Ultracold Bosons and Fermions in Optical Lattices

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CQG people in Firenze

1) Rb BEC

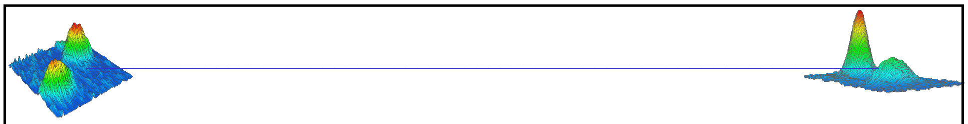
Chiara FORT, Leonardo FALLANI, Francesco MINARDI, Jessica LYE, Francesco CATALIOTTI (also Ct), Jacopo CATANI, Luigi De SARLO

2) K – Rb Fermi-Bose MIXTURES

Giovanni MODUGNO, Giacomo ROATI, Herwig OTT, Francesca FERLAINO, Estefania de MIRANDES

Theory

Michele MODUGNO, Andrea SIMONI (now NIST)

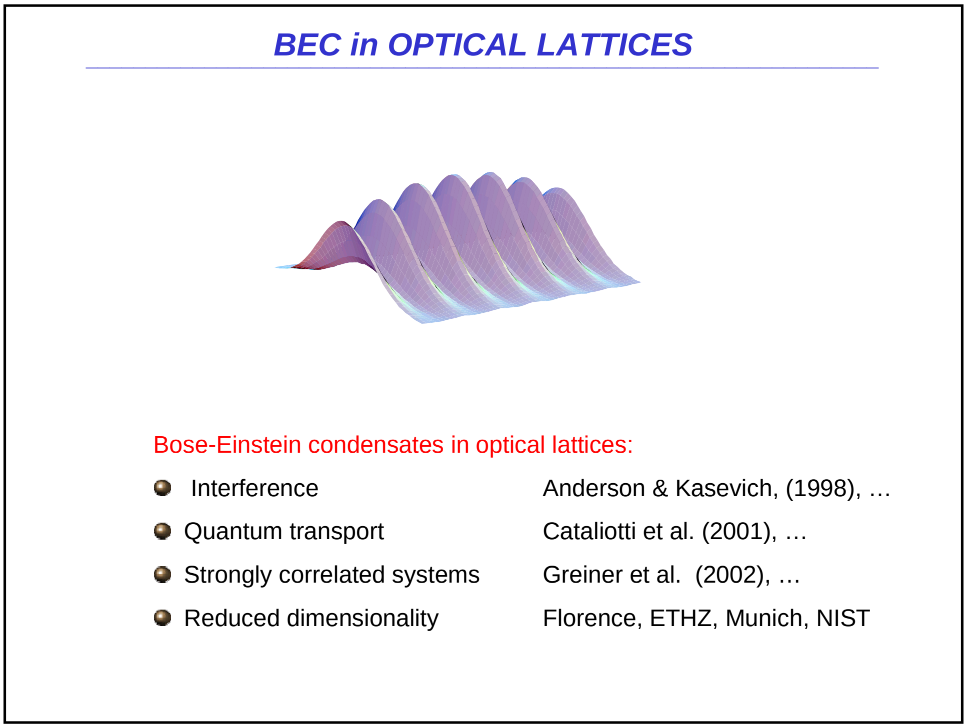


Dynamical instability of a BEC
Energetic instability of a BEC

Transport properties of fermions and bosons in a lattice
(Role of collisions)

Atomic Interferometry with Fermions

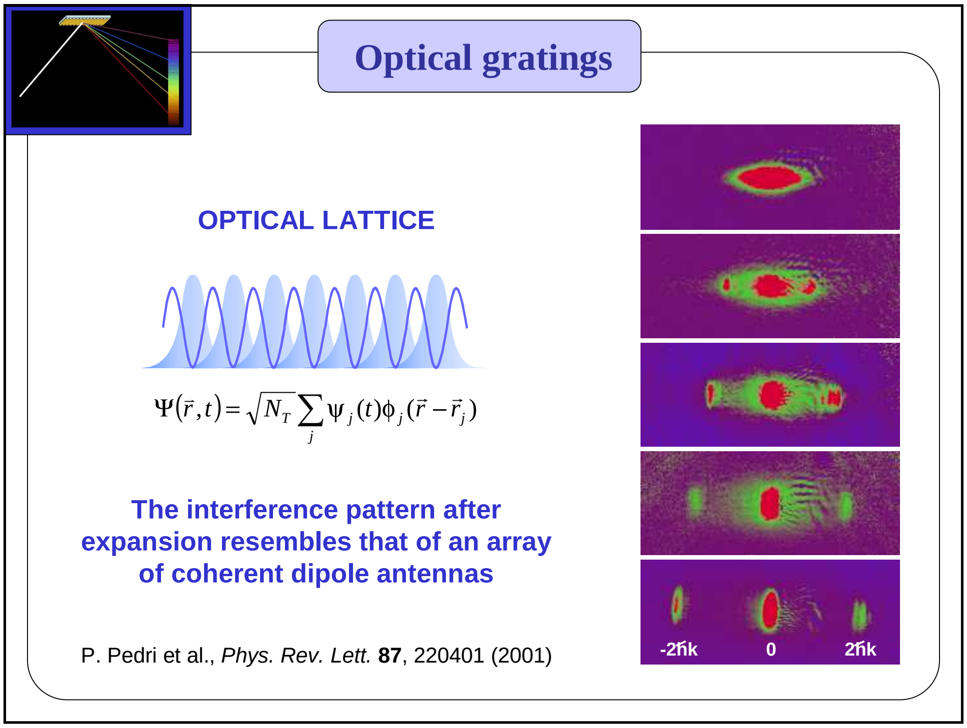
Transport of BEC
in a 1D optical lattice
(Dynamical instability)



BEC in OPTICAL LATTICES

Bose-Einstein condensates in optical lattices:

Interference	Anderson & Kasevich, (1998), …
Quantum transport	Cataliotti et al. (2001), …
Strongly correlated systems	Greiner et al. (2002), …
Reduced dimensionality	Florence, ETHZ, Munich, NIST



Optical gratings

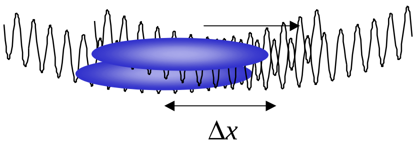
OPTICAL LATTICE

$$\Psi(\vec{r},t)=\sqrt{N_T}\sum_j \psi_j(t)\phi_j(\vec{r}-\vec{r}_j)$$

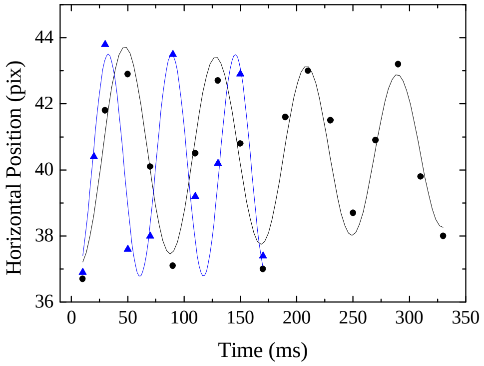
The interference pattern after expansion resembles that of an array of coherent dipole antennas

P. Pedri et al., *Phys. Rev. Lett.* **87**, 220401 (2001)

Transport in the lattice: dipolar oscillations

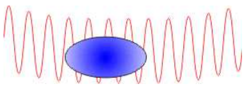


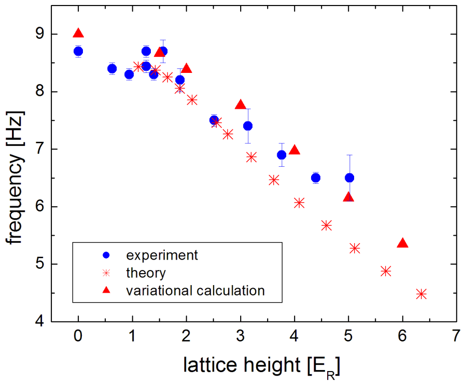
Dipolar oscillations excited with a single kick $\Delta x = 10 - 20\mu\text{m}$



Array of Josephson junctions

Collective dipole oscillation of a BEC in a harmonic trap + optical lattice





The oscillation frequency ω* is rescaled with an effective mass

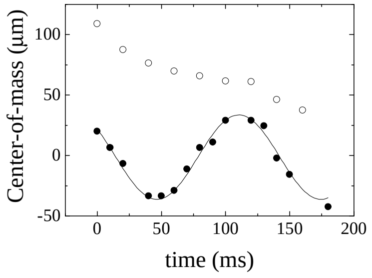
$$\omega^* = \sqrt{\frac{m}{m^*}}\omega$$

dependent on the tunneling rate K:

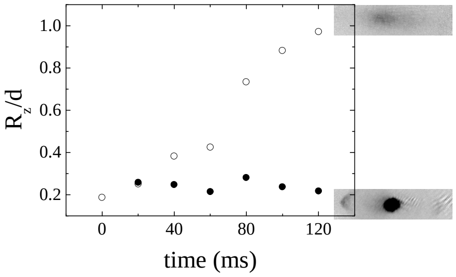
$$m^* = \frac{2\hbar^2}{\lambda^2 K} m$$

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

large amplitude dipole oscillations of a trapped BEC in presence of a 1D optical lattice:



THE CENTER-OF-MASS SLOWLY MOVES TOWARDS THE CENTER OF THE MAGNETIC POTENTIAL



LOSS OF LONG RANGE PHASE COHERENCE

We observe a transition from a regime in which the wavepacket coherently oscillates in the array to another one in which the condensates stop in the optical potential sites and lose their relative phase coherence.

"Superfluid current disruption in a chain of weakly coupled Bose-Einstein Condensates"
F. S. Cataliotti et al. *New journal of Physics* **5**, 71 (2003).

Dynamical instability of an array of condensates

$$\Psi(\vec{r},t)=\sqrt{N_T}\sum_j \psi_j(t)\phi_j(\vec{r}-\vec{r}_j)$$

GPE reduces to
Discrete Non-Linear Schrödinger Equation

$$i\hbar\frac{\partial\psi_n}{\partial t}=-K\left(\psi_{n-1}+\psi_{n+1}\right)+\left(\varepsilon_n+U\left|\psi_n\right|^2\right)\psi_n$$

tunneling rate

on site energy

non-linear coefficient

$$\omega_q=\frac{1}{m^*}\sin\ p\sin q+2\left|\sin q\right|\sqrt{\frac{1}{m^{*2}}\cos^2\ p\sin^2\frac{q}{2}+\frac{1}{m^*}\frac{\partial\mu}{\partial N}N\cos\ p}$$

When the Bogoliubov modes become imaginary ⇒dephasing among different sites (no interference) ⇒ the wave suddenly stops (no oscillation)

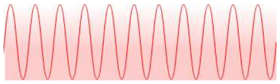
A. Smerzi et al., *Phys. Rev. Lett.* **89** 170402 (2002)

See also work of Wu & Niu, *Phys. Rev.* A **64** 061603(R) (2001),
Machholm, Pethick, Smith, Phys.Rev A**67** 053613 (2003)

Definitions and scales

Optical lattice: $V(x) = sE_R \cos^2(kx)$

$d = \frac{\lambda}{2} = 0.39\ \mu\text{m}$	lattice spacing
$E_R = \frac{\hbar^2 k^2}{2m} = h \cdot 3.77\ \text{kHz}$	recoil energy
$\text{v}_\text{B} = \frac{q_B}{m} = \frac{\hbar k}{m} = 5.80\ \text{mm/s}$	Bragg velocity

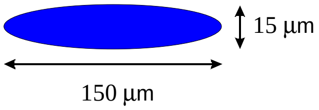


Bose-Einstein condensate of ^{87}Rb:

$\omega_z = 2\pi \times 9\ \text{Hz}$ $R_z = 75\ \mu\text{m}$

$\omega_\perp = 2\pi \times 90\ \text{Hz}$ $R_\perp = 7.5\ \mu\text{m}$

$N \approx 10^5$ atoms $\left| F = 1, m_F = -1 \right\rangle$



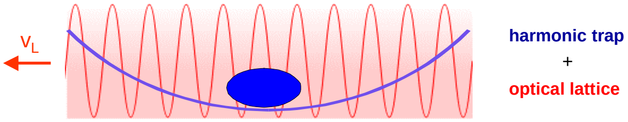
A typical BEC extends on ~10^3 lattice sites:

$$\Delta p \Delta z \approx \hbar \quad \rightarrow \quad \frac{\Delta p}{q_B} = \frac{\lambda}{2\pi \Delta z} = \frac{780\ \text{nm}}{2\pi\ 150\ \mu\text{m}} \approx 10^{-3}$$

The momentum spread of a BEC is a δ in the momentum space.

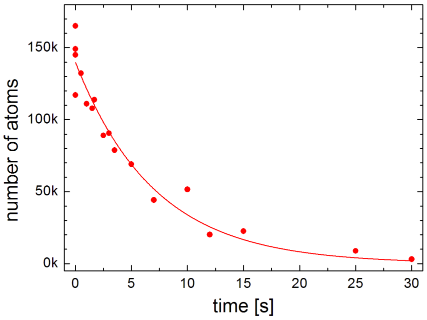
Instabilities of a BEC in a moving optical lattice

We adiabatically switch on a moving optical lattice in order to load the trapped BEC in a state with well defined quasimomentum q and band index n.

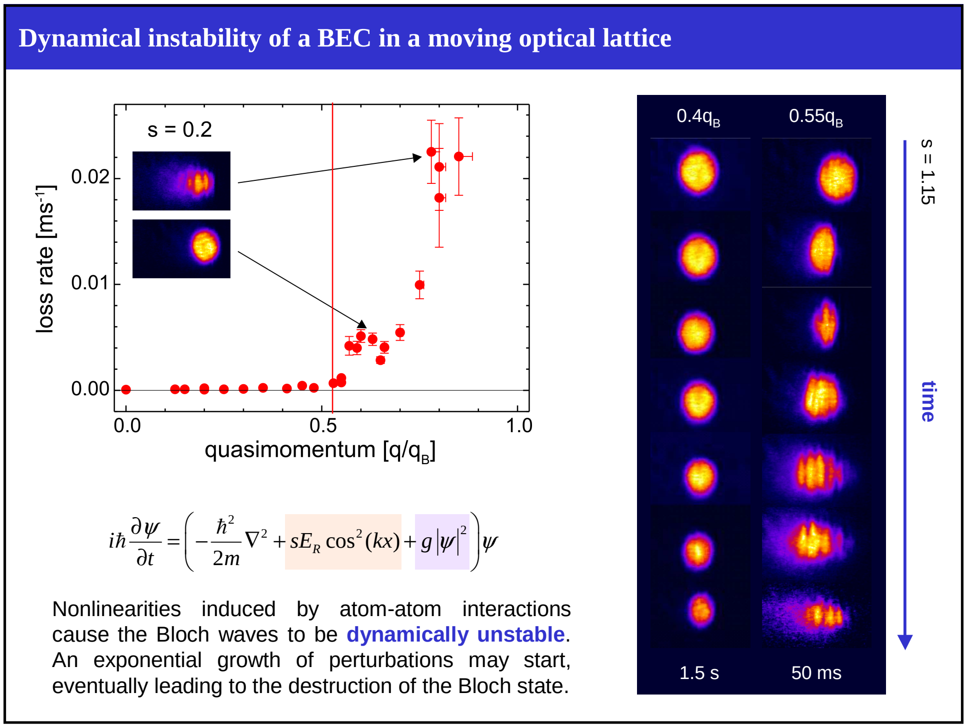


Since the time spent by the BEC in the lattice may be quite long (≈10 s) we use an RF-shield to remove the hottest atoms produced by heating of the sample.

After different evolution times in this potential we switch off both the magnetic trap and the lattice and measure the number of atoms in the BEC:



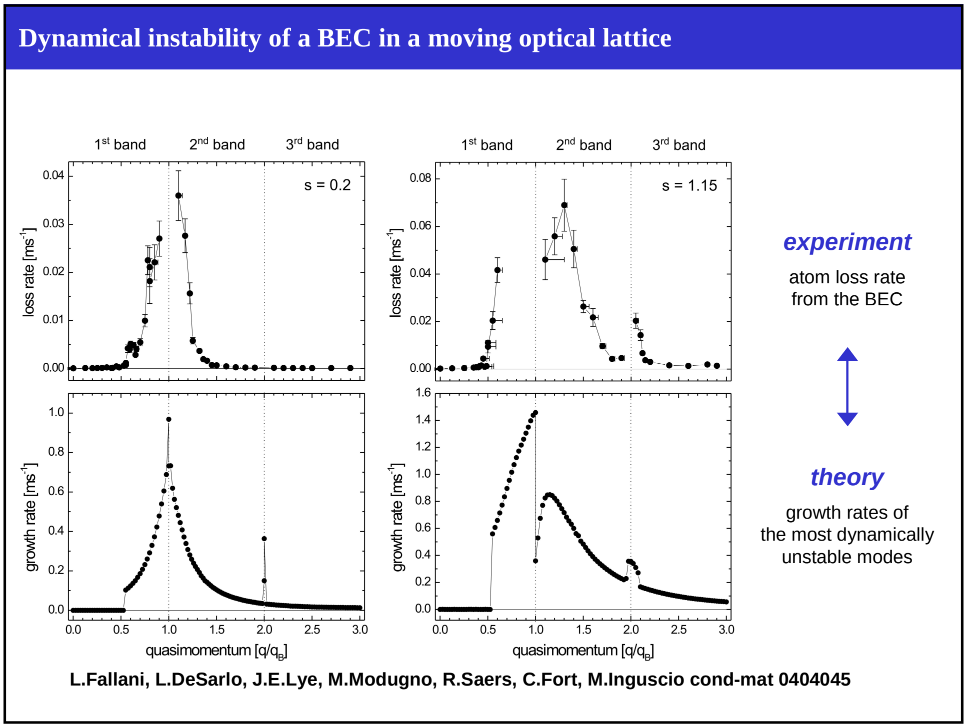
Exponential fit of number of atoms vs. time:



Dynamical instability of a BEC in a moving optical lattice

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

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.



Dynamical instability of a BEC in a moving optical lattice

experiment

atom loss rate
from the BEC

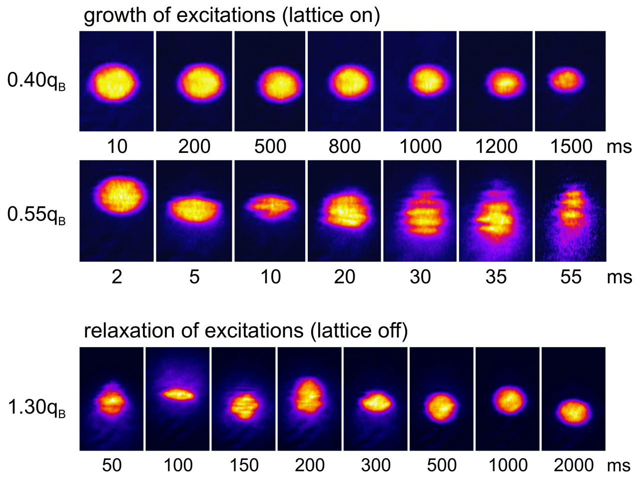
theory

growth rates of
the most dynamically
unstable modes

L.Fallani, L.DeSarlo, J.E.Lye, M.Modugno, R.Saers, C.Fort, M.Inguscio cond-mat 0404045

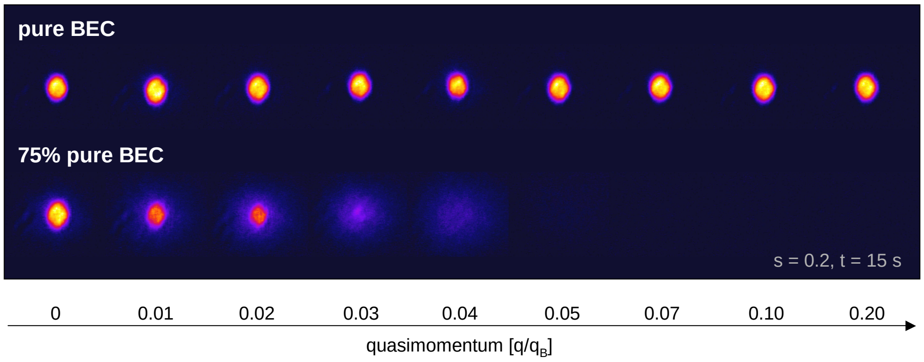
Dynamical instability of a BEC in a moving optical lattice

Uniformity can be restored …



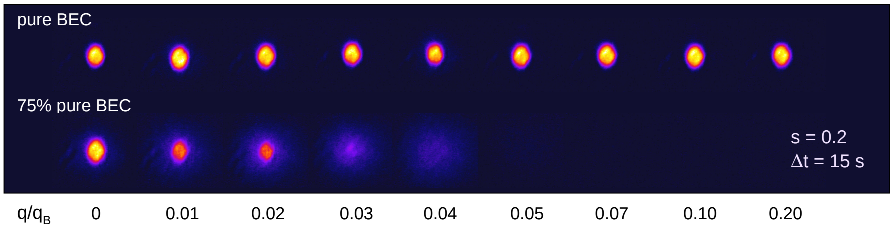
Energetic instability of a BEC in a moving optical lattice

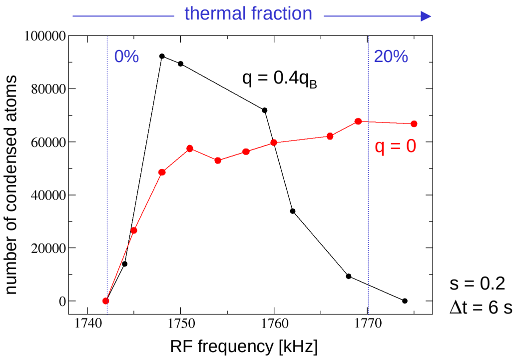
The presence of a small **thermal fraction** has a dramatic effect on the BEC lifetime in the moving lattice, causing the atomic sample to be completely destroyed in a much shorter time:



We attribute this behavior to the onset of **energetic instability** (in a inhomogeneous system), occurring in the presence of dissipative processes, as those provided by the thermal fraction.

Energetic instability of a BEC in a moving optical lattice



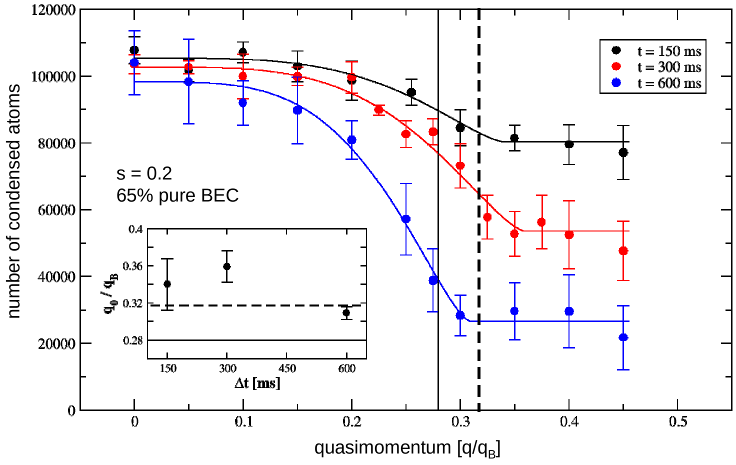


In presence of a thermal fraction, as soon as the optical lattice starts to move, the number of condensed atoms surviving after long times strongly decreases.

↓

A shallow optical lattice moving at low velocity works as a destructive detector of small thermal clouds surrounding the BEC.

Energetic instability of a BEC in a moving optical lattice



The threshold for the activation of energetic instability is not sharp, since the BEC is not homogeneous. Only a fraction of the BEC (dependent on q) has a local sound velocity higher than the velocity of the lattice (Landau criterion)

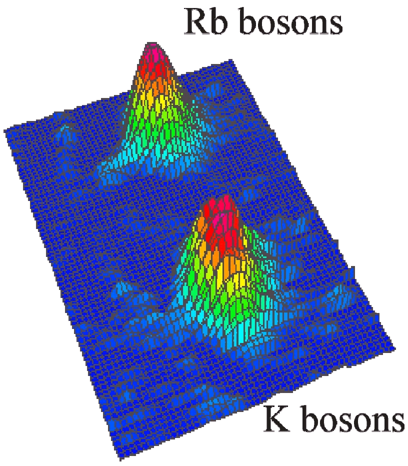
Energetic instability timescale:

$\tau \approx 400$ ms

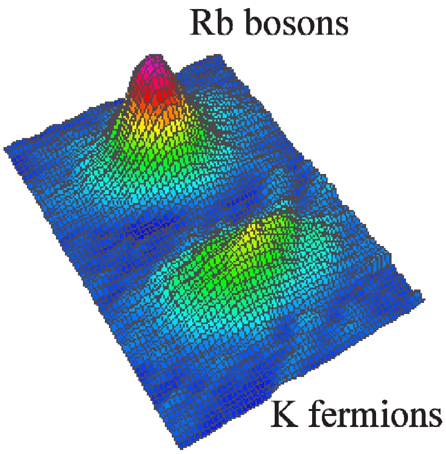
Dynamics in a 1D optical lattice

FERMIONS and THERMAL BOSONS

Atomic quantum mixtures

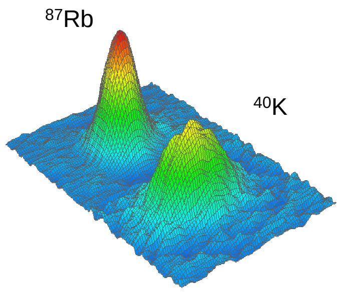


G. Modugno, G. Ferrari, G. Roati, R. Brecha, A. Simoni, and M. Inguscio ***Science*** **294, 1320 (2001)**

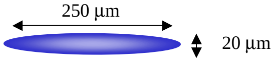


G. Roati , F. Riboli, G.Modugno, M. Inguscio Phys.Rev.Lett. 89, 150403 (2002).

The Fermi-Bose system



Fermi-Bose mixture in a magnetic trap



Numbers: $N_F, N_B = 10^4\text{-}10^5$

Temperatures: $< 0.5\ T_C$
$0.3\ T_F$

$$T_C = \frac{\hbar\overline{\omega}}{k_B}(N/1.2)^{1/3} \approx 150\,\text{nK}$$

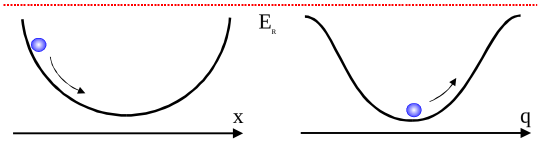
$$T_F = \frac{\hbar\overline{\omega}}{k_B}(6N)^{1/3} \approx 300\,\text{nK}$$

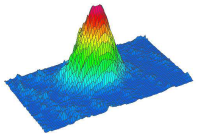
Spin-polarized fermions: no collisions

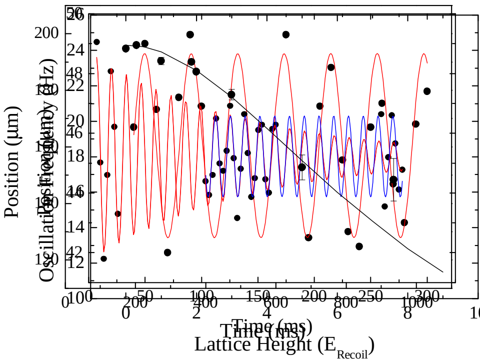
Spin mixtures of fermions, bosons or mixtures of bosons and fermions: adjustable collisions

Roati, Riboli, Modugno, Inguscio, PRL **89**, 150403 (2002).

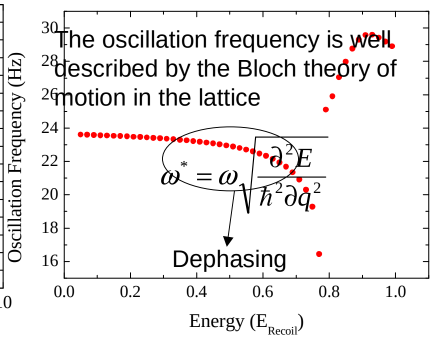
Fermions: shallow lattices







U=2 E_R E_F= 0.5E_R

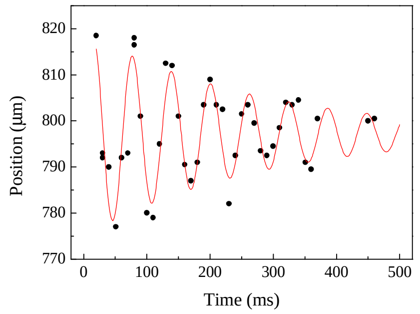


The oscillation frequency is well described by the Bloch theory of motion in the lattice

$$\omega^* = \omega\sqrt{\frac{\partial^2 E}{\hbar^2 \partial q^2}}$$

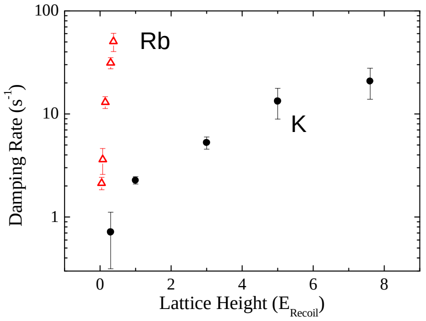
Dephasing

Transport of thermal bosons



Much larger damping in shallow lattices

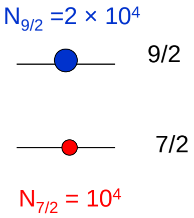
U=0.08 E_R k_BT=2 E_R

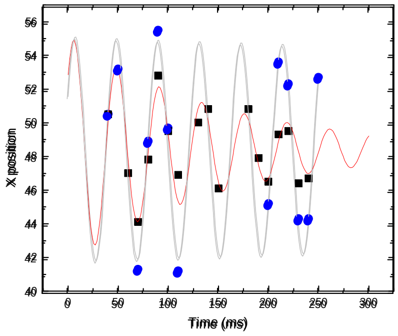


Collisions can assist the dephasing mechanism.

Fermions in two spin states

Add some m_F = 7/2 atoms: two colliding Fermi gases

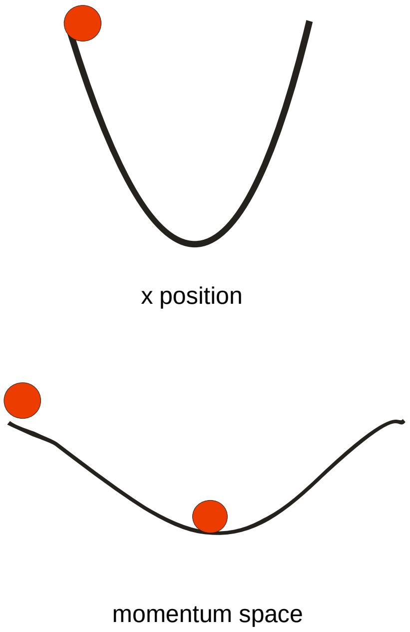




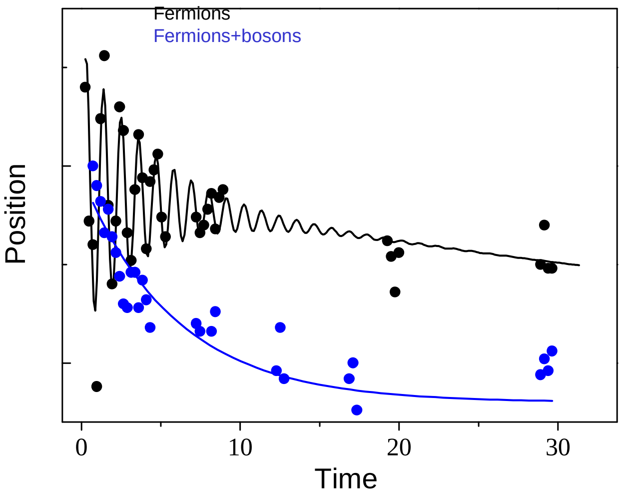
s = 0.6

T/T$_F$ = 0.5

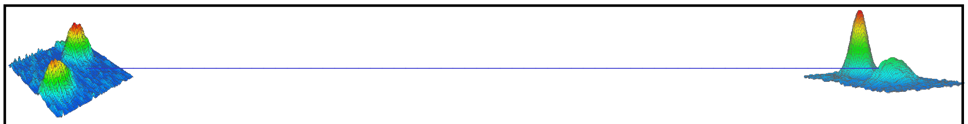
Larger damping due to the collisions as for thermal bosons.



Collision-induced transport in periodic potentials



Ott, de Mirandes, Ferlaino, Roati, Modugno, Inguscio Phys. Rev.Lett. 92, 160601 (2004)

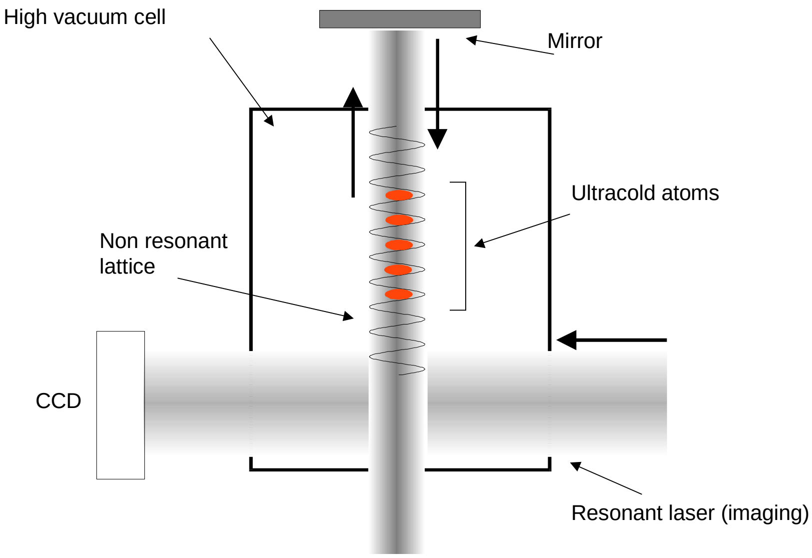


Dynamical instability of a BEC
Energetic instability of a BEC

Transport properties of fermions and bosons in a lattice
(Role of collisions)

Atomic Interferometry with Fermions

Interferometry with optical lattices



High vacuum cell

Mirror

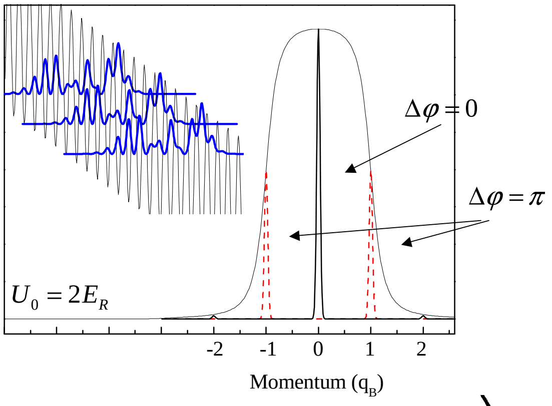
Ultracold atoms

Non resonant lattice

CCD

Resonant laser (imaging)

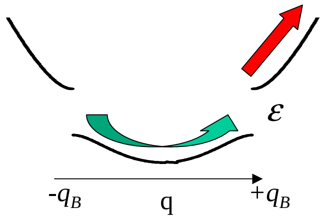
Wannier-Stark states



Energy spectrum in presence of gravity:

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

$$\Delta\varphi = \frac{\Delta E t}{\hbar}$$

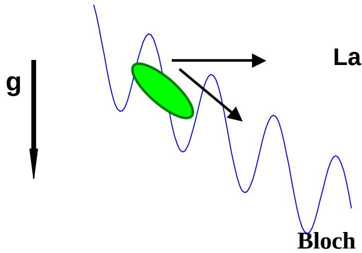


Semiclassical picture: Bloch oscillations

$$\dot{q} = -mg \qquad \omega_B = mg\lambda / 2\hbar$$

Linear external potential

Vertical lattice plus gravitational force: Bloch oscillations



Landau-Zener tunnelling $P = \exp(-\frac{\lambda\varepsilon^2}{8\hbar^2 g})$

Bloch oscillations period $T_B = \frac{2h}{mg\lambda}$

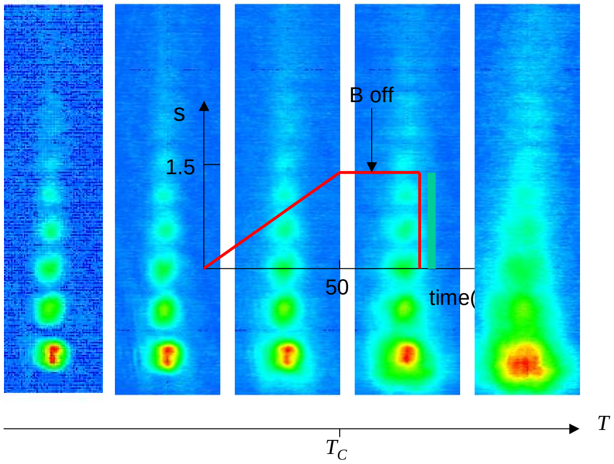
Shallow lattice: Zener tunnelling

$$P = \exp(-\frac{\lambda\varepsilon^2}{8\hbar^2 g})$$

$$U_0 = 1.5E_R$$

$$\Downarrow$$

$$P \approx 0.1$$

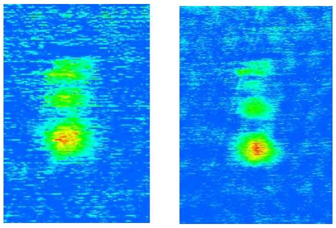


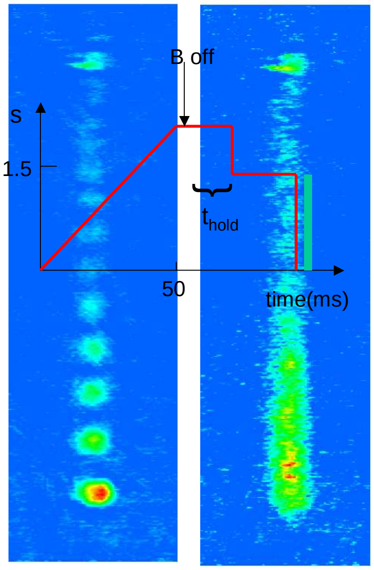
Spatially resolved Bloch oscillations of a BEC

YALE (1998), ENS (1996)

Fermi vs Bose

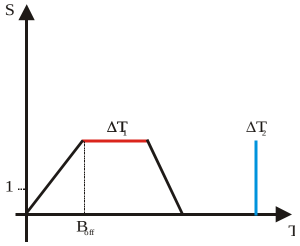
fermions

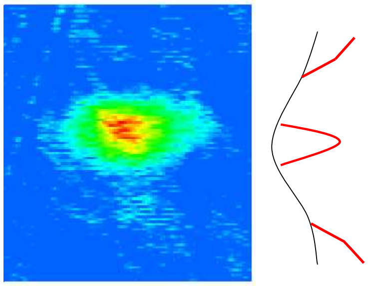

0 ms
7 ms



0 ms
2 ms

Time resolved Bloch oscillations





By adiabatically switching off the lattice, it is possible to map out the quasi-momentum states to momentum states: Bloch oscillations

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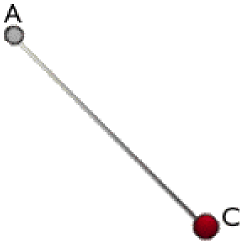
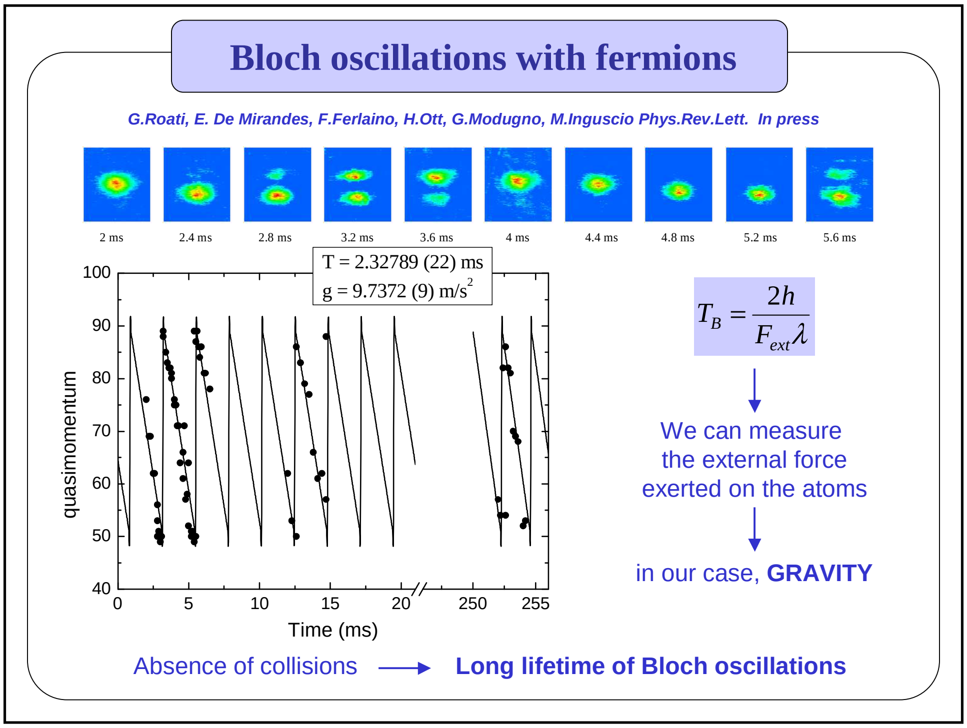
LONG LIVE FERMIONS !





Bloch oscillations with fermions

G.Roati, E. De Mirandes, F.Ferlaino, H.Ott, G.Modugno, M.Inguscio Phys.Rev.Lett. In press

$$T_B = \frac{2h}{F_{ext}\lambda}$$

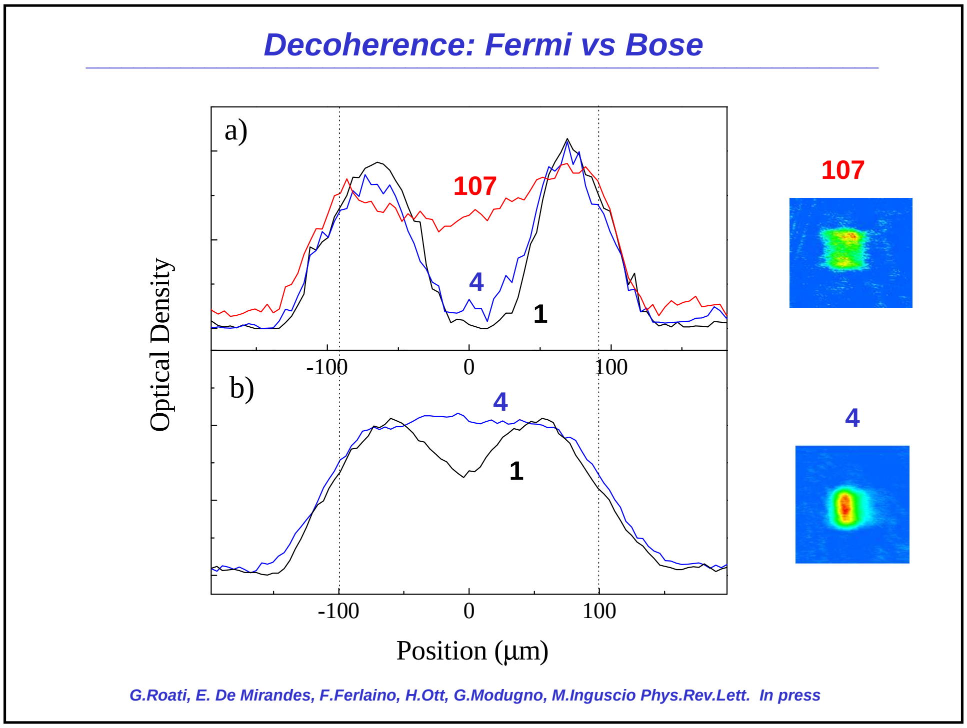
↓

We can measure the external force exerted on the atoms

↓

in our case, **GRAVITY**

Absence of collisions ⟶ **Long lifetime of Bloch oscillations**



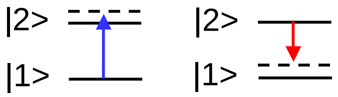
Decoherence: Fermi vs Bose

G.Roati, E. De Mirandes, F.Ferlaino, H.Ott, G.Modugno, M.Inguscio Phys.Rev.Lett. In press

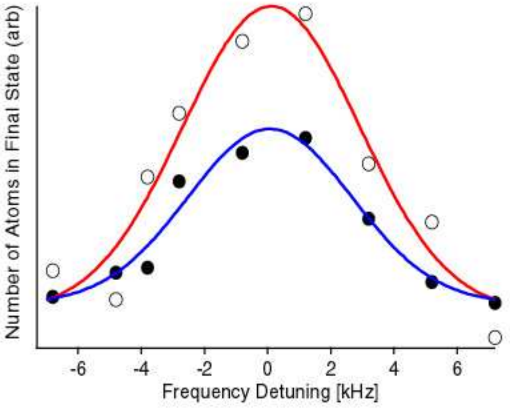
Absence of the clock shift for fermions

“Expected” splitting
of the blue and the red line:

$$\boxed{2\Delta\nu = \frac{4\hbar}{m} n a_{12} \sim 10kHz}$$



blue shift red shift
(a_{12}>0)



S. Gupta *et al.*, Science **300**, 1723 (2003)

A high spatial resolution interferometer

Trapped samples: high spatial resolution

In principle limited just by the extension of Wannier-Stark states: for K at λ=830 nm $\Delta z = 2\delta / F < 4\mu\mathrm{m}$, and decreases exponentially with increasing U.

Long-lived oscillations of fermions: high sensitivity

Presently limited by a broadening of the momentum distribution to $10^{-4}g$ over 100 oscillations: it can be improved

High accuracy:

Only h and m are in principle involved in the measurement of gravitational forces, but the trap might affect the measure

Possible applications:

Forces close to surfaces, Casimir, gravity at small length scales, …

Non-newtonian forces

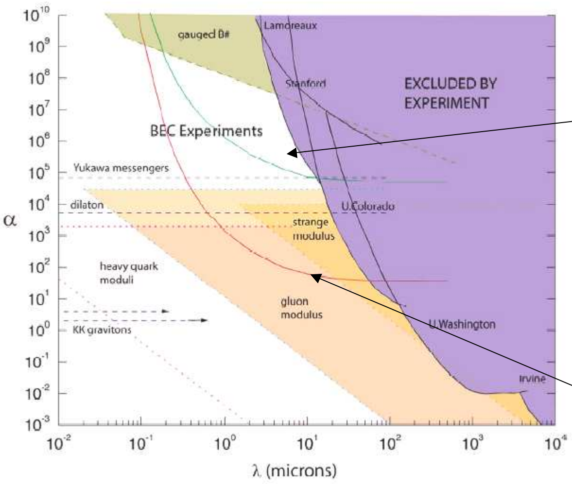


FIG. 1. Experimental bounds and theoretical expectations on new forces from potentials of the form $V(r)=-G_N(m_1m_2/r)(1+\alpha e^{-r/\lambda})$ below 1 cm. The projected reach of the first-round BEC experiments is shown as the upper "BEC Experiments" line. The lower line indicates the reach with an improved sensitivity of 10^{-7} Hz. Experimental data are from Refs. [8–10,14,15]. The shown theoretical expectations are discussed in the text.

S. Dimopulos and A. A. Geraci, Phys. Rev. D 68, 124021 (2003)

"Quantum gases" people in Firenze