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Workshop on
Noise and Instabilities in Quantum Mechanics

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Ultracold atoms in periodic potentials

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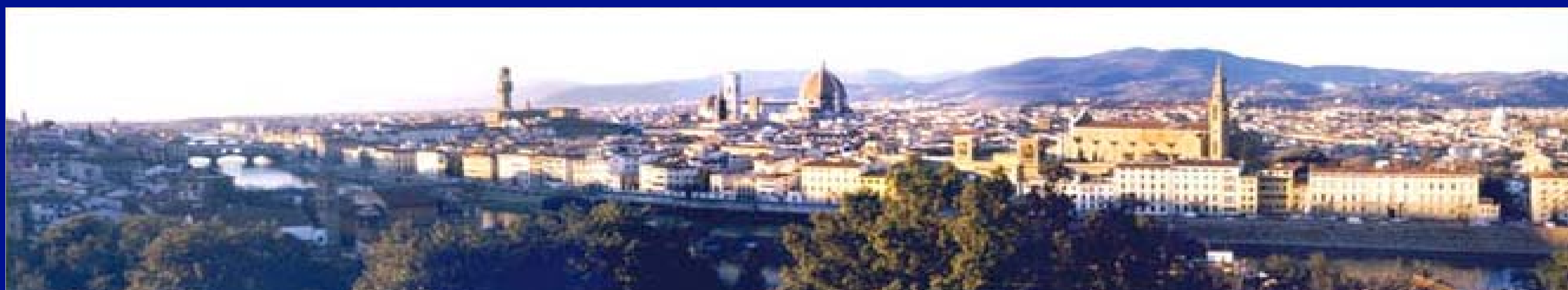


Introduction

MOTIVATIONS:

- Correlated Bosons and Fermions in optical potentials: potentially powerful model systems to study condensed-matter problems
- Quantum sensors
- Disorder
- Entanglement and decoherence

STRATEGY:

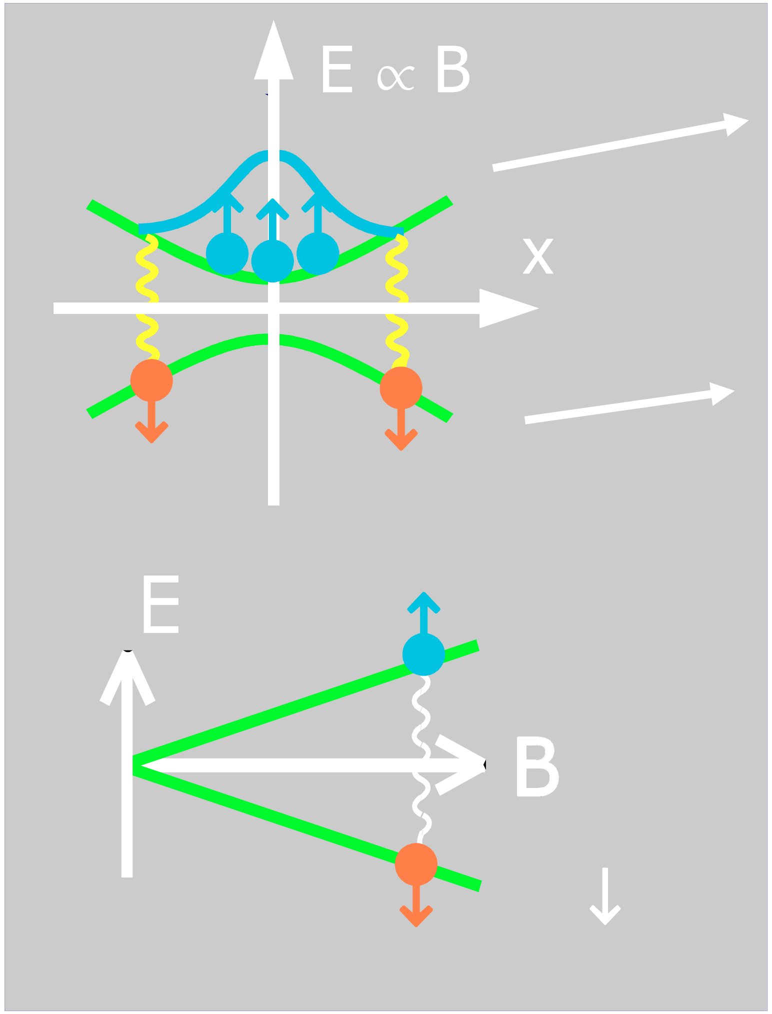
– study the dynamics and transport properties of atoms in several combined potentials

– adjust the interatomic interactions

Outline

- Trapping of ultracold atoms: the toolbox
- Transport of Bosons and Fermions in a corrugated harmonic potential: instabilities, conductors vs insulators...
- Fermions (and Bosons) in a corrugated linear potential: Bloch oscillations for interferometry
- Bosons in a random potential
- Control of the interactions: Fano-Feshbach resonances

Basic tools: MAGNETIC + optical potential



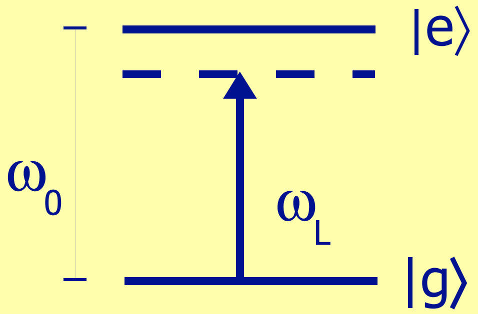
Trapping potential

Repulsive potential

Transitions at given RF and B values

Basic tools: magnetic + OPTICAL potential

Dipole Force

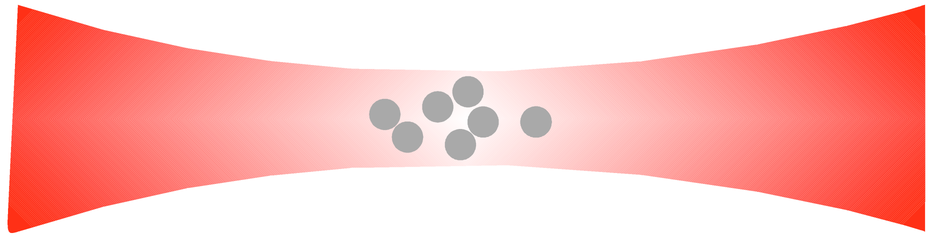


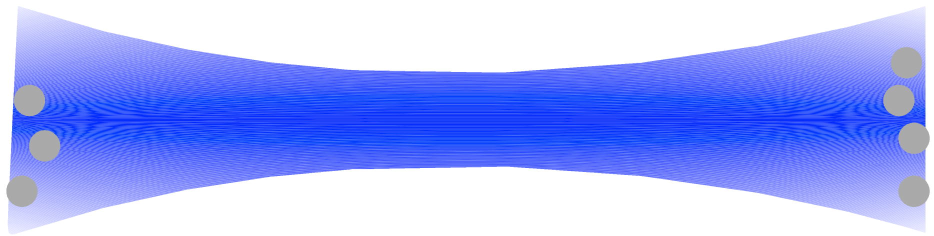
$$\Delta = \omega_L - \omega_0$$

$$U \sim (I_L / \Delta)$$

- propto intensity,
- inversely propto detuning

RED detuning, i. e. laser frequency below resonance
$\longrightarrow$ atoms seek HIGH intensity



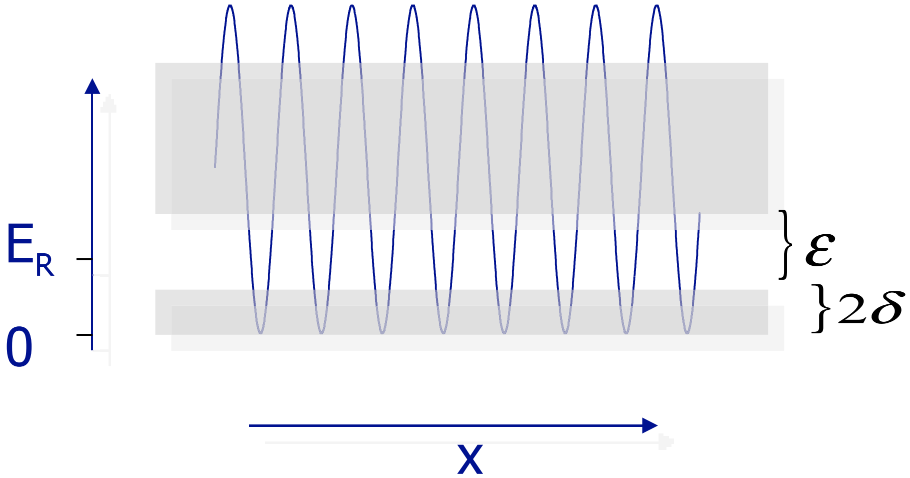


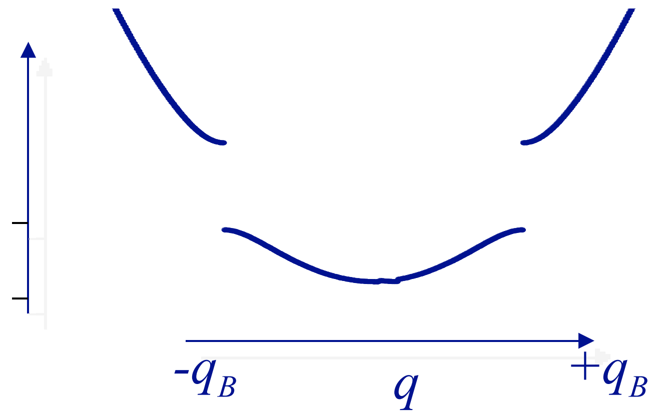
BLUE detuning, i. e. laser frequency above resonance
$\longrightarrow$ atoms seek LOW intensity

Basic tools: optical lattice = dipole force + standing wave

$$U(x) = s\frac{E_R}{2}(1+\cos(4\pi \; x/\lambda))$$

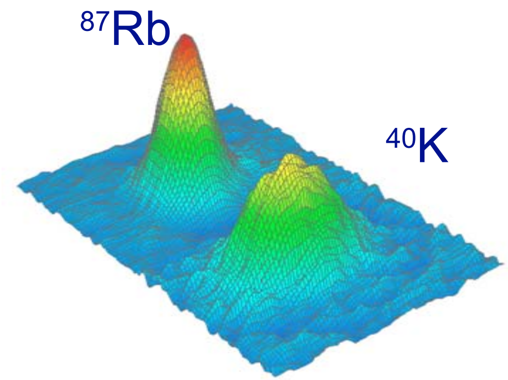
$$E_R = \frac{q_B^2}{2m} \qquad q_B = \frac{h}{\lambda}$$





Typical experimental parameters: $E_R \sim 0.2\ \mu K$, $\lambda \sim 800$ nm

Our atomic systems



G. Modugno et al., *Science* **294**, 1320 (2001)

- single species Bose gas
- Bose – Bose mixture (Rb + K)
- Fermi – Bose mixture (Rb + K)
- non interacting Fermi gas (K)

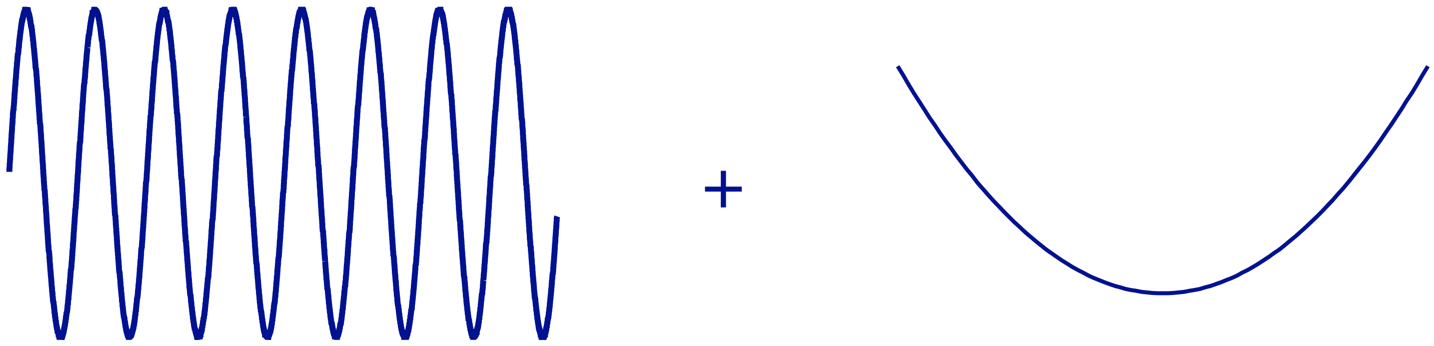
One last ingredient: interatomic interactions

Low temperature: for many purposes, interatomic interactions described by contact potential, depending on a single parameter, the s-wave scattering length a_s

Bosons: weak interactions ($n\ a_s$) << 1, but non-negligible

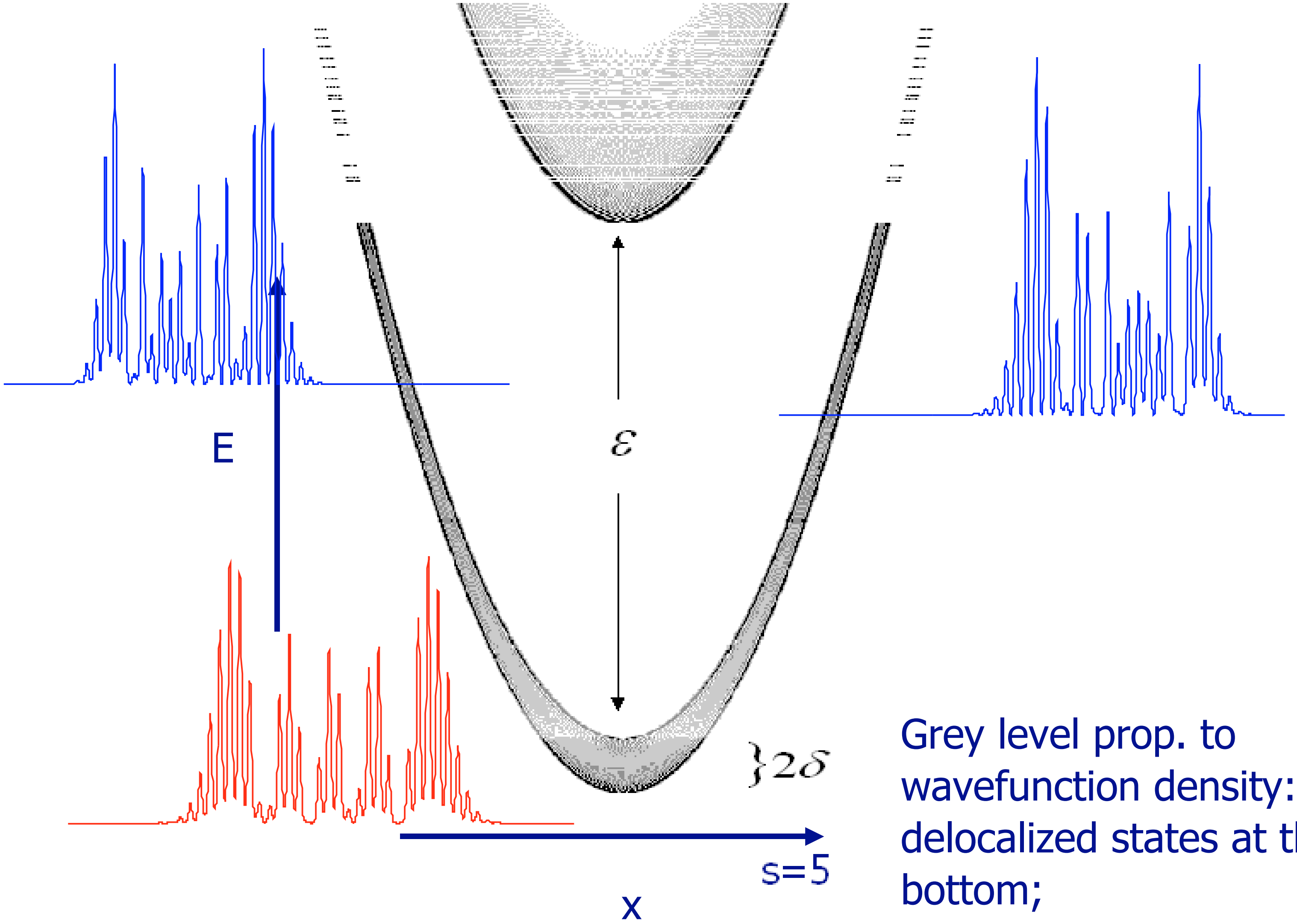
Fermions: non-interacting particles, s-wave scattering suppressed by symmetry,
(unless in different spin states)

1D dynamics: harmonic + periodic potential



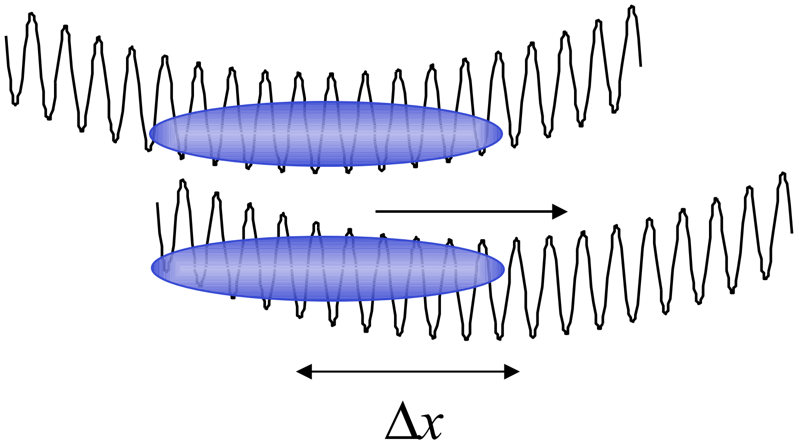
Approximation: neglect the motion in remaining directions,
(better fulfilled for high confinements freezing the degrees of freedom)

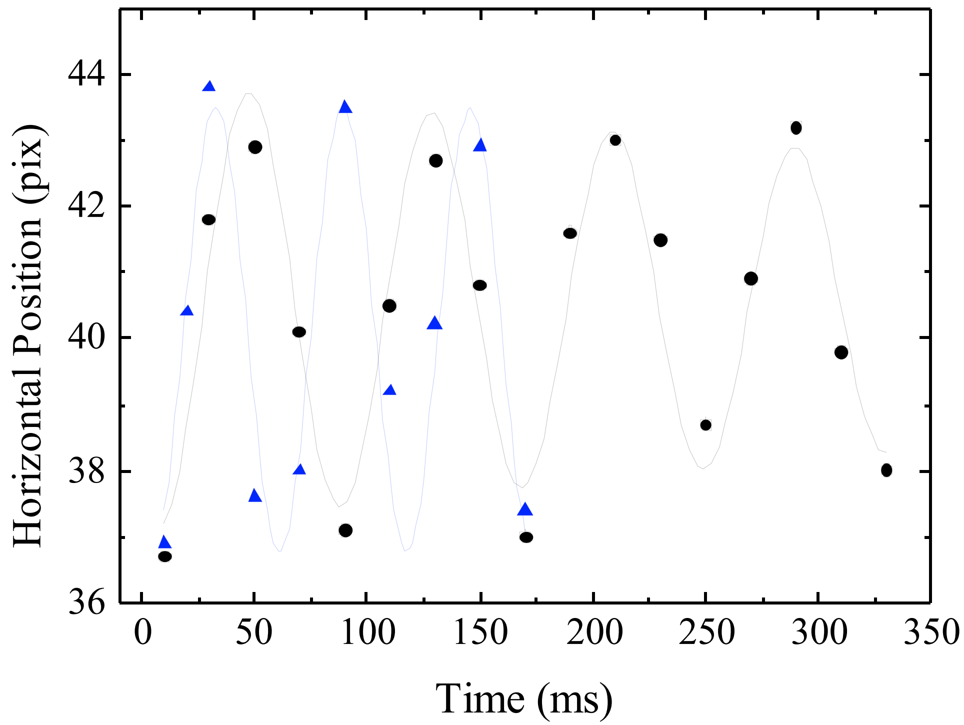
Single-particle energy spectrum in combined potential



Grey level prop. to wavefunction density:
delocalized states at the bottom;
localized states on the slopes

Bosons: “dipolar” oscillations





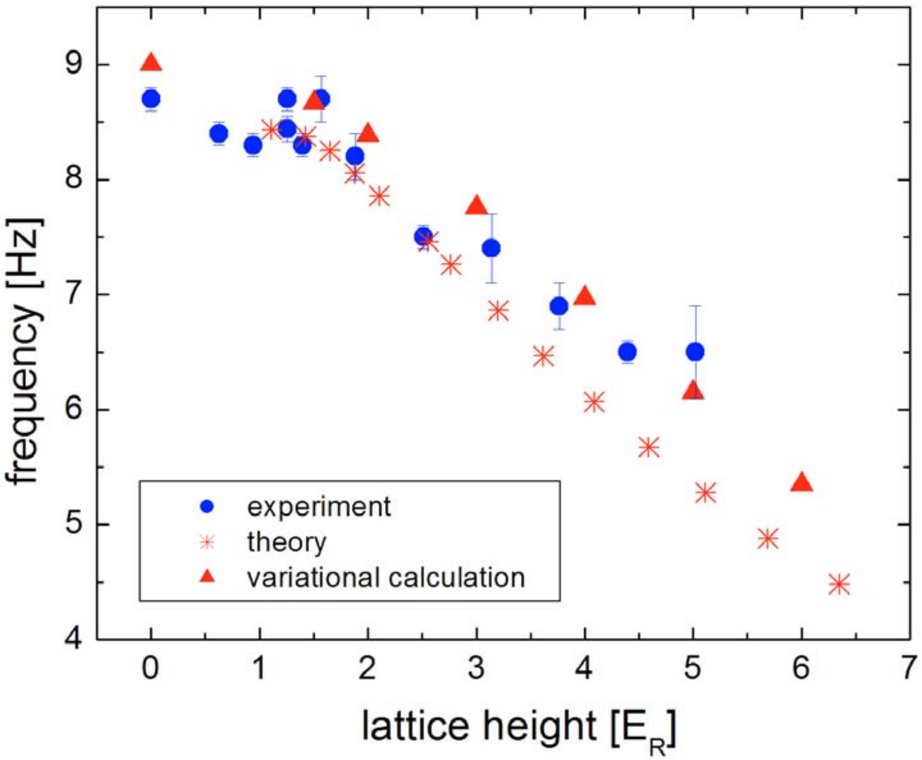
Dipolar oscillations excited with a sudden displacement of the magnetic potential

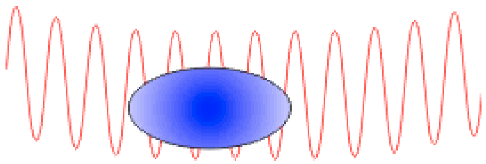
$\Delta x = 10 \div 20\ \mu m$

In presence of periodic potential the oscillation frequency decreases

Bosons: array of Josephson junctions

Frequency of the dipolar oscillation of a Bose condensate in combined potential





The oscillation frequency ω* is rescaled with an effective mass

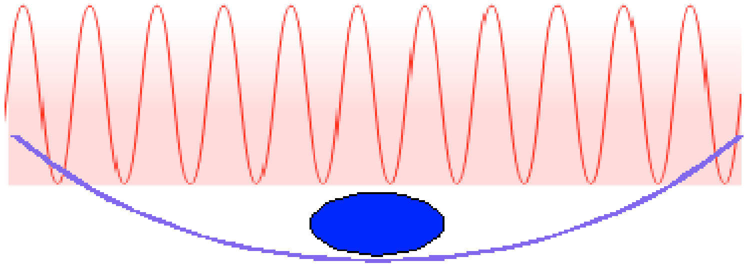
$$\omega^* = \sqrt{\frac{m}{m^*}}\,\omega$$

dependent on the tunneling rate K:

$$m^* = \frac{2h^2}{\lambda^2 K}\,m$$

F. S. Cataliotti et al., Josephson junctions arrays with BECs, *Science*, **293**, 843 (2001)

Bosons: modulation instability

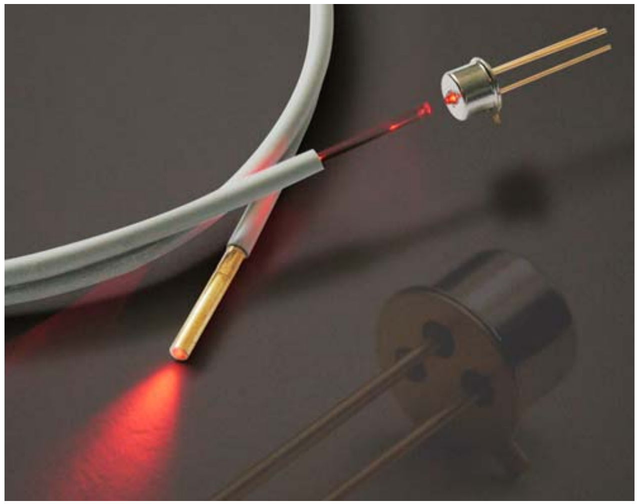


Nonlinear Schroedinger equation; complex frequencies in the eigenspectrum of the excitations ⟶

Dynamical instability above a *critical velocity*

Non-linearity for EM waves in dielectric media: optical Kerr effect

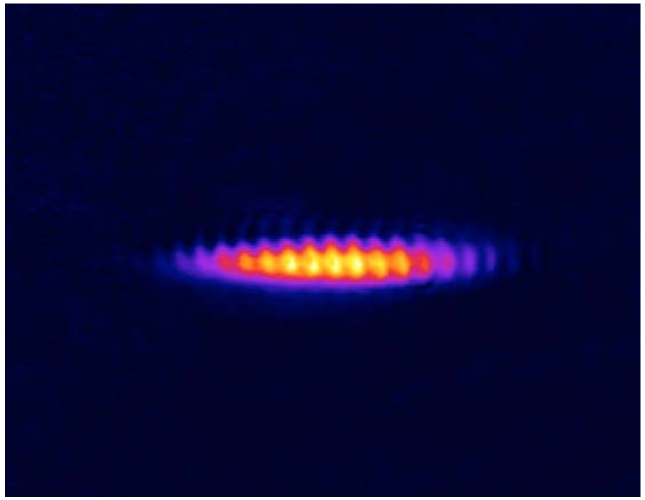
$$i\frac{\partial E}{\partial z} = -\frac{k''}{2}\frac{\partial^2 E}{\partial \tau^2} + \frac{\omega n_2}{2c}|E|^2 E$$



K. Tai *et al.*, Phys. Rev. Lett. **56**, 135 (1986)

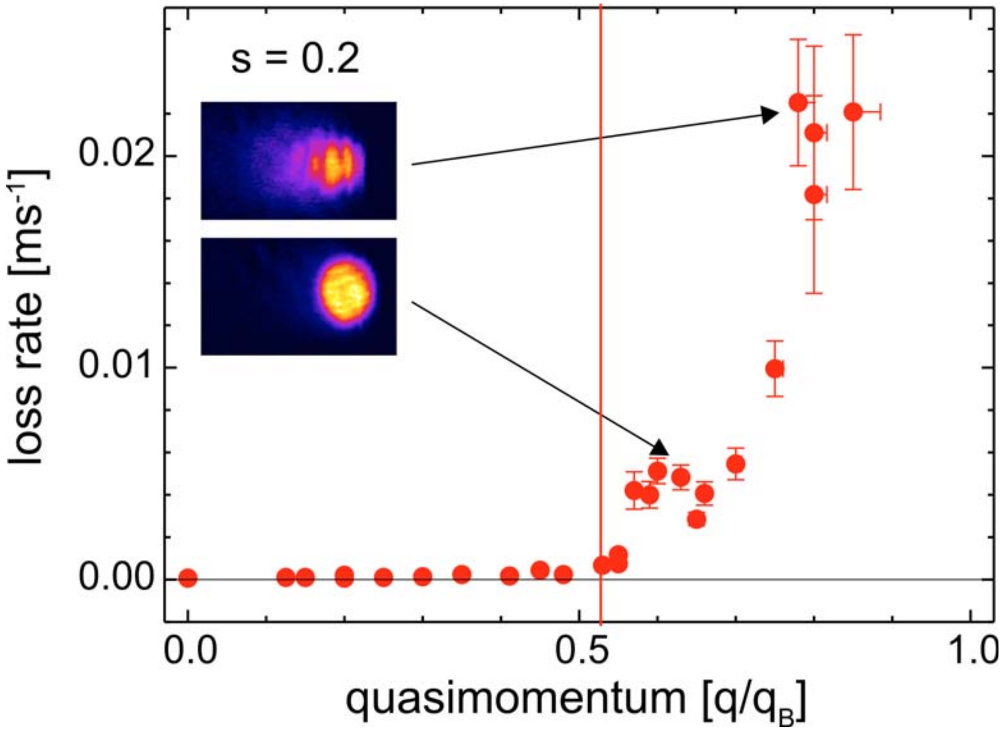
Non-linearity for matter waves: atom-atom interaction

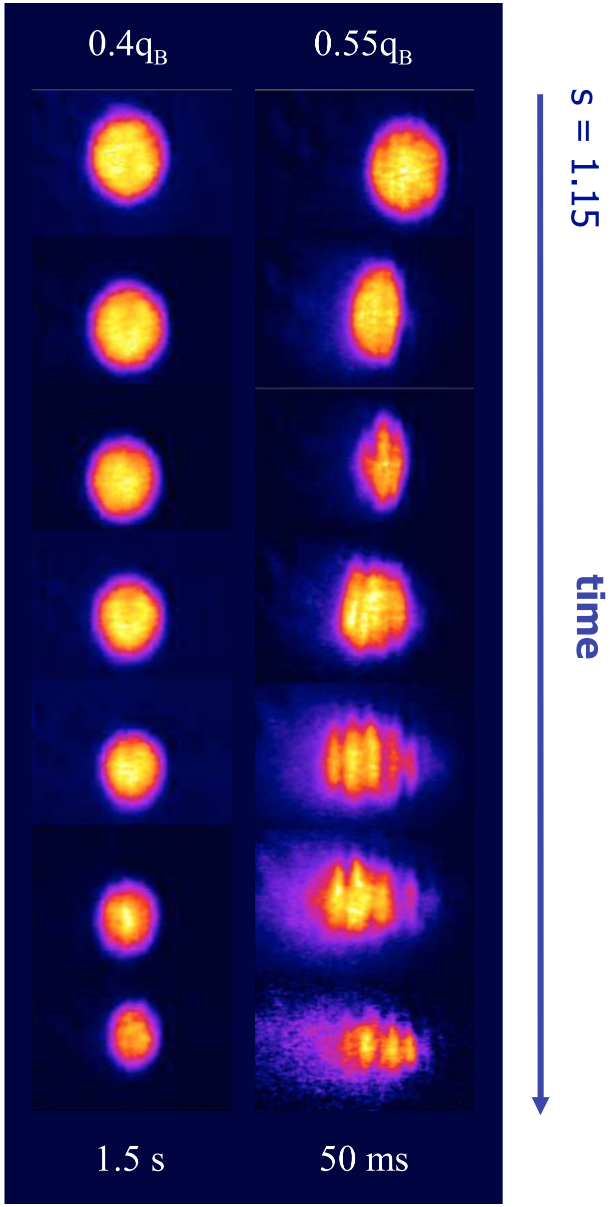
$$i\hbar\frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2 \psi}{\partial z^2} + g|\psi|^2 \psi$$



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

Bosons: modulation instability (2)

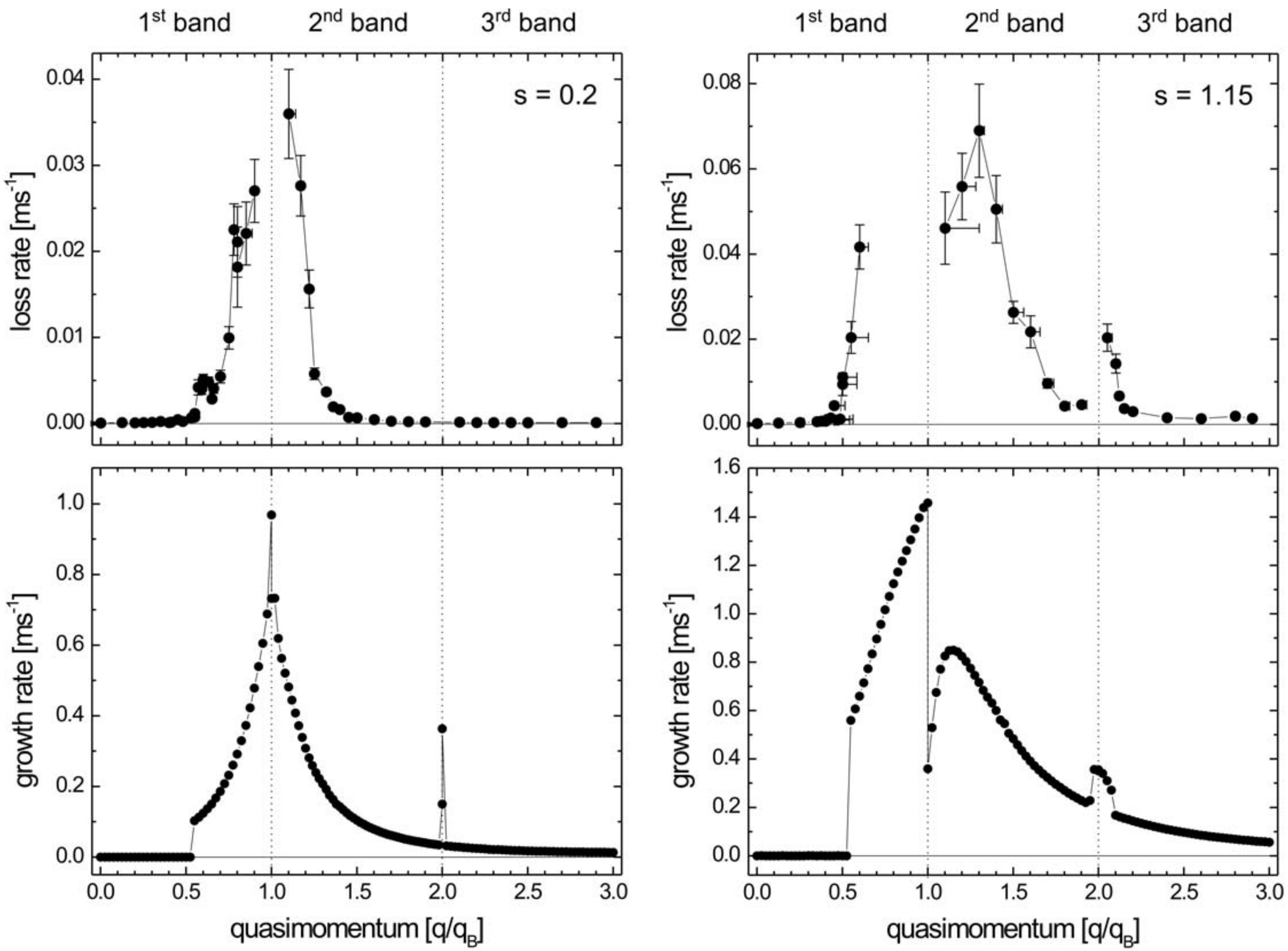




Measure the loss of atoms as a function of the relative velocity of the lattice w/ respect to the atoms

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

Bosons: modulation instability (2)



Experiment

atom loss rate from the BEC

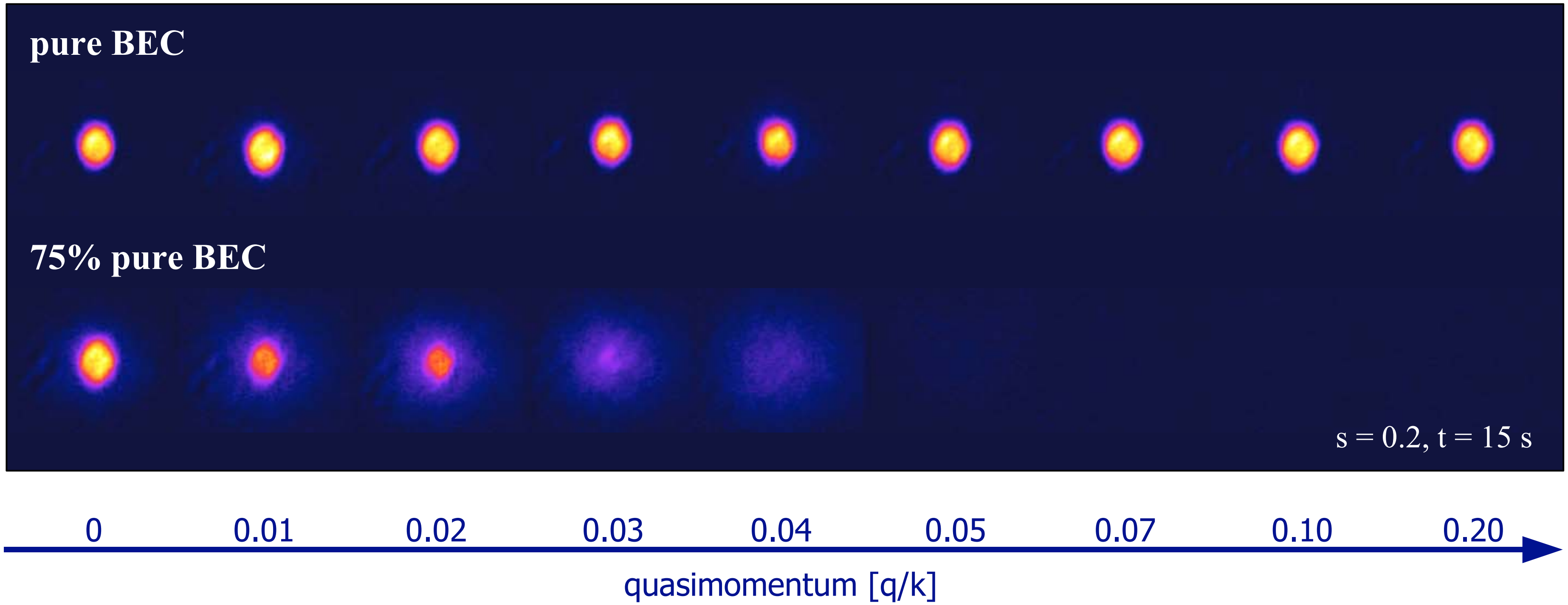
↕

Theory

growth rates of the most dynamically unstable modes

Bosons: Landau energetic instability

Even small *thermal fraction* ⟶ BEC lifetime much shorter

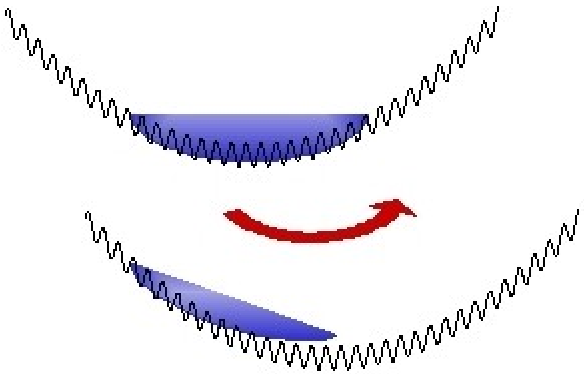


Onset of *Landau energetic instability* (inhomogeneous system), occurring in the presence of dissipative processes, as those provided by the thermal fraction.

L. De Sarlo et al., PRA **72** 013603 (2005)

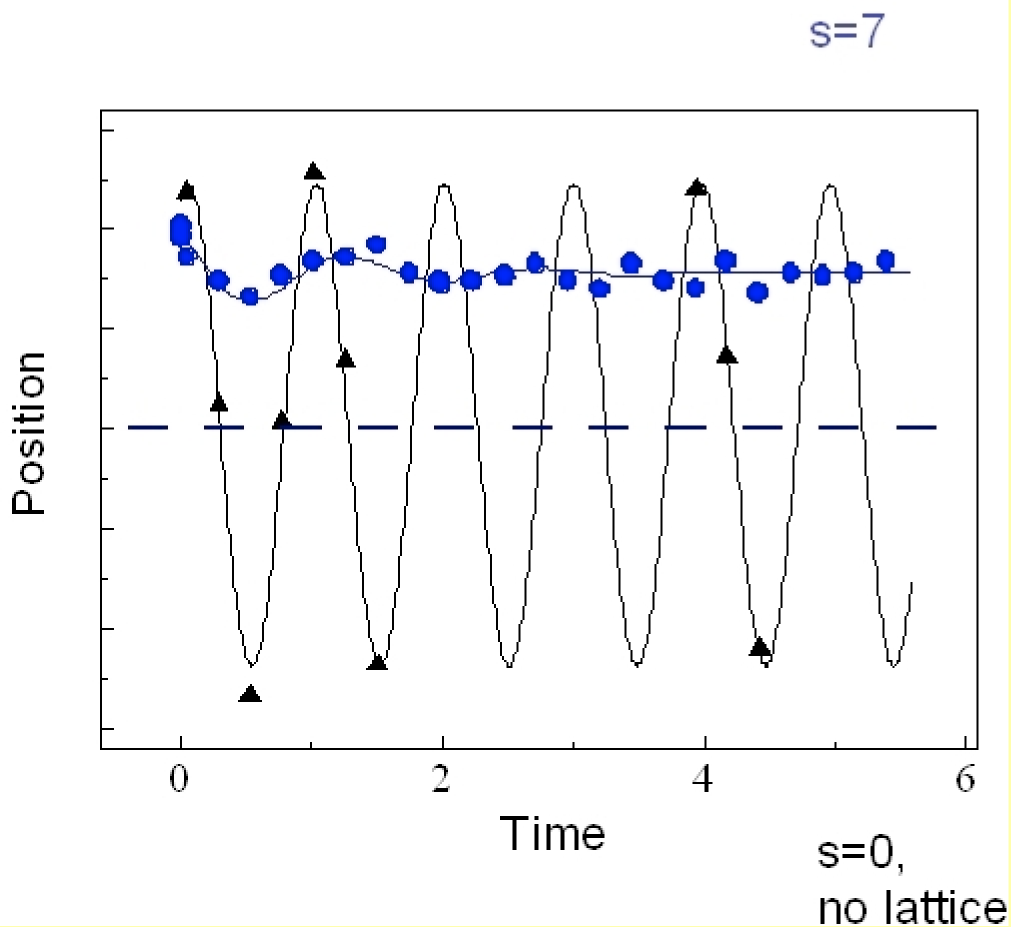
Fermions: dipolar oscillations

Collective “dipole” oscillations



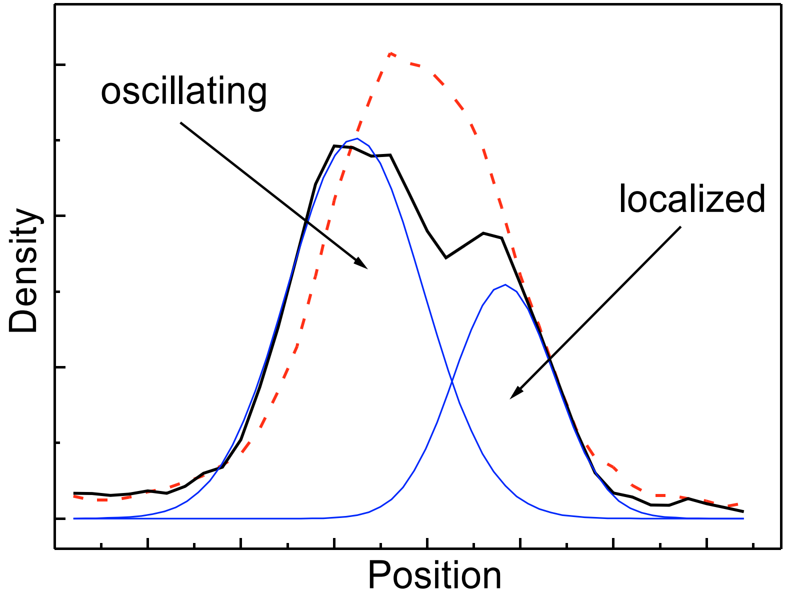
excitation:
sudden displacement of the harmonic magnetic “bowl”

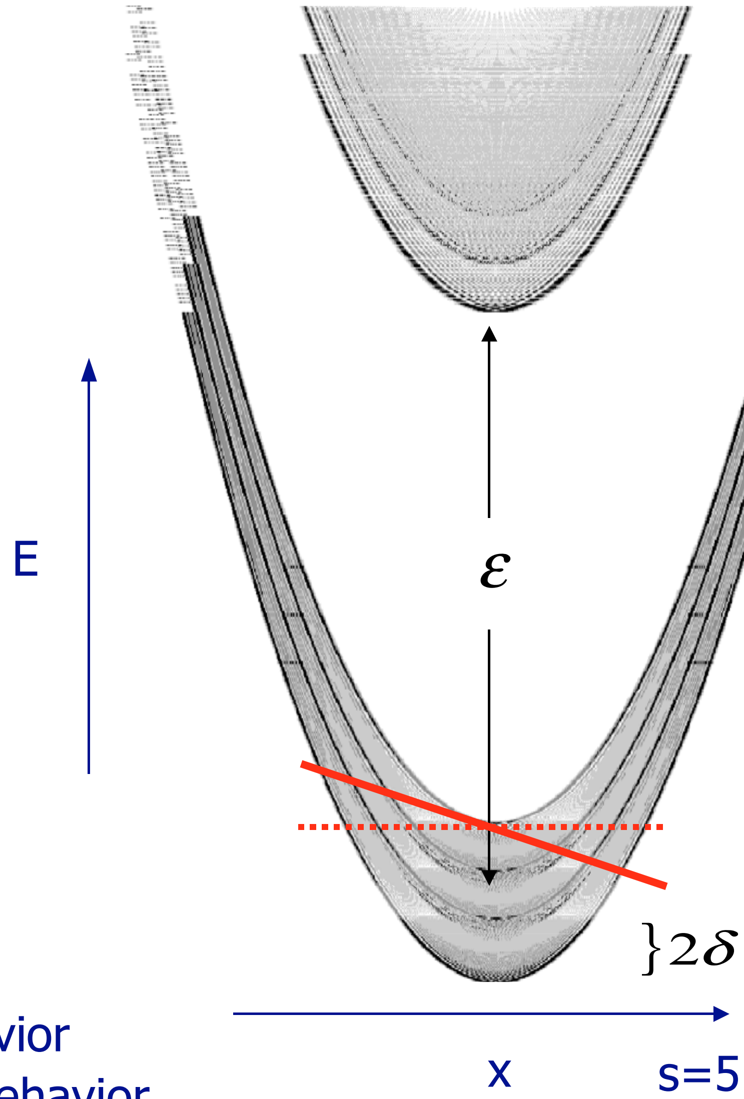
s = lattice depth (units of recoil energy)



Fermions remain trapped on the side of the harmonic potential

Fermions: conduction and insulation



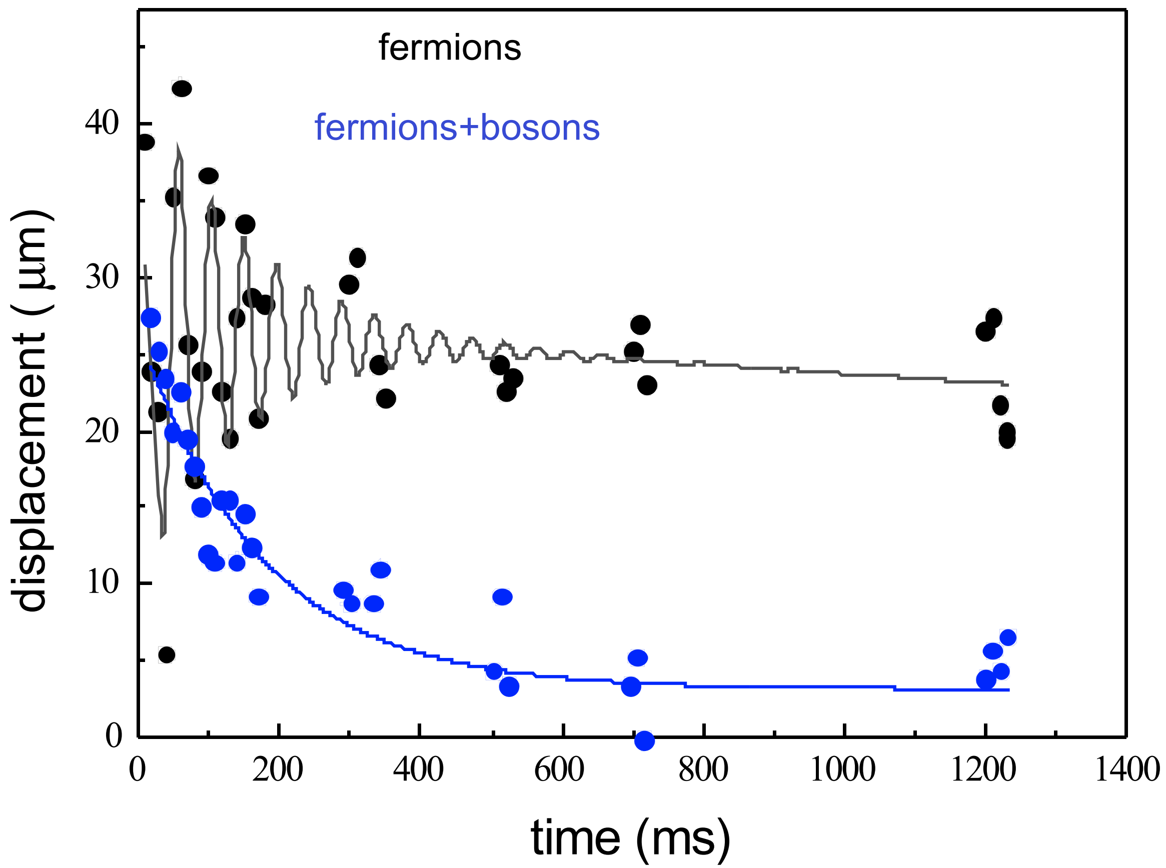


Two-components gas

fraction in *localized* states: *insulating* behavior

fraction in *delocalized* states: *conducting* behavior

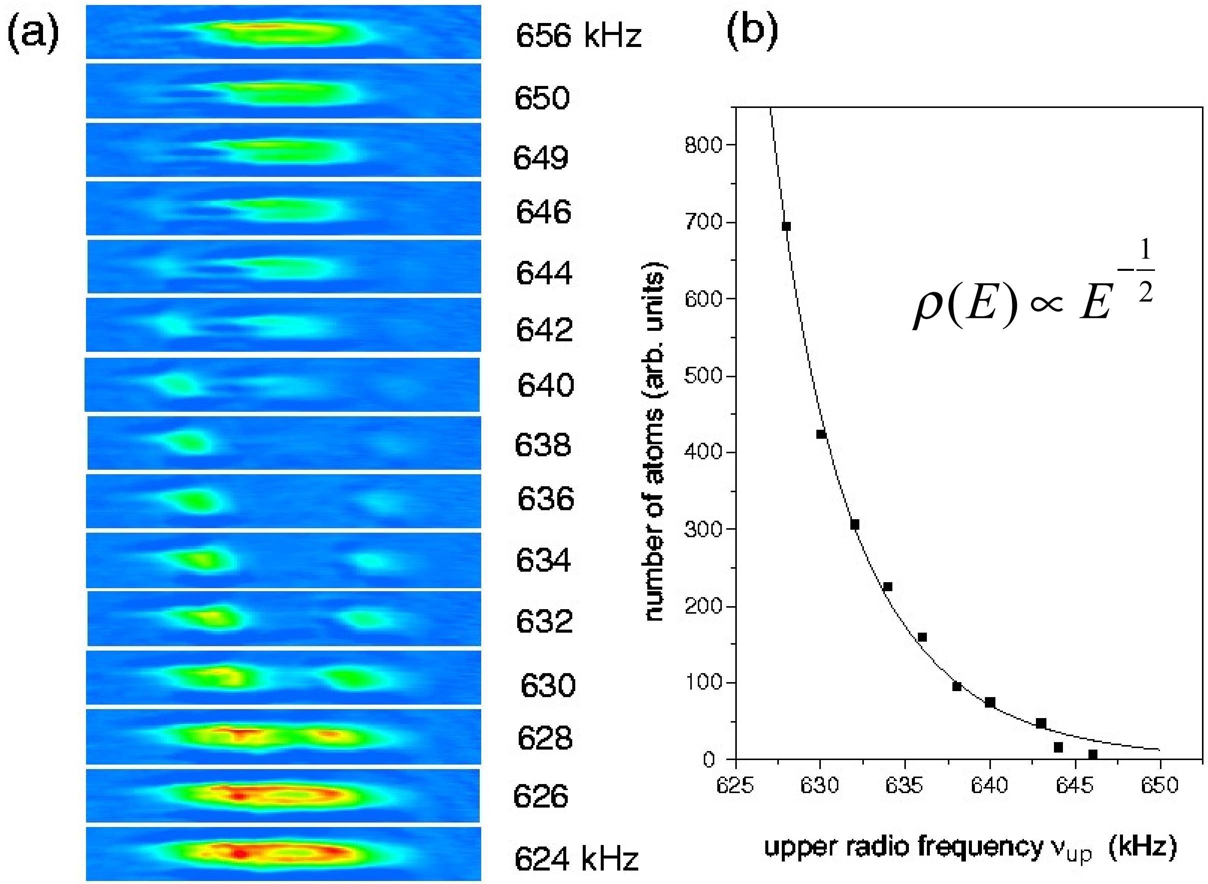
Fermions: conduction induced by collisions



Collisions lead to a decay of localized states: *scattering* is needed to estabilish a current

H. Ott et al., Phys. Rev. Lett. **92**, 160601 (2004)

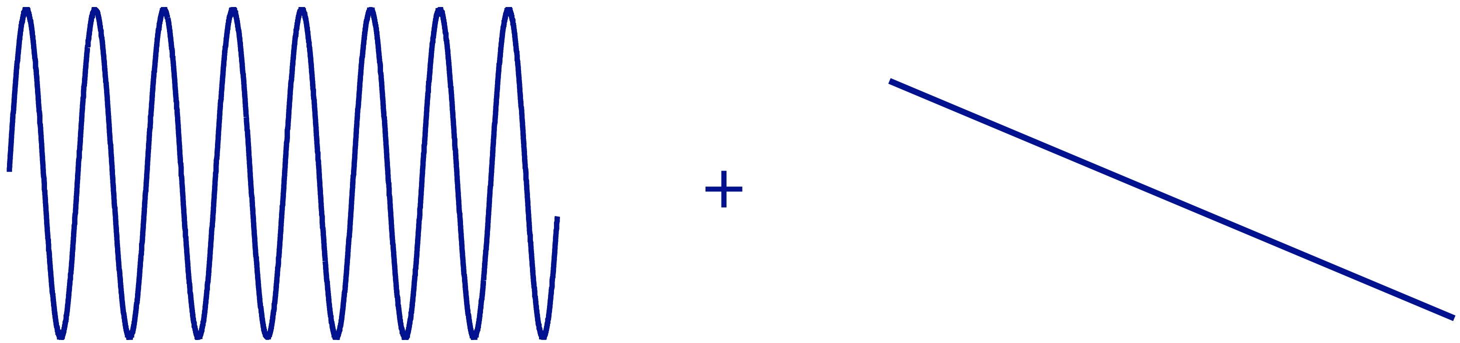
RF spectroscopy of localized states



Tighter lattices and larger magnetic field gradients:
towards addressing of particles localized in individual lattice sites

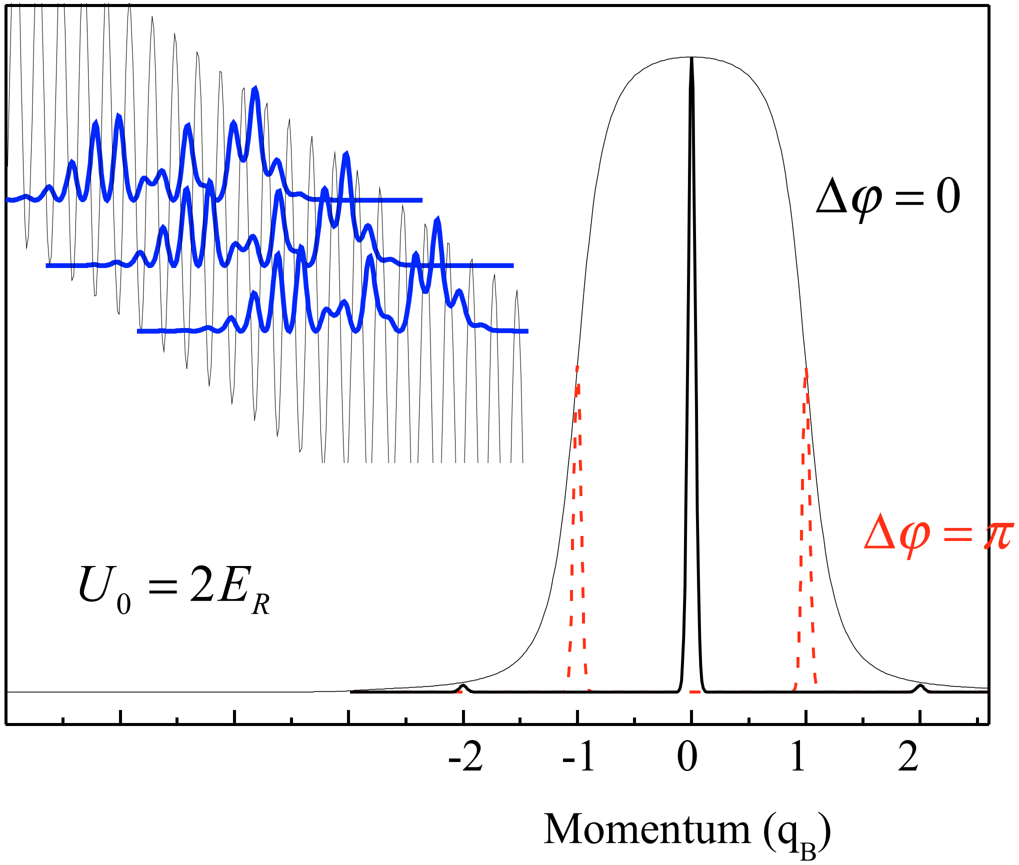
H. Ott et al., Phys. Rev. Lett. **93**, 120407 (2004).

1 D dynamics: periodic + linear potential



Simplest realization: vertical optical lattice + gravity,
alternatively optical lattice + magnetic field gradient

Single-particle spectrum: Wannier-Stark states

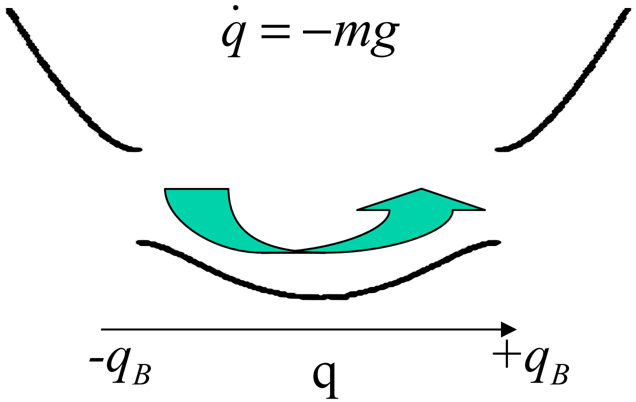


Localized Wannier-Stark states in a tilted lattice:

$$\Delta x = 2\delta / F \qquad \Delta E = \frac{mg\lambda}{2}$$

Their *interference* oscillates at:

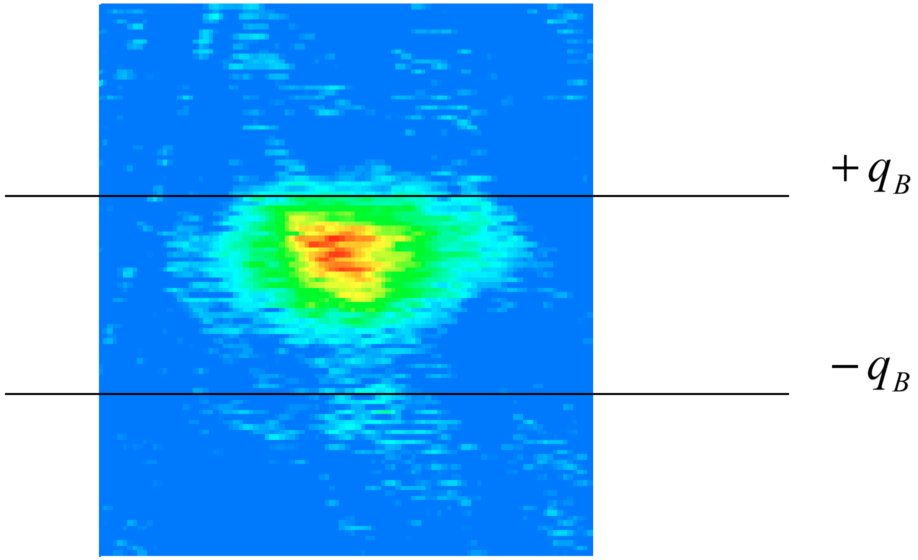
$$\omega_B = mg\lambda/2\hbar$$



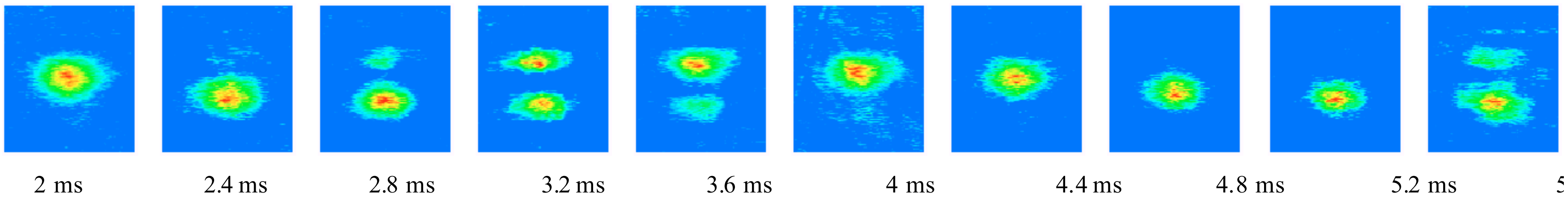
Semiclassical picture: Bloch oscillations

BenDahan et al. Phys. Rev. Lett. **76**, 4508 (1996) (ENS, Paris)
Morsch et al. Phys. Rev. Lett. **87**, 140402 (2001) (Pisa)

Dynamics in momentum space

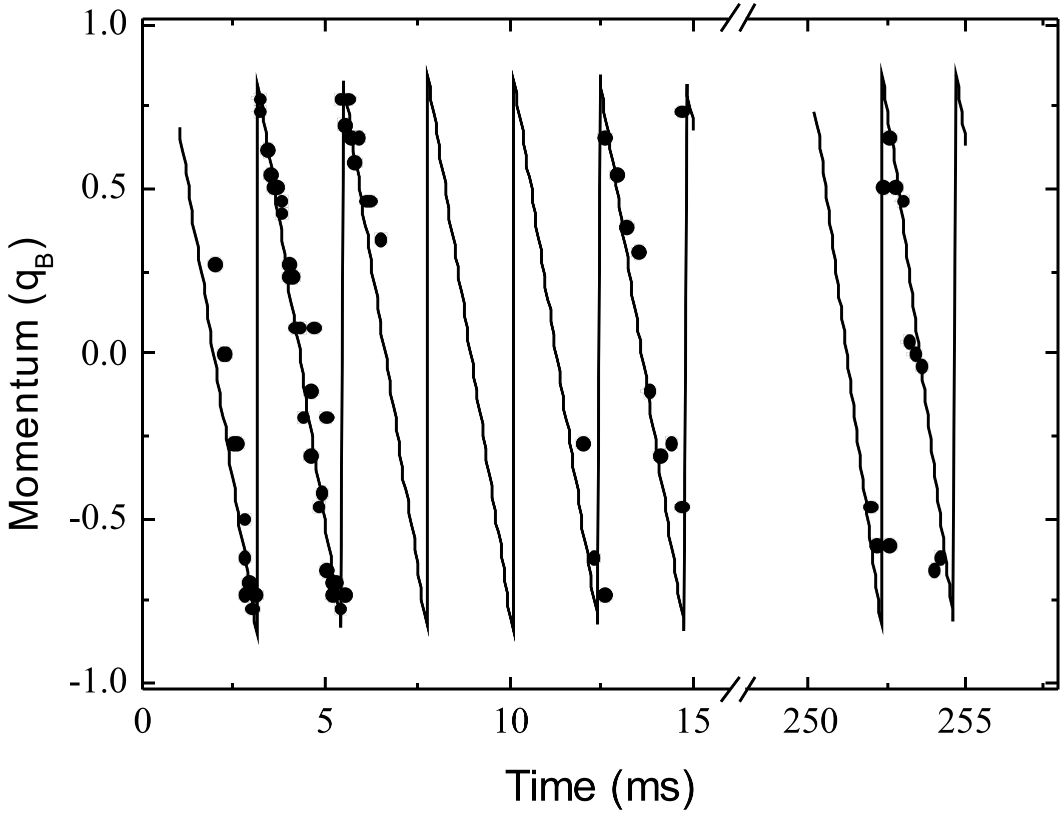


Time-resolved Bloch oscillations of trapped, non-interacting fermions



G. Roati et al., Phys. Rev. Lett. **92**, 230402 (2004).

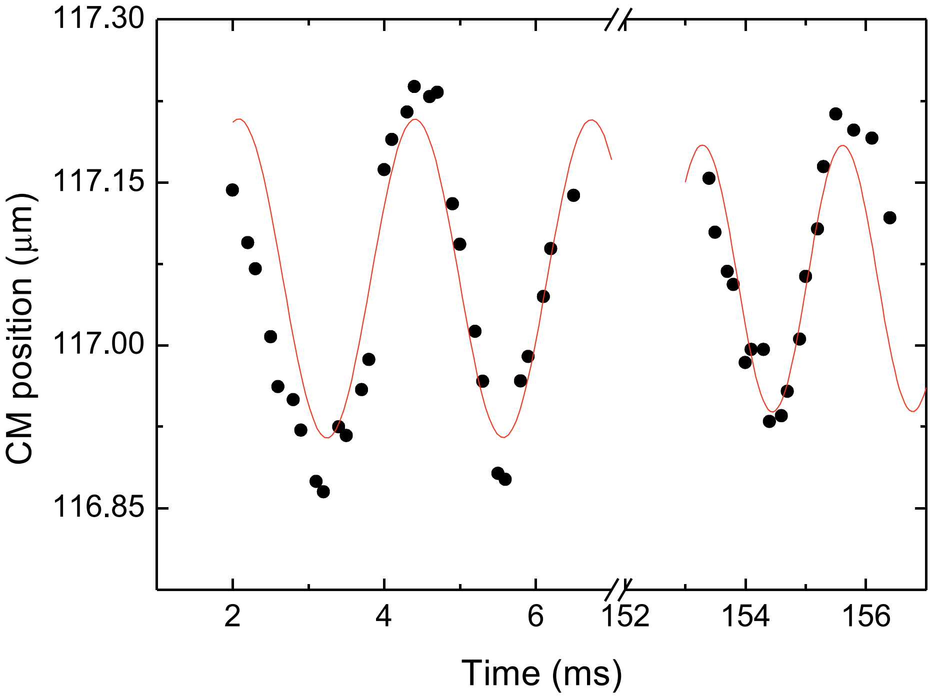
A long lived Bloch oscillator



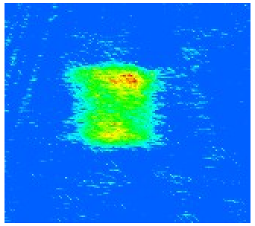
$$T_B = 2h/mg\lambda \qquad T_B = 2.32789(22)\text{ms} \Rightarrow g = 9.7372(9)\text{m/s}^2$$

Fermions trapped in lattices: a *force sensor* with *high spatial resolution*
(presently 50 um, but no fundamental limitations down to a few lattice sites)

Decoherence: FERMI vs Bose

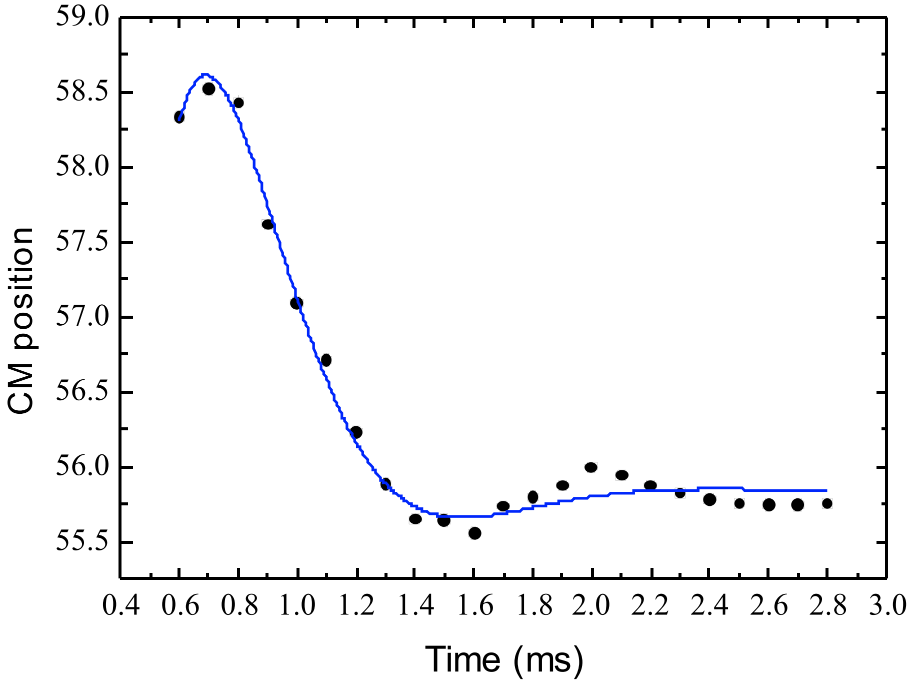


N=107

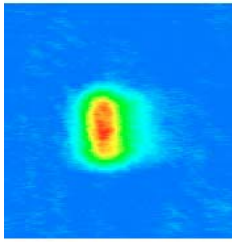


Main sources for fermions: lattice fluctuations, longitudinal curvature

Decoherence: Fermi vs BOSE

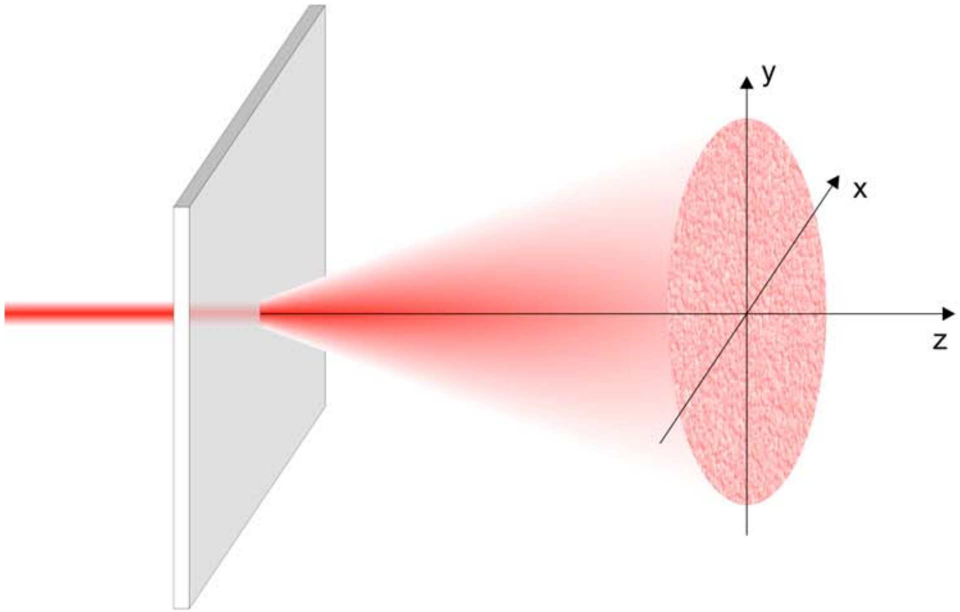


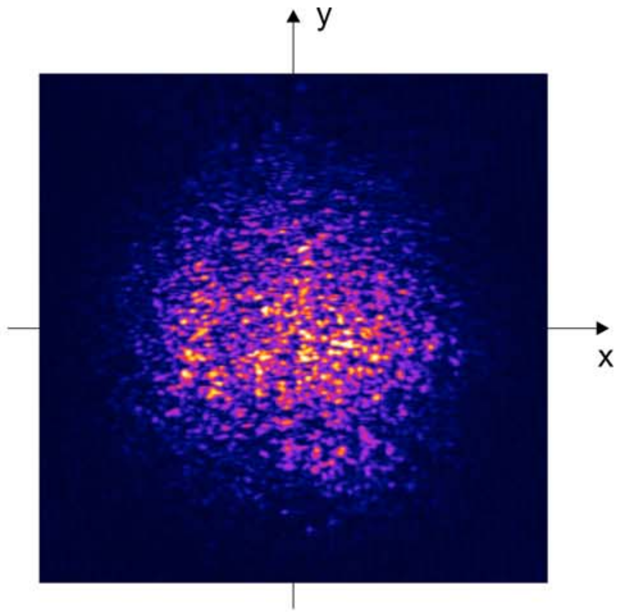
N=4



Main sources for bosons: interactions (Kasevich, 1998)
use of Fano-Feshbach resonances (?)

Experimental realization of random potential



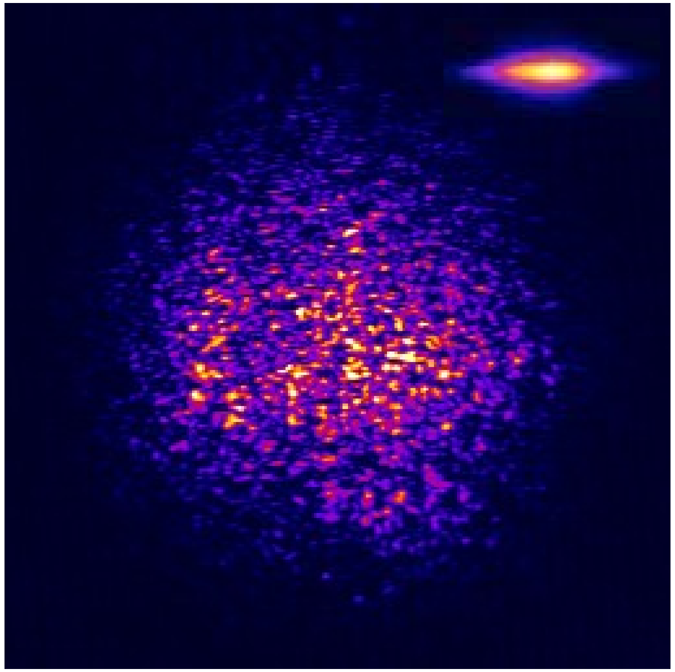


$$V(x,y)=\frac{3\pi c^2}{2\omega_0^3}\frac{\Gamma}{\Delta}I(x,y)$$

Stationary in time;
Random variations in space
(different realizations are possible)

Experimental realization of random potential

speckle pattern

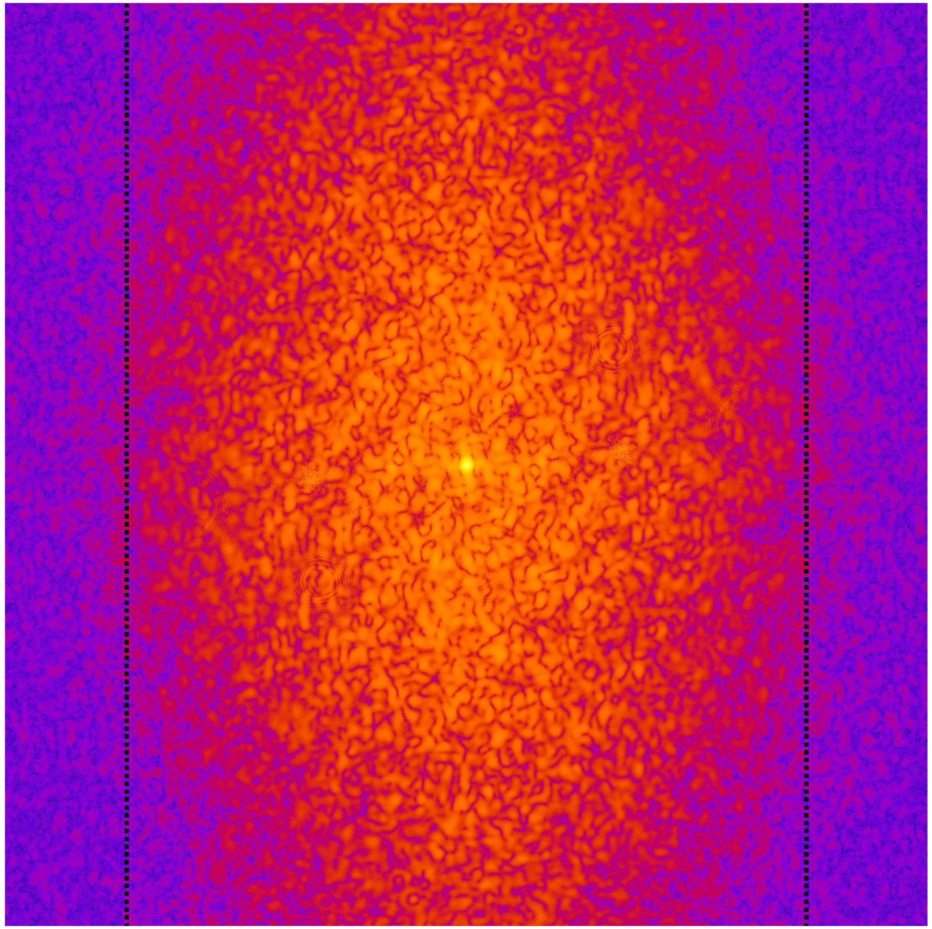


BEC

400 μm

Finite resolution of optical system: interspeckle distance along the BEC axis > 8 μm.

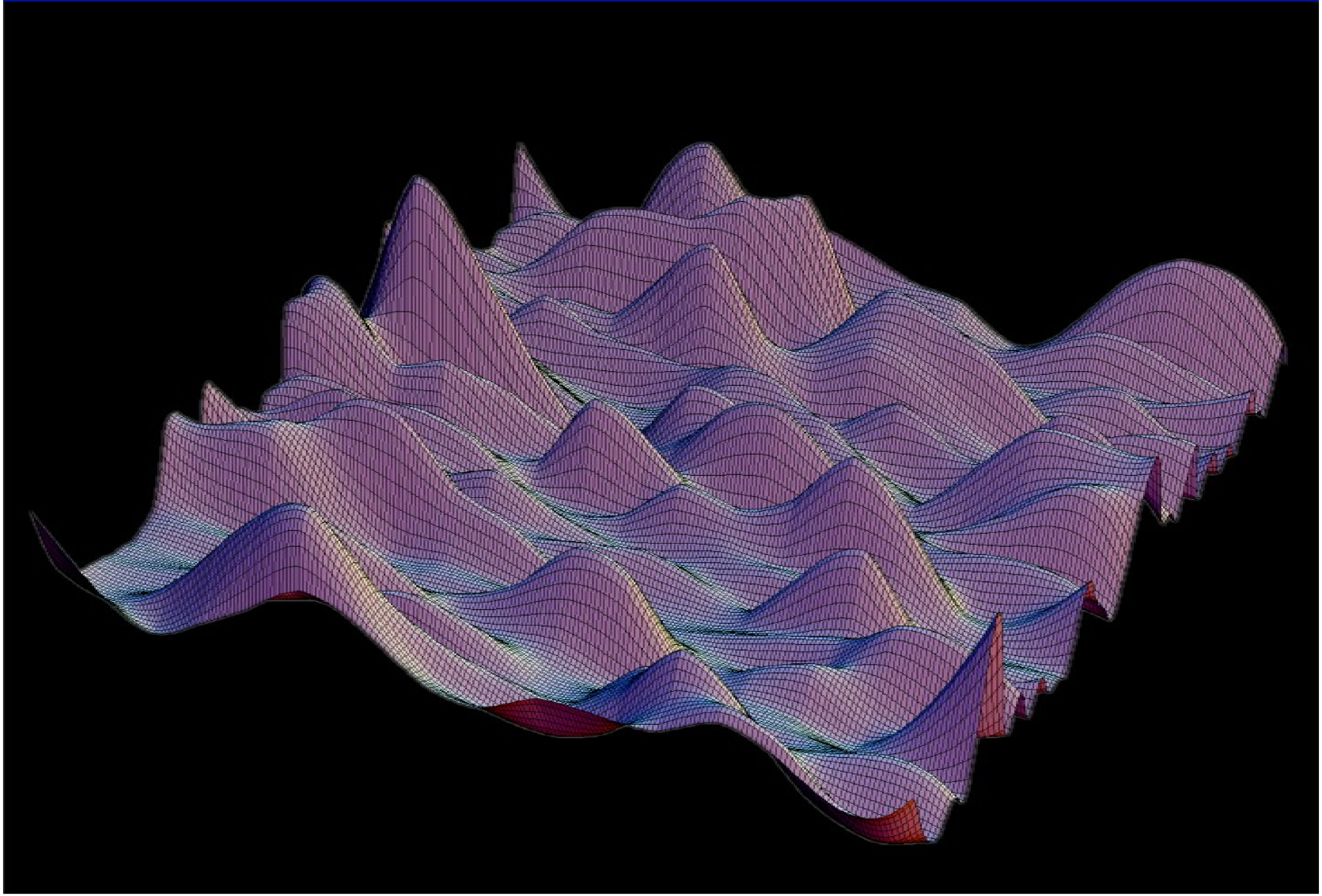
FFT speckle pattern



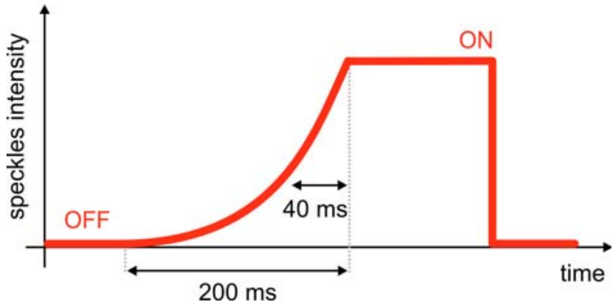
k^{-1}= - 8 μm

k^{-1}=-8 μm

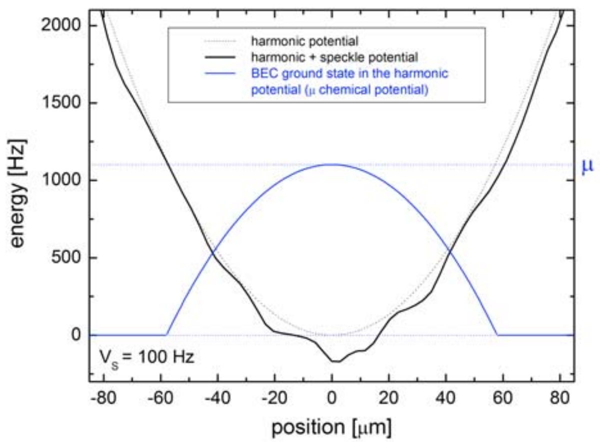
How the “speckle” random potential looks like



BEC in a “speckle” potential

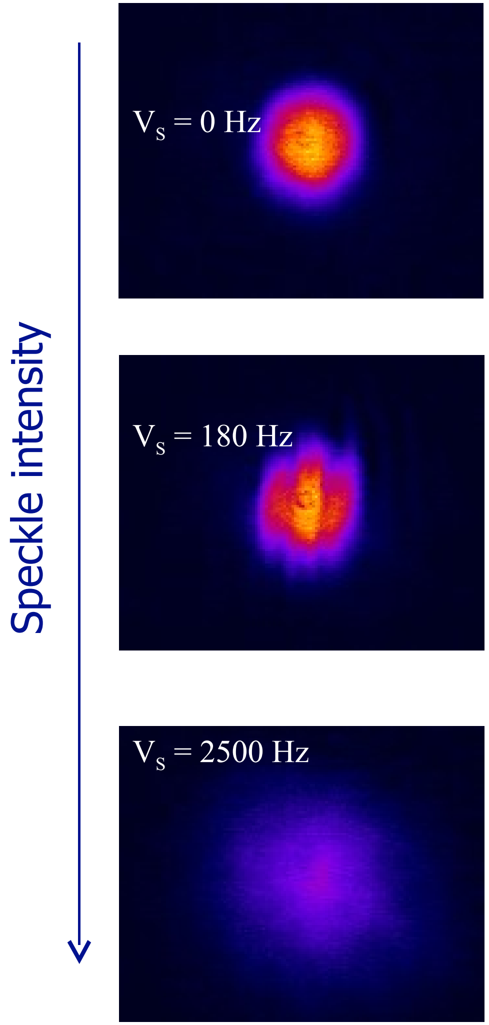


BEC ground state,
harmonic + speckle potential



μ chemical potential (1 kHz)

Density profile after 18 ms of free expansion



No disorder

Moderate disorder ($V_S < \mu$):
- long wavelength density modulations
- breaking phase uniformity

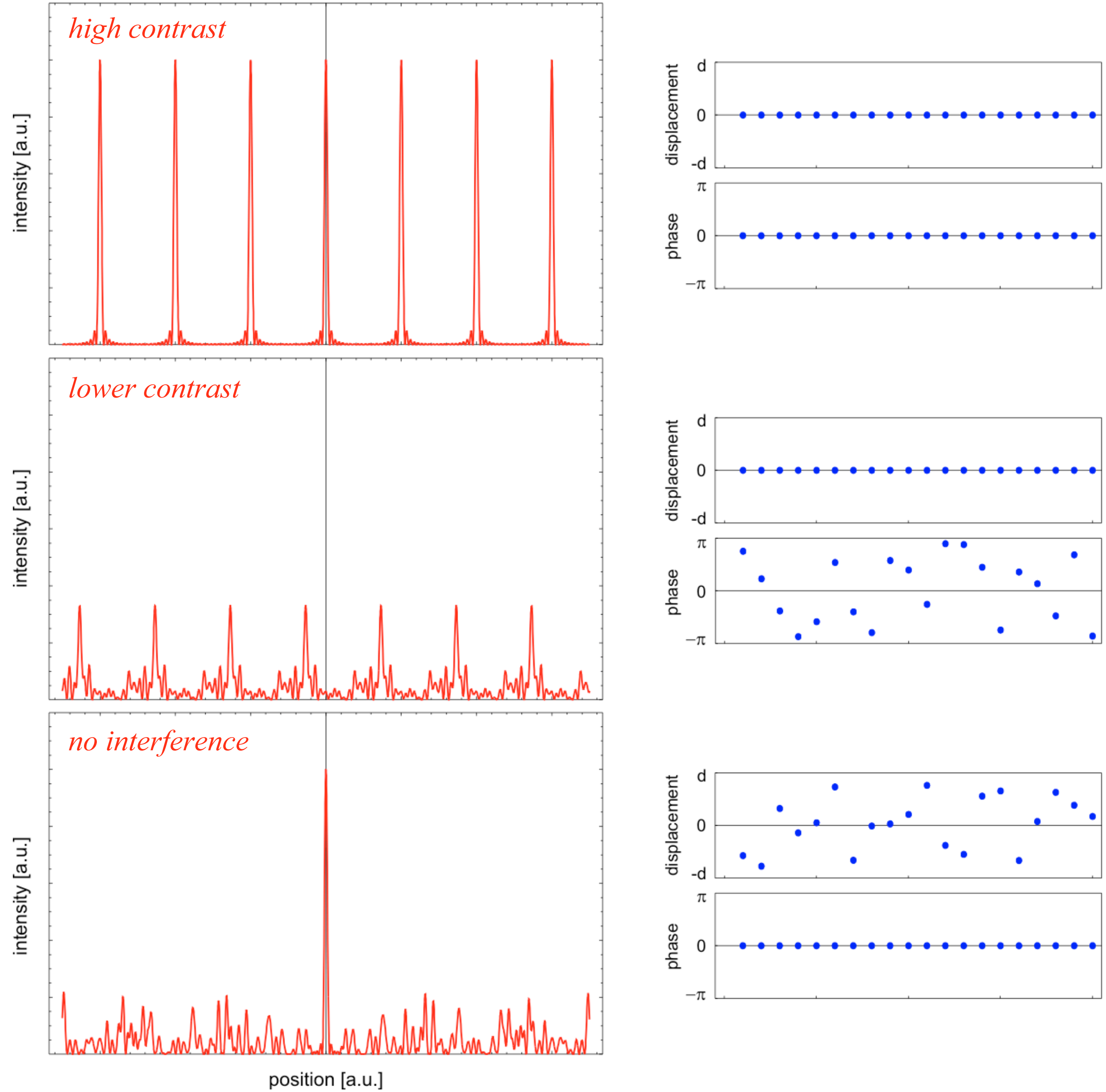
Strong disorder ($V_S > \mu$):
- broad unstructured gaussian
- localization in the speckles sites
- vanishing interference from not equispaced array

Interference from a finite number of point-like emitters

regular spacing
coherent sources

regular spacing
incoherent sources

disordered spacing
coherent sources

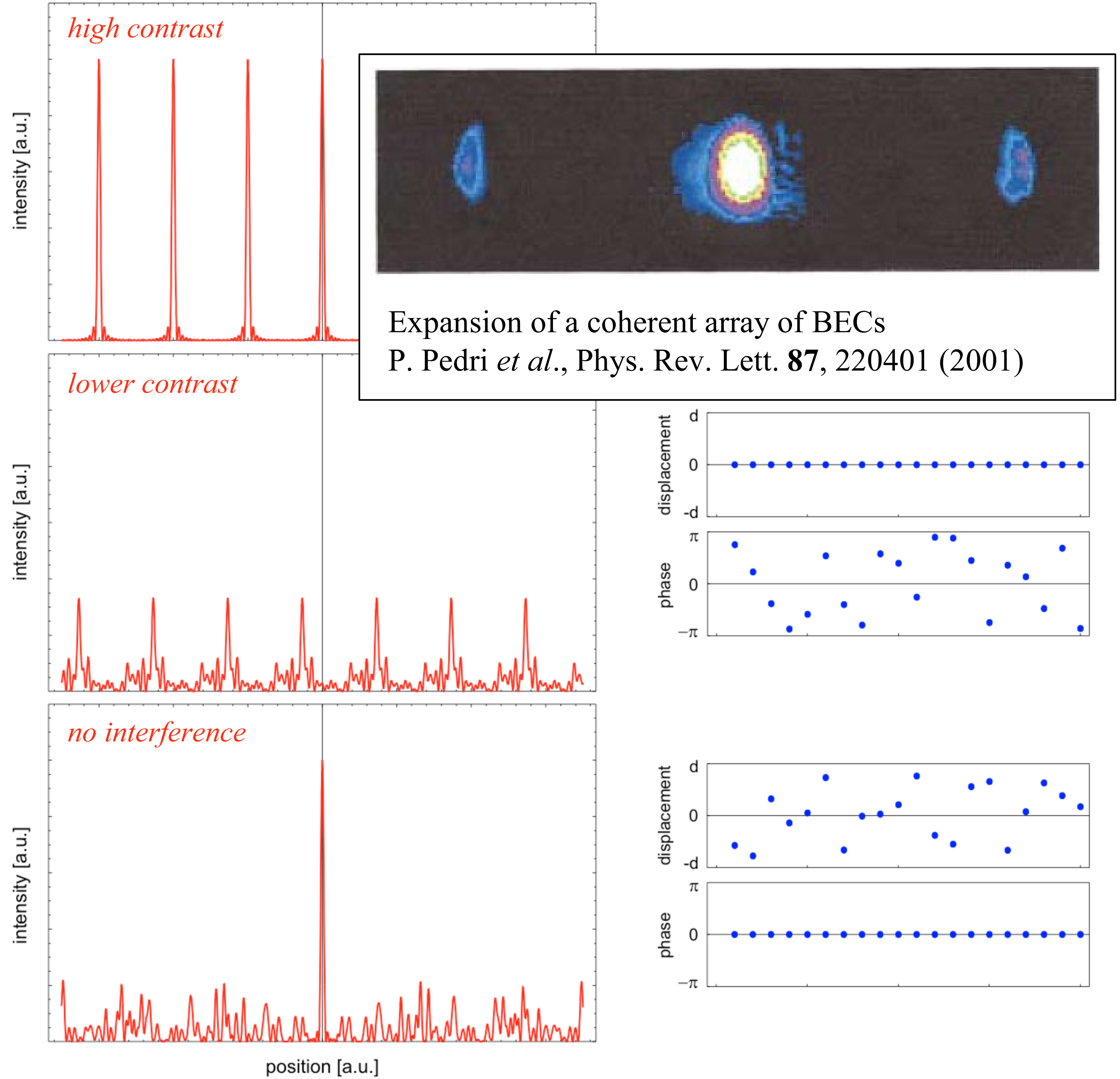


Interference from a finite number of point-like emitters

<u>regular</u> spacing
<u>coherent</u> sources

<u>regular</u> spacing
<u>incoherent</u> sources

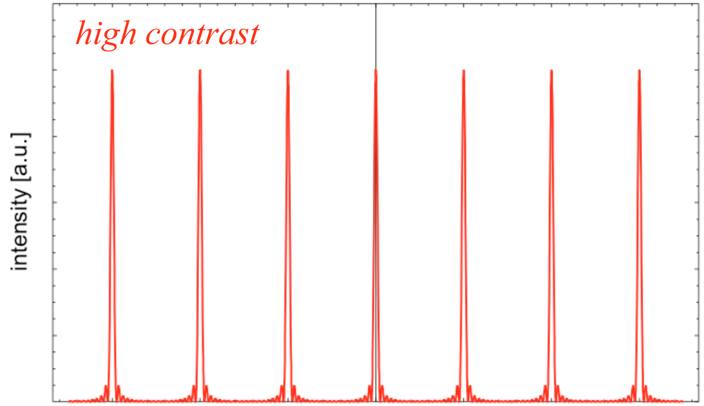
<u>disordered</u> spacing
<u>coherent</u> sources

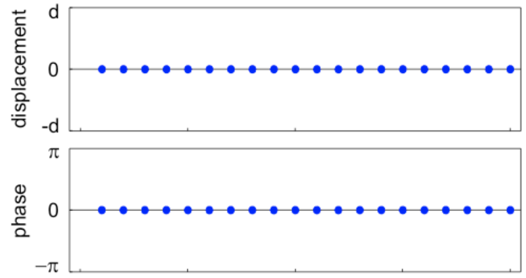


Expansion of a coherent array of BECs
P. Pedri *et al*., Phys. Rev. Lett. **87**, 220401 (2001)

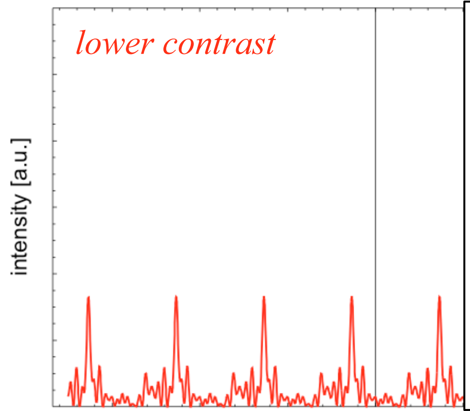
Interference from a finite number of point-like emitters

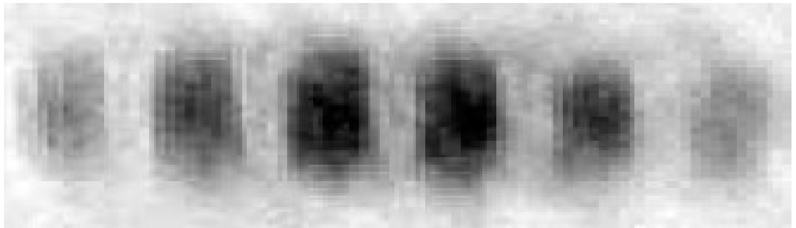
regular spacing
coherent sources





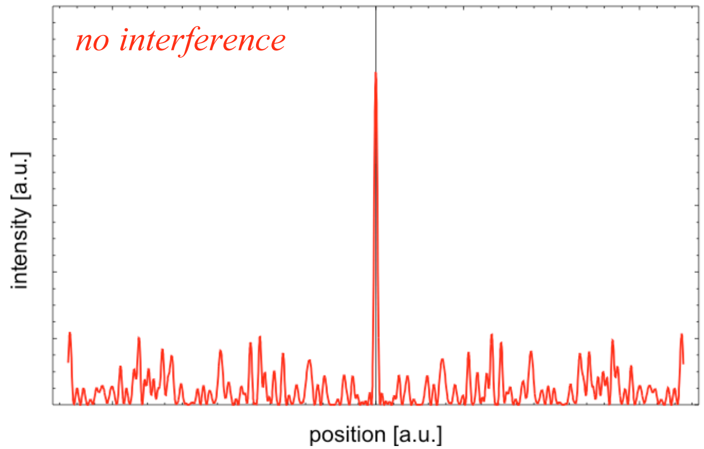
regular spacing
incoherent sources

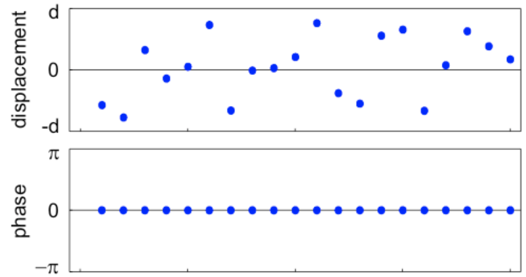




Interference of an array of independent BECs
Z. Hadzibabic *et al.*, cond-mat/0405113 (2004)

disordered spacing
coherent sources



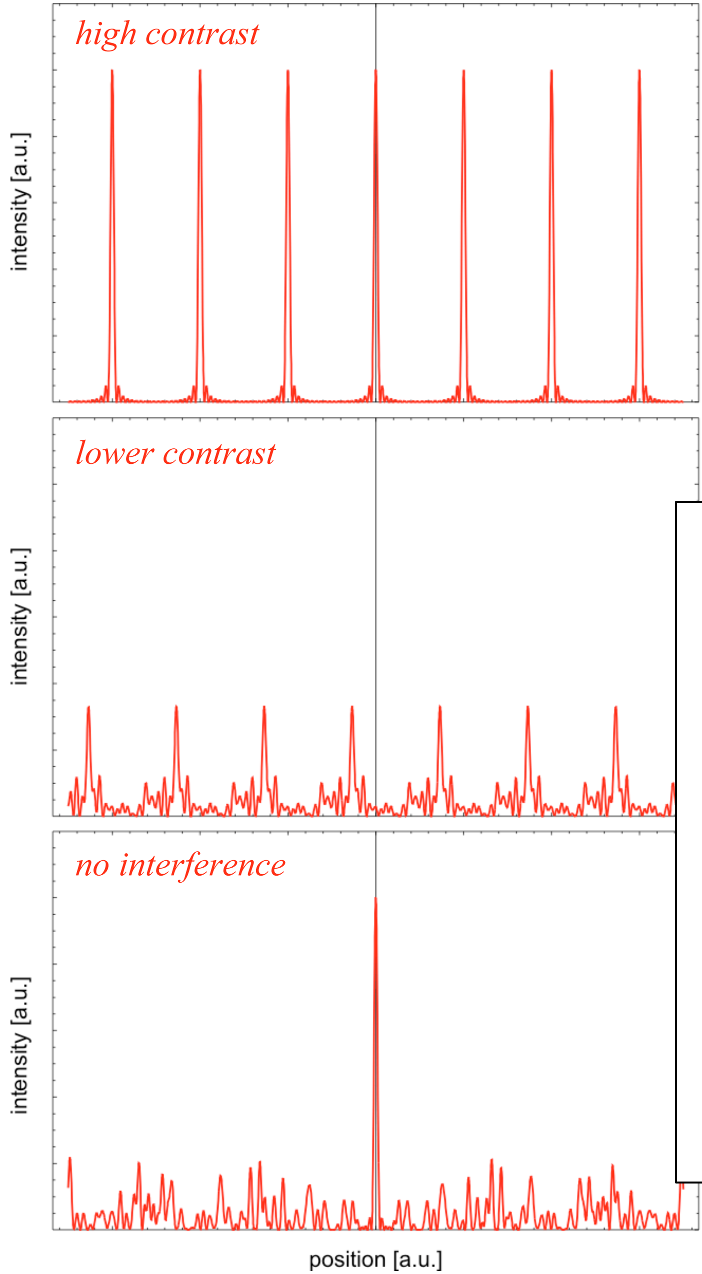


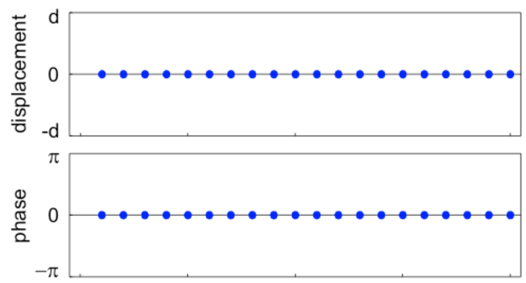
Interference from a finite number of point-like emitters

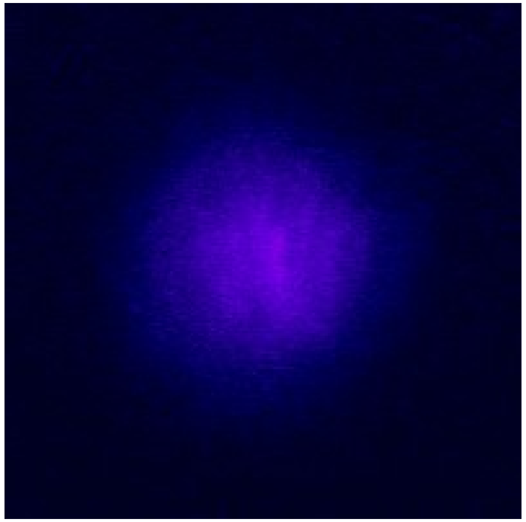
regular spacing
coherent sources

regular spacing
incoherent sources

disordered spacing
coherent sources





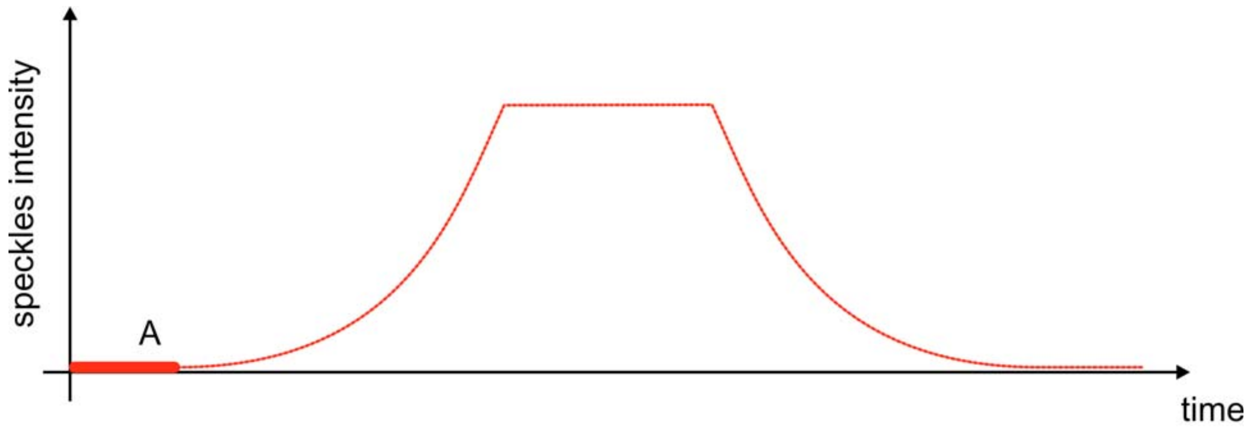


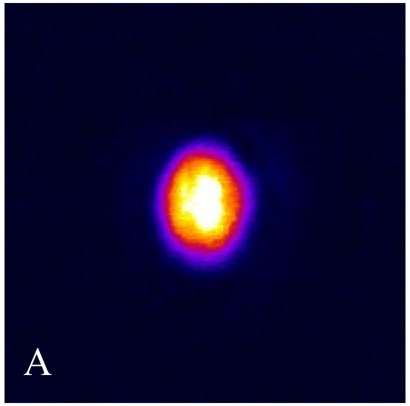
Interference from randomly spaced BECs located at different sites

BEC in “speckle” potential

Loss of interference pattern simply due to loss of coherence, i.e. Heating ?

First, condensate ...

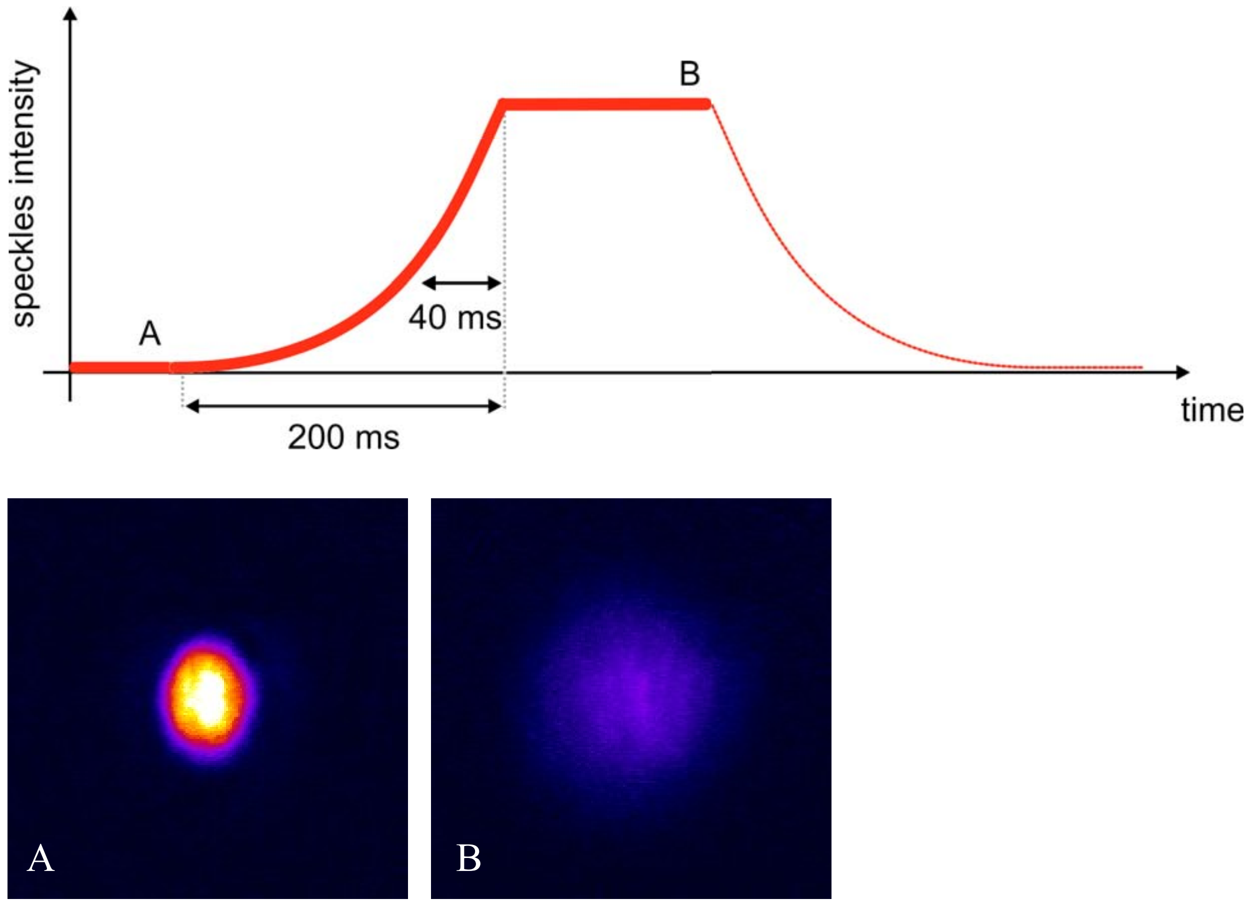




BEC in “speckle” potential

Loss of interference pattern simply due to loss of coherence, i.e. Heating ?

First, condensate; then, broad density distribution ...

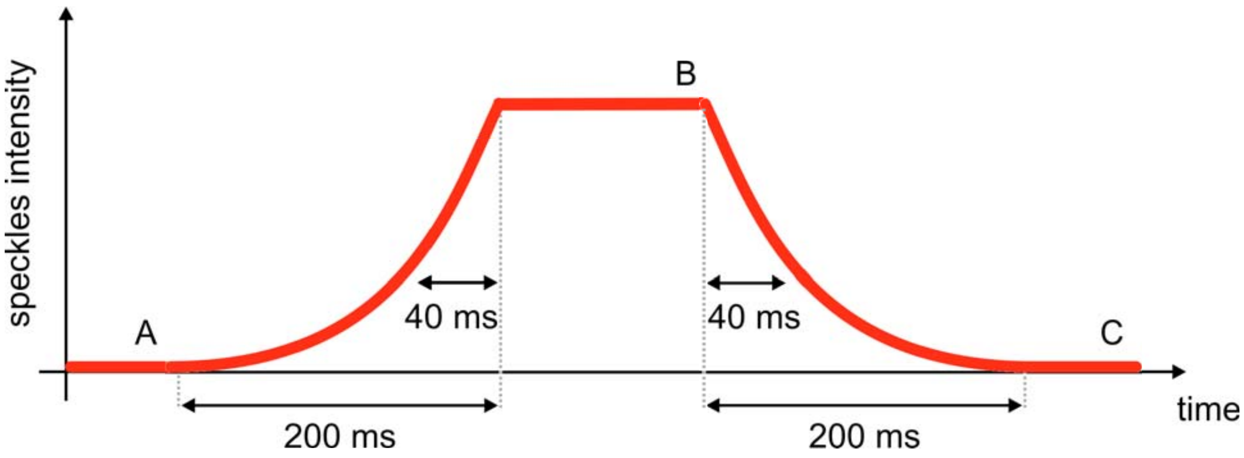


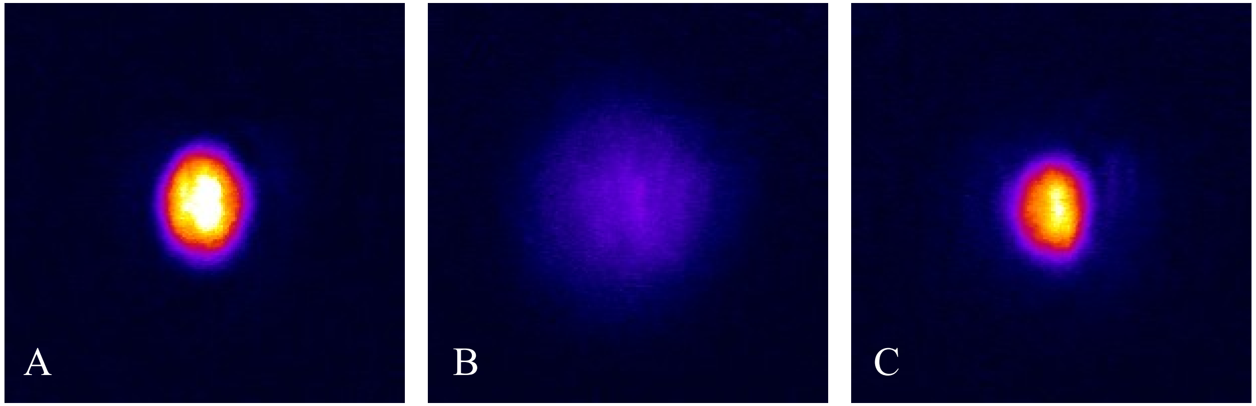
BEC in "speckle" potential

Loss of interference pattern simply due to loss of coherence, i.e. Heating ?

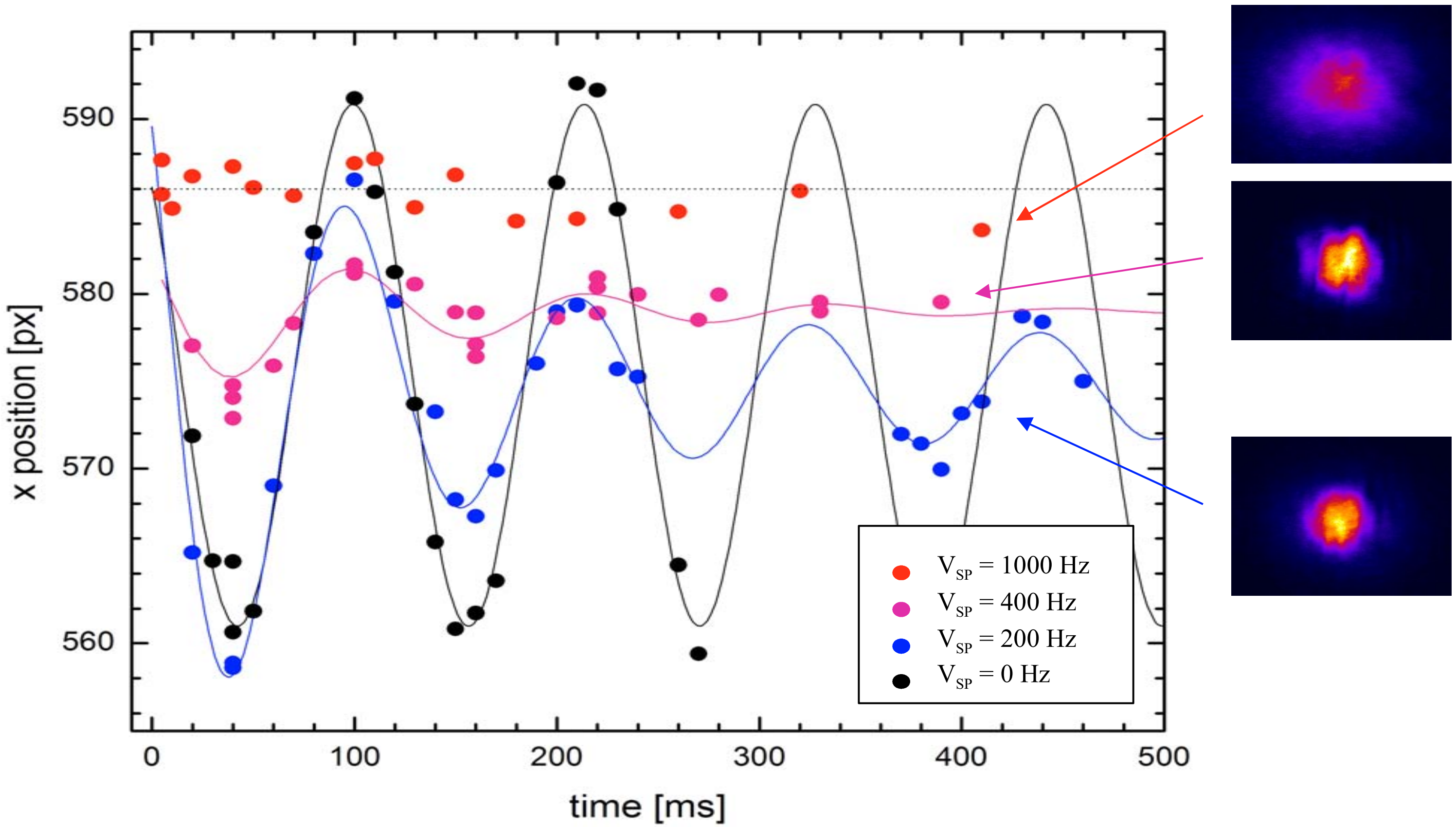
First, condensate; then, broad density distribution; finally BEC again.

NO HEATING





Dipolar oscillations in “speckle” potential



- Weak-medium disorder (60÷400 Hz): no change in dipole frequency within our experimental resolution (1%)
- Strong disorder (>1 kHz): no appreciable oscillation of the atomic cloud

Anderson localization with atoms ?

Anderson localization

interference phenomenon occuring in waves propagating in a static disorder: waves localized in space as consequence of the interference among multiple elastic random scattering.

Some example for classical waves…

Propagation of light waves in very strongly scattering semiconductor powders.

D. S. Wiersma et al. Nature 390, 671 (1997)

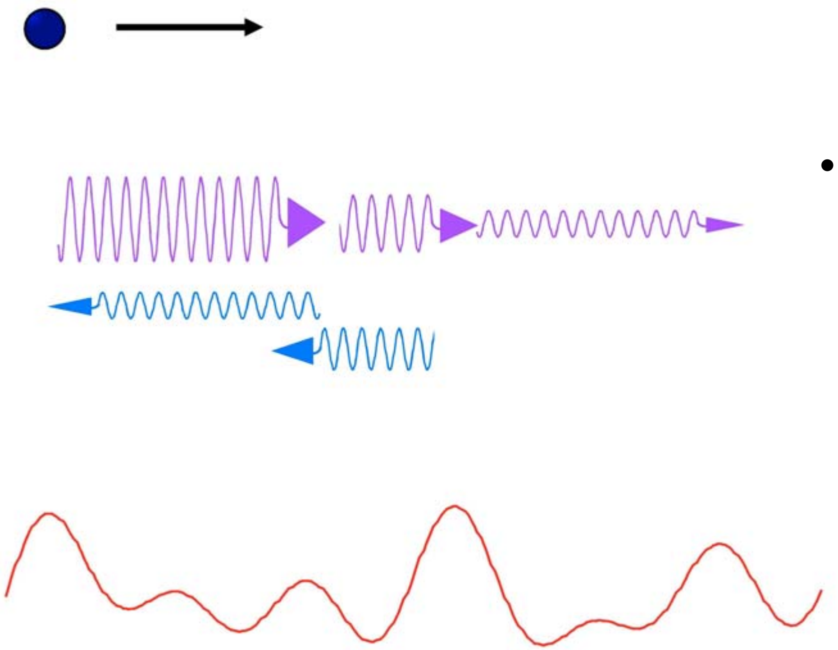
…and quantum matter waves

Indirect evidence in electrons' diffusion in condensed matter systems.
Due to the presence of defects in the solid, it behaves as an insulator.

T.Ando, H.Fukuyama, vol.28, Springer, Berlin (1988)

Anderson localization with atoms ?

Anderson localization should be observable for ultra-cold atoms as matter waves propagating in a random potential with the advantage of *controllable* disorder and interactions.



- A classical particle:

  confined iff

  kinetic energy < potential depth

- A quantum particle / wave:

  partial reflections and transmission occur at each scattering

  secondary waves, emitted at random positions, interfere

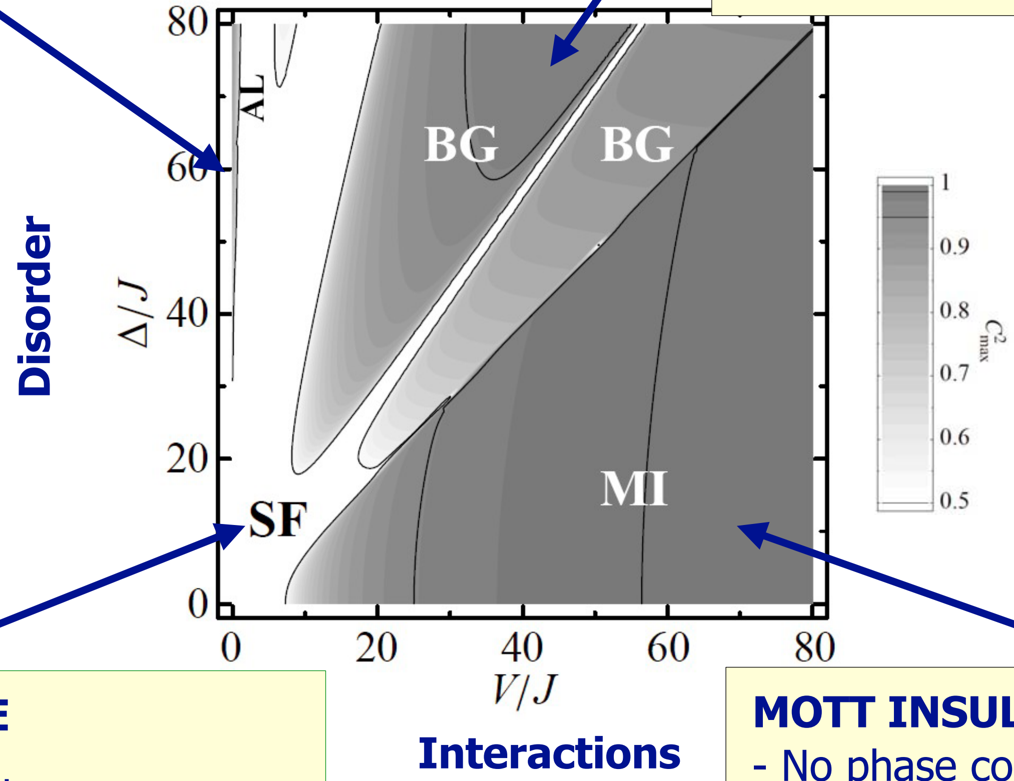
  by destructive interference, localization in space over a length scale depending on the typical distance among scatterers

Phase diagram

ANDERSON LOCALISATION
- Long-range phase coherence
- High number fluctuations
- No gap in the excitation spectrum
- Vanishing superfluid fraction

BOSE-GLASS PHASE (BG)

- No phase coherence
- Low number fluctuations
- No gap in the excitation spectrum
- Vanishing superfluid fraction



*R. Roth and K. Burnett, PRA **68**, 023604 (2003)*

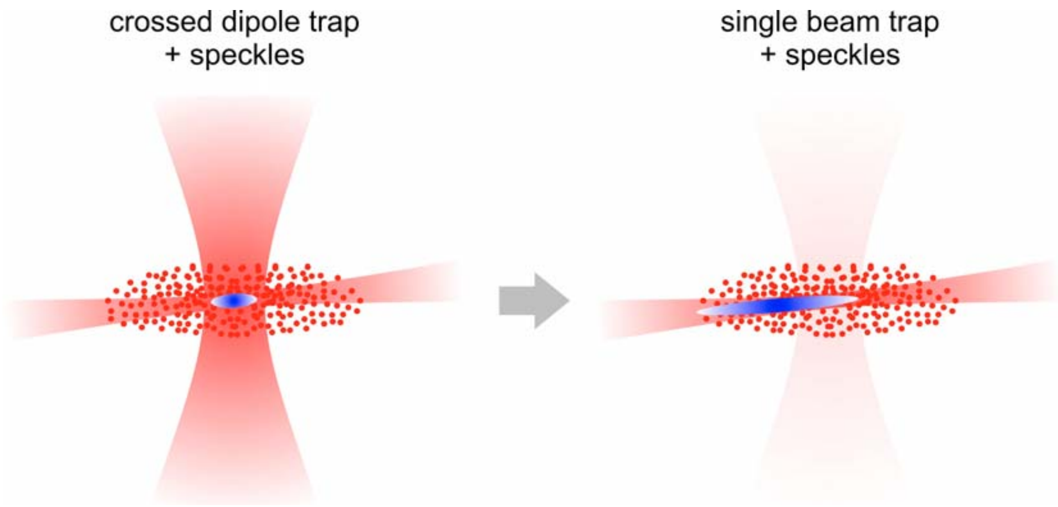
SUPERFLUID PHASE

- Long-range phase coherence
- High number fluctuations
- No gap in the excitation spectrum

MOTT INSULATOR PHASE (MI)
- No phase coherence
- Zero number fluctuations
- Gap in the excitation spectrum
- Vanishing superfluid fraction

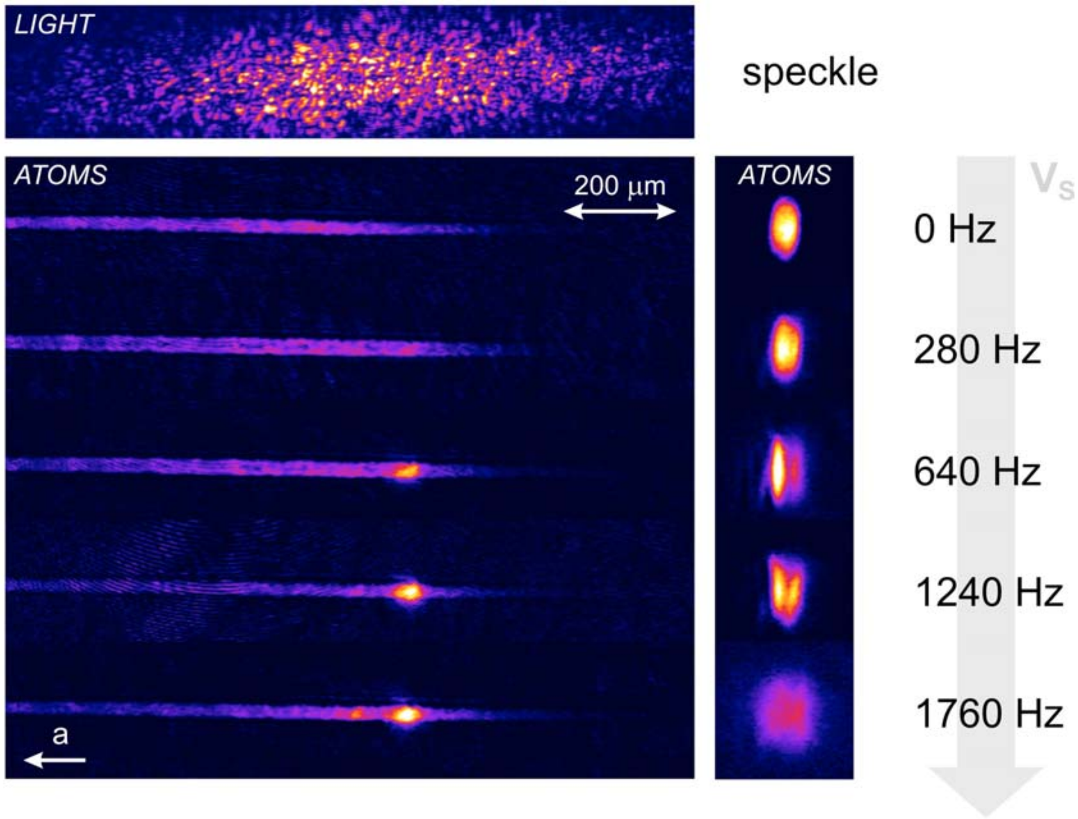
Expansion of a BEC in a "speckle" potential

Search for Anderson localization in a low-density, i. e. low interactions, regime: free expansion



Condensate released and expanding in a randomly corrugated waveguide

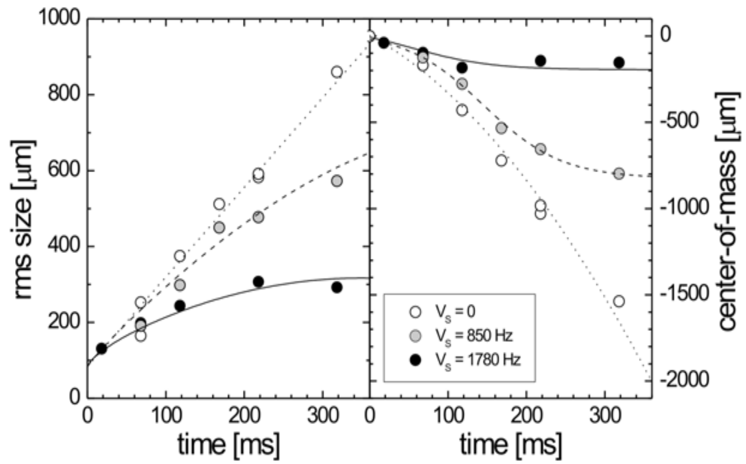
Expansion of a BEC in a "speckle" potential



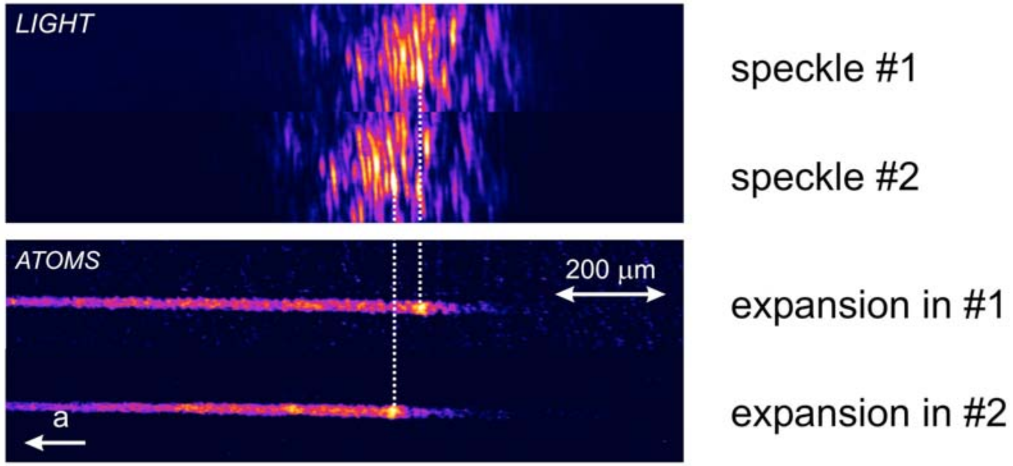
Upon "speckle" intensity increase:

- center-of-mass evolution slows

- high density peaks form
⟶ density rms decreases

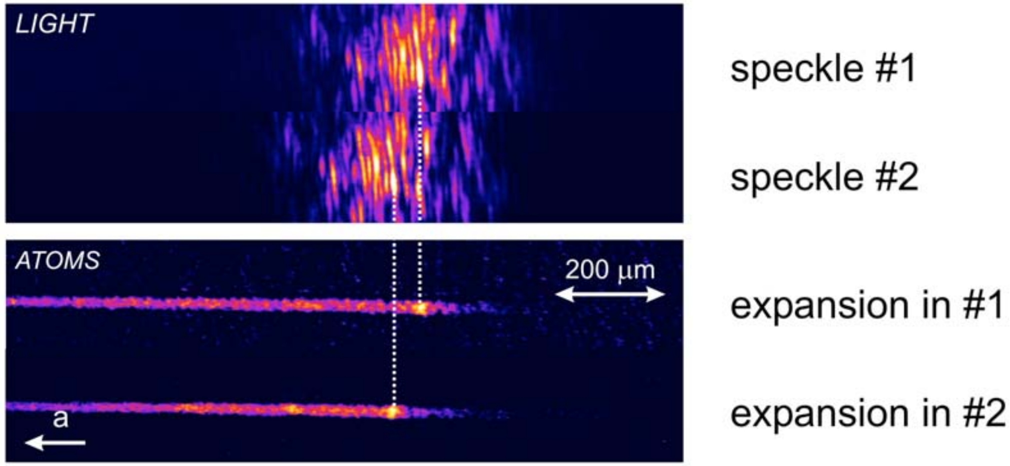


Anderson localization ?



The density maxima are correlated with the intensity maxima of the speckle pattern (potential minima)

Anderson localization ?



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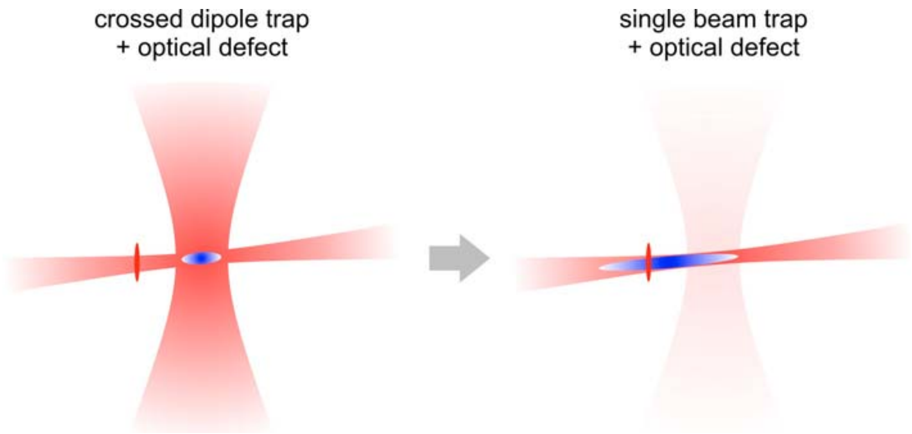
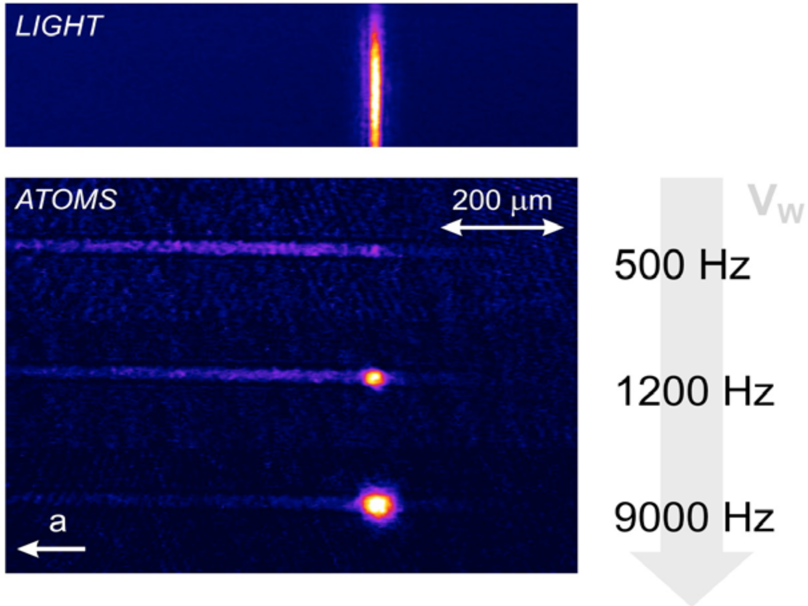


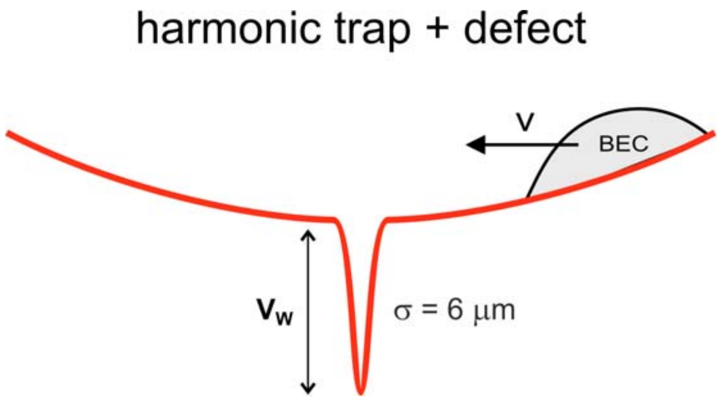
Repeat the experiment with a single optical "defect", i. e. a single potential well

Trapping in optical “defects”

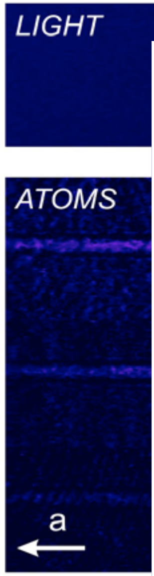


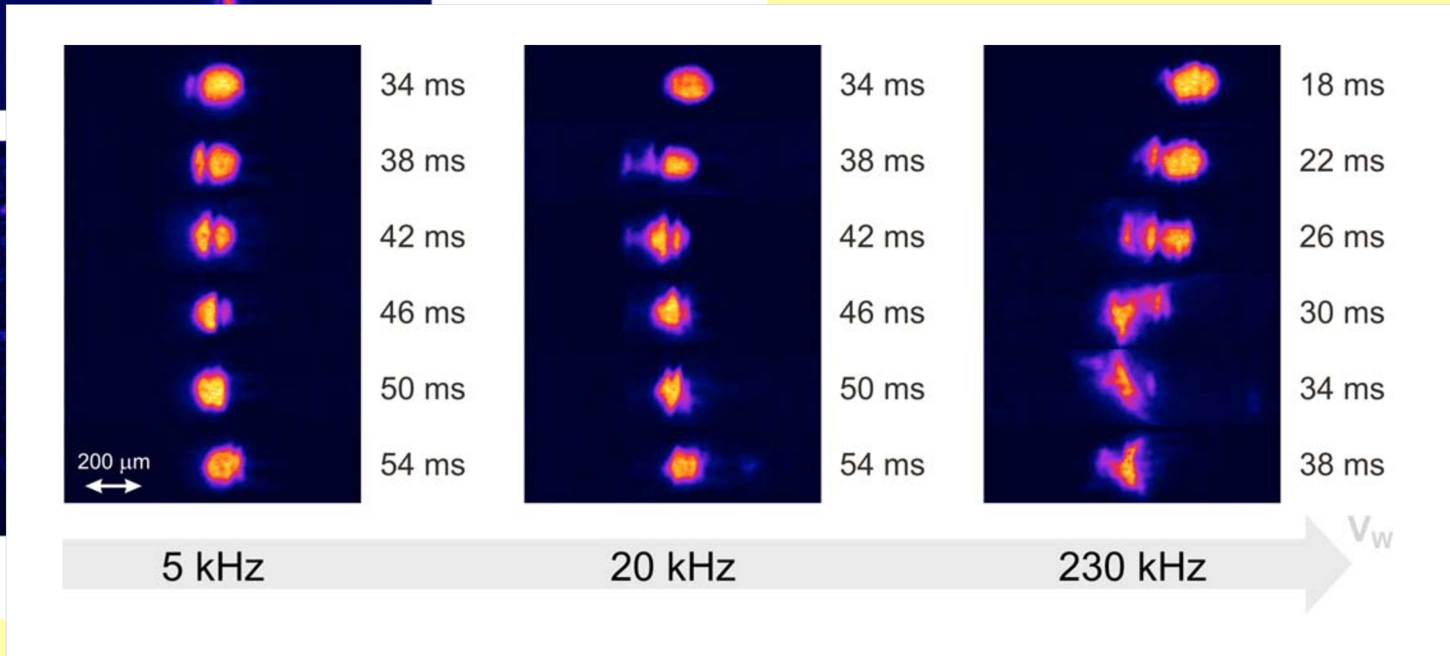
Same behavior observed: a small component expands freely, while a large fraction is trapped in the defect.

Picture confirmed by dipole oscillations of the trapped condensate in presence of the “defect”



Trapping in optical "defects"



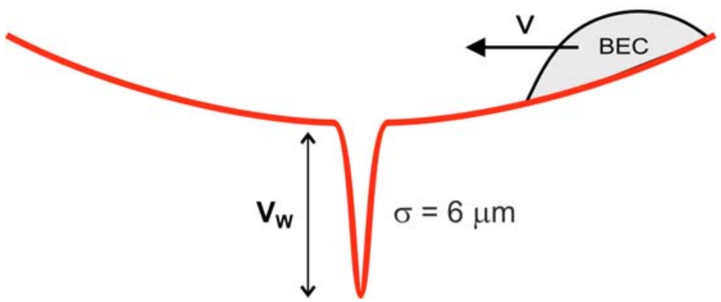


a small
e a large

Picture confirmed by dipole oscillations of the trapped condensate in presence of the "defect"

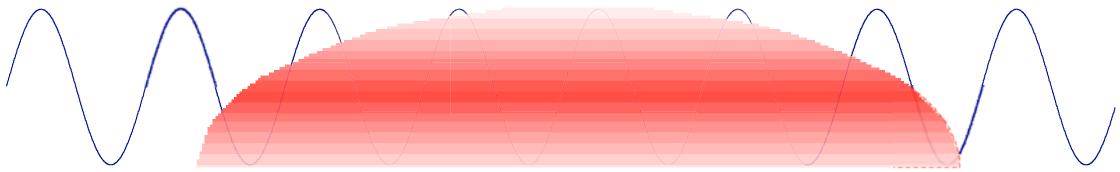
NO QUANTUM REFLECTION
NO ANDERSON LOCALIZATION

harmonic trap + defect



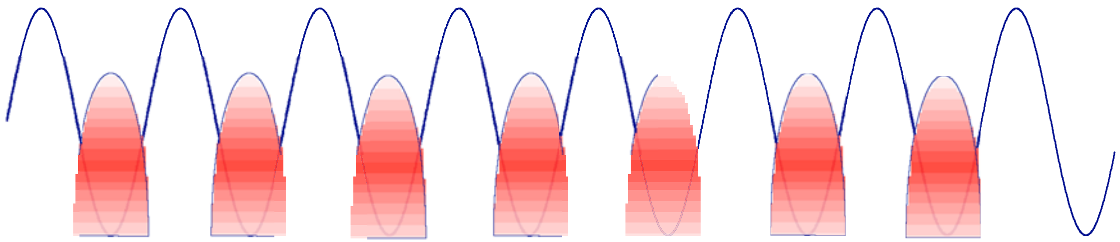
C. Fort et al., cond-mat/0507144, PRL (accepted).

Adjustable interactions in periodic potential



Optical lattice + homogenous magnetic field
(to adjust the interactions)

Realization of attractive Bose-Hubbard model



$$\hat{H} = -t \sum_i \left(\hat{b}_i^\dagger \hat{b}_{i+1} + \hat{b}_{i+1}^\dagger \hat{b}_i \right) + \frac{U}{2} \sum_i \hat{n}_i (\hat{n}_i + 1)$$

- Tight binding approximation: in each site only lowest bound state occupied (already good approximation for s > 5)
- Only nearest-neighbour coupling
- t and U adjustable parameters

Adjust U: Fano-Feshbach resonances

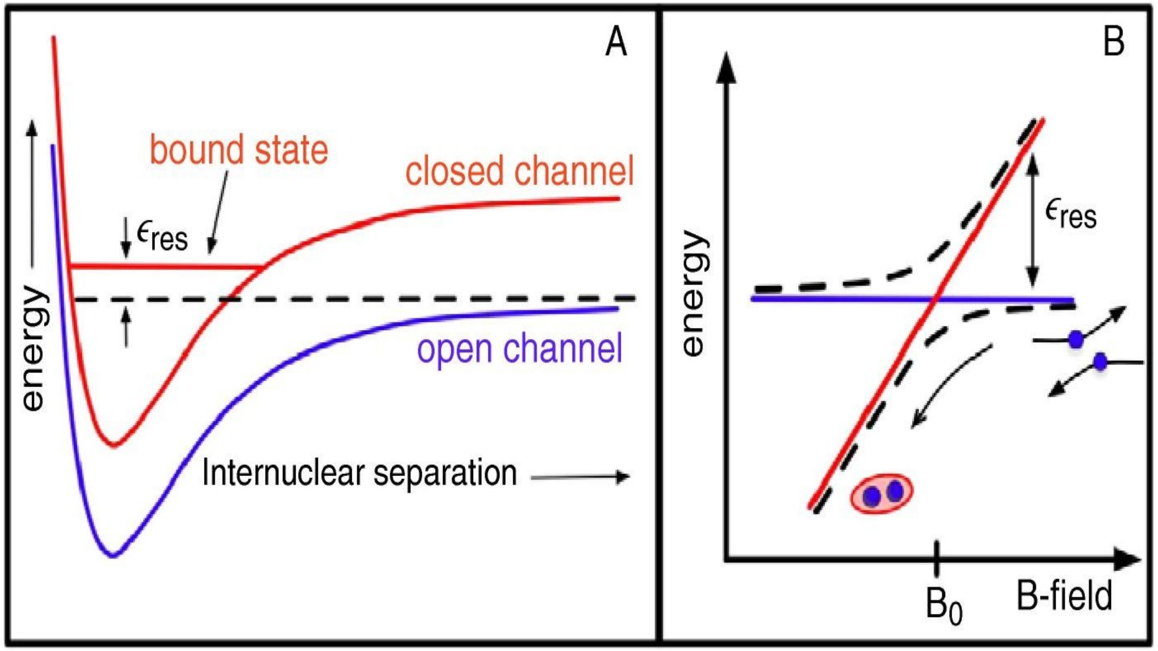


Figure from: J.Williams et al, New Journal of Phys. **6**, 123 (2004)

Energy of the unbound atoms = energy of bound state linked to different asymptotic states

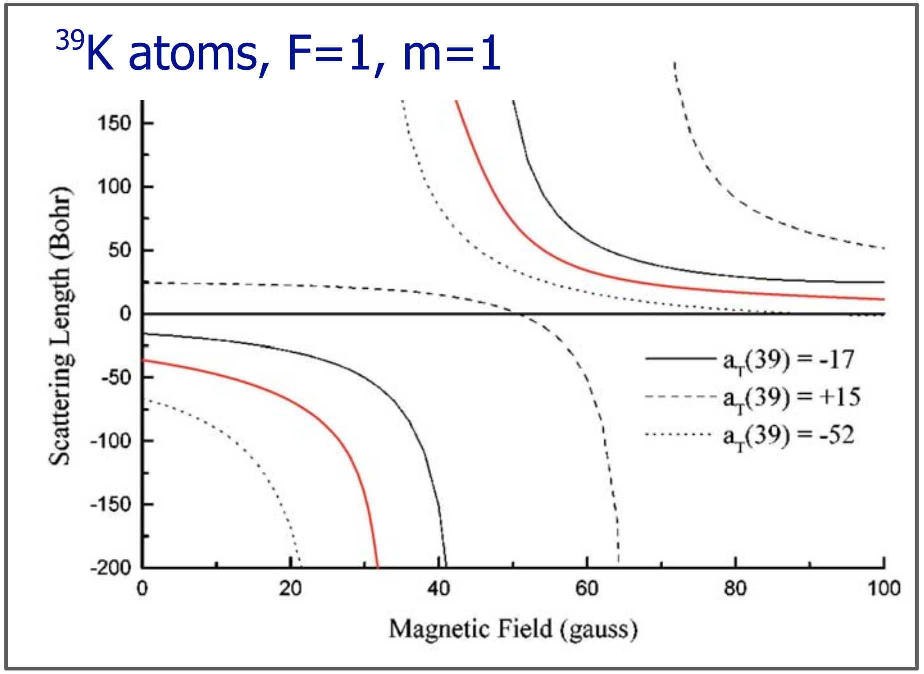
Coincidence can be forced by applying external magnetic field

The scattering length undergoes a resonant dispersive behaviour

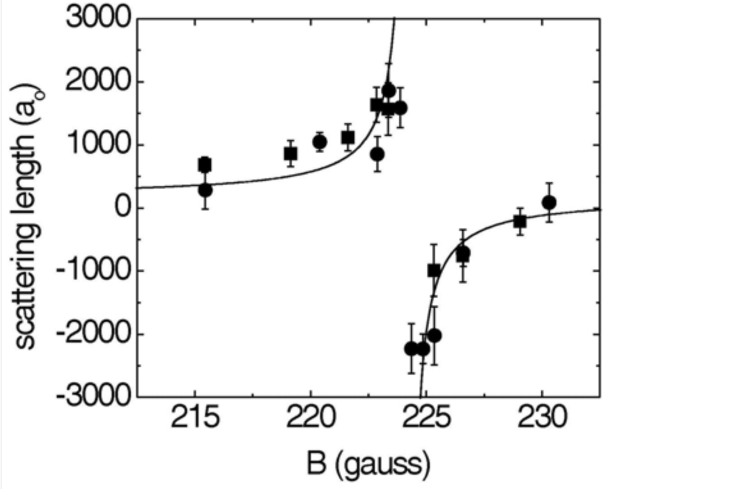
Molecular BECs have been formed

Fano-Feshbach resonances in K

Figure from: J. Bohn et al., Phys. Rev. A **58**, 3660 (1999)



C. A. Regal and D. Jin., PRL 90 230404 (2003)

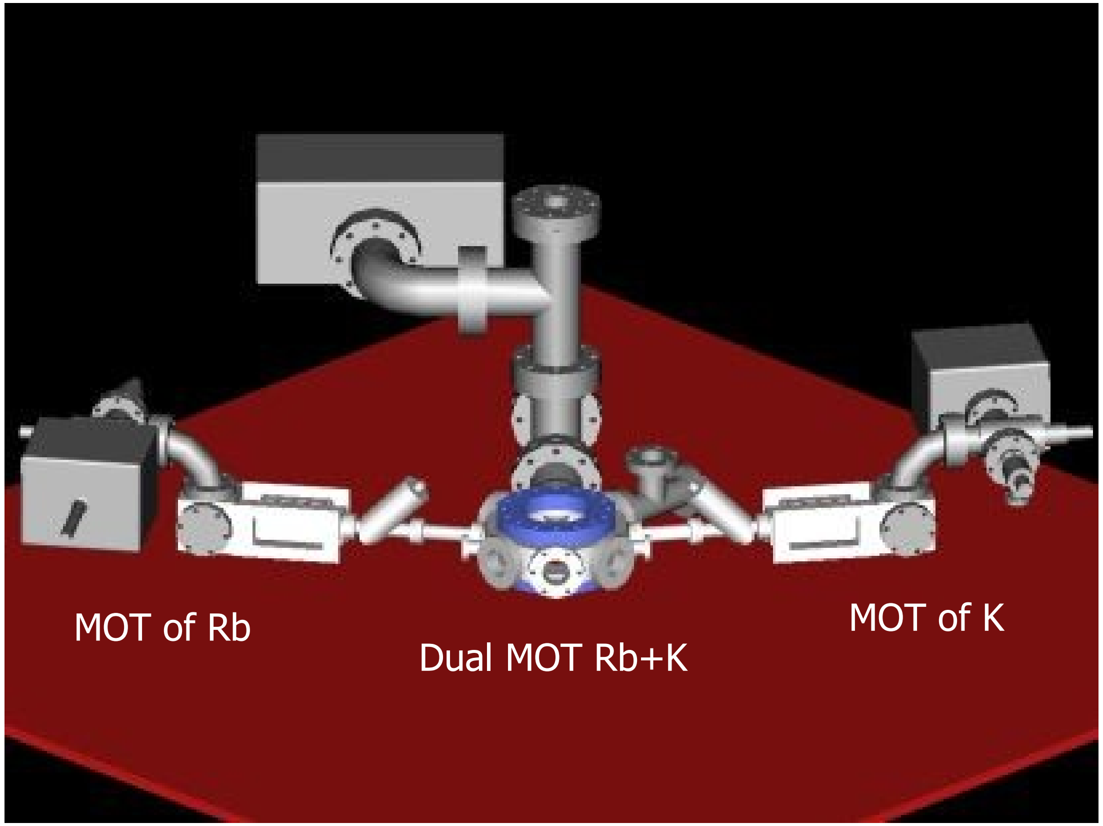


^{40}K atoms
F=9/2, m=-9/2 and -5/2

Calculations of FF resonances ab initio extremely difficult and hardly accurate ⟶ need to pinpoint parameters with experimental data

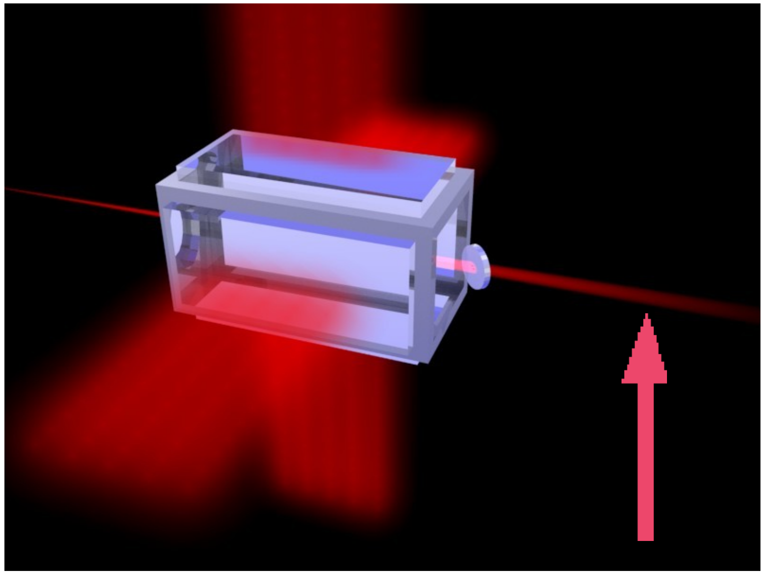
- FF between ^{40}K atoms already observed (JILA)
- FF between ^{40}K and ^{87}Rb atoms also observed (JILA, LENS)
- Predictions of FF ^{41}K-^{41}K and ^{39}K-^{39}K atoms in the range 50 to 100 Gauss

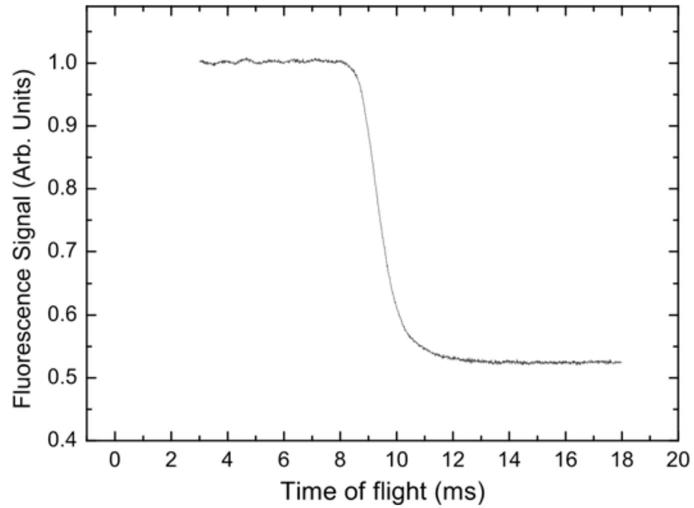
Status of experiment



- ✔ 2 dimensional MOT of Rubidium
- ✔ 2 dimensional MOT of Potassium
- ✔ Dual MOT
- ✗ Magnetic trapping and evaporation
- ✗ Potassium (and Rubidium) BEC
- ✗ Fano-Feshbach resonances

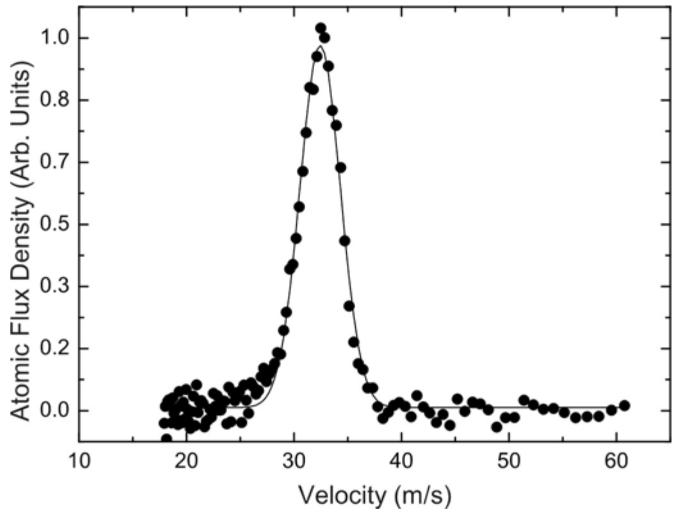
2-Dimensional Magneto-Optical Trap (2D-MOT)





2D-MOT with bosonic Potassium, high efficiency:

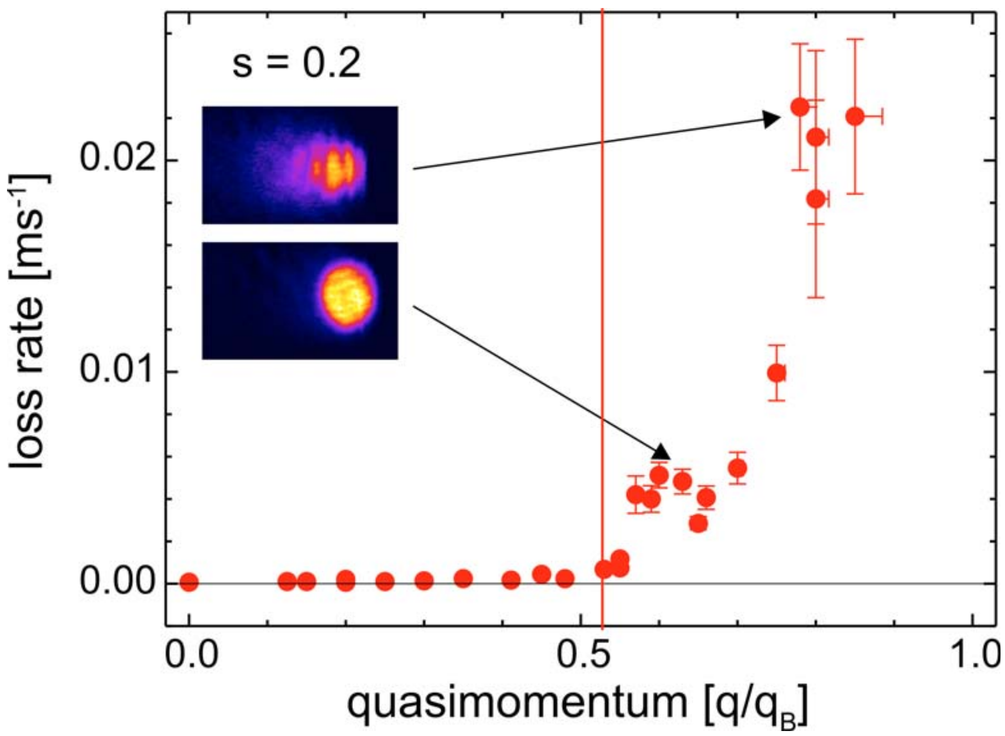
atomic flux > 1e10 atoms/s
mean velocity = 30-35 m/s



CONCLUSION and outlook

Transport behavior of Boson and Fermion atoms in combined potentials

• Bosons tunnel but the motion is hindered by atomic interactions above a critical quasi-momentum



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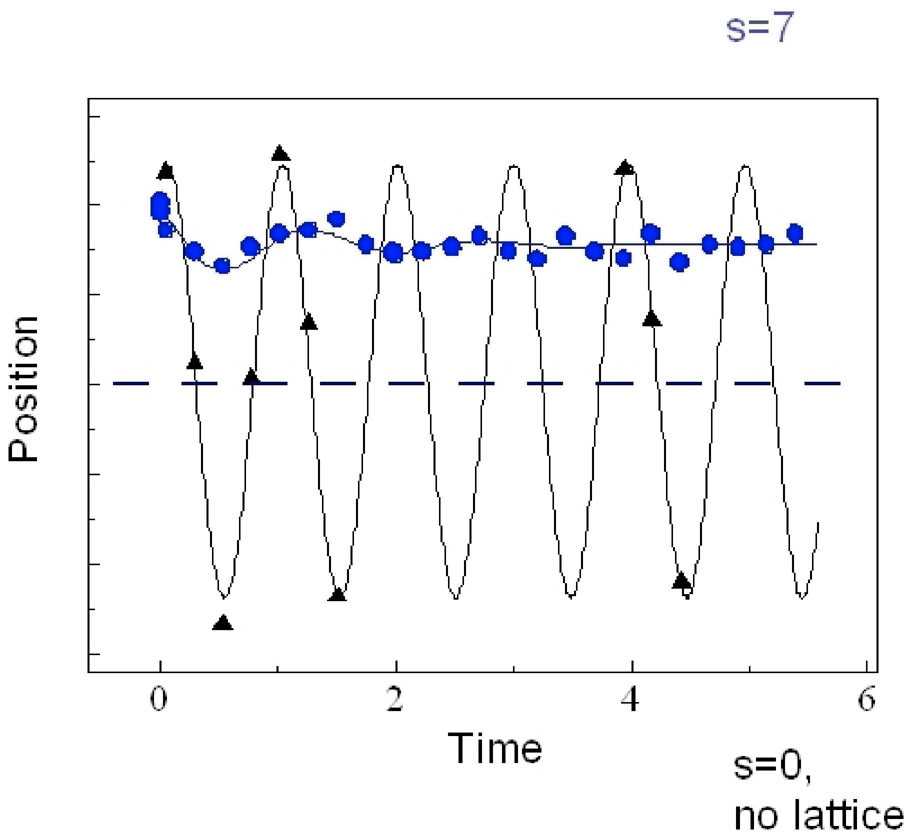

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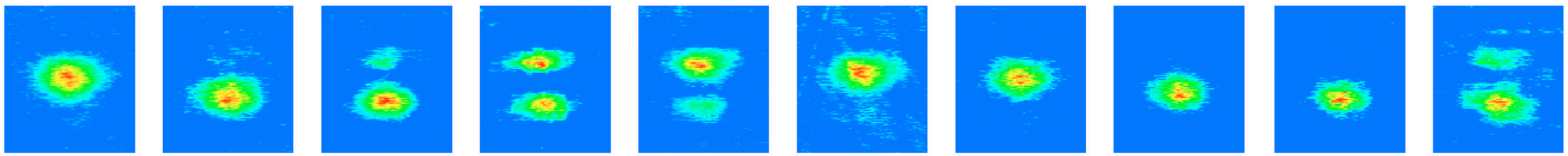

2 ms 2.4 ms 2.8 ms 3.2 ms 3.6 ms 4 ms 4.4 ms 4.8 ms 5.2 ms 5.6 ms

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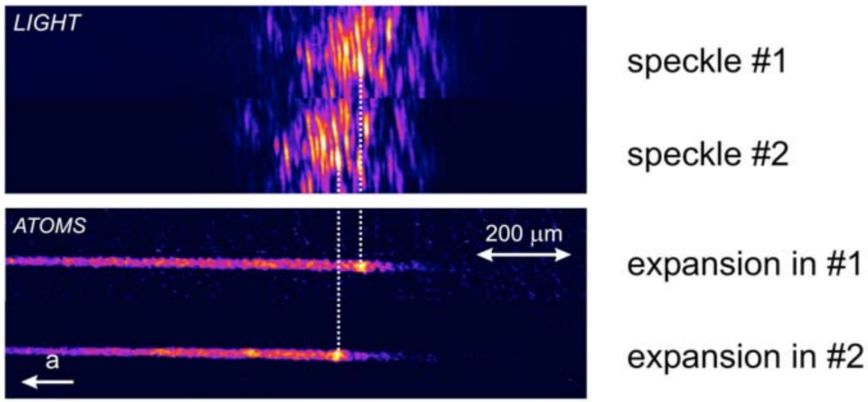

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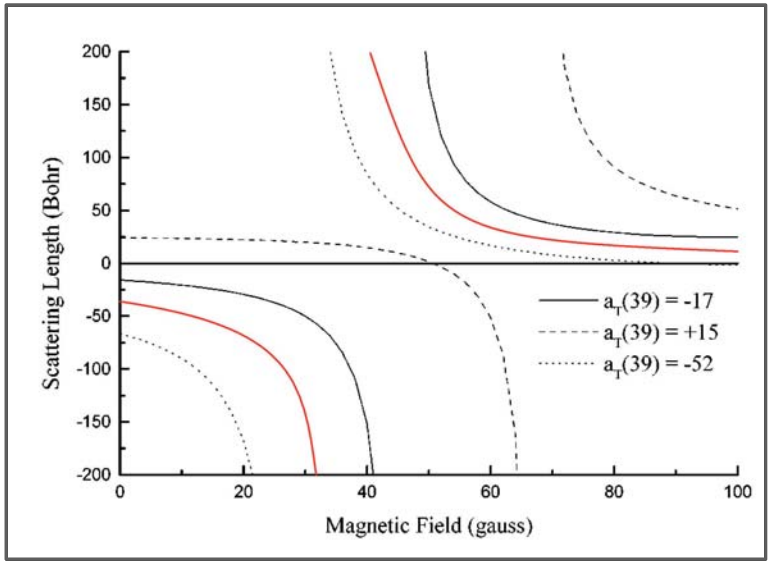
- Fermions localize in *Wannier-Stark*-like states
- Non-interacting Fermions undergo long-lived Bloch oscillations
- Anderson localization requires steeper potential scatterers
- Potassium offers the prospect of tuning interactions



Conclusions and OUTLOOK

Bosons and fermions in optical lattices are candidate systems for Quantum Simulators, Quantum Sensors and Quantum Information Processing

As for Quantum Sensors:

• principle demonstration of interferometry w/ trapped fermions, acceleration sensing with micrometric spatial resolution

• proposal for Heinsenberg-limited interferometrywith maximally entangled states (Schroedinger cats) or with number-squeezed states

FUTURE DIRECTIONS:

• Lattices in D > 1 NEW: Mott insulator observed in 3D lattice

• Creation of heteronuclear molecules (long-range interactions)

• Control of atomic interactions via Fano-Feshbach resonances, attractive condensates

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Massimo Inguscio

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