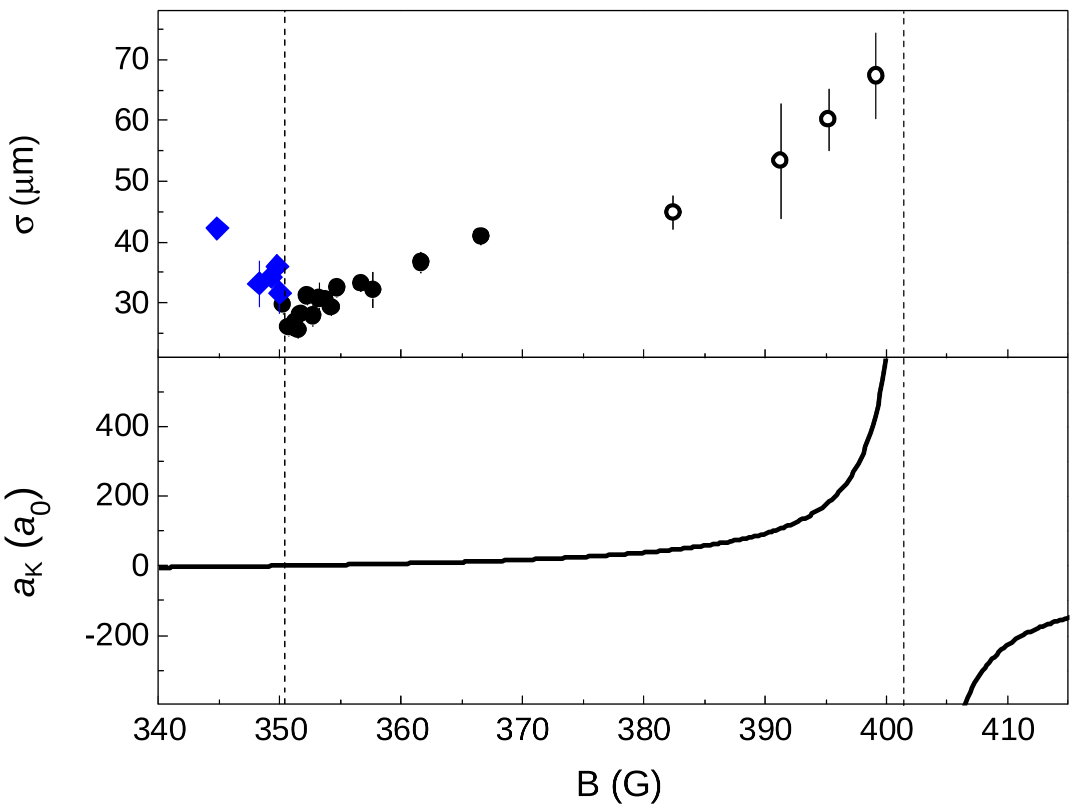
N_K = 7*10^4

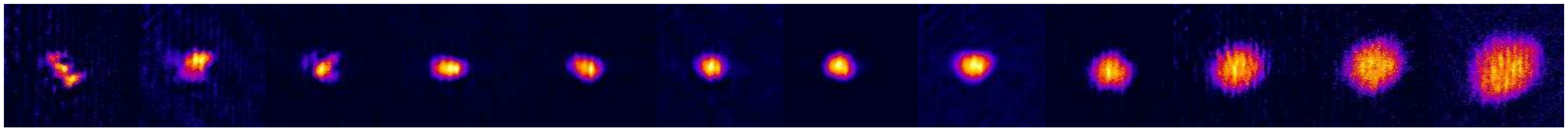
T_c~ 100 nK

We have explored the 52 G-wide magnetic-field region below the homonuclear resonance in which the condensate is stable



39K BEC with tunable interactions





Roati et al. PRL 99, 010403 (2007)

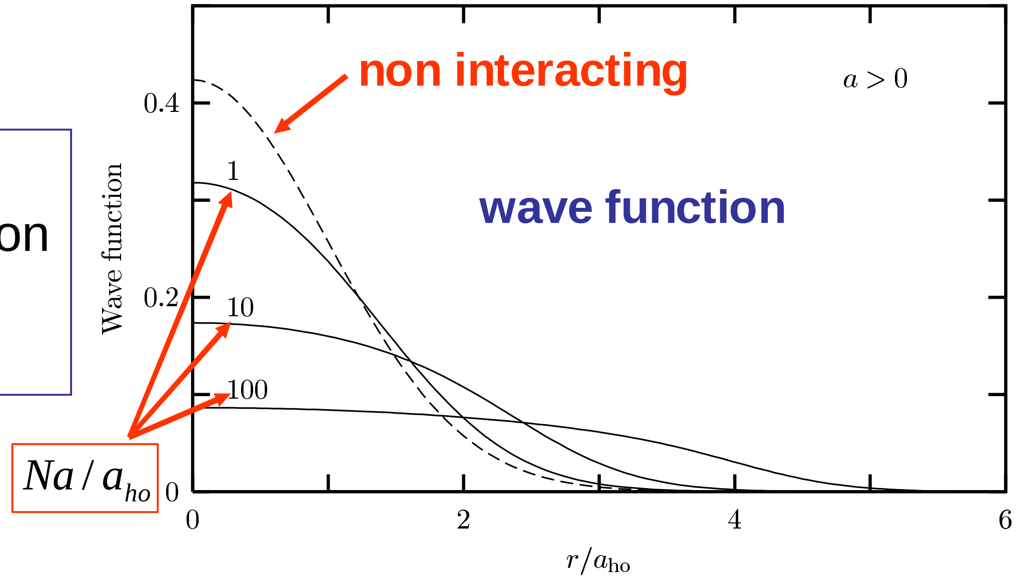
Bosons

Some conclusions concerning equilibrium profiles

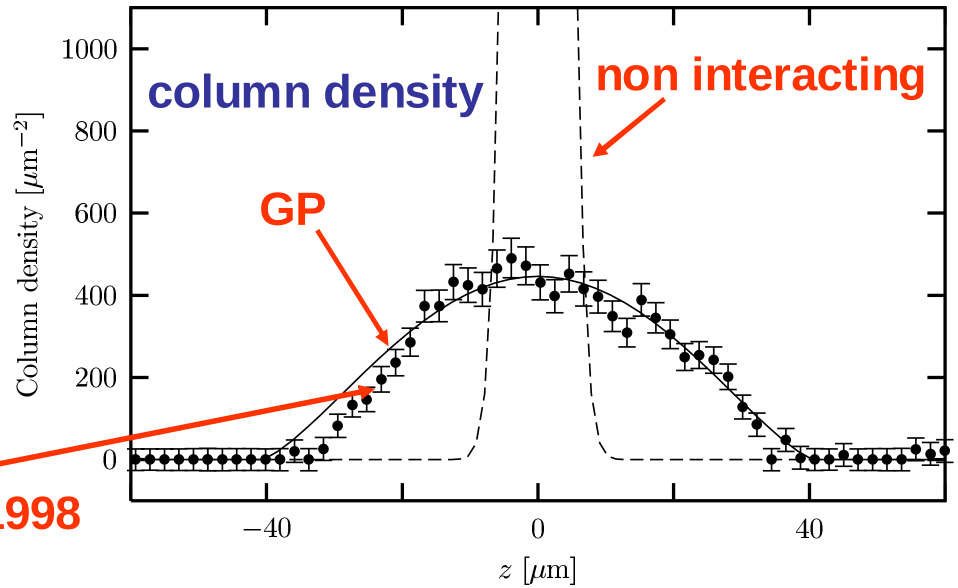
a >0

STRINGARI

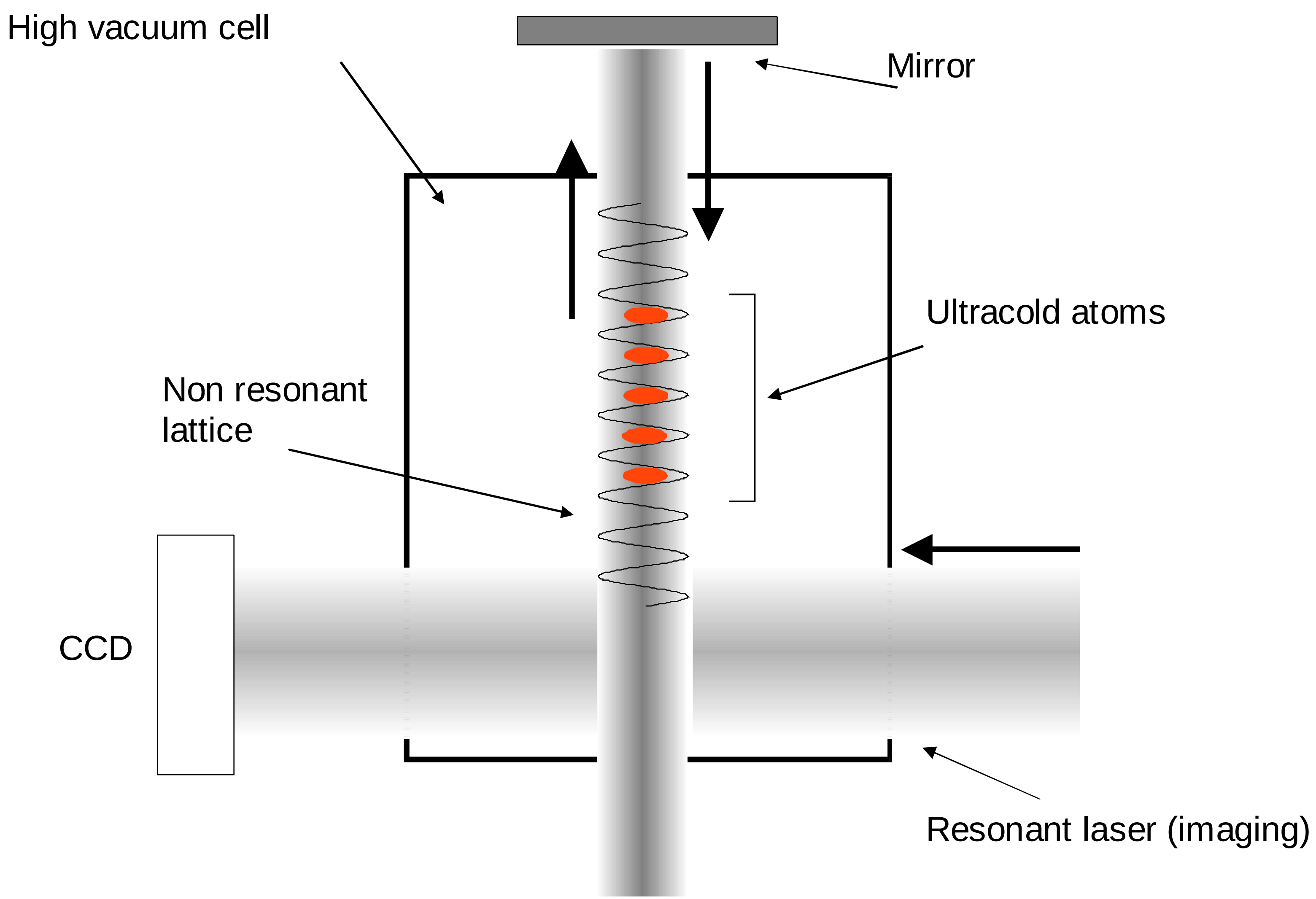
Thomas-Fermi parameter Na/a_{ho} drives the transition **from non interacting** to **Thomas-Fermi** limit



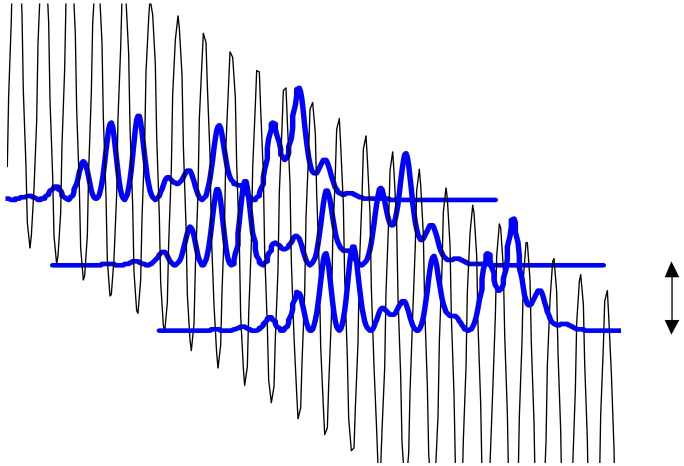
Huge effects due to **interaction** at equilibrium; **good agreement** with **experiments**



Interferometry with optical lattices



Localized Wannier-Stark states



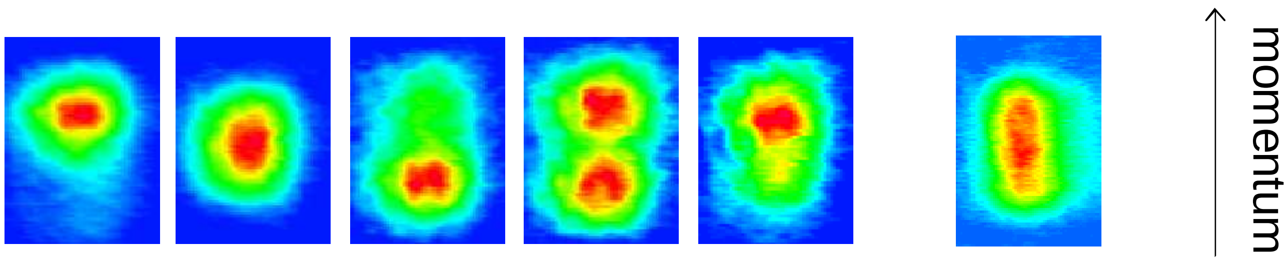
$$\Delta E = \frac{F\lambda}{2}$$

Interference of WS states:
Bloch oscillations

$$\omega_B = F\lambda / 2\hbar$$

The interaction energy reduces the contrast of the interferogram, and causes decoherence

Int. BEC

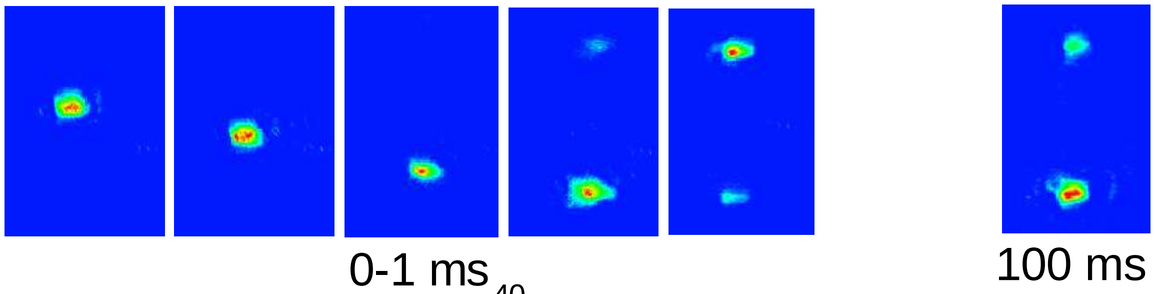


0-1 ms

10 ms

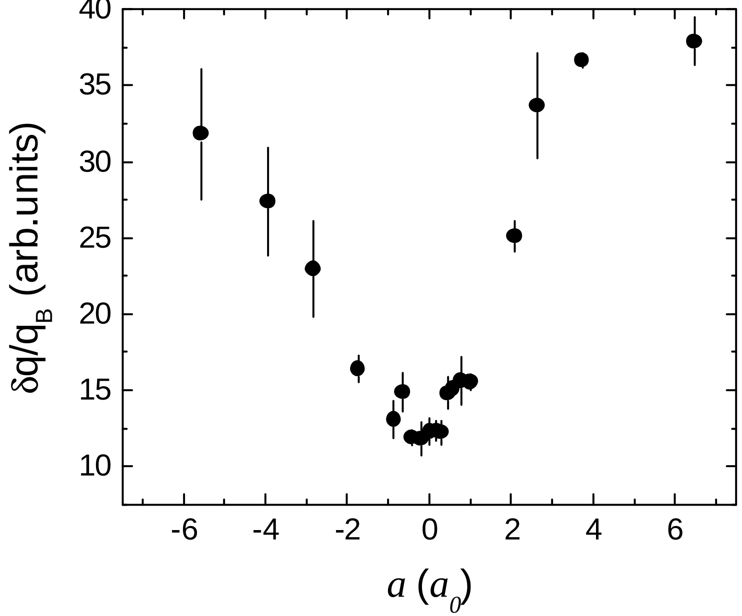
M.Fattori, C.D'Errico, M.Jona-Lasinio, M.Modugno,G.Roati, M.Zaccanti, G.Modugno, M.Inguscio

non int.
BEC

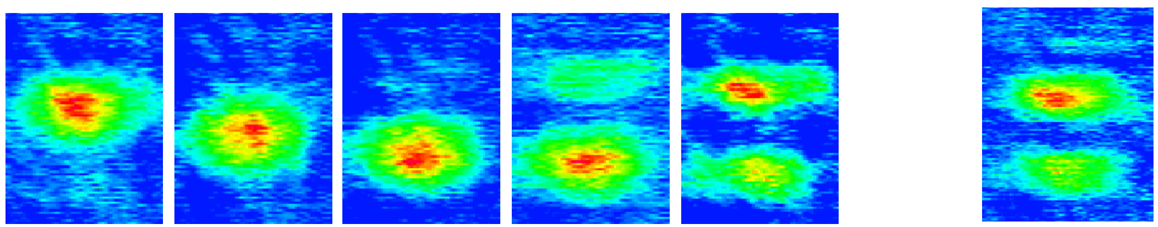


Possibility to investigate the effect of interactions down to zero

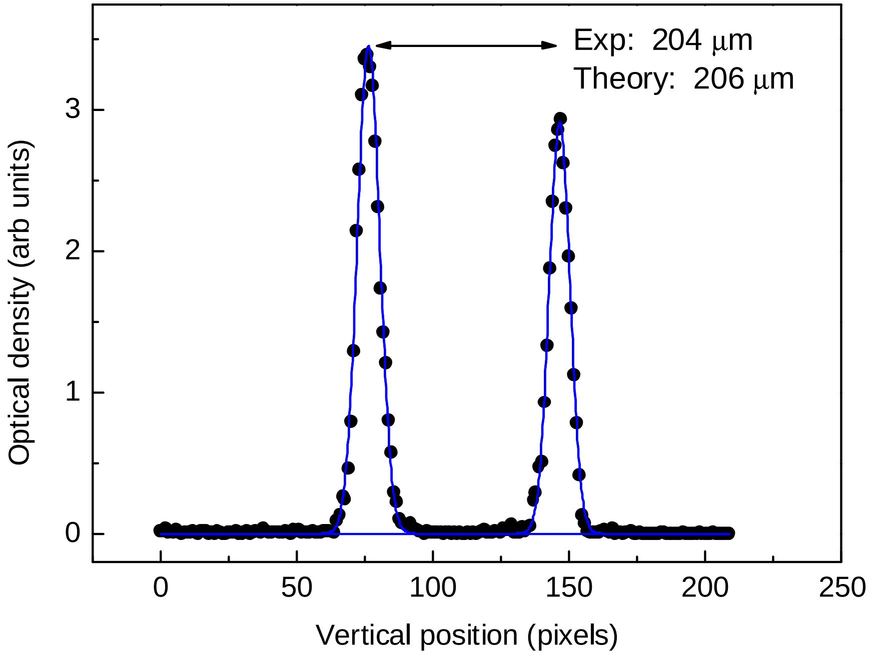
Complementary to **Interferometry** by squeezing of atom numbers:
Jo et al. Phys.Rev.Lett. 98, 03047 (2007)
Li et al. Phys.Rev.Lett. 98, 040402 (2007)



non int.
Fermi gas



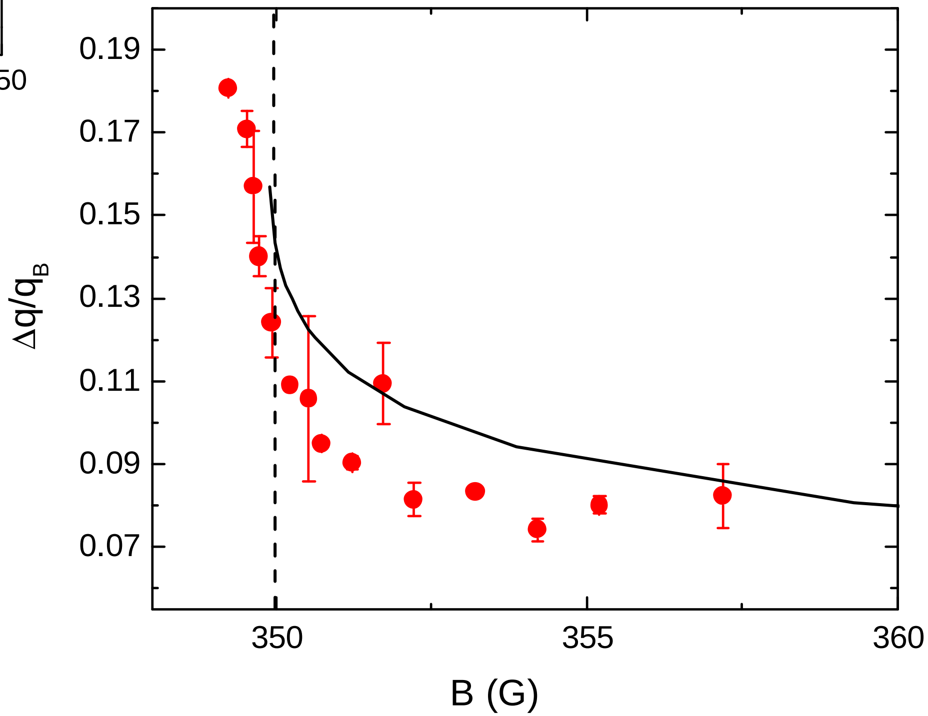
Spatial resolution



The spatial extent can be extracted from the momentum distribution

Tuning *a* :

the size can be adjusted by down to 4 μm.



^{39}K BEC

is promising for future experiments with weakly interacting
Bose gases, Anderson localization, Bloch oscillations and precision atomic interferometry…
attractive condensates in optical lattices …

Also Cs, ^{7}Li

The coldest side of Florence

http://quantumgases.lens.unifi.it