Fermi gases in optical lattices

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Introduction

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 — ETHZ, Munich, NIST

Fermi gases in optical lattices: not many experiments, … but many interesting theoretical proposals: strongly correlated systems, reduced dimensionality, high Tc superfluidity, detection of superfluidity, …

We study non-interacting fermions in a 1D lattice and make a comparison with interacting systems

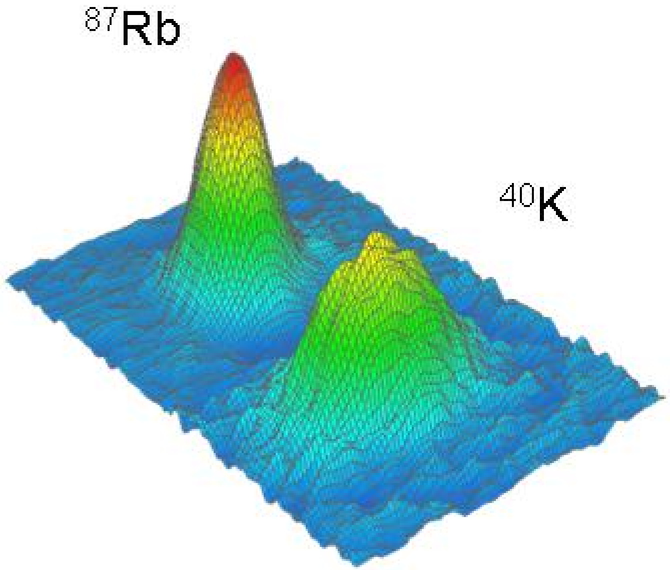
Outline

- Insulating behavior of non-interacting Fermi gases in harmonic potentials

- Collisions and transport

- Atom interferometry with trapped Fermi gases and precision measurements

The atomic system



Fermi-Bose mixture in a magnetic trap

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

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

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

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

Spin-polarized fermions: no collisions

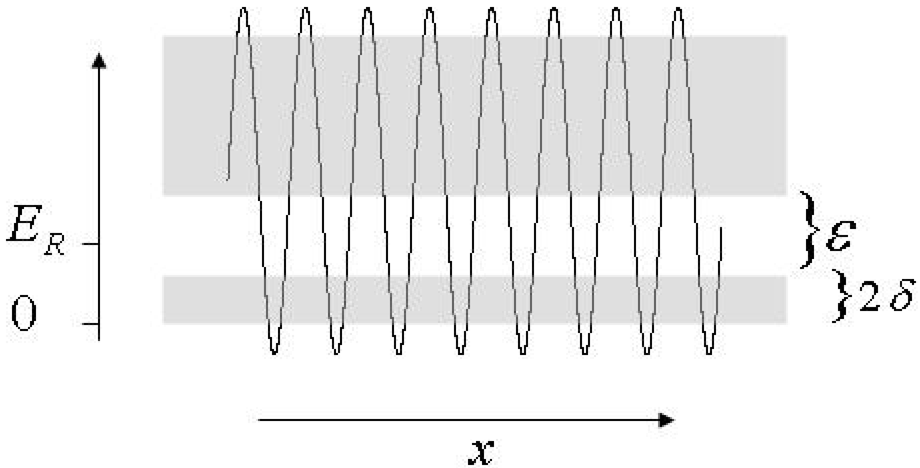
Spin mixtures of fermions, bosons or mixtures of bosons and fermions: adjustable collisions

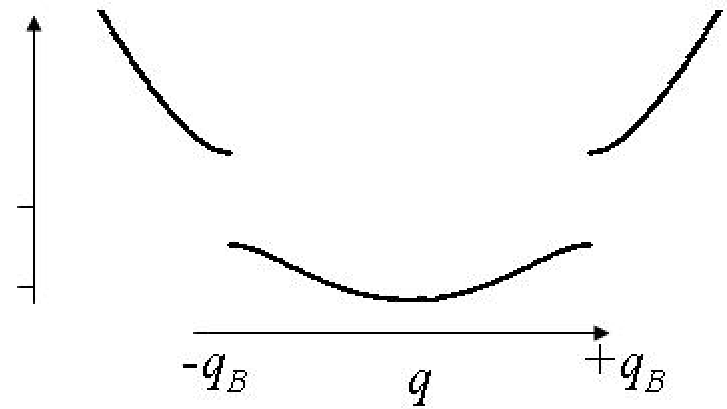
Roati, Riboli, Modugno, Inguscio, PRL **89**, 150403 (2002).

1D optical lattice

$$U(x) = U_0(1 + \cos(4\pi \quad x/\lambda))$$

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





BEC: only the ground state is occupied

Fermions: the position of Fermi energy is relevant

$$\lambda = 870\mathrm{nm} \quad \Rightarrow \quad \mathrm{E_R} \approx k_B T_F \approx k_B T_C$$

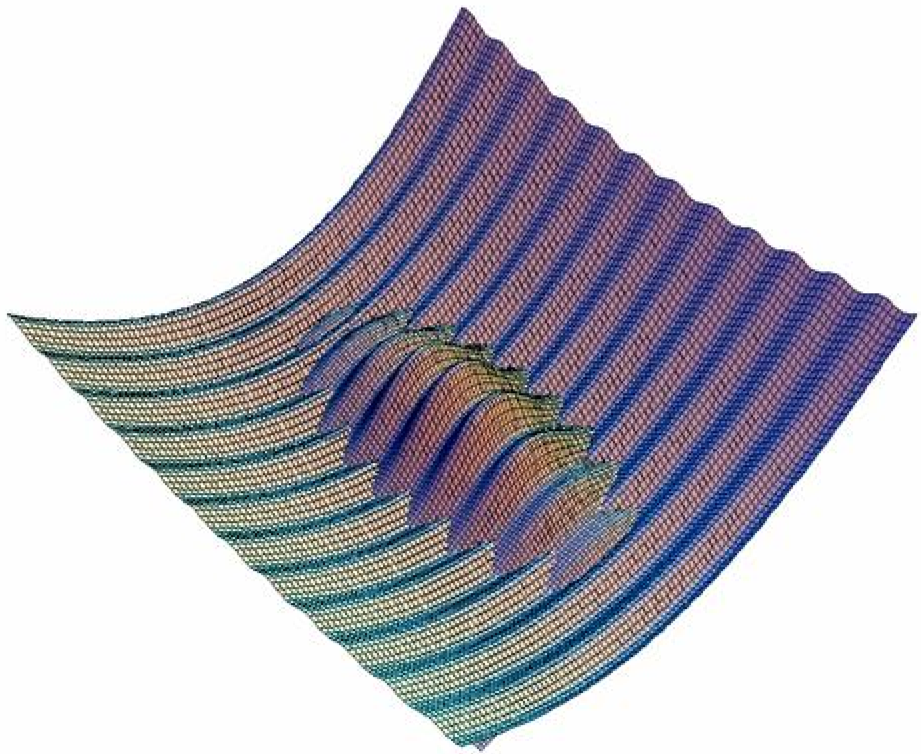
Outline

- **Insulating behavior of non-interacting Fermi gases in harmonic potentials**

- Collisions and transport

- Atom interferometry with trapped Fermi gases and precision measurements

Optical lattice + harmonic potential



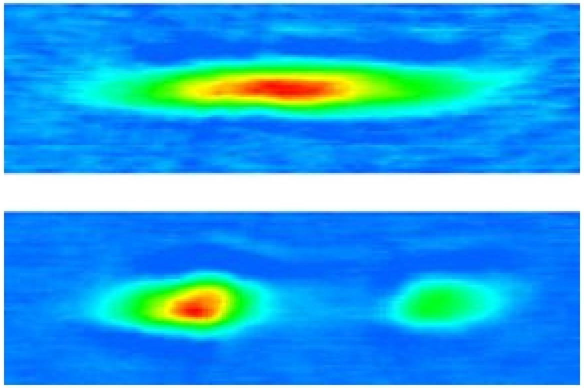
Localization in harmonic potentials

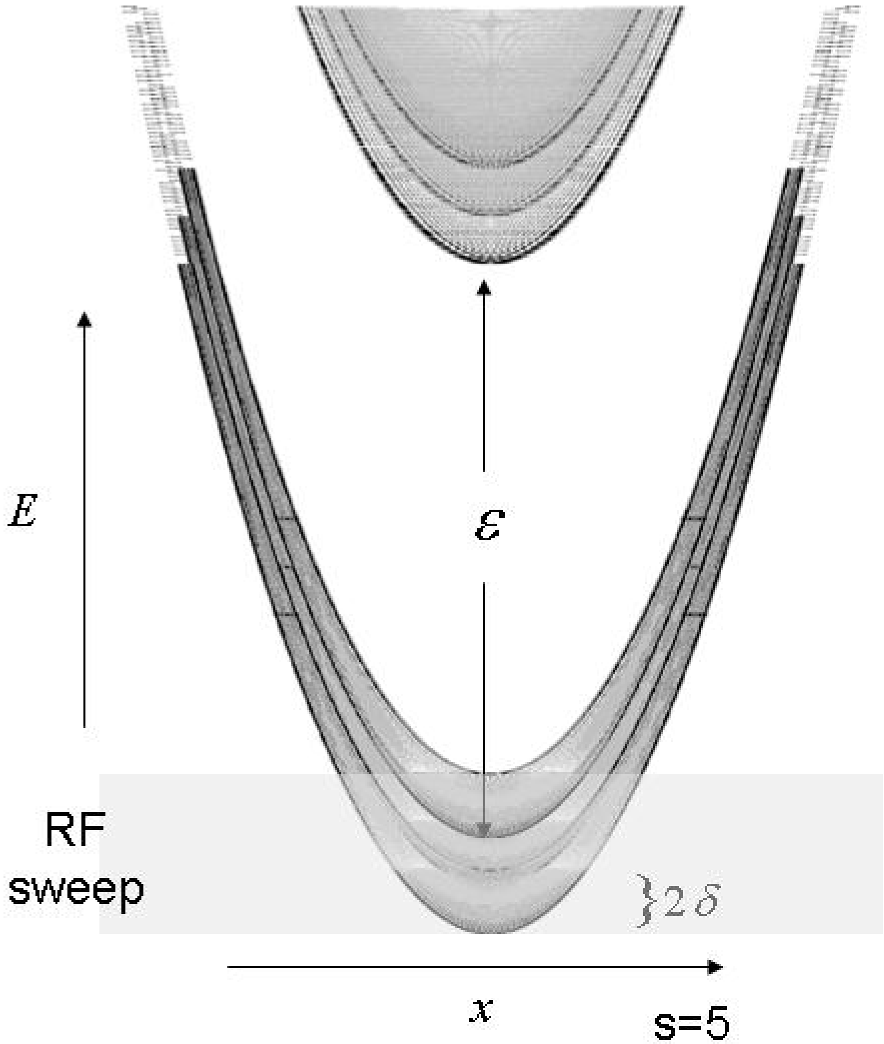
Numerical solution of the 1D Schrödinger equation

$$\mathrm{H} = \frac{p^2}{2m} + \frac{m\omega^2 x^2}{2} + s\frac{E_R}{2}(1-\cos(4\pi x/\lambda))$$

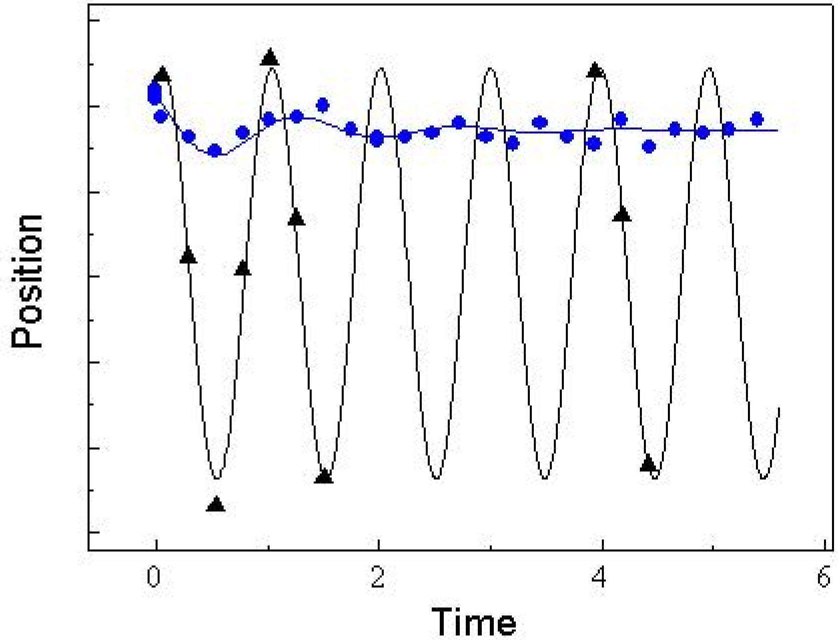
Delocalized states within the first band

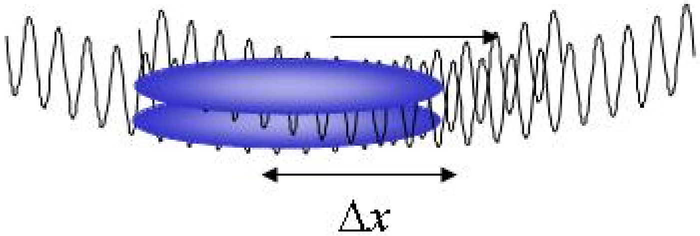
localized states in the gap





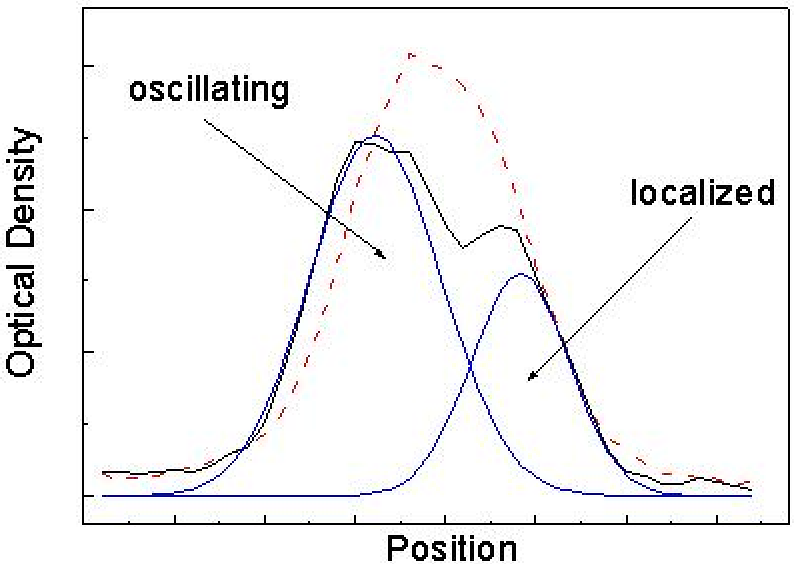
Dipole oscillations





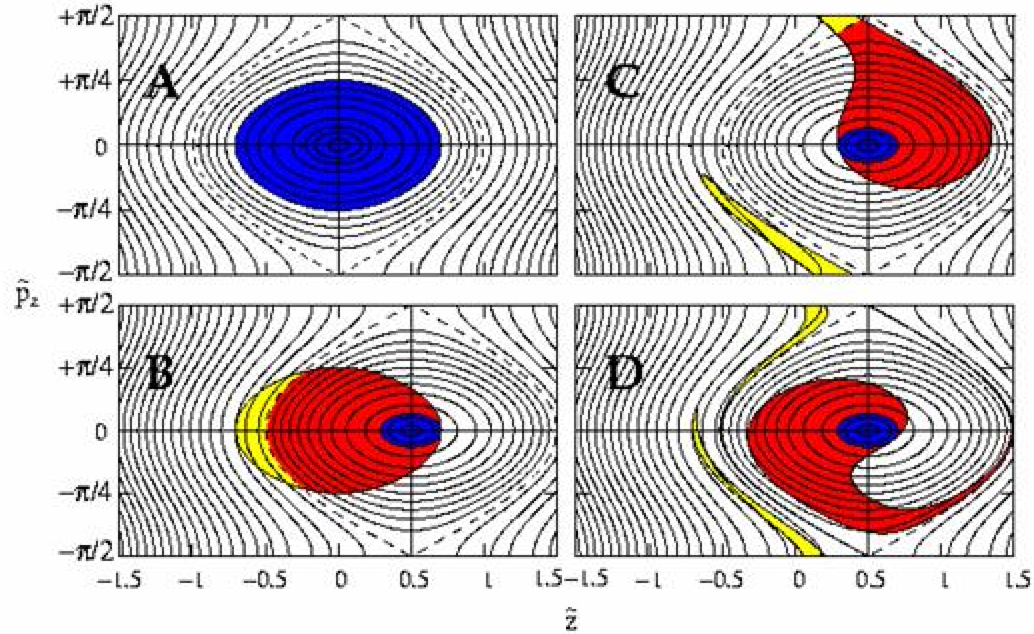
Offset: localized states

Oscillations: delocalized states



Modugno, Ferlaino, Heidemann, Roati, Inguscio, PRA **68**, 011601(R) (2003).

Dipole oscillations

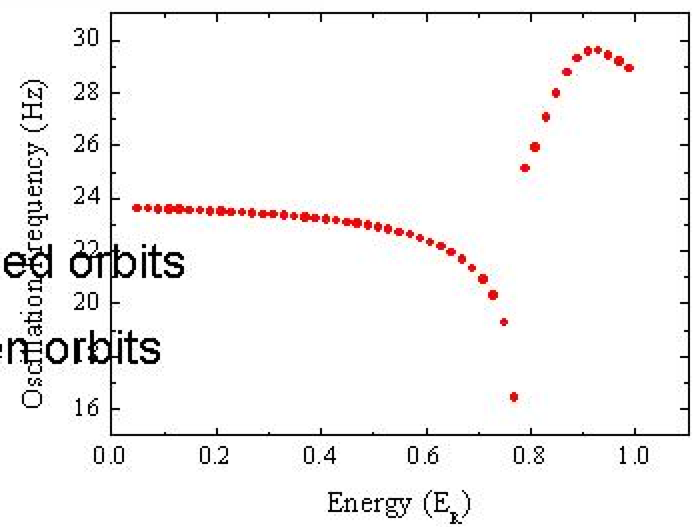


Semiclassical model:

Damping: dephasing of single particle orbits

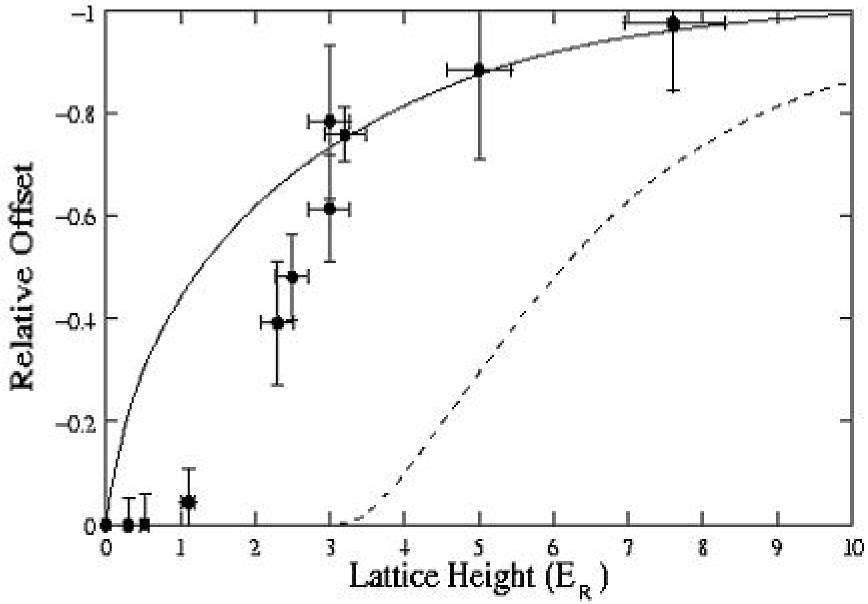
Delocalized states ⟷ closed orbits

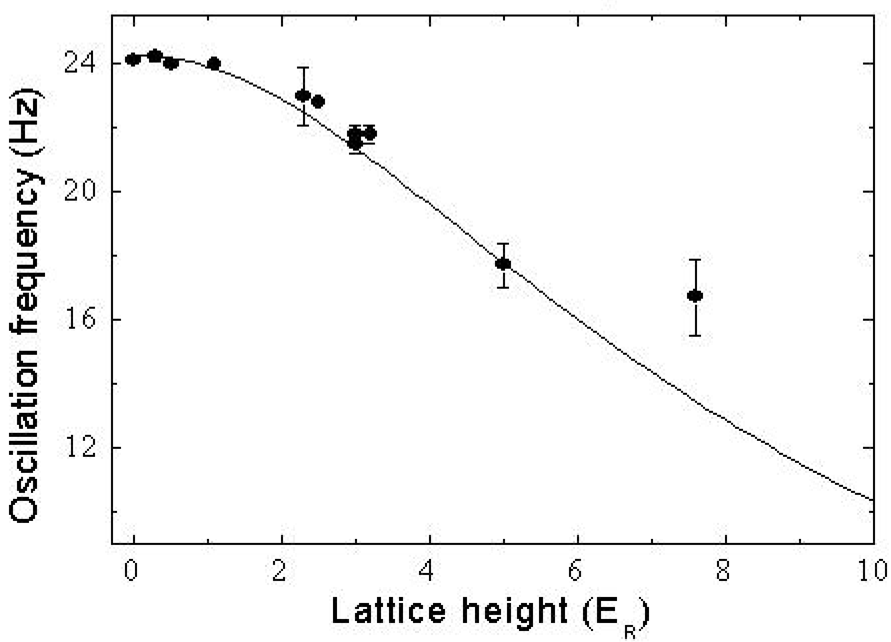
Localized states ⟷ open orbits



Pezzè, Pitaevski, Smerzi, Stringari , Modugno, de Mirandes, Ferlaino, Ott, Roati, Inguscio, cond-mat/0401643

Dipole oscillations

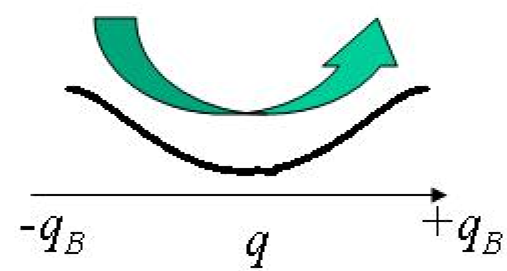




Crossover from a conducting to an insulating behavior

Macroscopic insulation of a non interacting system of particles under an external force: incoherent Bloch oscillations

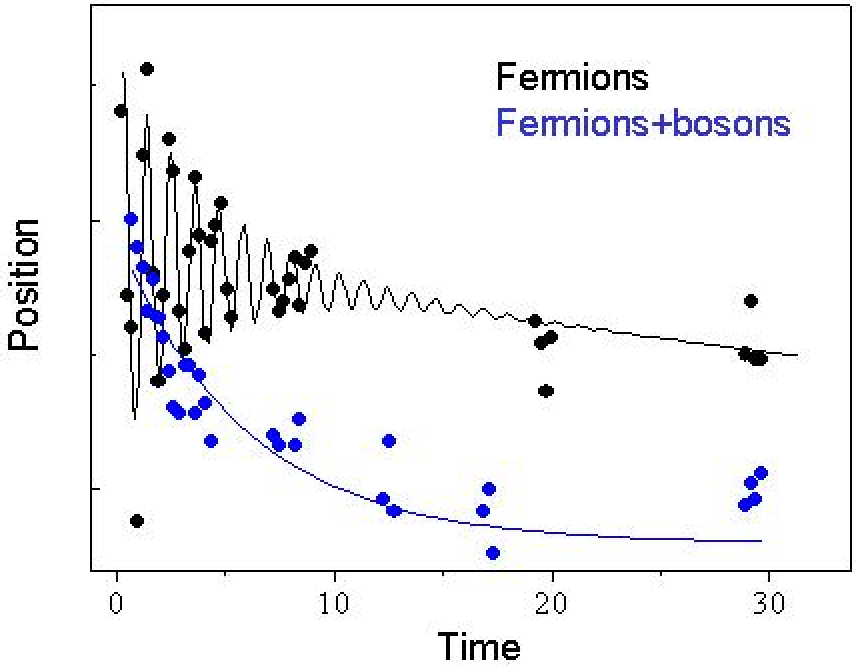
$$\dot{q} = F$$



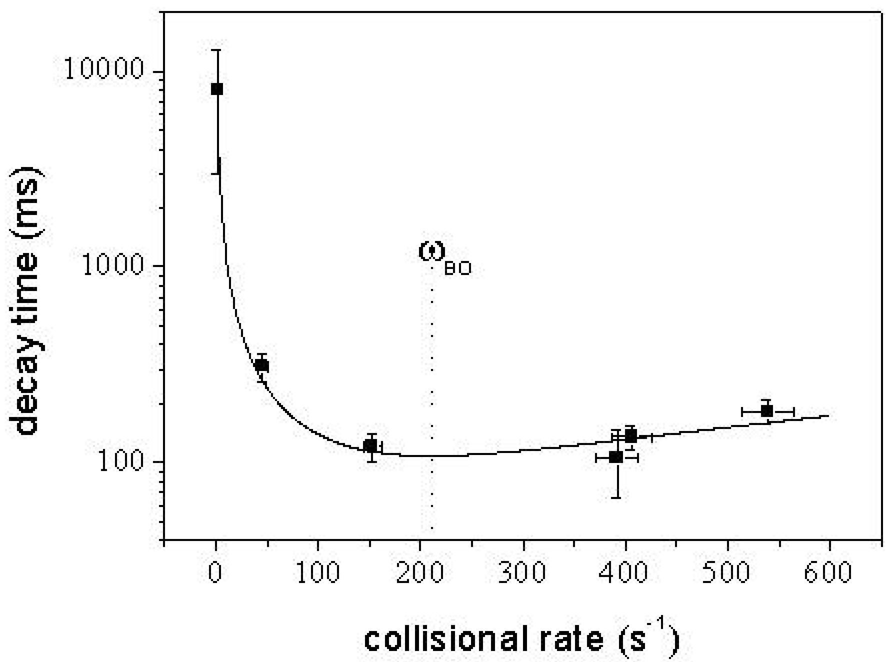
Outline

- Insulating behavior of non-interacting Fermi gases in harmonic potentials
- **Collisions and transport**
- Atom interferometry with trapped Fermi gases and precision measurements

Collision-induced transport



Collisional decay of localized states in fermion-boson mixtures:
transition from an ideal insulator to a real conductor



Esaki-Tsu model for drift of electrons in superlattices:

$$v_d \propto 2\delta \frac{\omega_{BO}\tau}{1+(\omega_{BO}\tau)^2}$$

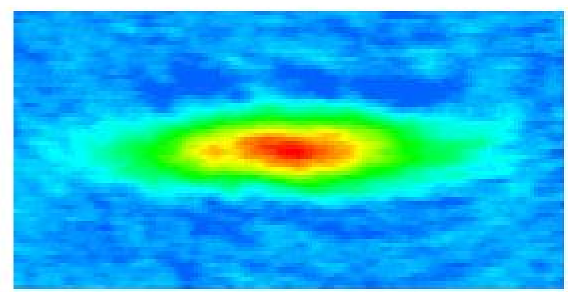
$$2\delta = E_R \exp(-s/3.8) \qquad \omega_{BO} = F\lambda/2\hbar$$

Ott, de Mirandes, Ferlaino, Roati, Modugno, Inguscio, PRL in press; cond-mat/0311261.

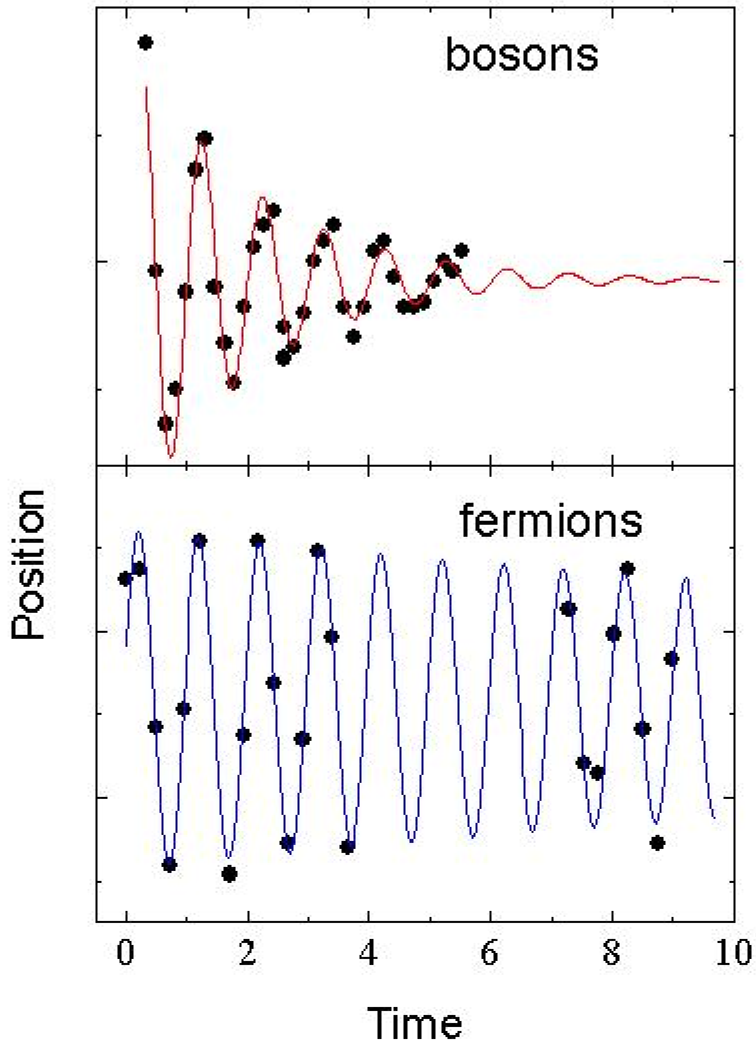
Collision-induced transport

Experiment with bosons: selective removal of delocalized states by means of radiofrequency

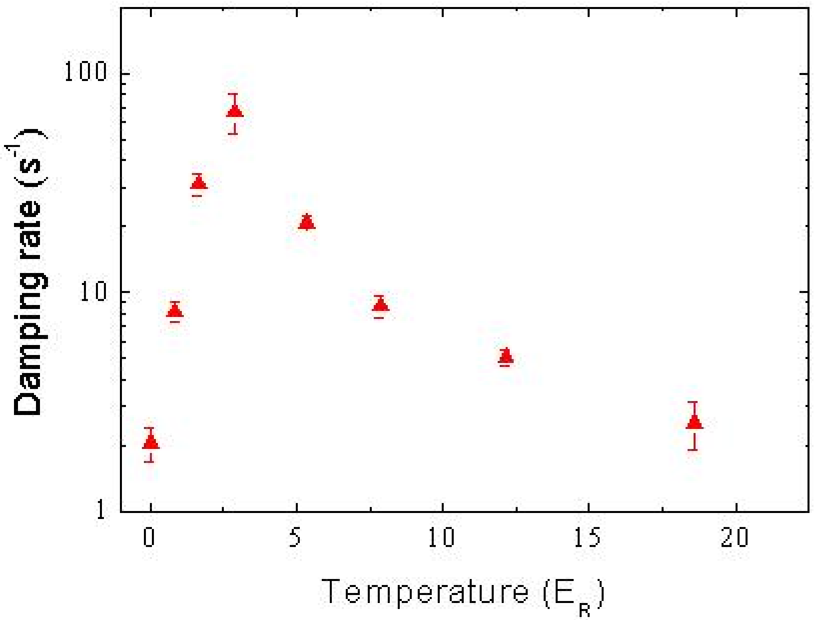
Localized states decay to the trap center through collisions.

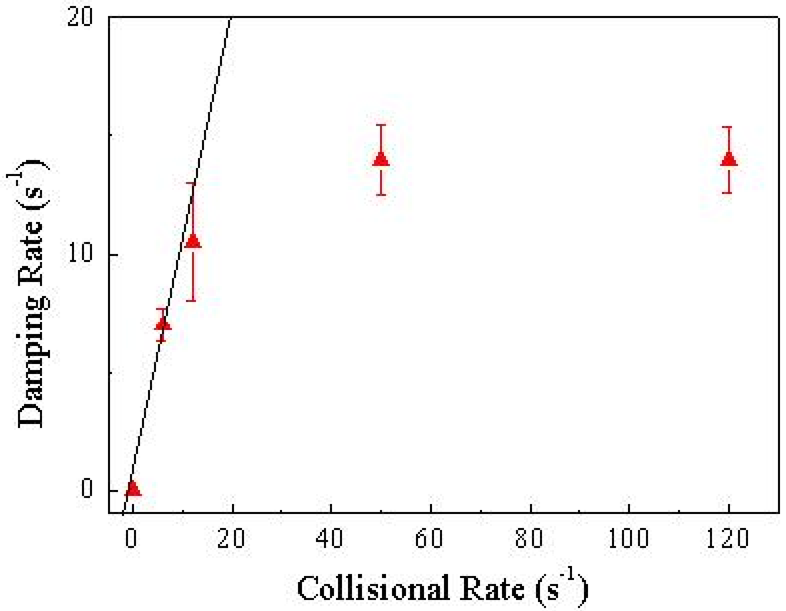


Interactions in shallow lattices



Shallow lattices





Outline

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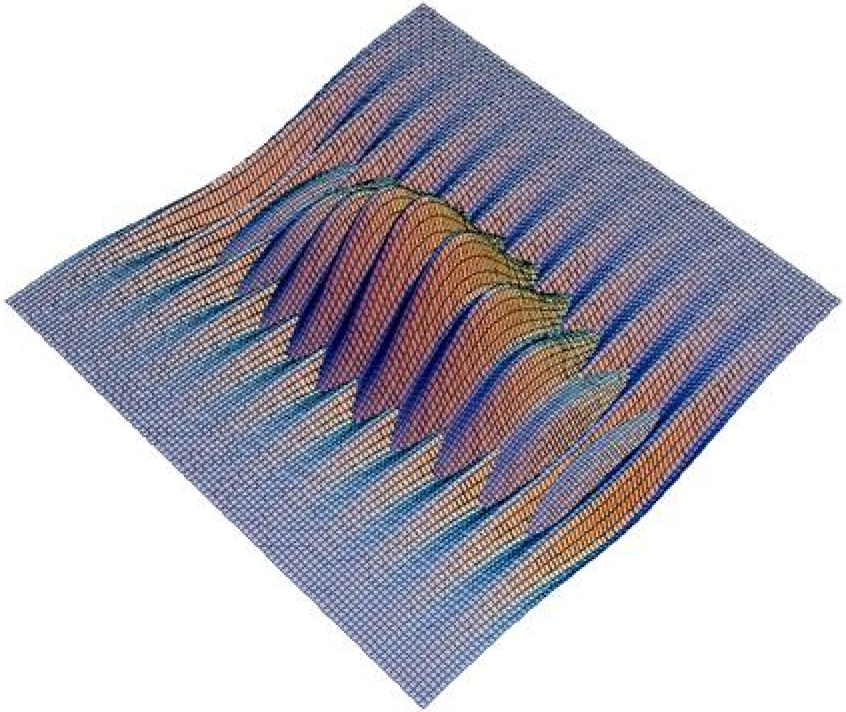
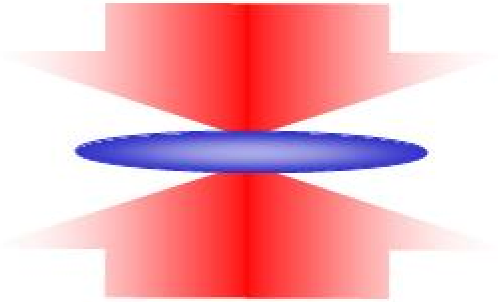
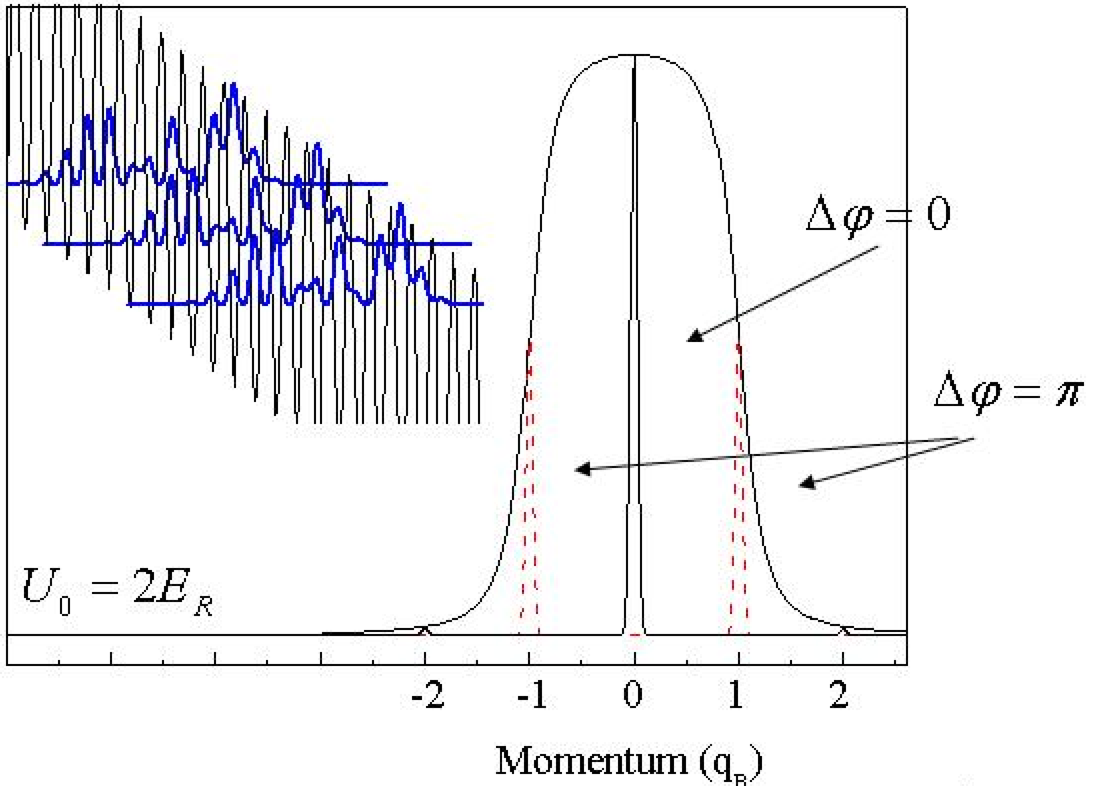
- **Atom interferometry with trapped Fermi gases and precision measurements**

Optical lattice + gravity





Wannier-Stark states



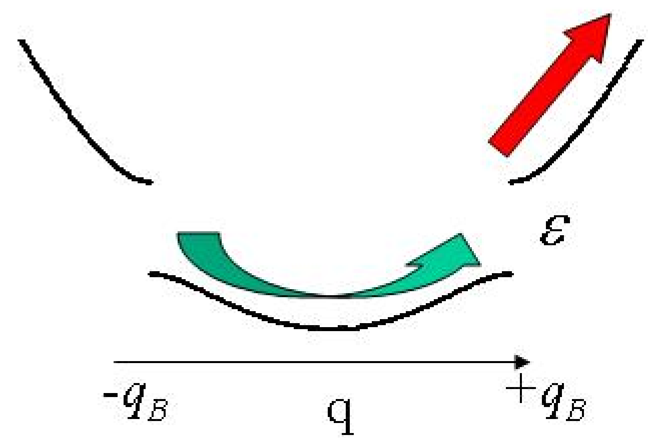
Energy spectrum in presence of gravity:

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

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

Semiclassical picture: Bloch oscillations

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



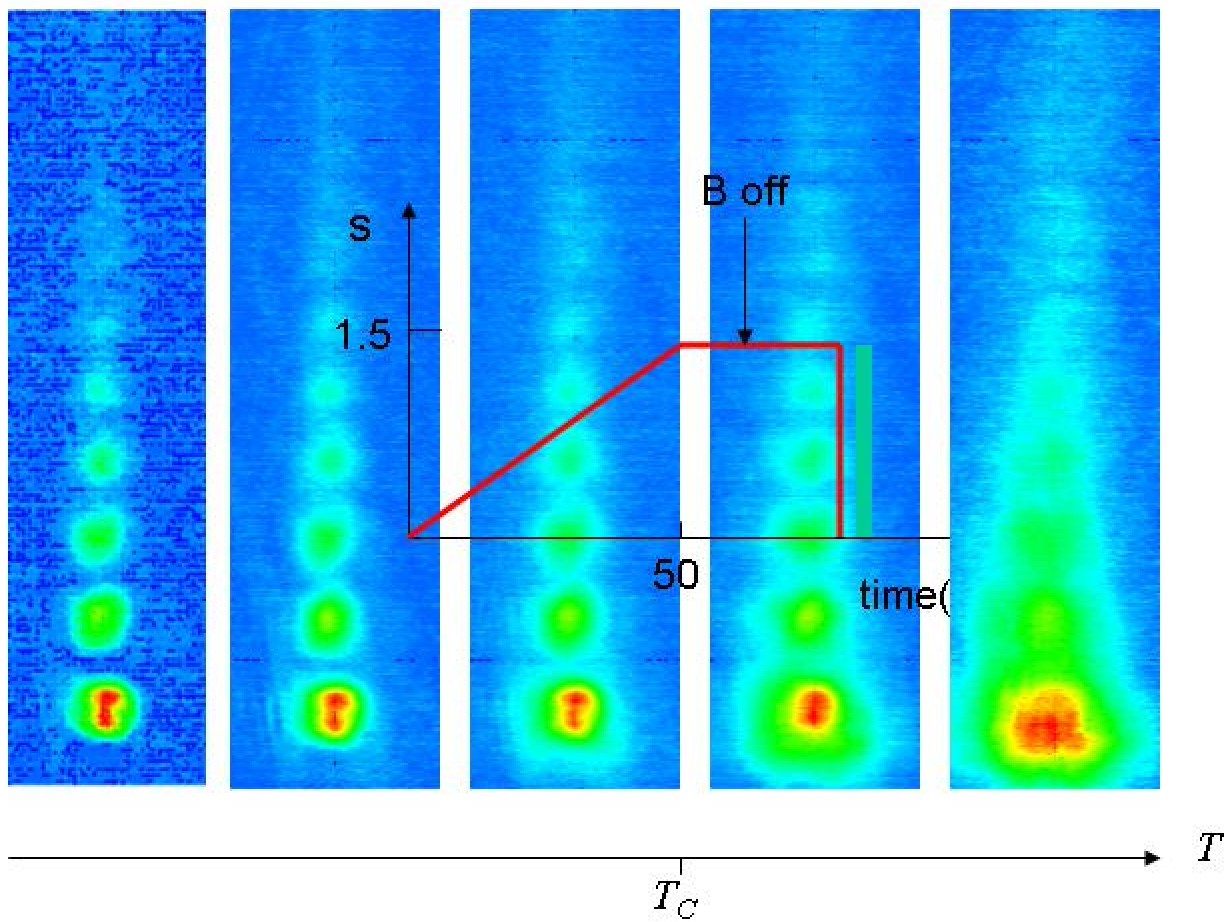
Shallow lattice: Zener tunnelling

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

$$U_0 = 1.5 E_R$$

$$\Downarrow$$

$$P \approx 0.1$$

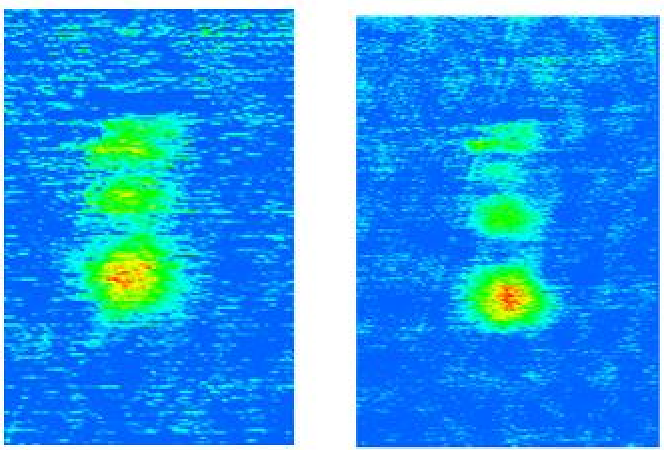


Spatially resolved Bloch oscillations of a BEC

YALE (1998), ENS (1996)

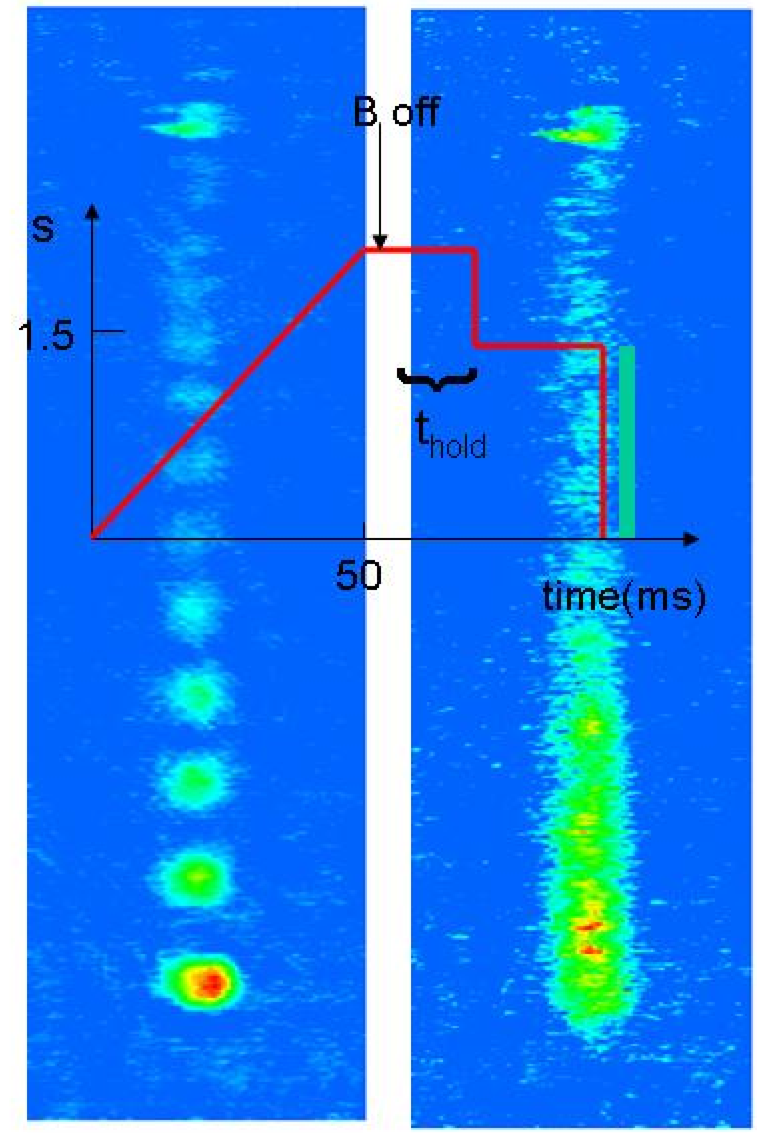
Fermi vs Bose

Bloch oscillations of fermions



0 ms

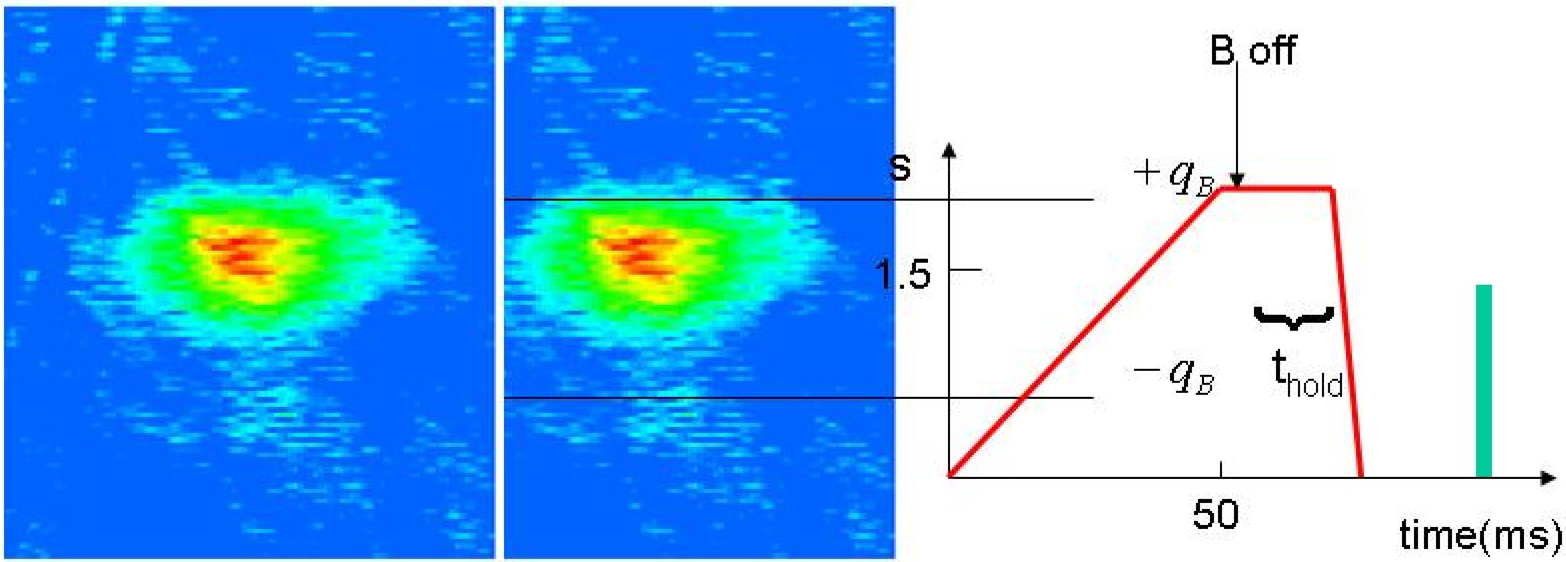
7 ms



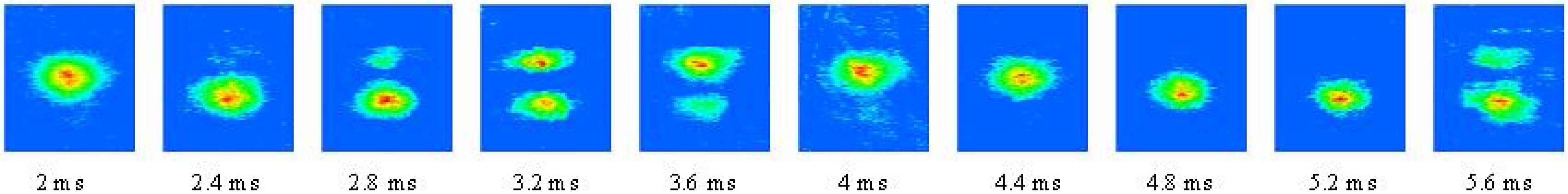
0 ms

2 ms

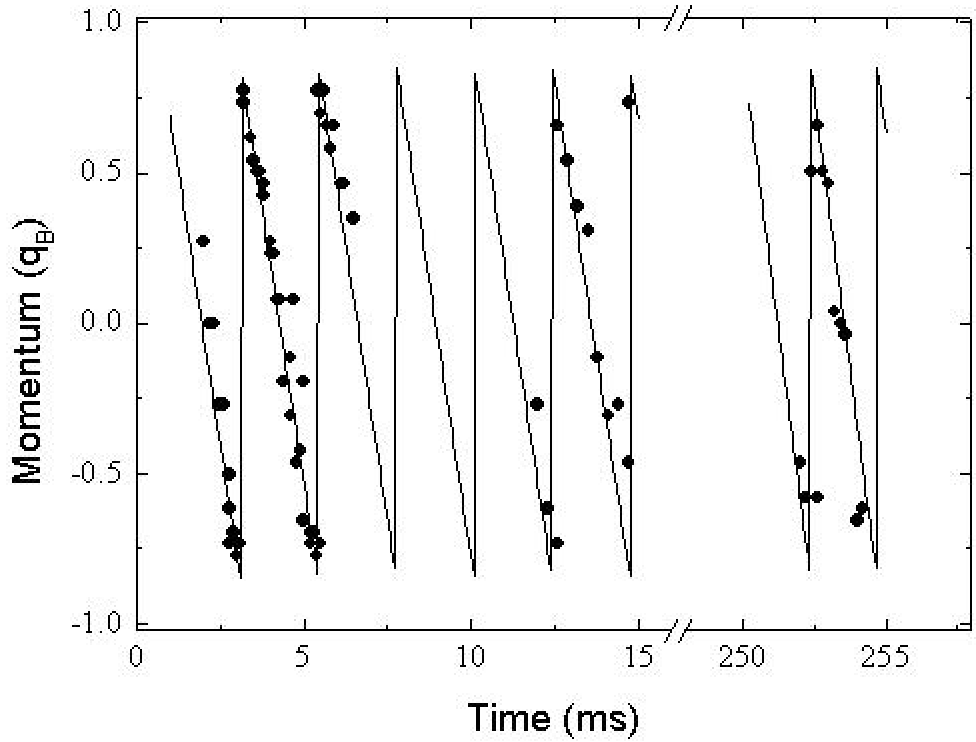
Tight lattices



Time-resolved Bloch oscillations of non-interacting fermions



Long lived Bloch oscillations: determination of g

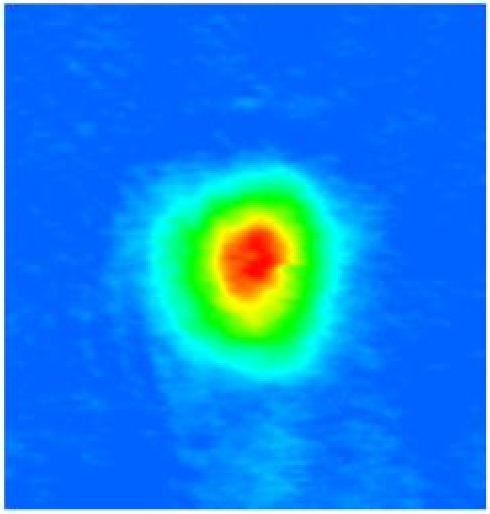


Bloch oscillations period under gravity: $T_B = 2h/mg\lambda$

We measure: $T_B = 2.32789(22)\text{ms} \quad \Rightarrow \quad g = 9.7372(9)\text{m/s}^2$

Roati, de Mirandes, Ferlaino, Ott, Modugno, Inguscio, cond-mat/0402328

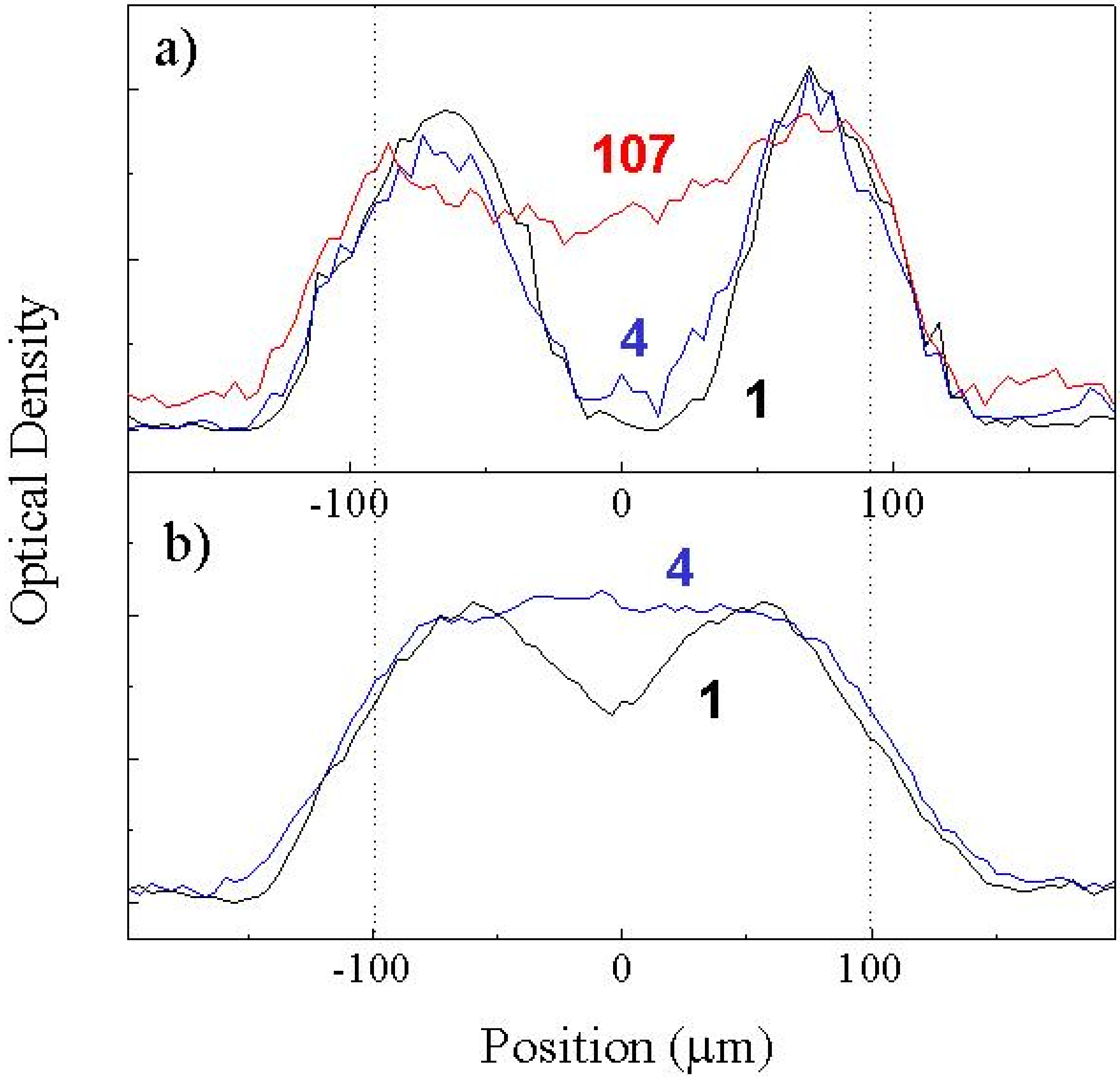
What about using a BEC?



$$T_B = 1.13ms$$

The interaction energy masks the much narrower momentum distribution of the BEC

Decoherence: Fermi vs Bose



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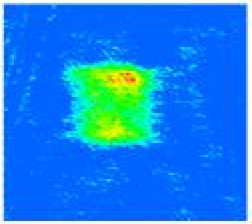

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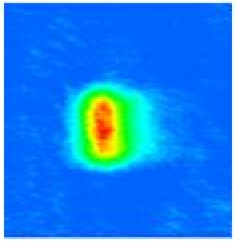


A high spatial resolution interferometer

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, gravity at small length scales, ...

Non-newtonian forces

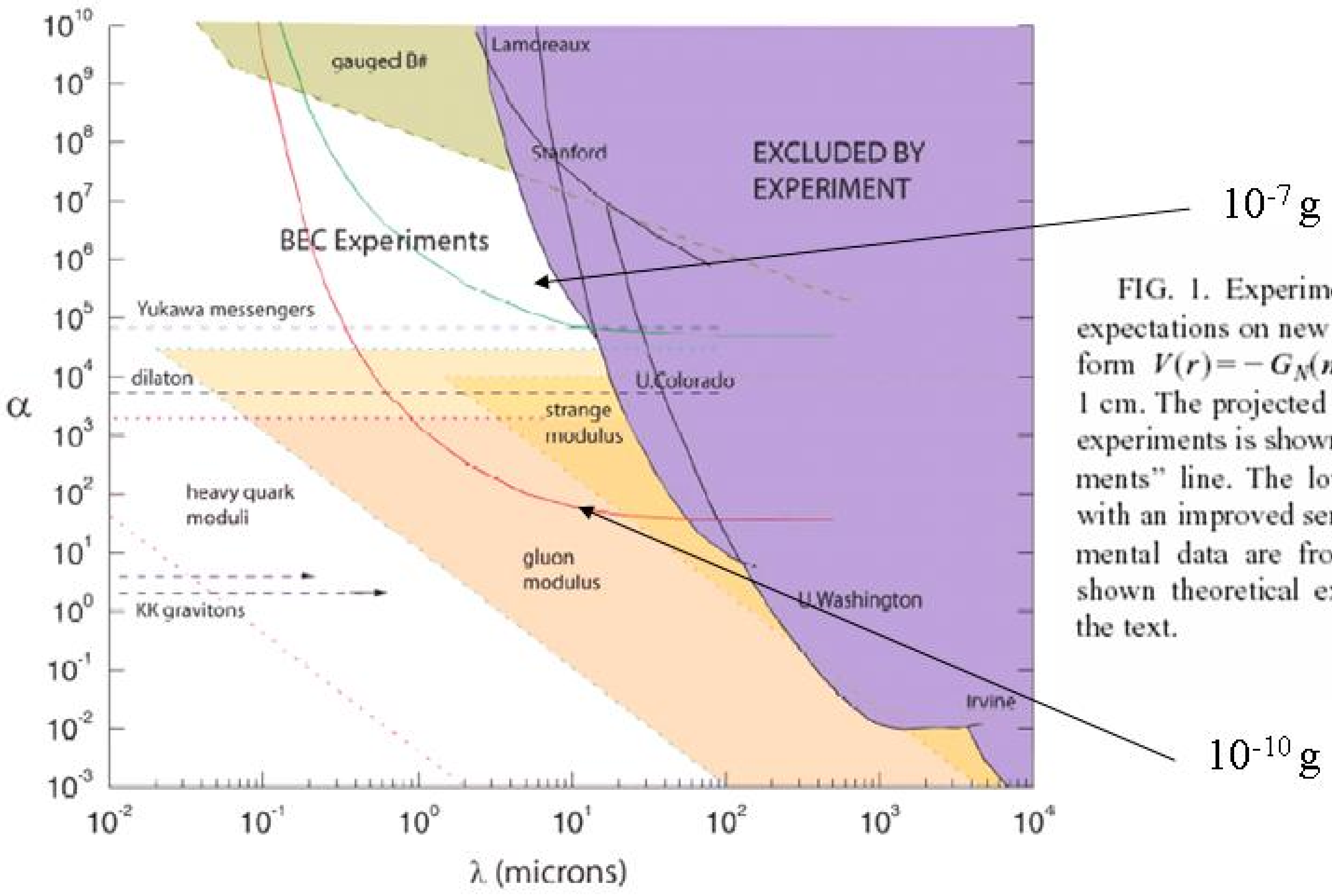


FIG. 1. Experimental bounds and theoretical expectations on new forces from potentials of the form $V(r) = -G_N(m_1 m_2/r)(1+\alpha e^{-r/\lambda})$ below 1 cm. The projected reach of the first-round BEC experiments is shown as the upper "BEC Experiments" line. The lower line indicates the reach with 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)

Optical dipole forces?

Ideal 1D optical lattice:

$$U(z) = U_0(1+\cos(4\pi \quad z/\lambda))$$

"External" optical force

$$F_{ext} = \frac{\partial U}{\partial z} = 0$$

Realistic 1D optical lattice with two beams:

$$U(z,r) = U_0(1+\cos(4\pi \quad z/\lambda))\exp(-r^2/2w_r^2)\exp(-(z-z_0)^2/2w_z^2)$$

$$\boxed{\frac{\partial U}{\partial z} \neq 0}$$

In the experiment we have checked the absence of dipole forces at the $10^{-4}g$ level

Present limitations to sensitivity (time-dependent momentum broadening)

Longitudinal curvature

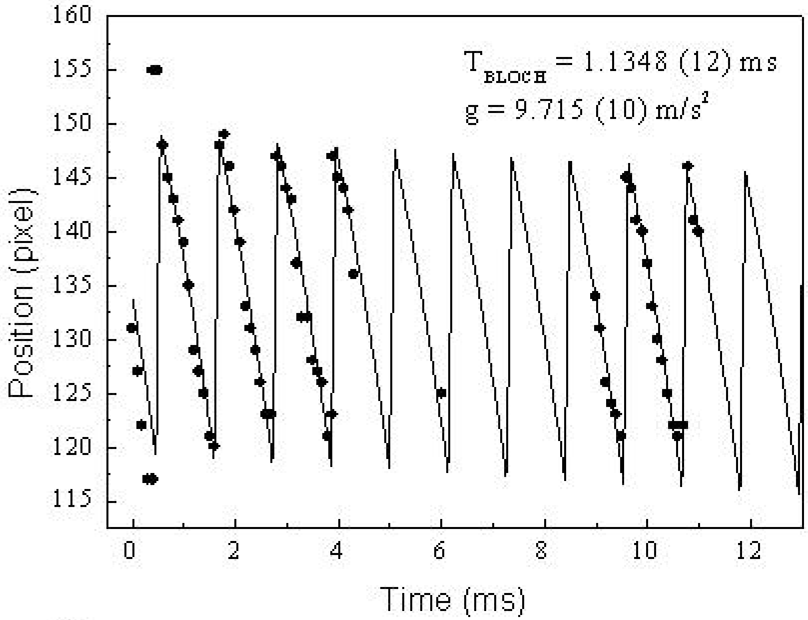
$$\frac{\partial^2 U}{\partial z^2} \neq 0$$

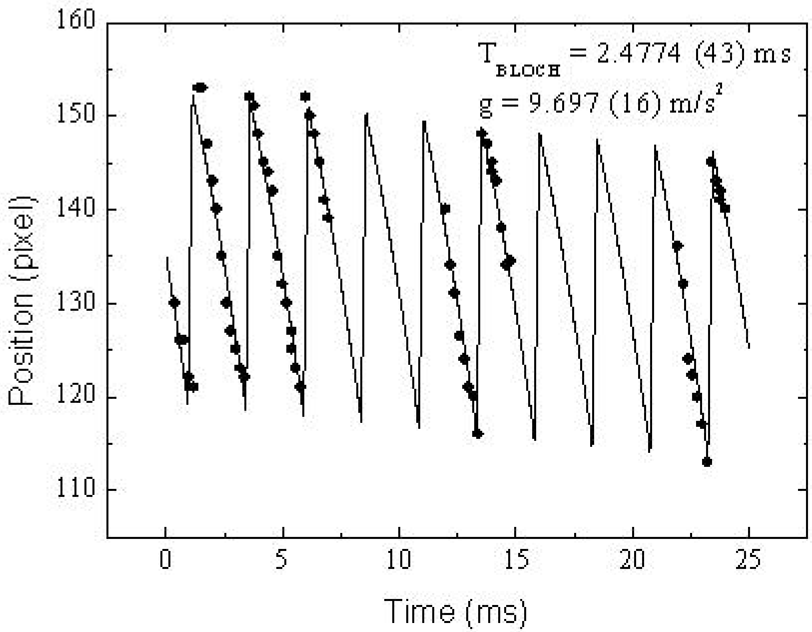
Ergodic radial-longitudinal mixing

$$U(r,z) \neq U(r) + U(z)$$

Phase fluctuations of the lattice

Accuracy: magnetic forces?





Fermions have a magnetic moment:

$$F = mg + \mu B$$

$$\mu = \mu_B$$

Magnetic forces can be measured independently using two different ratios

$$\mu / m$$

different internal states

different masses

Conclusions

Non-interacting fermions in optical lattices + external potentials

⬇

Long-lived localization of particles

- Insulating behavior of trapped Fermi gases in traps
- Atom interferometry with Fermi gases
- Interactions:
  - Collision-induced delocalization and transport
  - Collision-induced damping of dipole oscillations
  - Decoherence of Bloch oscillations of a BEC

Implications for: superfluid dynamics of fermions in lattices, interacting Fermi and Fermi-Bose systems in optical lattices, quantum computing, ...