A quantum degenerate Bose gas in 1D

Kioloa Workshop
5 December 2004

experiments at the

National Institute of Standards and Technology
Gaithersburg, Maryland, USA

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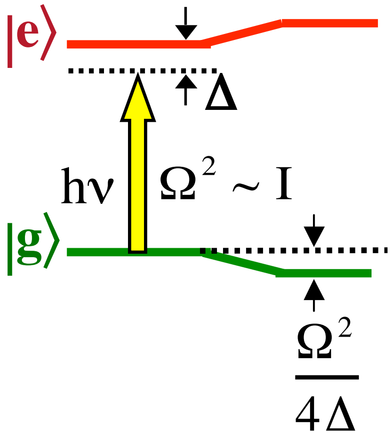
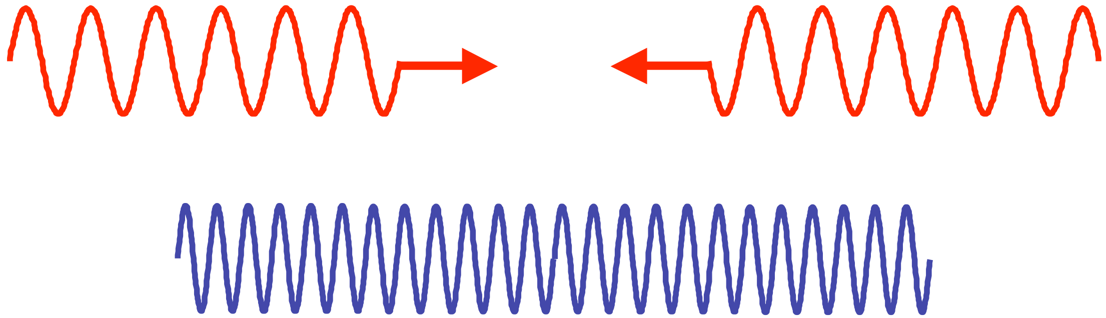
$upport: Office of Naval Research, NASA, and
ARDA/NSA (for quantum information applications)

An optical lattice holds and manipulates atoms through the light shift

Light shift



Counter-propagating laser beams

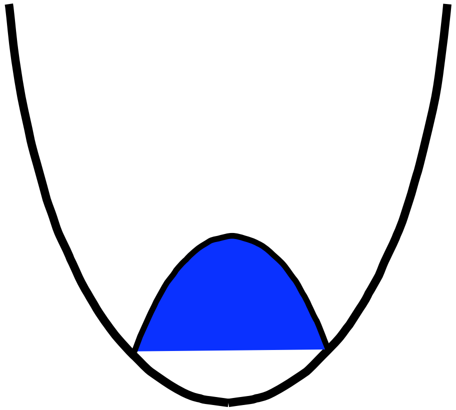


create a standing wave. Periodic light-shift potential = optical lattice.

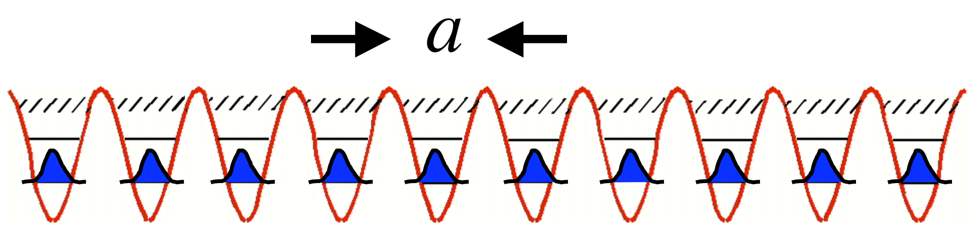
Photon scattering (decoherence) ~ Ω^2/Δ^2 so decoherence can be made negligible with large detuning and high power

A BEC in a optical lattice

Load a BEC, in a harmonic, magnetic trap…

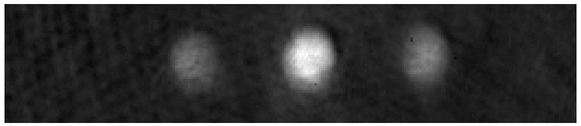


…into an optical lattice by "adiabatically" turning on the laser beams



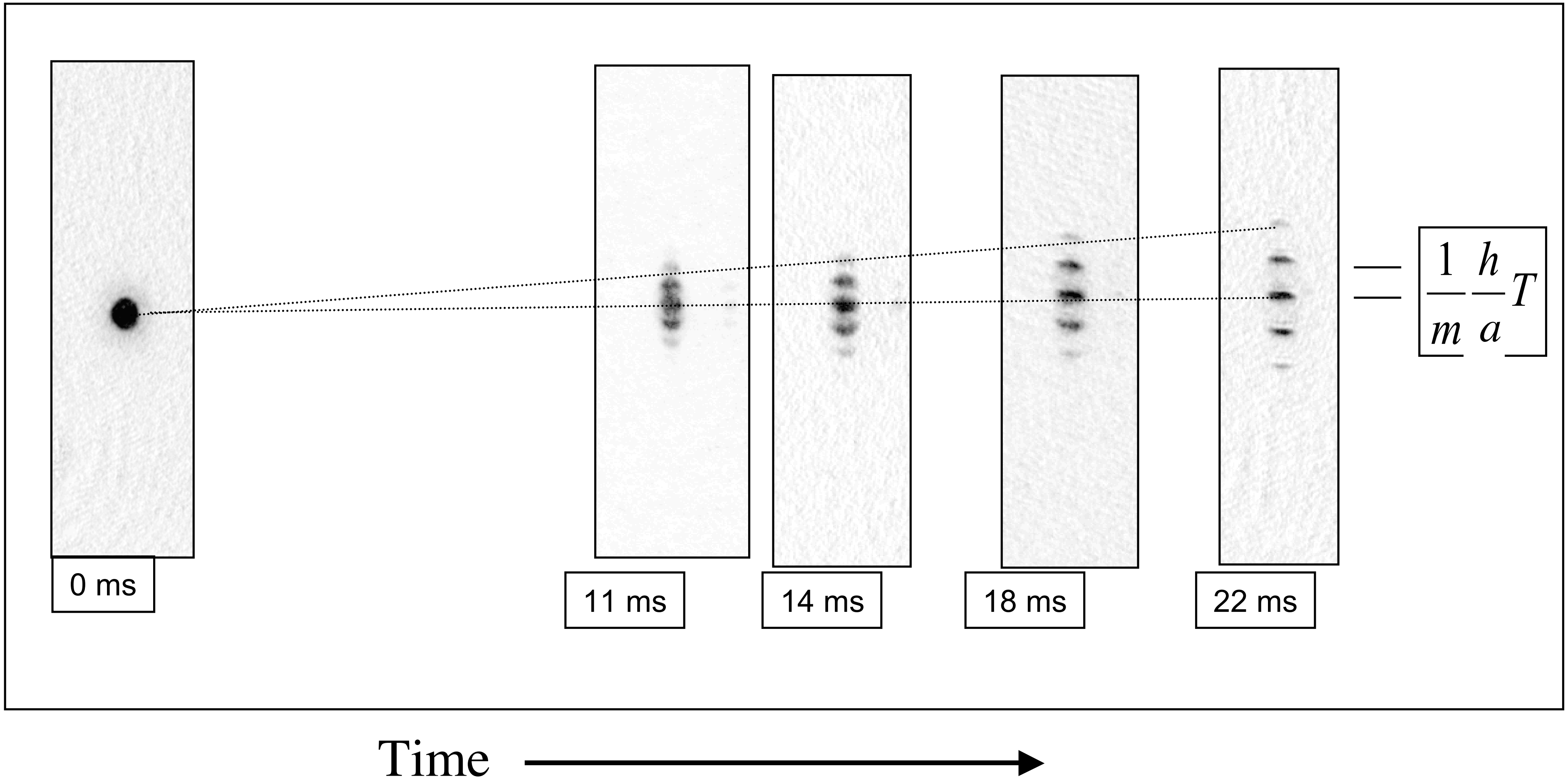
For non-interacting atoms this makes a mini-BEC in each potential well

Release non-adiabatically; after free-flight see momentum states- -periodic wavefunction implies momentum components at multiples of twice the photon momentum ($2n\hbar k$)

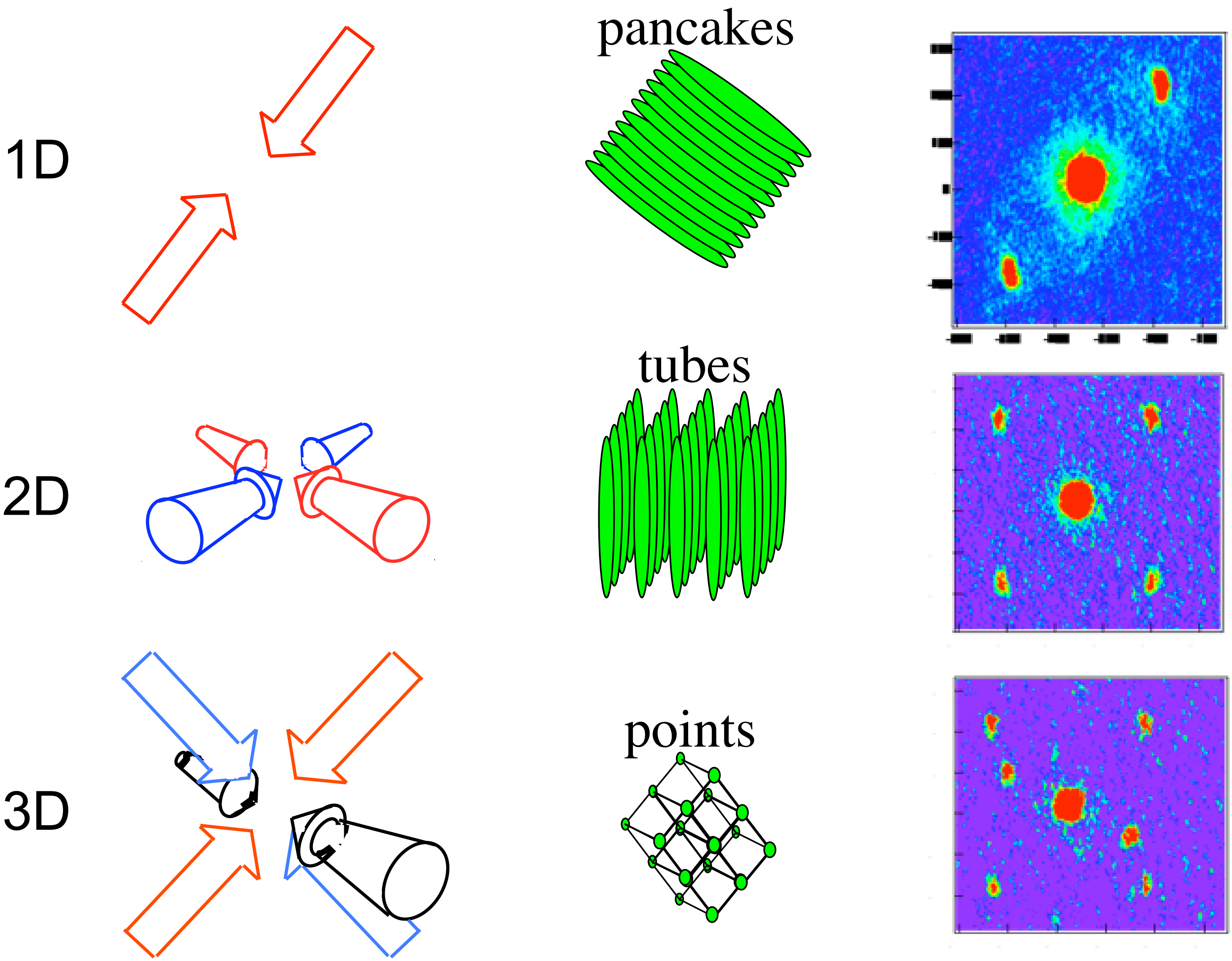


(This is the same as diffraction)

Diffraction of a BEC upon release from a 1-D lattice



Atomic diffraction from 1, 2, and 3 dimensional lattices



Much of the behavior of atoms in optical lattices follows the bandstructure theory familiar from solid state physics.

Bloch functions:

$\psi_{n,q}(x) = u_{n,q}(x)e^{iqx/\hbar}$

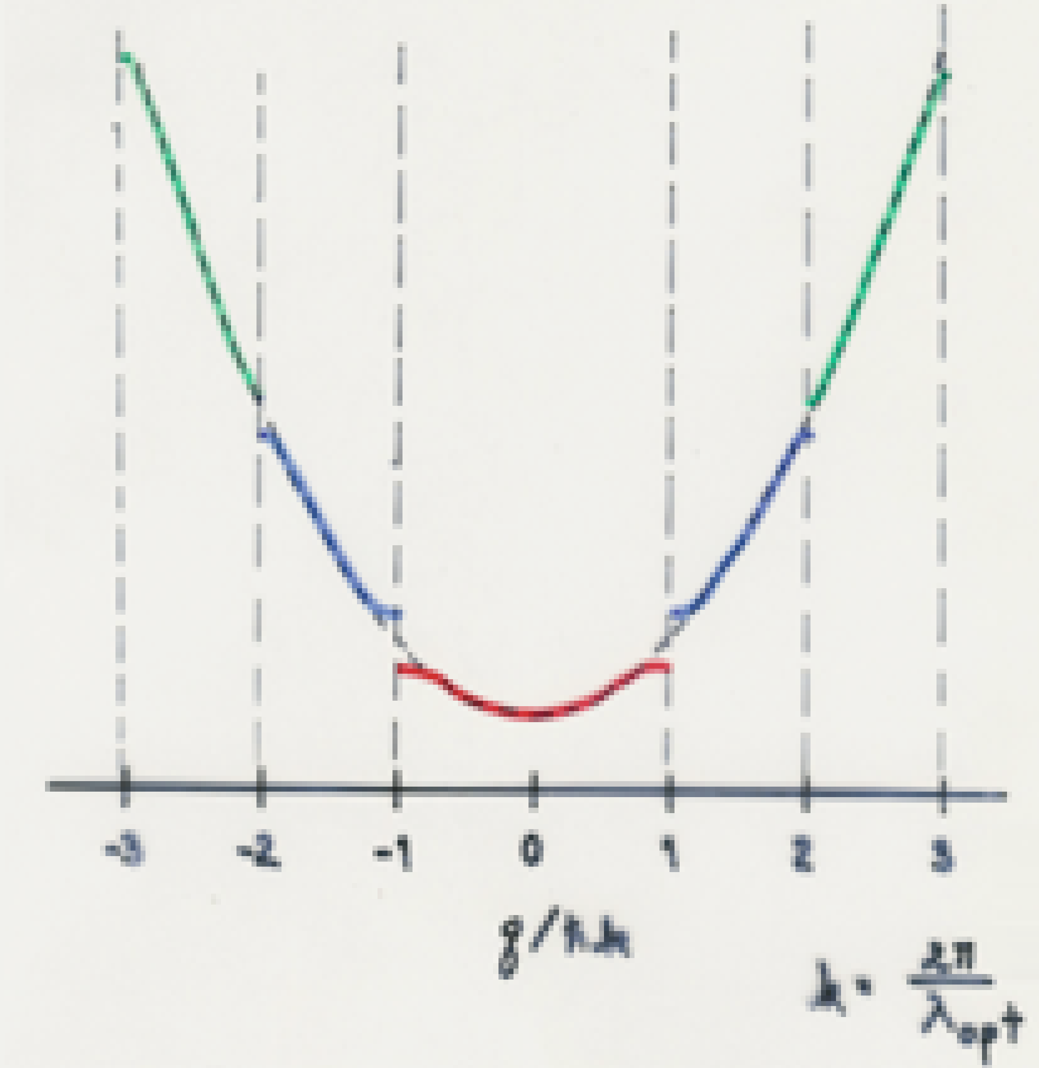
where $u(x+a) = u(x)$.

i.e., $\psi_{n,q}(x)$ is periodic, except for a phase $e^{iqx/\hbar}$;

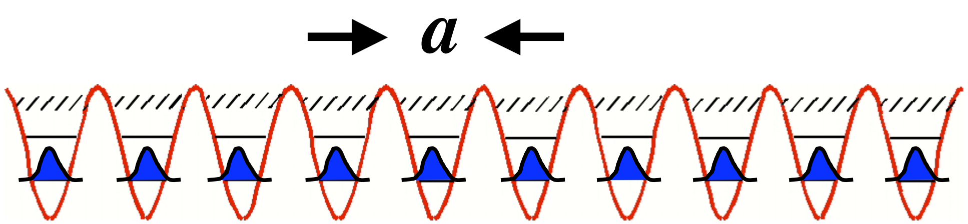
q = quasimomentum.

q is modulo $\hbar K = 2\hbar k = h/a$, the reciprocal lattice momentum.

Note: changing the lattice depth doesn't change q.



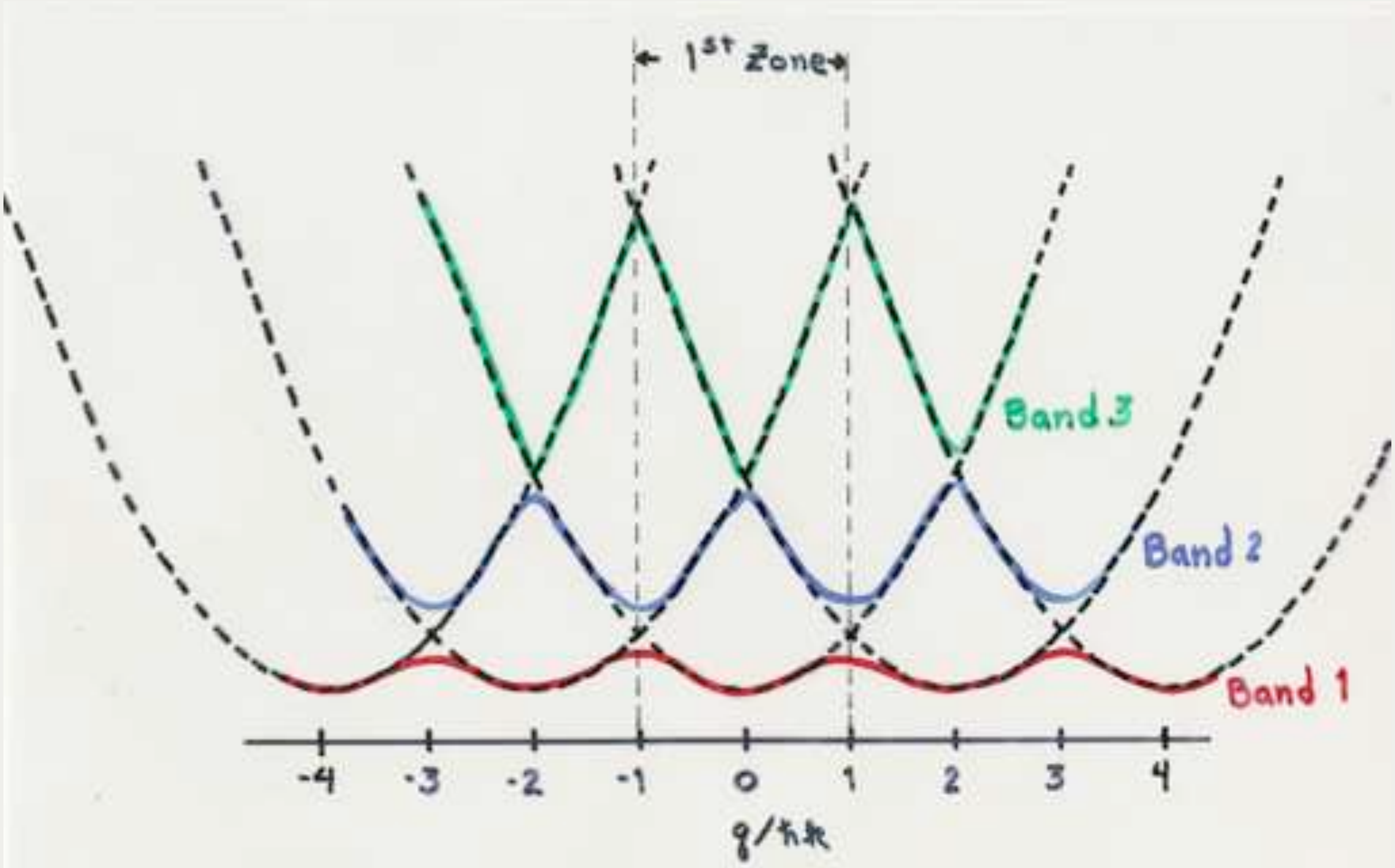
(quasi) periodic wavefunction in a periodic potential



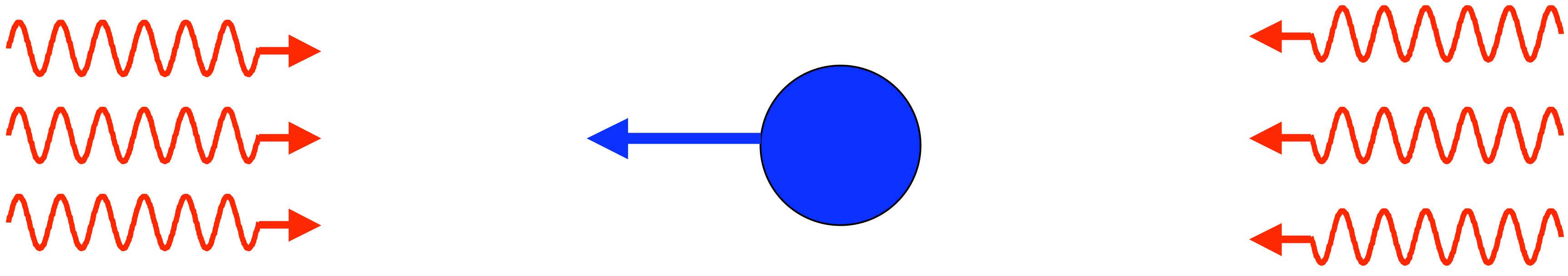
The quasi momentum gives the well-to-well phase change of the wavefunction

An extra 2π phase change from well to well (equivalent to adding a reciprocal lattice vector to the quasi momentum) does not change the wavefunction.

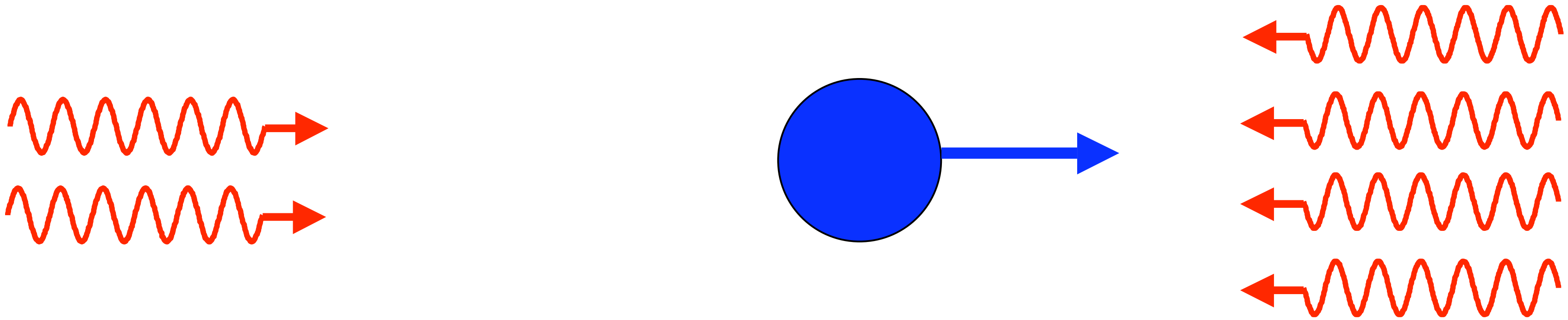
Periodic Zone Scheme; note anticrossings



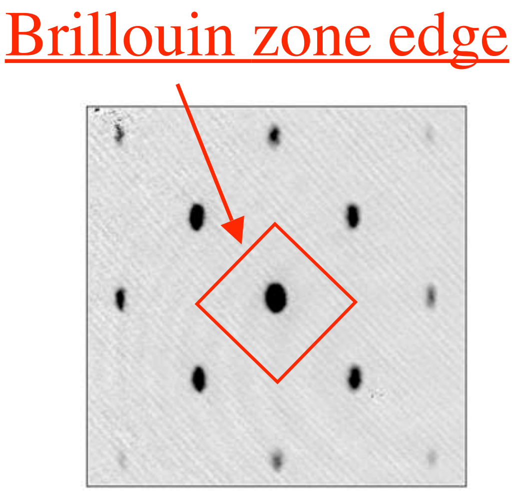
Bragg scattering couples degenerate states separated by $2\hbar k$



$$v = v_{rec} = \hbar k/m$$



Diffraction depends on sudden lattice turn-off.

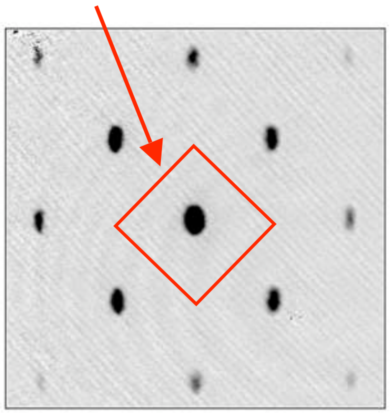


Sudden turn-off

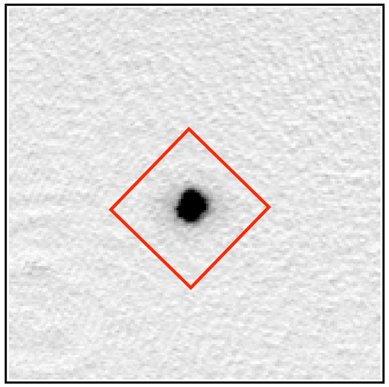
Diffraction depends on sudden lattice turn-off.

"Adiabatic" loading/unloading returns the original condensate: q maps into p within the lowest band.

Brillouin zone edge



Sudden turn-off



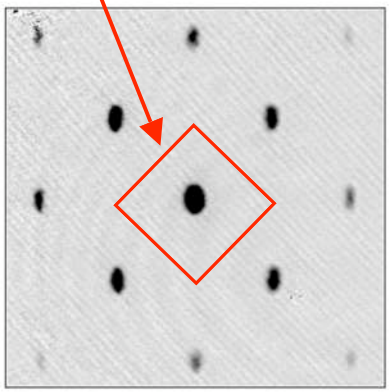
Turn on and off adiabatically for band excitation

Diffraction depends on sudden lattice turn-off.

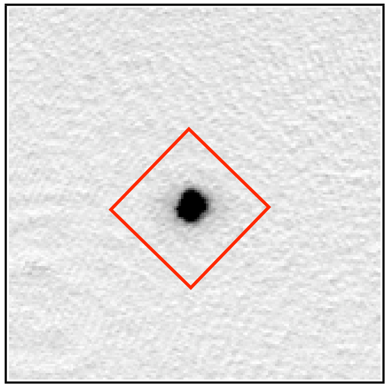
"Adiabatic" loading/unloading returns the original condensate: q maps into p within the lowest band.

Still slower loading allows the interactions to scramble the phase of wavefunction between lattice sites, filling the BZ.

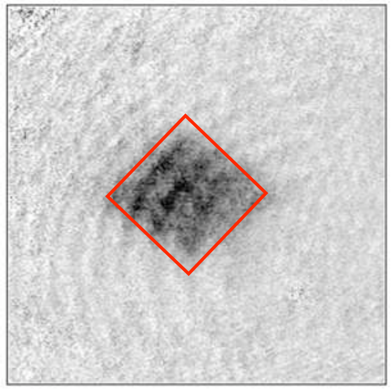
Brillouin zone edge



Sudden turn-off



Turn on and off adiabatically for band excitation



Load adiabatically for atom-atom interaction, turn off adiabatically for band excitation

The interactions that induce the phase shifts that filled the Brillouin zone in the previous figure can also induce correlations between the particles.

In an uncorrelated gas, the probability of finding a particle at a given place is unrelated to whether another particle is nearby. Any high-temperature, low density gas is essentially uncorrelated.

Photon bunching, Hanbury Brown-Twiss effect, is an example of correlation in a non-interacting Bose gas. The correlation disappears in the case of degeneracy: a laser (or a Bose condensate.)

By contrast, a degenerate , non-interacting Fermi gas is strongly anticorrelated.

Interactions also produce correlations--and the effects are very different in 1-D compared to 3-D.

Correlation in 3-D and 1-D gases with repulsive interactions.

At issue is the relative size of the interaction energy E_{int}, which is large when the atoms are close together, compared to the kinetic energy cost E_{cor} to localize the atoms to the mean inter-particle separation, thus keeping them apart.

3-D

$$E_{int} \sim \hbar^2 a_s n/m$$

$$E_{cor} \sim (\hbar n^{1/3})^2/\mathrm{m}$$

$$E_{int}/E_{cor} \sim a_s n^{1/3}$$

A 3-D gas becomes correlated when $na_s^3 > 1$, *i.e.*, at high density.

1-D

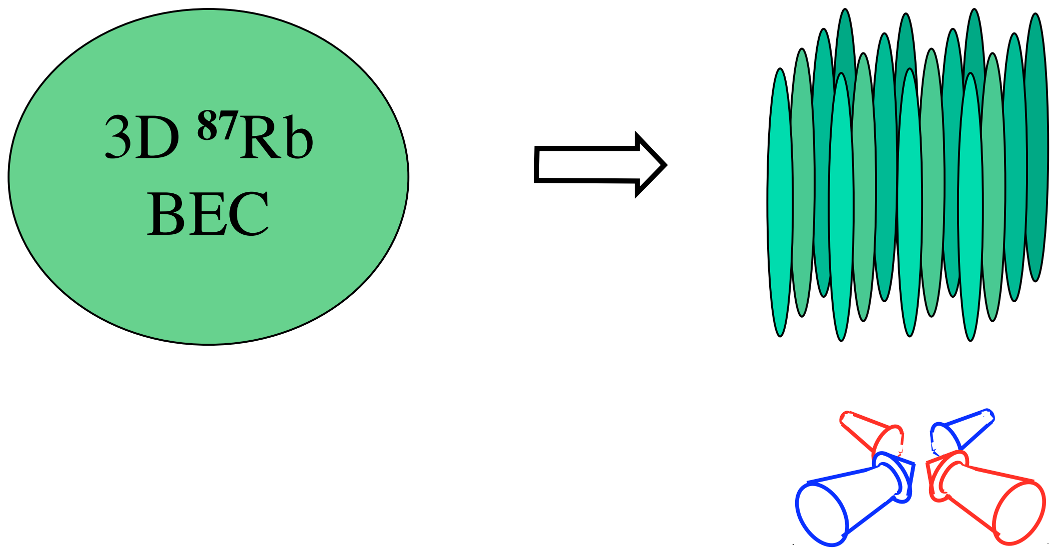
$$E_{int} \sim \hbar^2 a_s n/m \sim \hbar^2 a_s n_{1D}/a_\perp^2 m$$

$$E_{cor} \sim (\hbar n_{1D})^2/m$$

$$E_{int}/E_{cor} \sim a_s/(a_\perp^2 n_{1D})$$

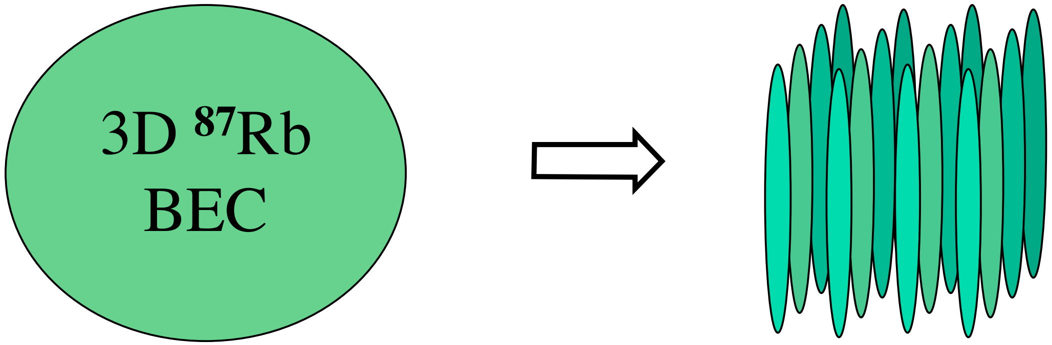
A 1-D gas becomes correlated when $a_s/(a_\perp^2 n_{1D}) > 1$, *i.e.*, at LOW density!

Making a 1D gas

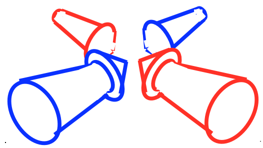


Array of
1D tubes

Making a 1D gas



Array of 1D tubes



What makes the tubes truly 1-D?
Radial trapping frequency much larger than all other energies in the system:

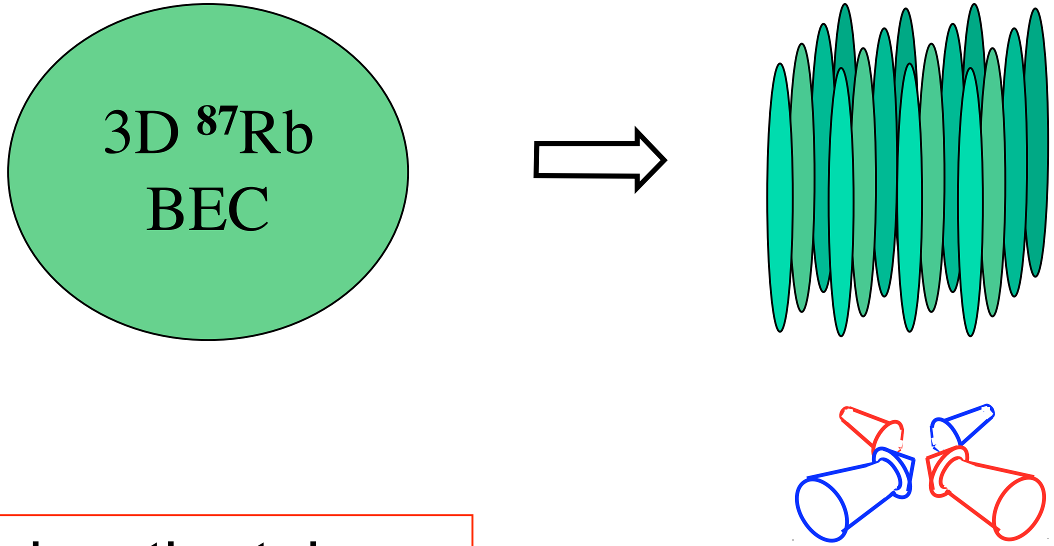
$$f_{\perp} \sim 20 - 40 \text{ kHz}$$

$f_{\perp} >> \mu$ interaction

$>> k_B T$ temperature

$>> f_z$ axial frequency

Making a 1D gas



Array of 1D tubes

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(For our system, $\boldsymbol{a_\perp > a_s}$, so the scattering is still in 3D)

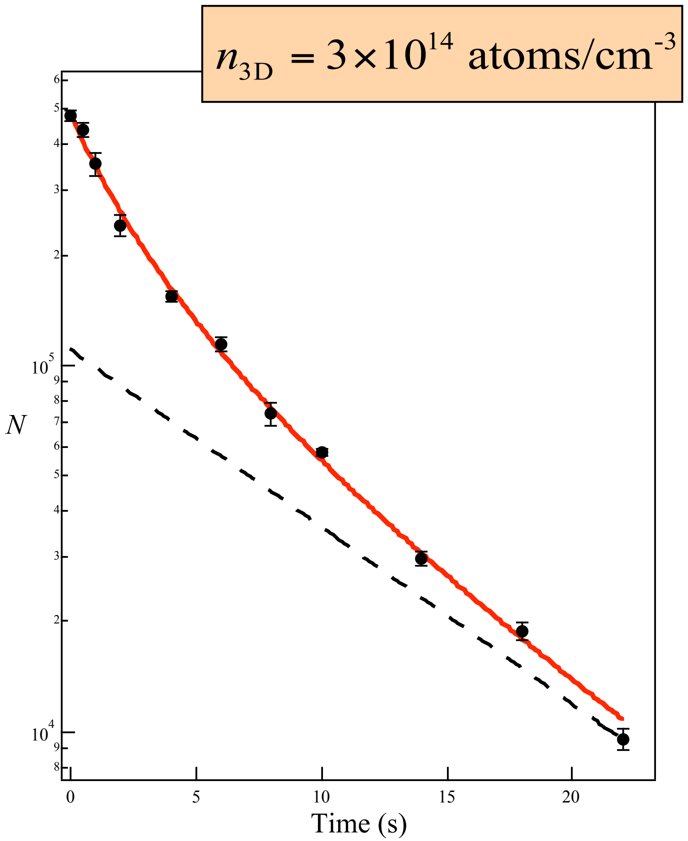
3-body Decay as Correlation Probe

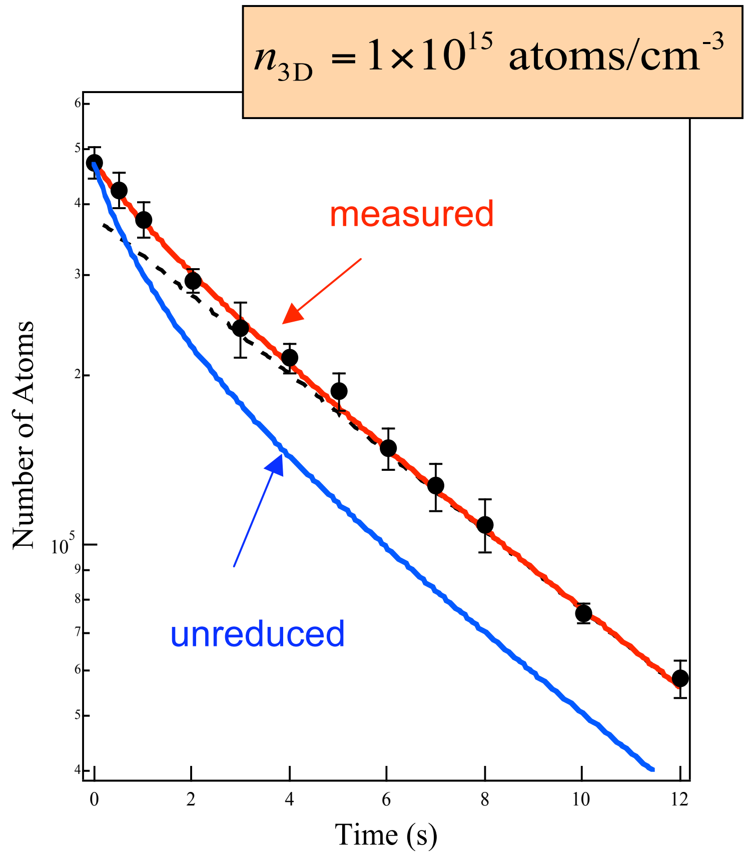
$F, m_F = |1,-1\rangle$

3-body loss in 3D gas

3-body loss in 1D gas

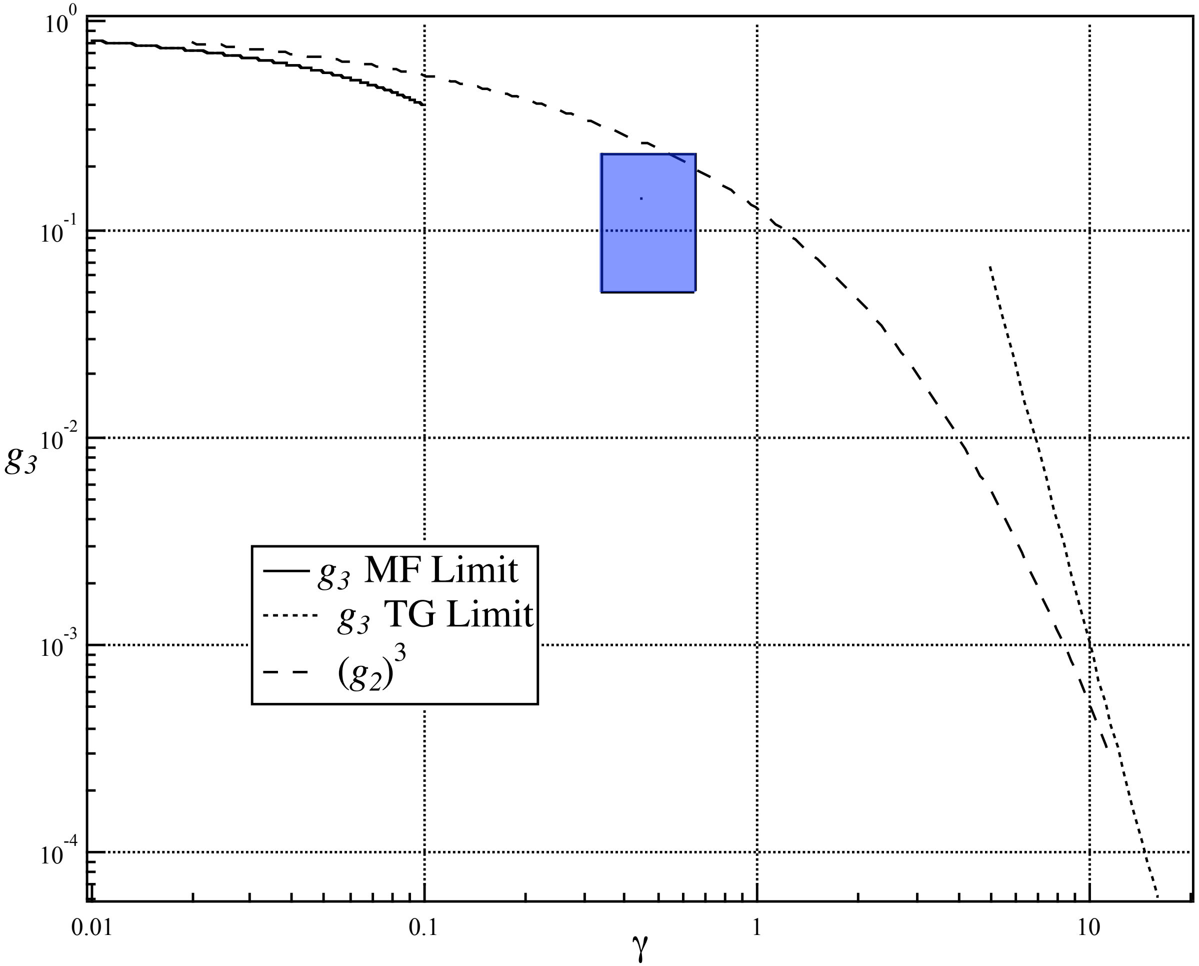
$K_3^{1D} = g_3(0) K_3^{3D}$





→ factor of 7 reduction in 3-body loss

Measured reduction in Three Body Loss



MF and TG limits: Gangardt and Schlaypnikov (2003)

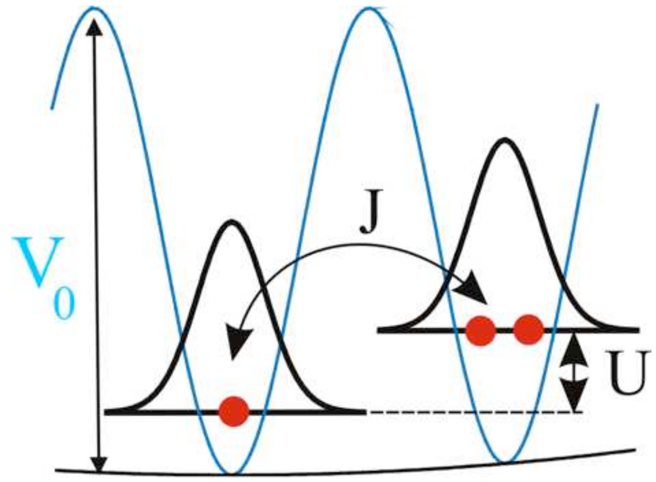
g_2: Kheruntsyan, Drummond, Gangardt, Schlyapnikov (2003)

$$\gamma = E_{int}/4E_{cor}$$

These correlations are in a 1D system that is nearly homogeneous along its axis.

How do things change when when we add a lattice along the 1D axis?

Bose Hubbard Model



J ... tunneling

U ... onsite interaction

$$H = -J \sum_{<i,j>} b_i^\dagger b_j + \\ + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

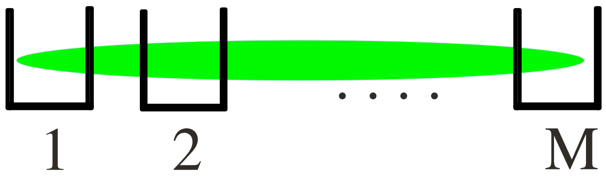
Both J and U change with the lattice depth: J is strongly dependent and U is weakly dependent.

Slide:Courtesy of Peter Zoller

“Superfluid”-Mott insulator phase transition

D. Jaksch et al., PRL '99

- “superfluid” phase



tunneling >> on site interaction

- Mott insulator

commensurate filling

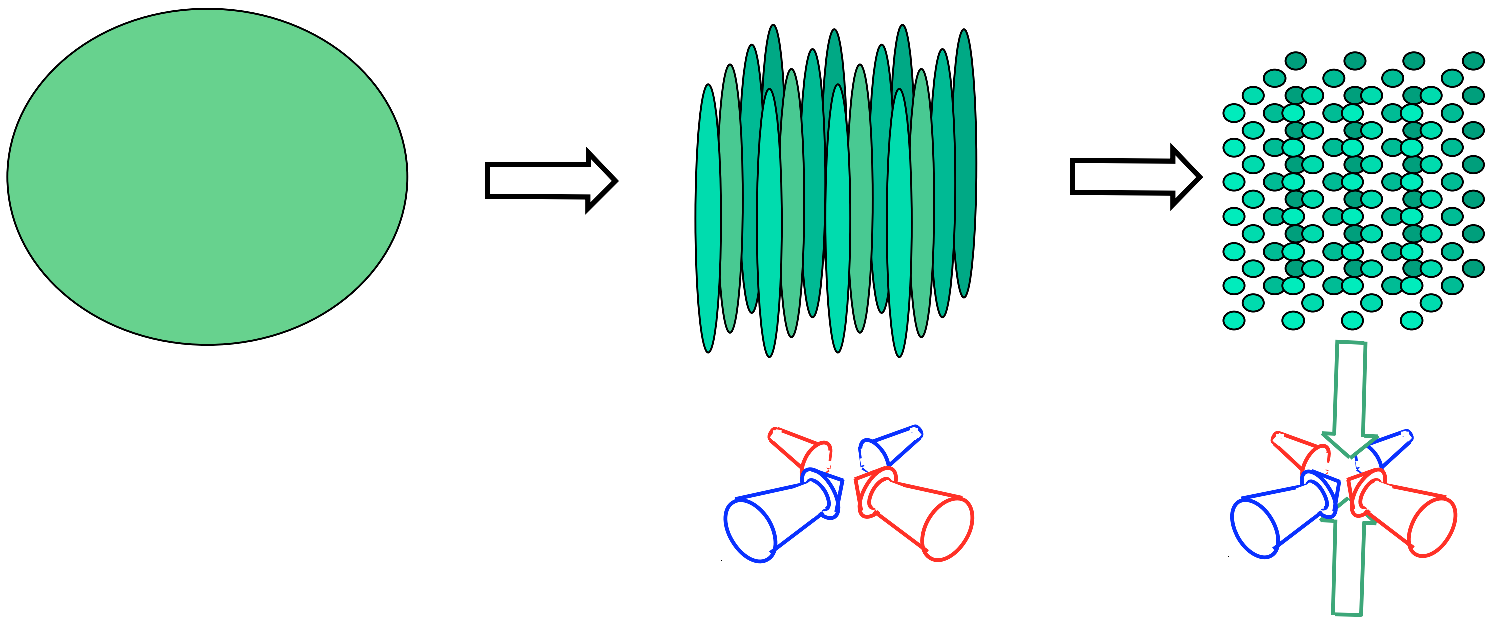
"Fock states"

tunneling << on site interaction

Phase transition is achieved when laser parameters are changed adiabatically with respect to tunneling.

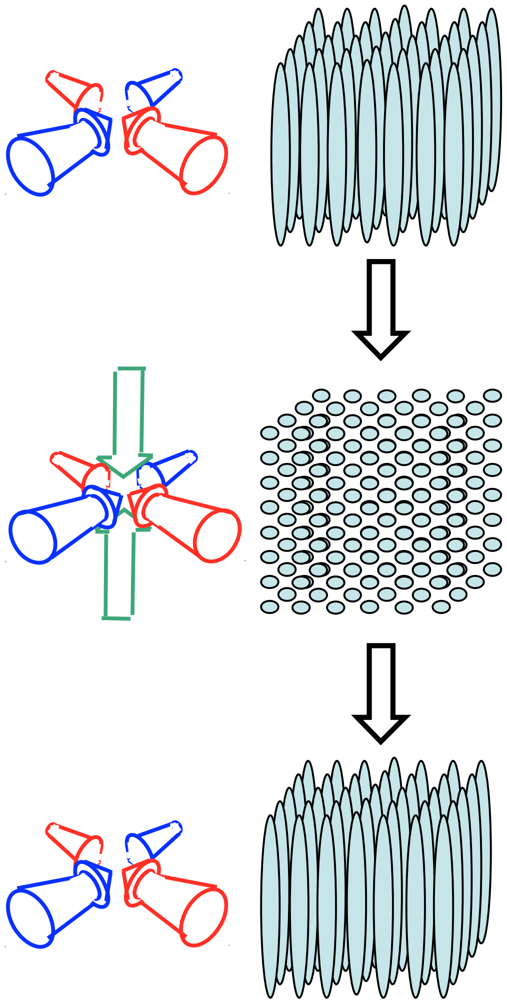
Slide: Courtesy of Peter Zoller

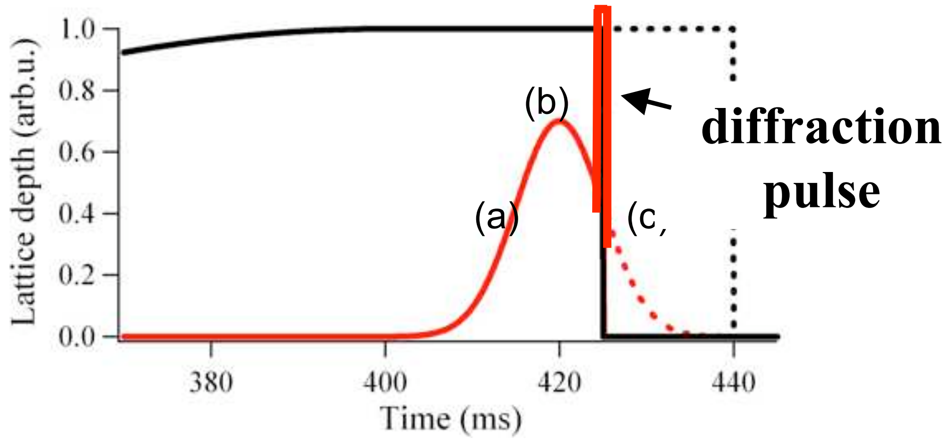
Create a 1-D gas, then apply a lattice along it

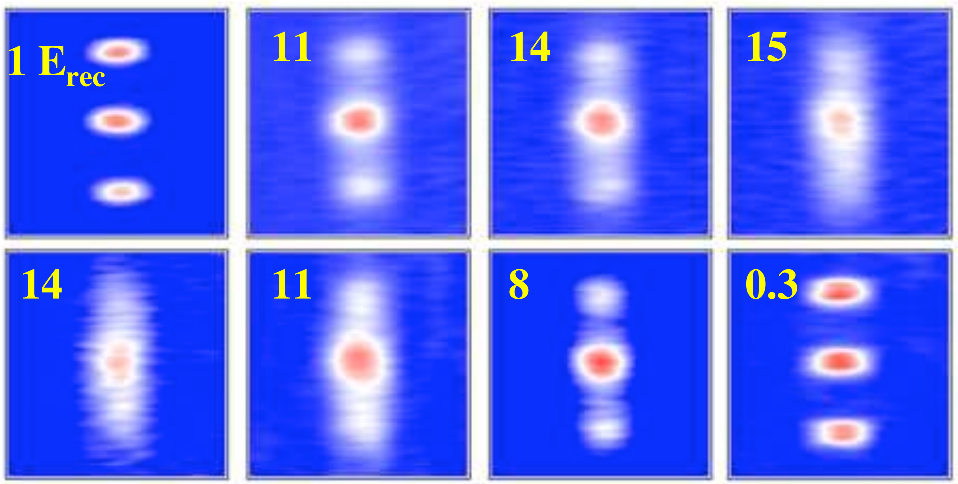


different from a 3D Bose gas in 1D lattice of “pancakes”
e.g. Kasevich, Inguscio, Arimondo

Reversible Loss of Phase Coherence
(? a signature of the Mott transition ?)



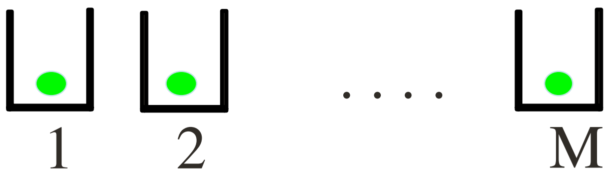




Similar to 3D version in Munich *Nature* 415, 40 (2002); Gaithersburg *Phil.Trans Roy.Soc.* 361, 1417 (2003)
Similar to 1D experiments in Eslinger's group.

Fock state means undefined relative phase

commensurate filling



"Fock states"

tunneling << on site interaction

A lattice of atoms, deep in the Mott state, is useful as a qubit register for quantum information applications.

Is the disappearance of interference really showing the Mott transition?

The reversible loss of coherence is an expected result of the Mott transition, but it is not coincident with the Mott transition.

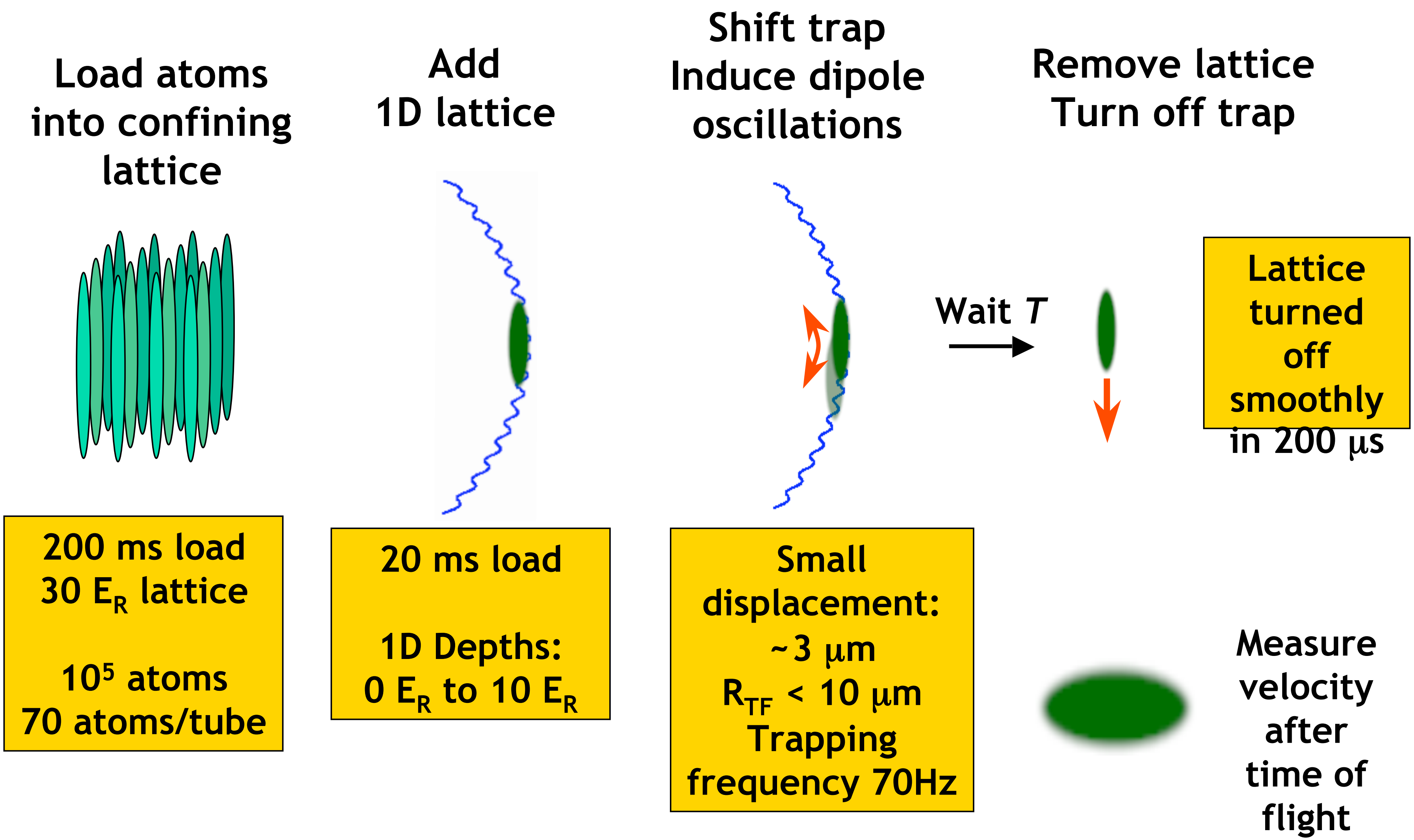
The lattice depth for our observed total loss of coherence is higher than expected for the Mott transition.

(Note that the situation is complicated by being inhomogeneous.)

An abrupt change in transport is expected at the Mott transition and would be a more reliable indicator.

We have studied transport in the 1-D system with an optical lattice, with truly surprising results.

Outline of Experiment



Experimental Conditions

All lattice loading slow (adiabatic)

Lattice unloading adiabatic with respect to band, fast with respect to interactions.

increases the signal to noise of center of mass (no diffraction)

gives information about momentum distribution

Oscillation amplitude small compared to band edge (velocity of oscillating cloud << v_{rec})

remain in harmonic part of band

avoid known dynamic instabilities

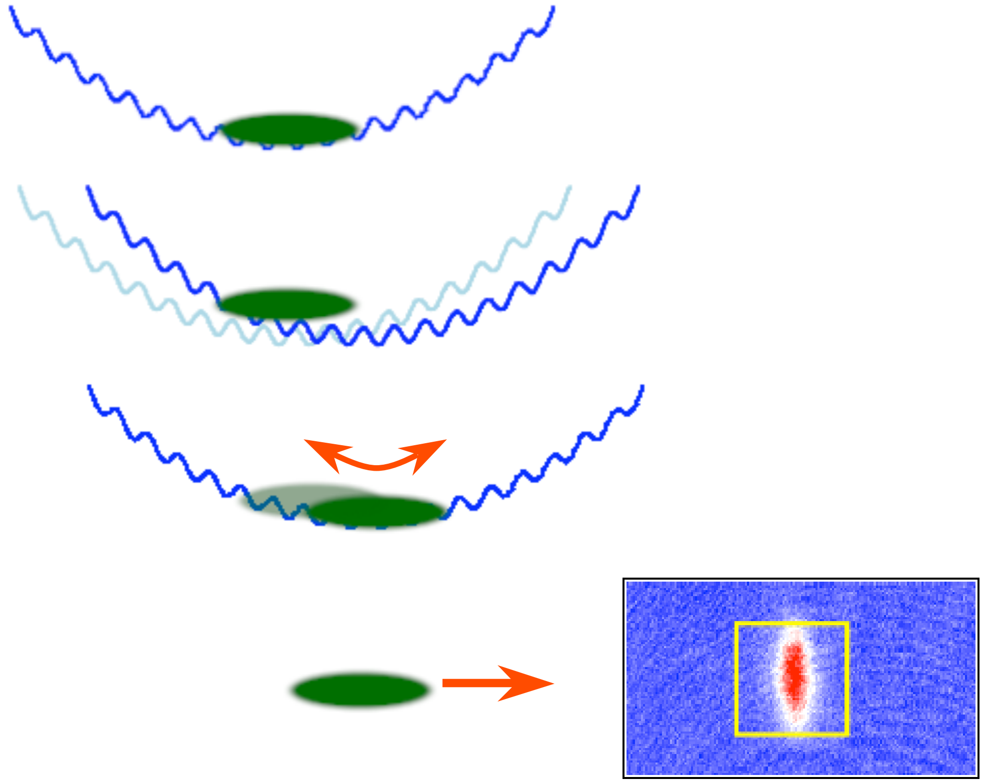
Underdamped Dipole Oscillations

Load atoms
into lattice:

Displace
Harmonic Trap:

Wait variable
delay then turn
off trap/lattice:

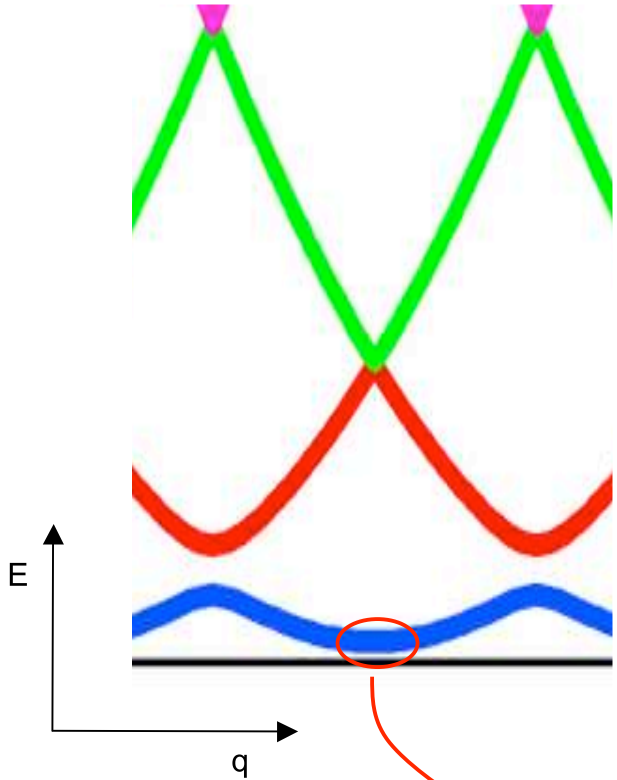
Image position after
Time-of-Flight (velocity):

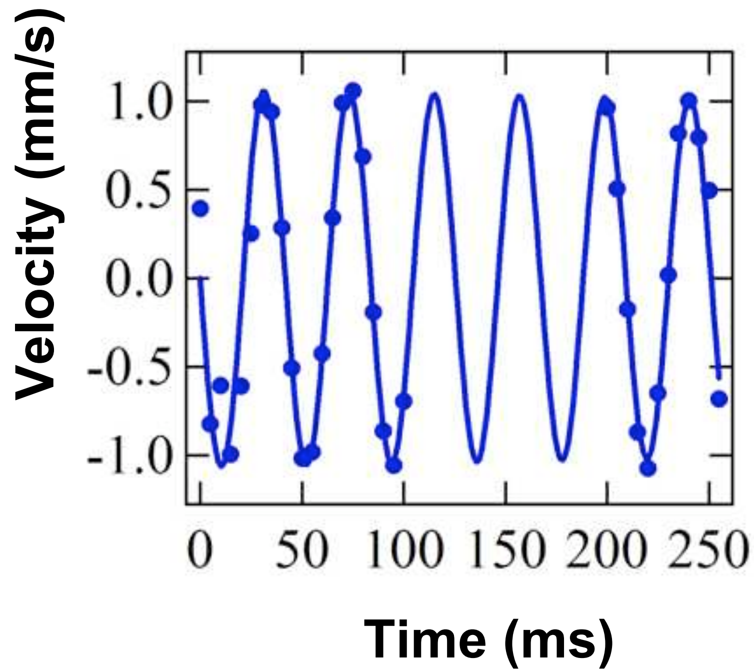


- Harmonic Trap Displaced by 3 μm (Cloud Radius ~10 μm)
- v_{max} = 1 mm/s (less than 1/5 of recoil velocity)
- Maximum Gradient: 40 Hz/(λ/2) (<< 2 kHz/(λ/2))
- ~2 particles/site maximum

Weakly Interacting Harmonic Oscillation

Example:
1D Lattice only, no confining tubes
"pancakes" configuration



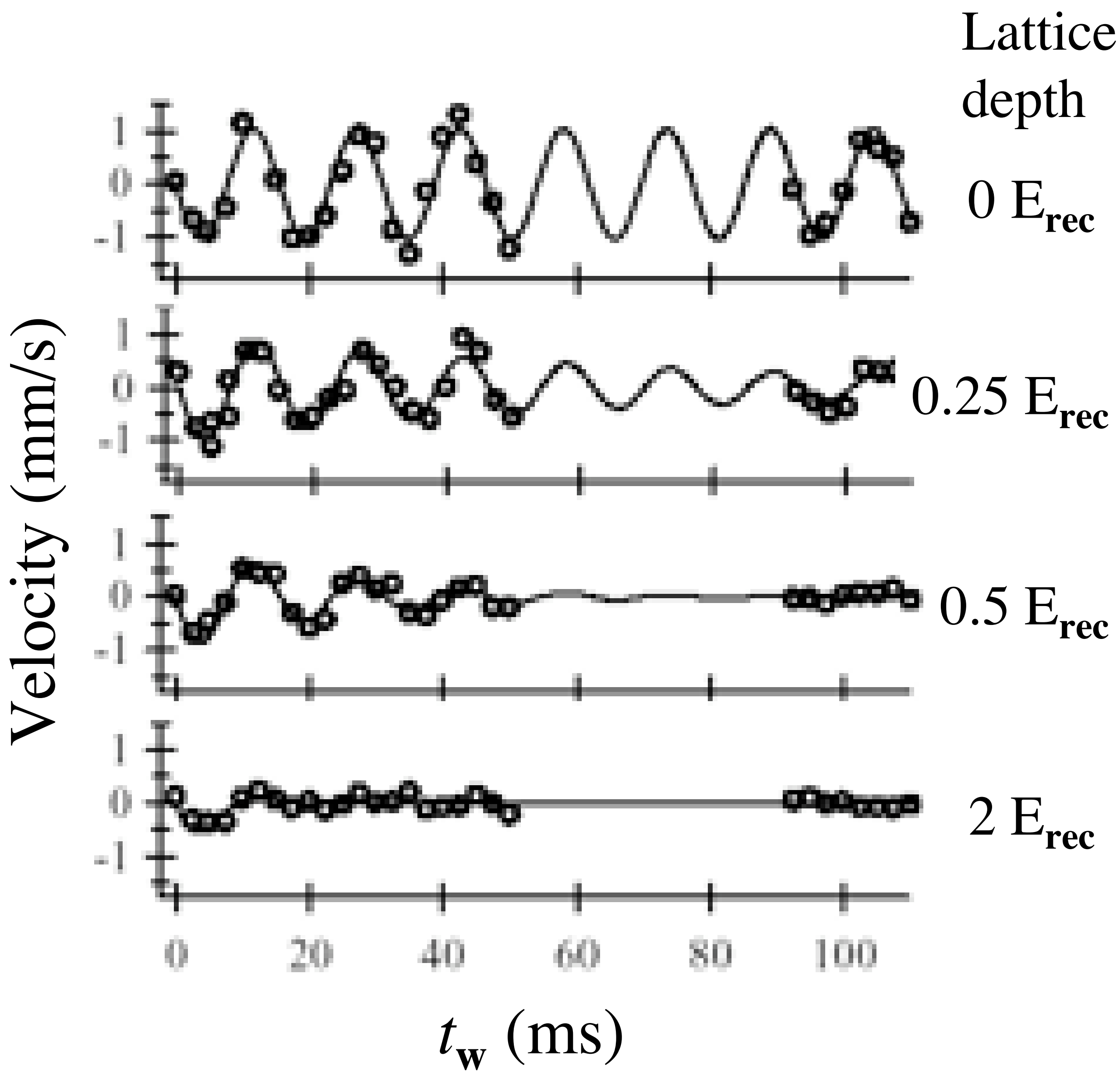


2 E_R

Motion confined to parabolic dispersion:
effective mass frequency shift, no damping

e.g. Kasevic, Inguscio, Arimondo

Damped Oscillations



Overdamped Measurements

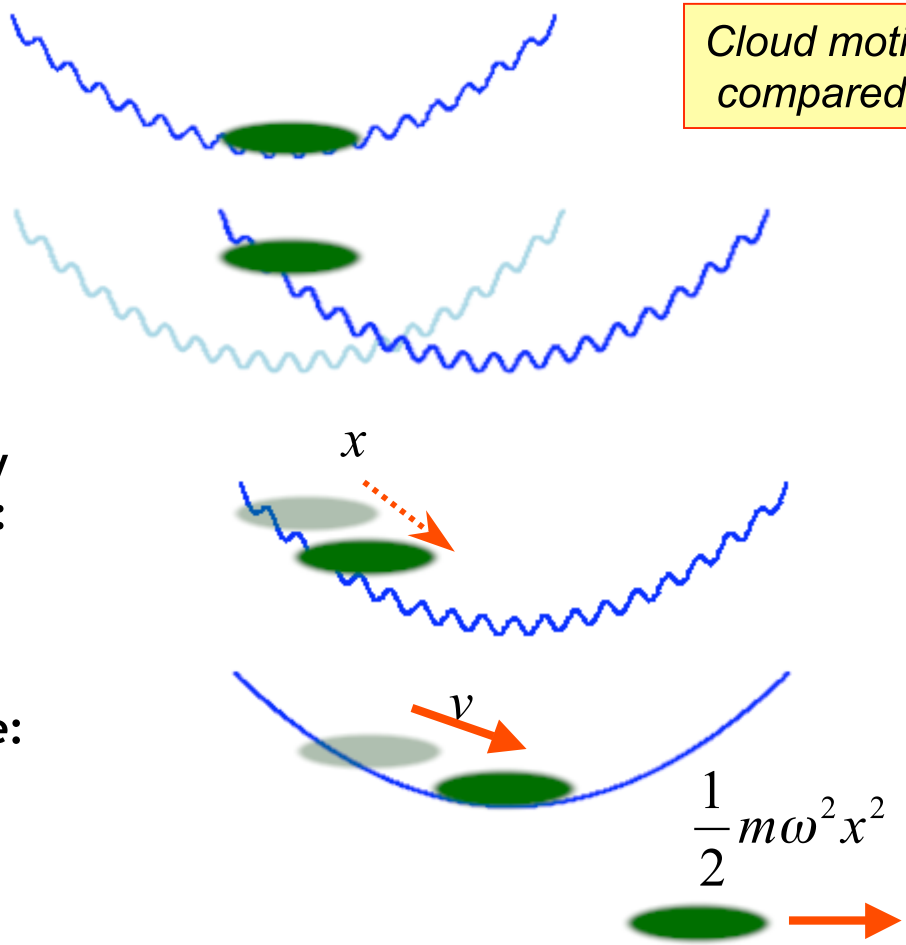
Load atoms into lattice:

Displace Harmonic Trap:

Wait 90 ms (cloud slowly returns to equilibrium):

Turn off 1D lattice:

Release after T/4

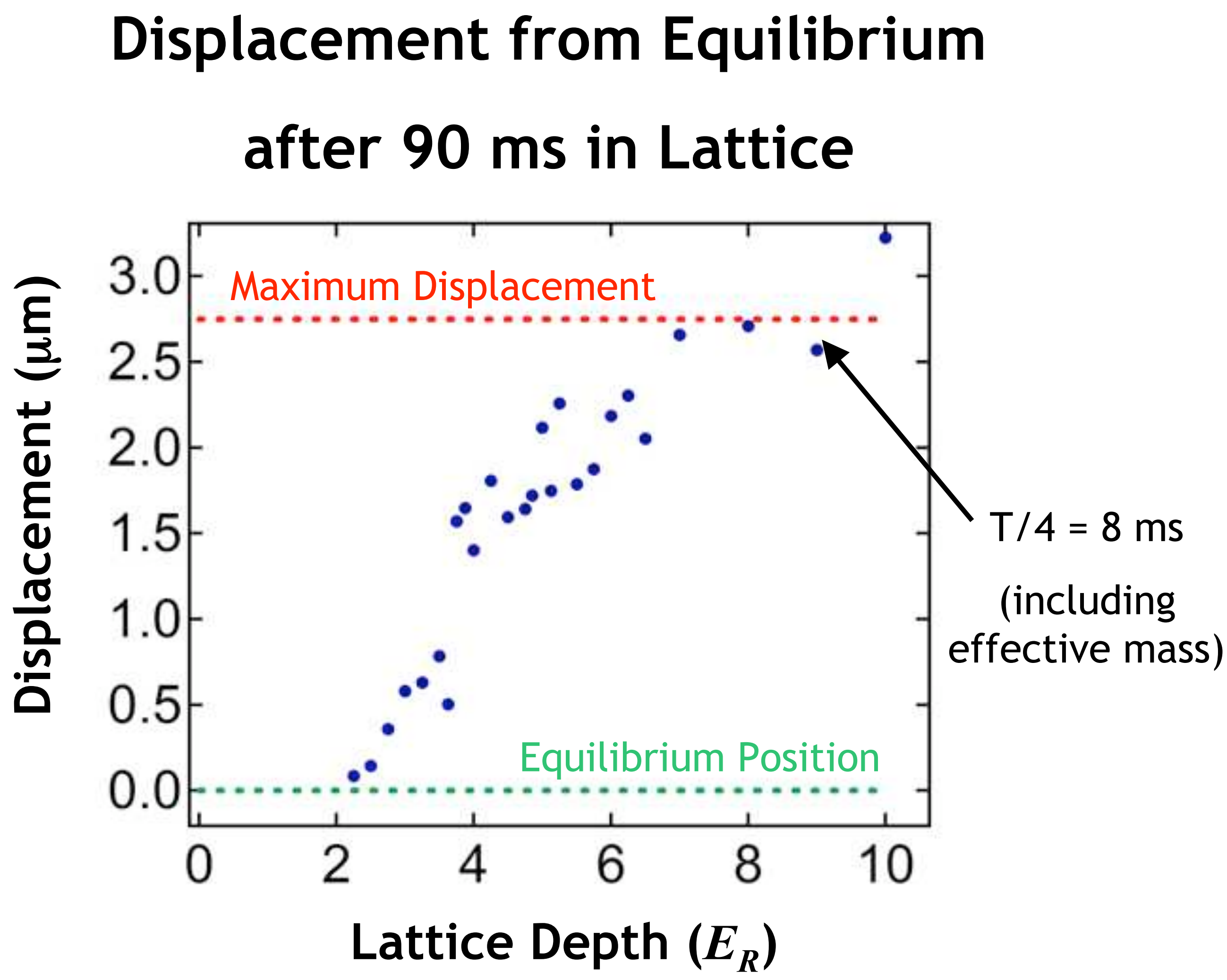


Cloud motion small compared to size!

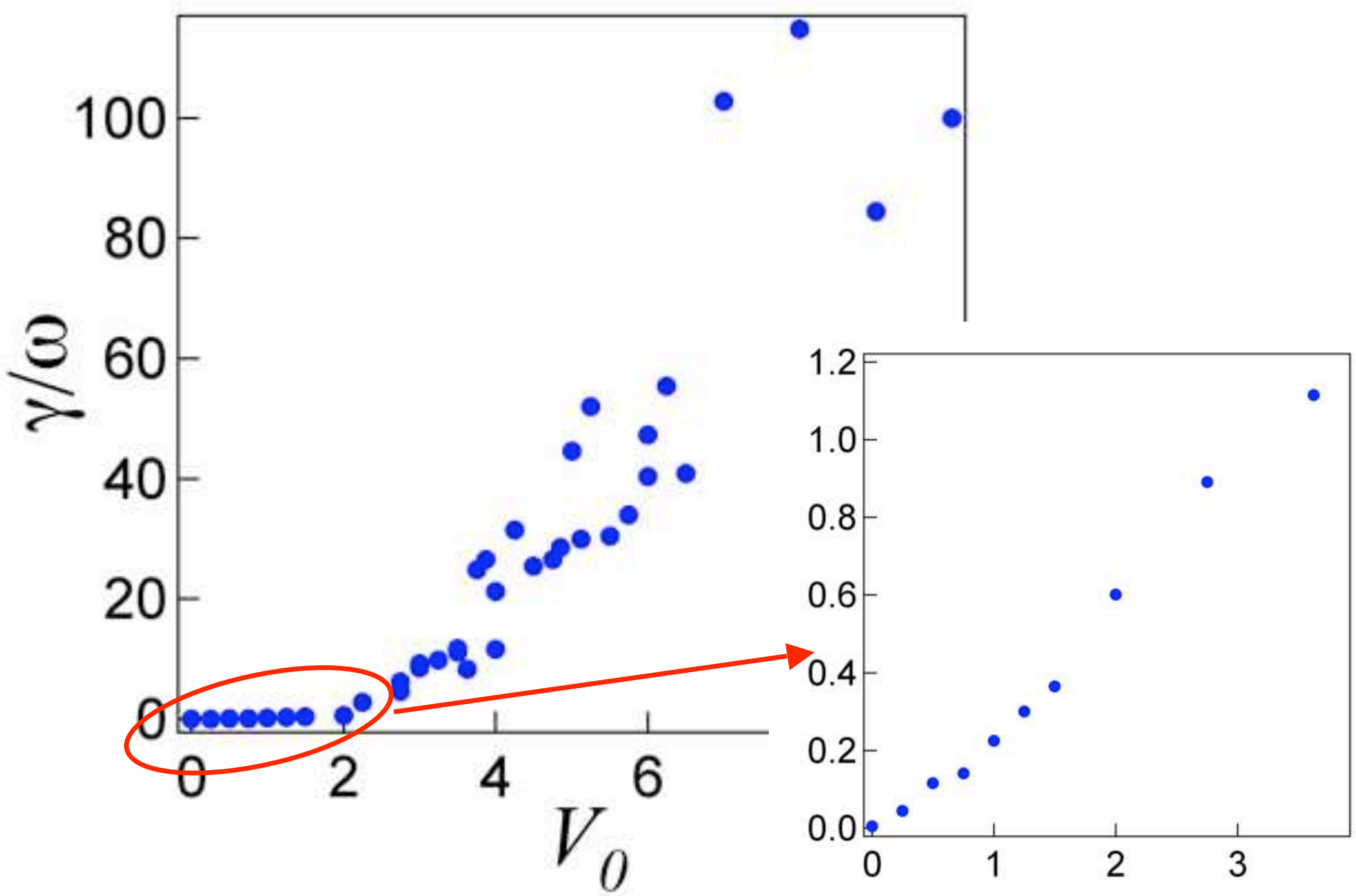
$$\frac{1}{2}m\omega^2x^2 = \frac{1}{2}mv^2$$

Velocity measured in TOF proportional to displacement from equilibrium after 90ms.

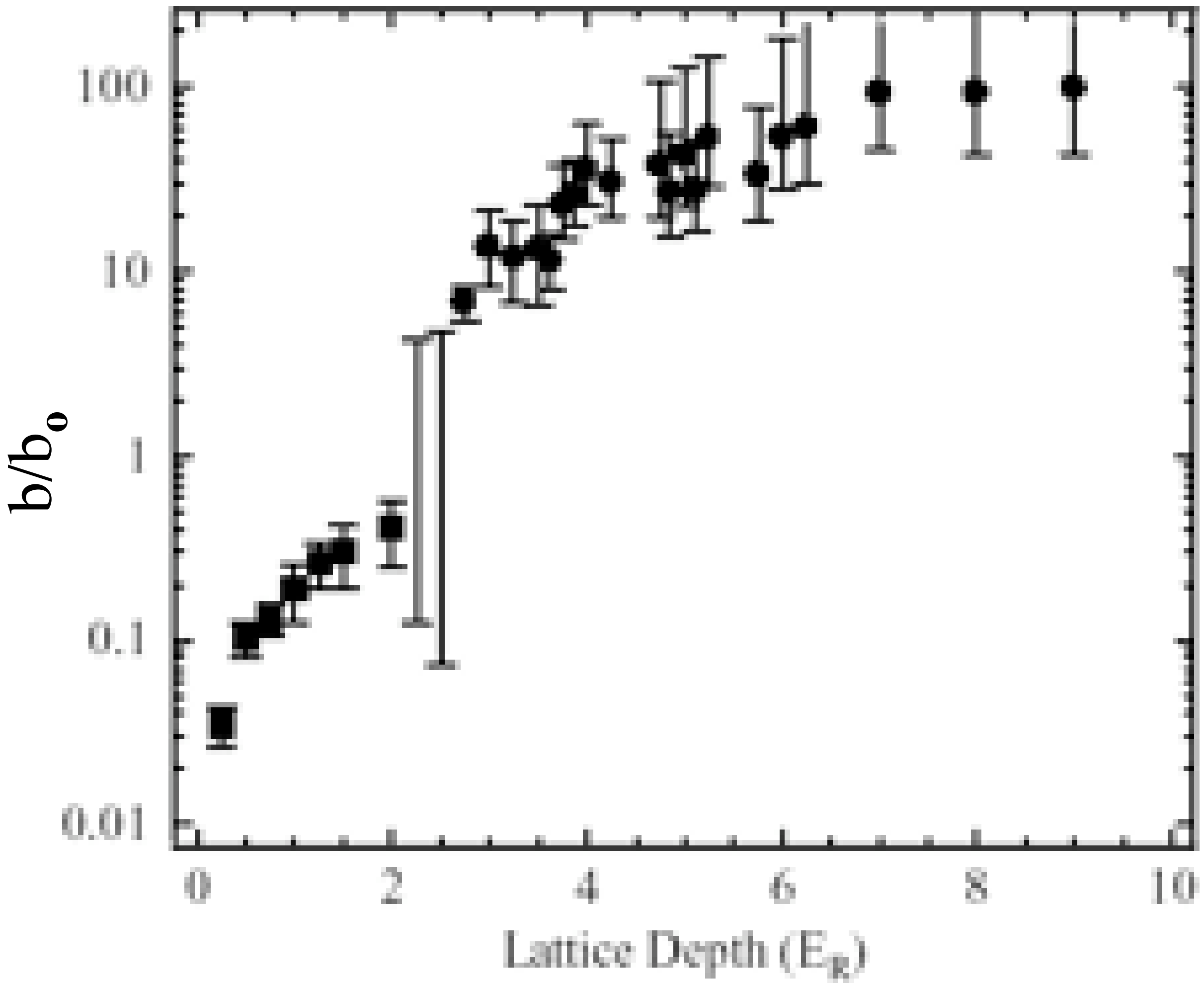
Overdamped Motion



Damping Constant



Manuscript in preparation



100
10
1
0.1
0.01
b/b$_o$
0
2
4
6
8
10
Lattice Depth (E_R)

The explanation of this remarkably strong damping is "beyond the scope of this presentation"….but….

The quantum depletion of the 1D gas is quite large, even with no lattice (20- 30%). It is suggested that this depletion (excitations) interact with the condensate so as to damp it:

J. Gea-Banacloche, A. M. Rey, G. Puipillo, C. L. Williams, C. W. Clark cond-mat-0410677 (2004)

A. Polkcvnikov and D.W. Wang, PRL **93**, 070401 (2004).

(and related work at Harvard by: E. Altman, A. Plkovnikov E. Demler, B. Halperin, M. Lukin)

What next for cold atoms in 1D?

New experiments in Gaithersburg will test the theoretical explanations.

Lots of 1-D experimental work going on, elsewhere, e.g., in Munich/ Mainz (Bloch), Zurich (Esslinger),Yale/Stanford (Kasevich), Penn State (Weiss). Mott, squeezing, correlations, Tonks gas, etc.

Applications to quantum information: Mott state initializes qubits in a natural register; 1-D physics should make the Mott transition more robust. (Gaithersburg)

Mott-related cat states for sub-shot-noise performance? (Oxford)

Theory is advancing rapidly in many places

The End