Optical lattice experiments at NIST

Trey Porto

NIST
Laser Cooling and Trapping Group

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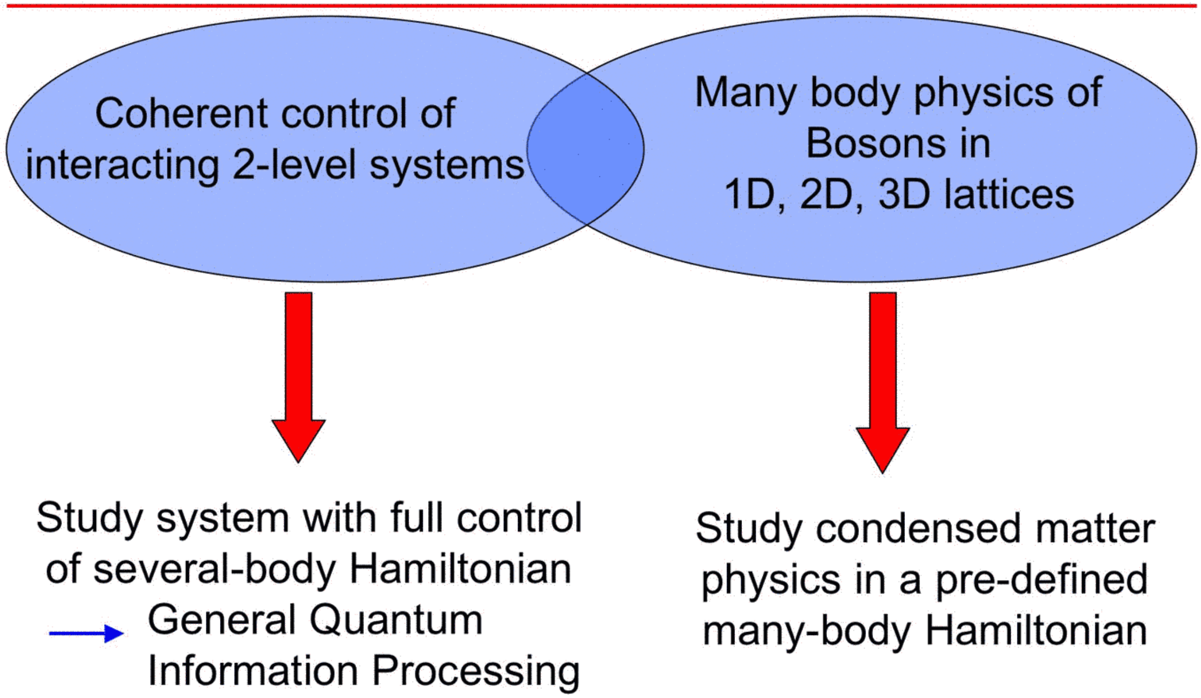
National Institute of Standards and Technology
Technology Administration, U.S. Department of Commerce

NIST Physics Laboratory

Our Research Directions



First useful quantum computer will probably be an "analogic" condensed matter simulator.

Outline

- Experiments on simple, correlated 1D Bose Gases
  - Optical lattice geometry/control
  - Creating 1D systems
  - Correlations in 1D
  - Transport of 1D Gas in a Lattice

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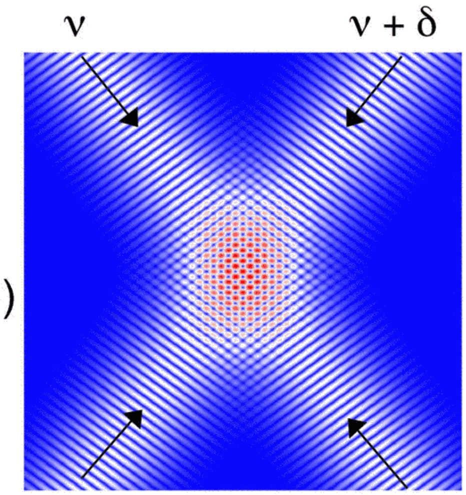
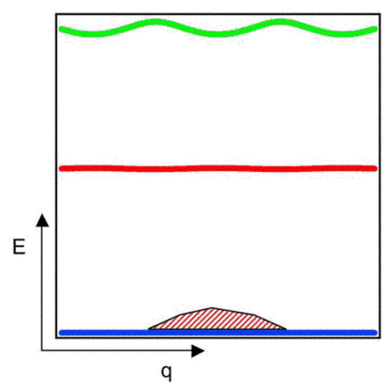
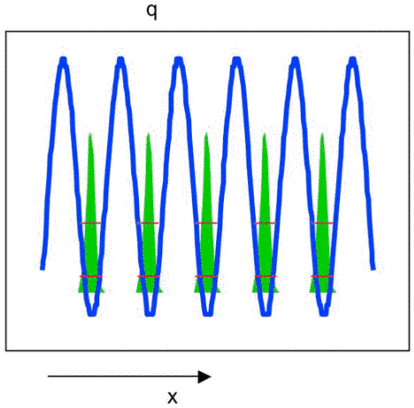
Optical Lattices for Neutral Atoms

Detuning beams
→ atoms average over high frequency interference terms
→ independent (non-interfering) lattices



Loading BEC and Dynamic Lattice Control





Time scales for loading/unloading the lattice

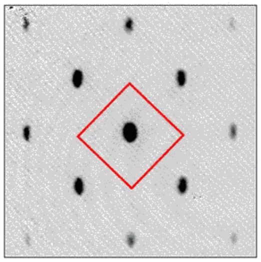
Sudden: (<< 100 μs)
→ State projection

Fast compared to interaction/tunneling,
Slow compared to non-interacting band
→ "Map" band distribution

Slow compared to all times: (>> few ms)
→ "full" adiabaticity

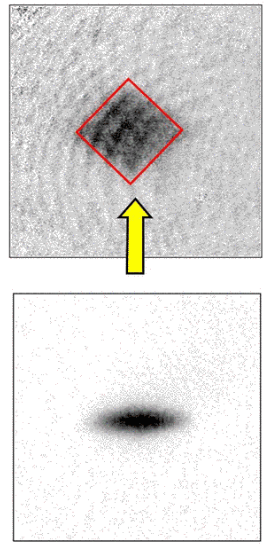
Example: “Mapping” Band Occupation

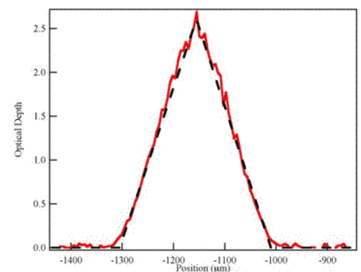
Project BEC Quasi-Momenta onto Free-Particle States:



Sudden pulse

Adiabatically Map Filled Band Quasi-Momenta onto Free-Particle States:

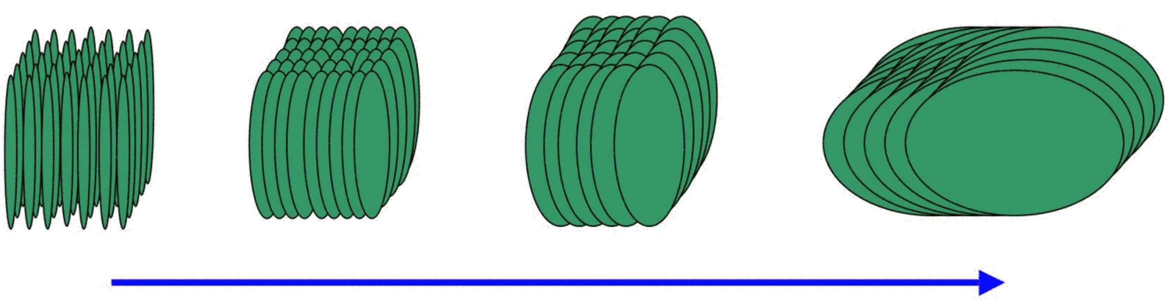




Viewed from side

Contributions to Time of Flight Imaging

- Initial cloud size
- Initial momentum distribution (thermal or quantum)
- Interactions (repulsive) during flight



Fast de-loading of lattice = quickly decreased density/interactions

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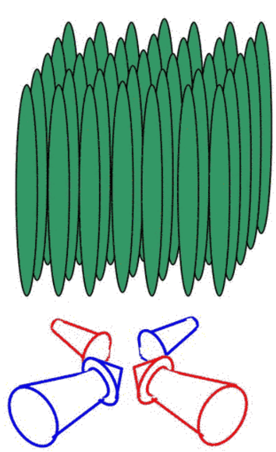
1D Bose gas: 2D lattices as an array of tubes

"Adiabatically" load 3D BEC into a 2D lattice
Radial degrees of freedom → "frozen out"



$f_\perp \sim 35$ kHz

$f_\perp >> \mu,\ k_B T,\ f_z$

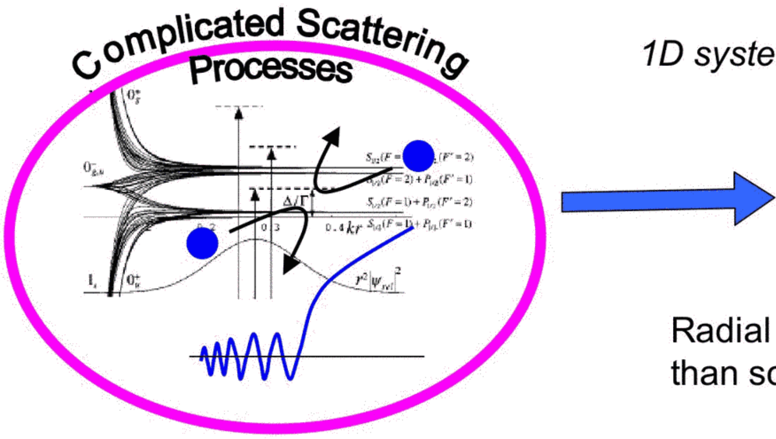
< 200 atoms/tube

^{87}Rb → *weak repulsive interactions*

$\mu \approx 1kHz \quad f_z \approx 50Hz - 70Hz$

Provides an array of independent 1D systems with repulsive interactions

What does1D system mean?



1D system, 3D "scattering"

$$V(z) = g\delta(z)$$

Radial confinement much larger than scattering length

$$a_\perp \approx 0.1 a_s$$

1D interaction strength =
3D interaction, integrated over radial degrees of freedom

(3 body processes?)

Olshanii, PRL (1998)
Bolda et al. PRA (2003)

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Some Experimental Observables

Phase coherence/momentum distribution

along tubes
across tubes

Petrov, *et al.* PRL (2000)
Expt: Bloch *et al.*

Collective modes

compare center of mass
to breathing modes

Menotti & Stringari PRA (2002)
Expt: Esslinger *et al.*

Correlation dependent physics

measure 3-body loss

also … 2-body loss,
photo-association rates

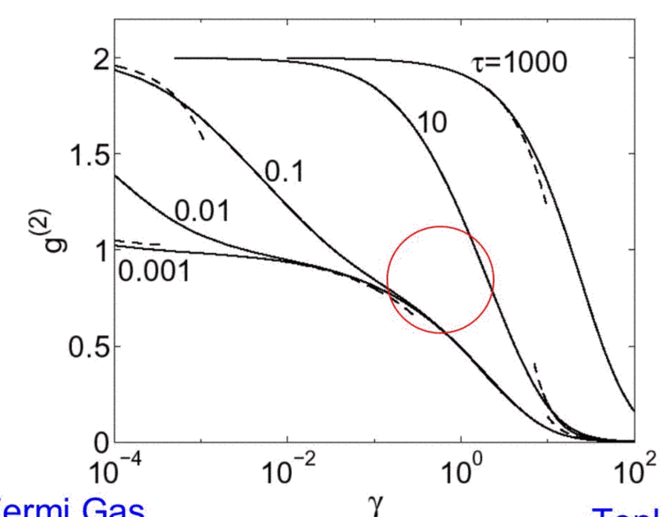
Kheruntsyan *et al.*
Gangardt & Shlyapnikov PRL (2003)

Size/shape vs. number

Dunjko, *et al.* PRL (2001)

Reduced 2-Particle Correlations

Kheruntsyan, et al. PRL (2003)



$$\tau = \frac{T}{T_{\text{degen}}}$$

Thomas-Fermi Gas

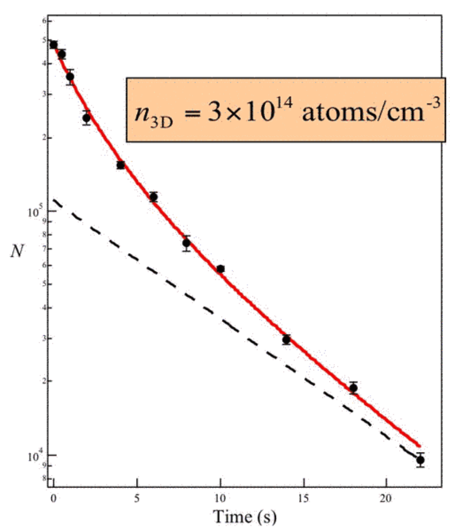
Tonks-Girardeau Gas

$g_3 \approx (g_2)^3$ → substantial reduction in 3-particle correlations

3-body Decay as Correlation Probe

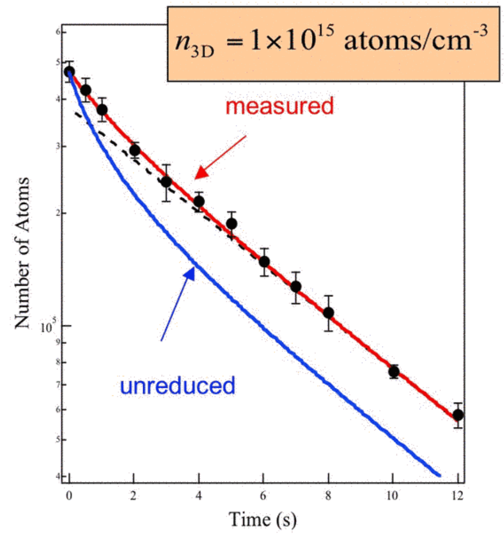
3-body loss in 3D gas

$F = |1,-1\rangle$



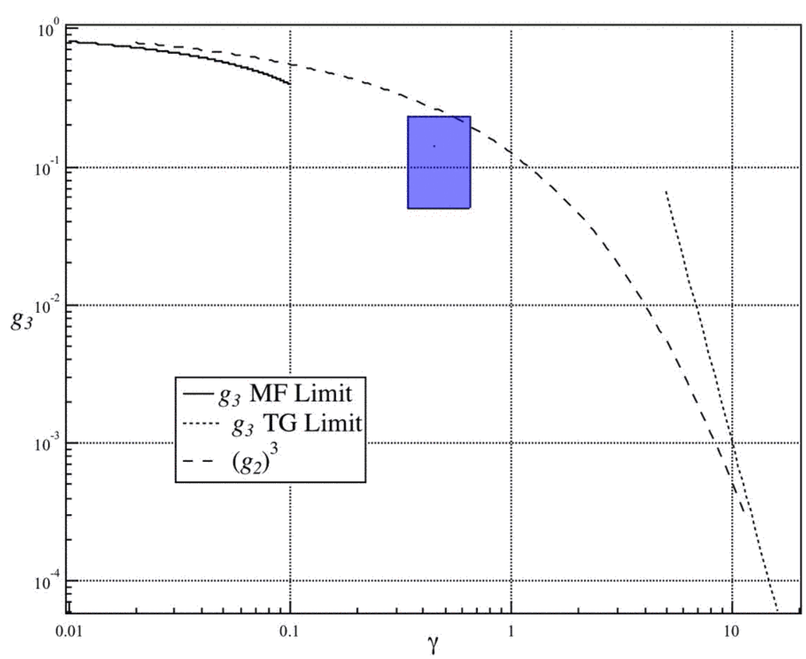
3-body loss in 1D gas

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



→ factor of 7 reduction in 3-body loss

Measured reduction in Three Body Loss



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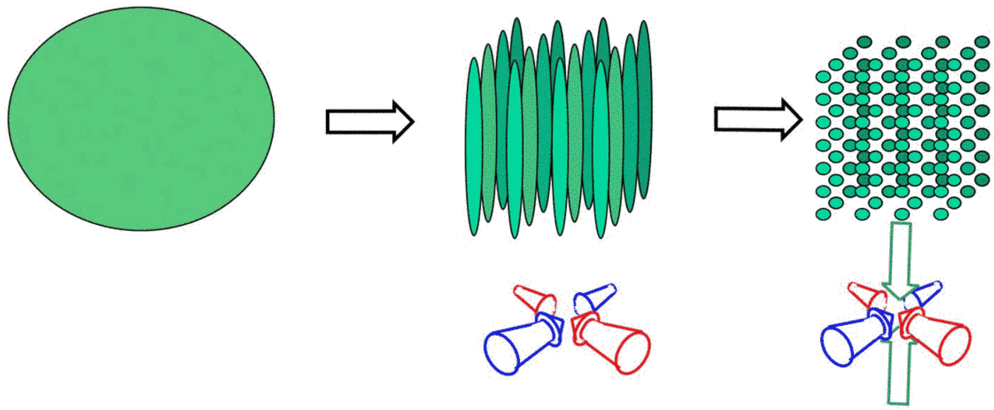
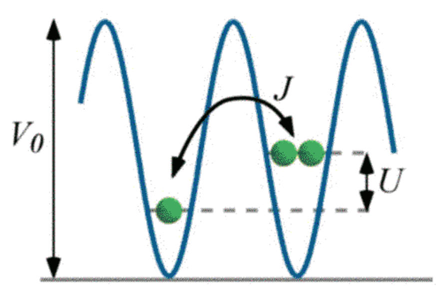
1D Bose gas in a lattice





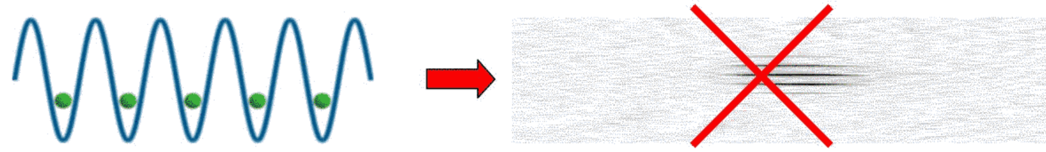
$$H = -J\sum_{\langle i,j\rangle}\hat{a}_i^\dagger \hat{a}_j + \frac{1}{2}U\sum_i \hat{n}_i(\hat{n}_i - 1) + \sum_i \varepsilon_i \hat{n}_i$$

different from a Bose gas in 1D lattice of "pancakes"

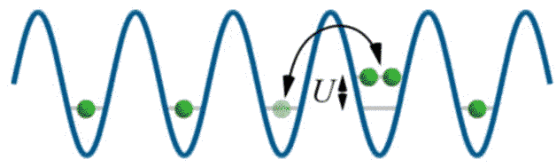
e.g. Kasevic, Inguscio, Arimondo

Some Signatures of the Mott Insulating State

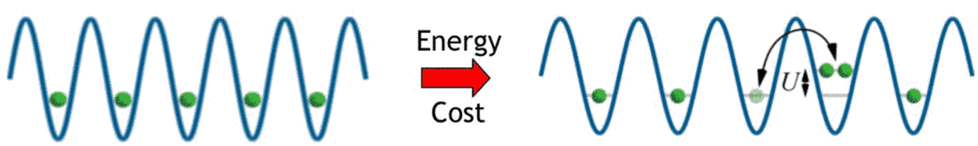
Reversible Loss of Phase Coherence



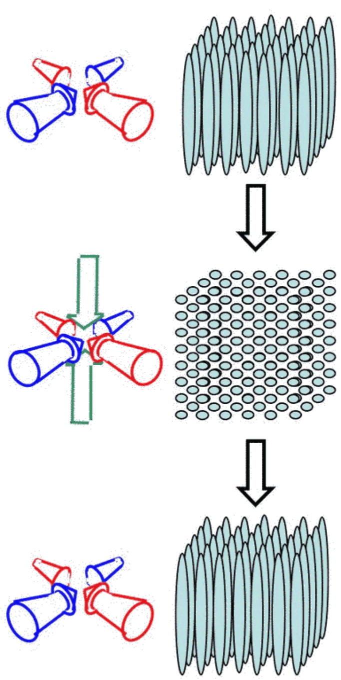
Gap in Excitation Spectrum

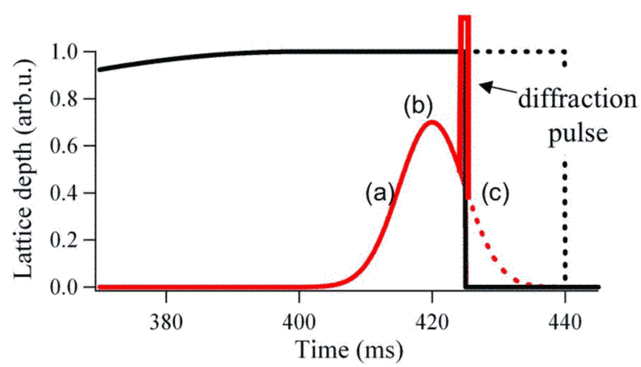


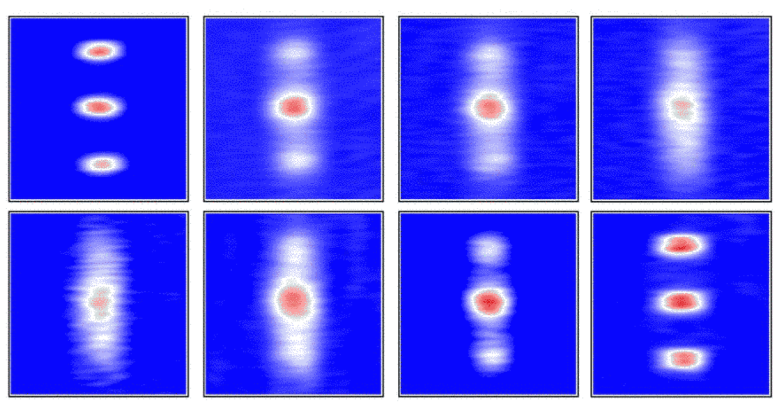
Inhibited Transport



Loss of Phase Coherence



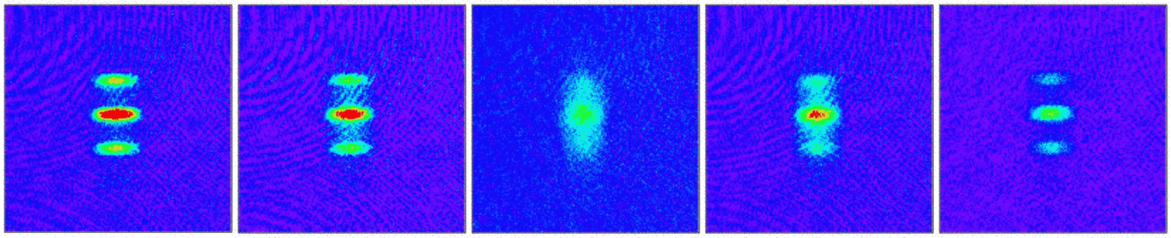




Similar to 3D version in
Munich *Nature* **415**, 40 (2002)

Projections and Quantum Beats

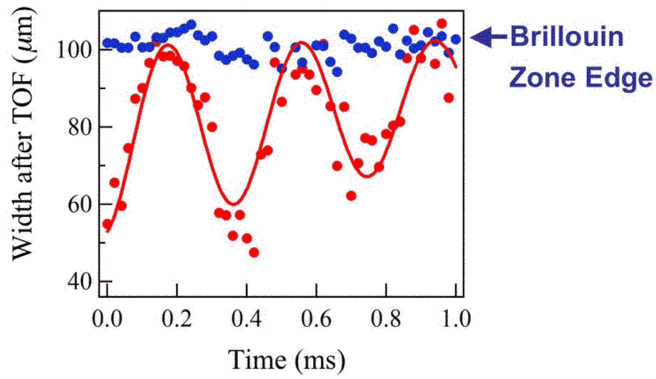
Project Coherent State onto Fock States: superpostion of 1, 2, 3 … atoms/site



Revivals of Coherent State at multiples of Revival Time:

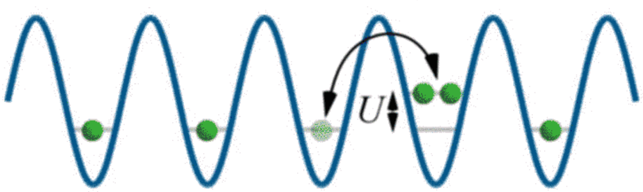
$$T = \frac{h}{U} \cong 400\ \mu s$$

Similar to 3D version in
Munich *Nature* **419,** 51 (2002)

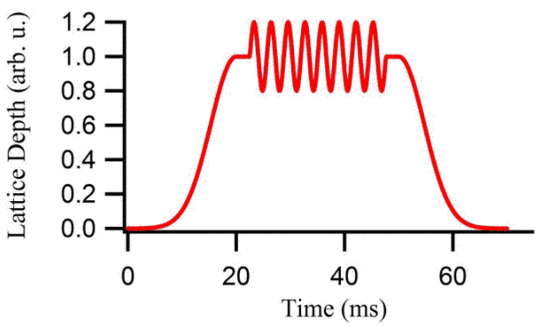


Excitation Spectrum

Discrete Excitation Spectrum

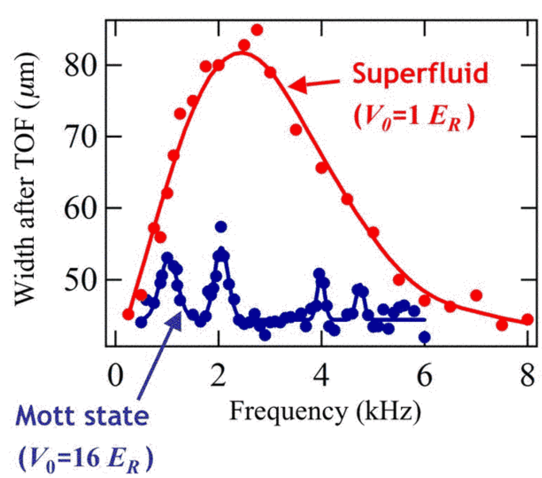


Excitation Resulting from Amplitude Modulation:



See also, T. Esslinger, et. al. cond-mat\0312440

Superfluid/Mott Insulator Spectra:



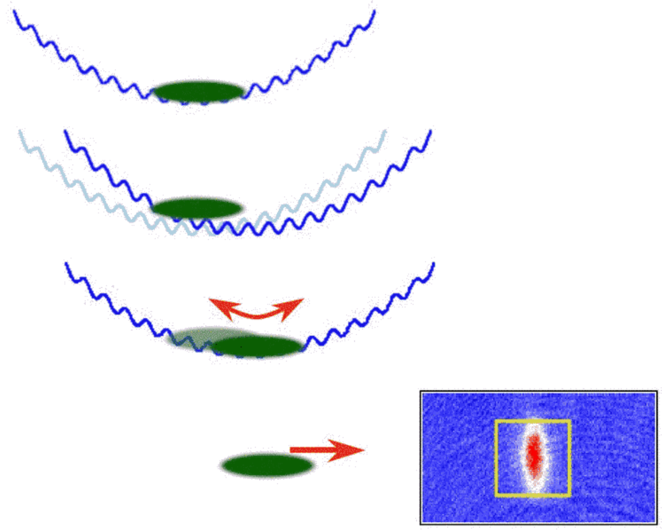
Transport in 1D Lattice

Load atoms into lattice:

Displace Harmonic Trap:

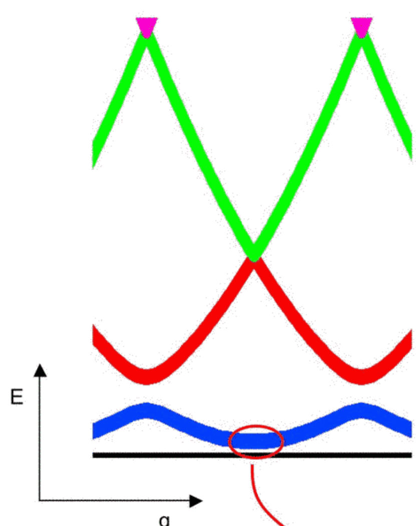
Wait variable delay then turn off trap/lattice:

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

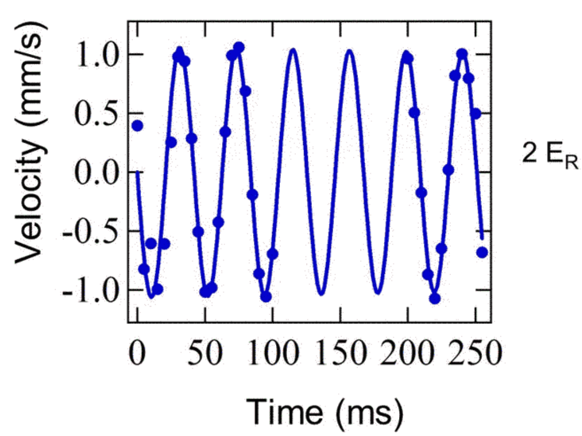


- Harmonic Trap Displaced by 2.5 μm (Cloud Radius ~10 μm)
- v_{max} = 1 mm/s   (less than 1/5 of recoil velocity)
- Maximum Gradient: 40 Hz/(λ/2) (<< 2 kHz/(λ/2))
- ~2 particles/site

Weakly-Interacting Harmonic Oscillation



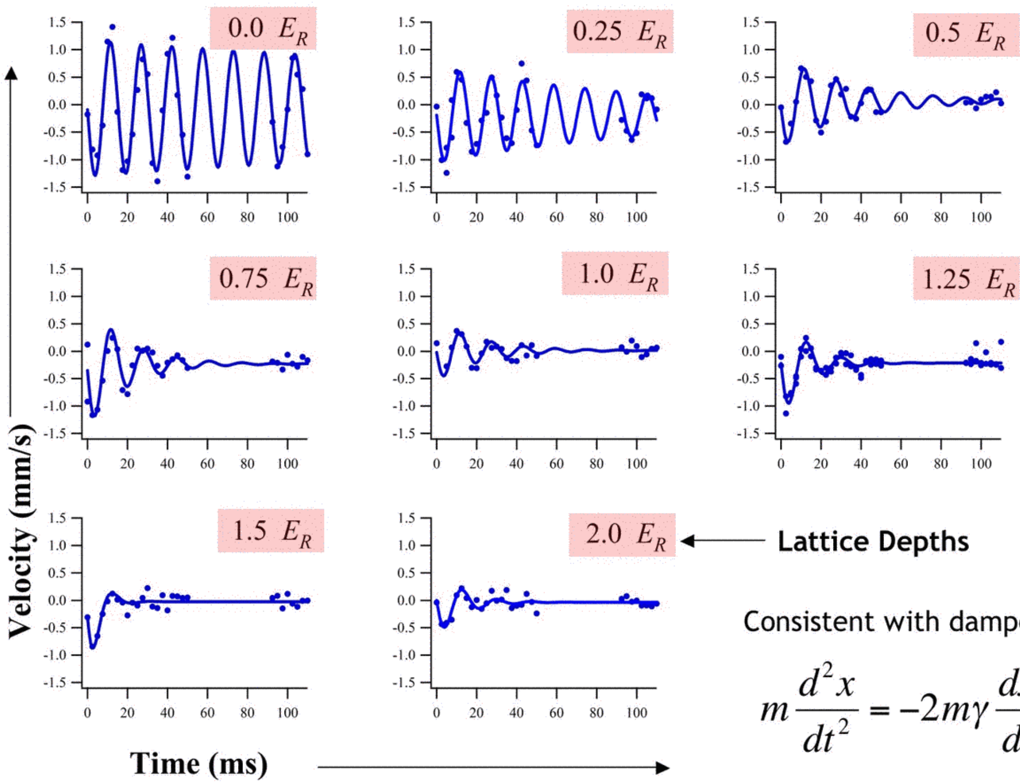
Example:
1D Lattice only, no confining tubes
"pancakes" configuration



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

See Inguscio et al.

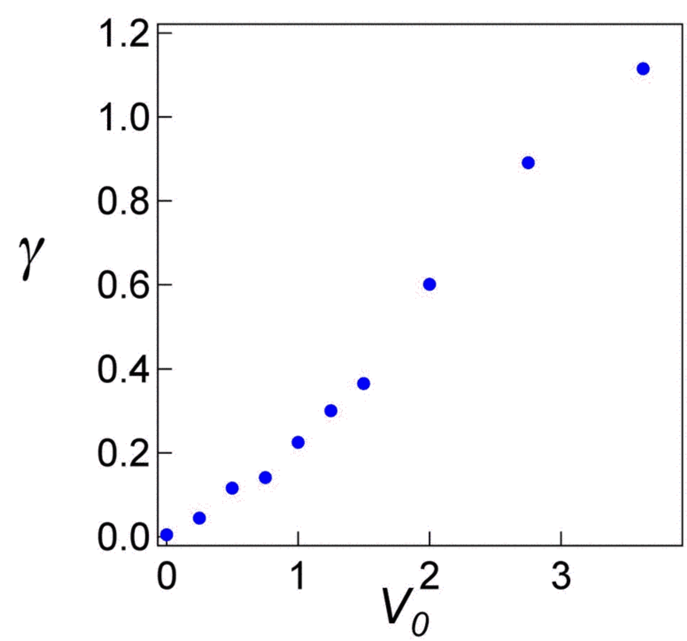
Transport in 1D Lattice



Consistent with damped oscillator:

$$m\frac{d^2x}{dt^2} = -2m\gamma\frac{dx}{dt} - kx$$

Transport in 1D Lattice



Damping begins immediately

Measuring Damping Constant, Overdamped

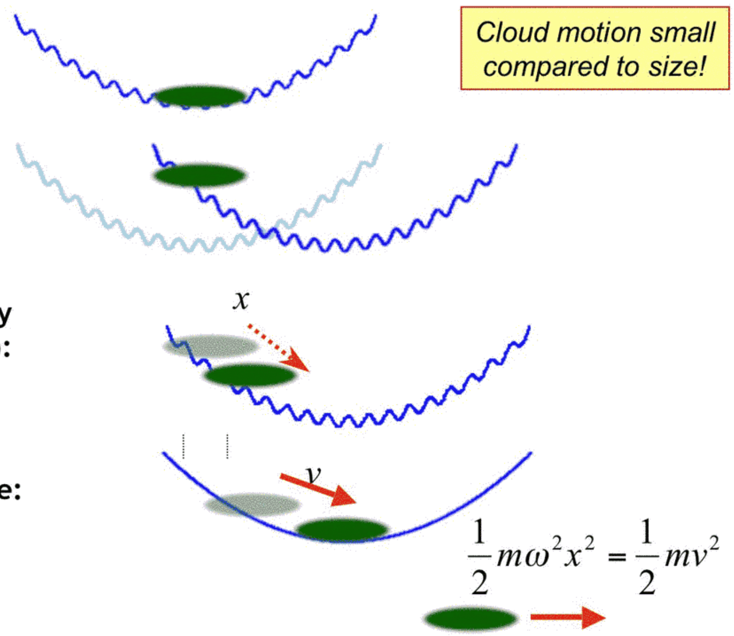
Load atoms into lattice:

Displace Harmonic Trap:

Wait 90 ms (cloud slowly returns to equilibrium):

Turn off 1D lattice:

Release after T/4



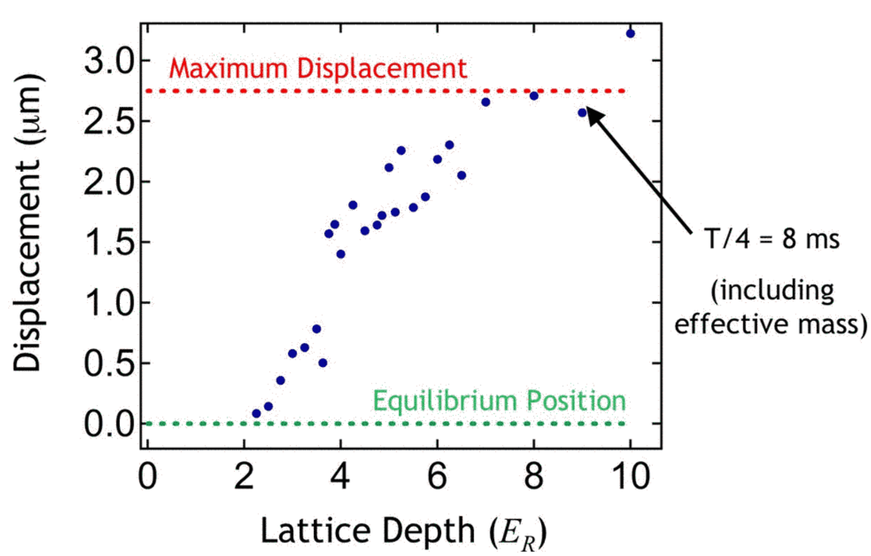
$$\frac{1}{2}m\omega^2 x^2 = \frac{1}{2}mv^2$$

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

Overdamped Motion

Displacement from Equilibrium

after 90 ms in Lattice



Transport in 1D Lattice

Model as damped harmonic motion

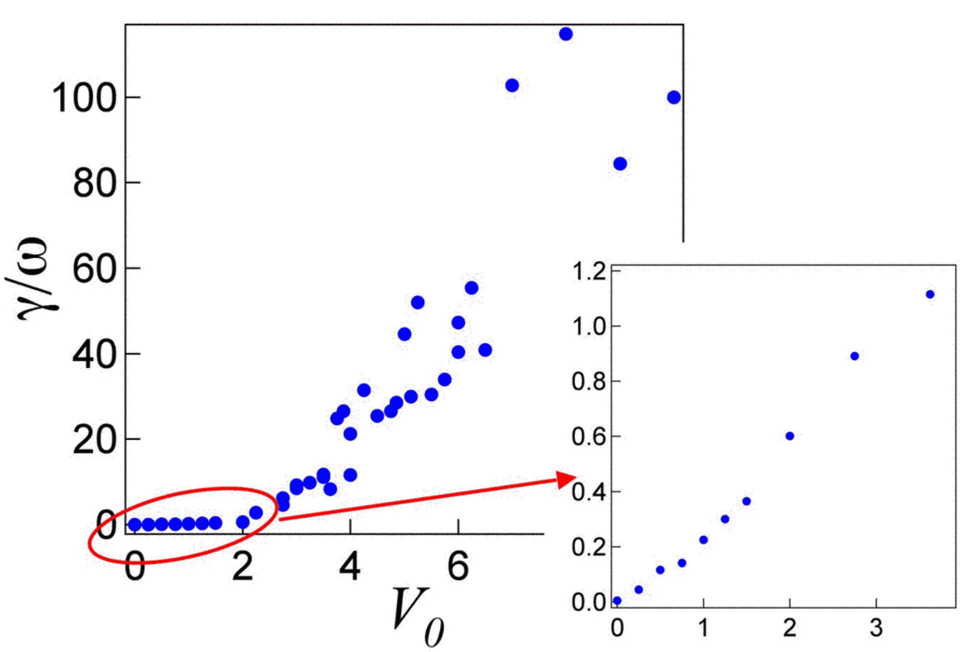
$$m\frac{d^2x}{dt^2} = -2m\gamma\frac{dx}{dt} - kx$$

Underdamped motion:
fit velocity to damped harmonic oscillator

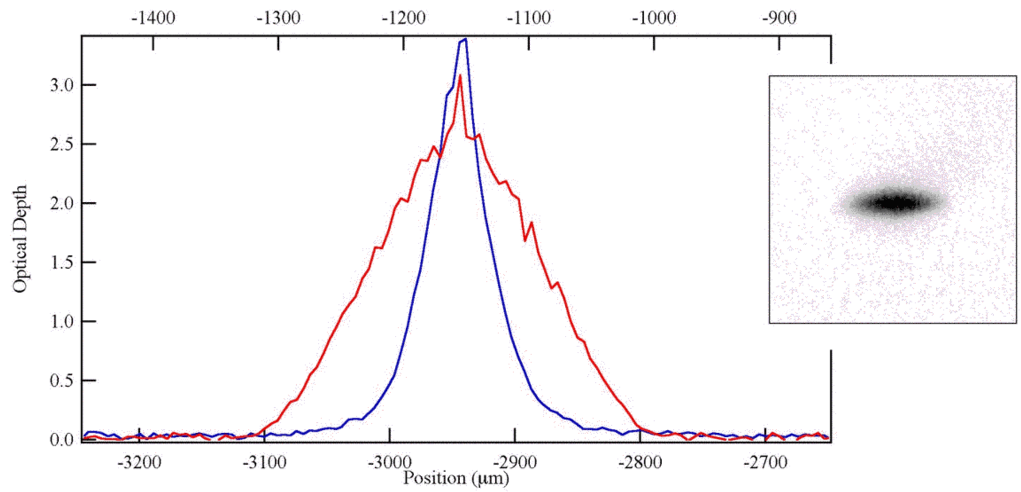
Overdamped motion:
measure relaxation to equilibrium position

Extract a damping constant as a function of lattice depth

Transport in 1D Lattice



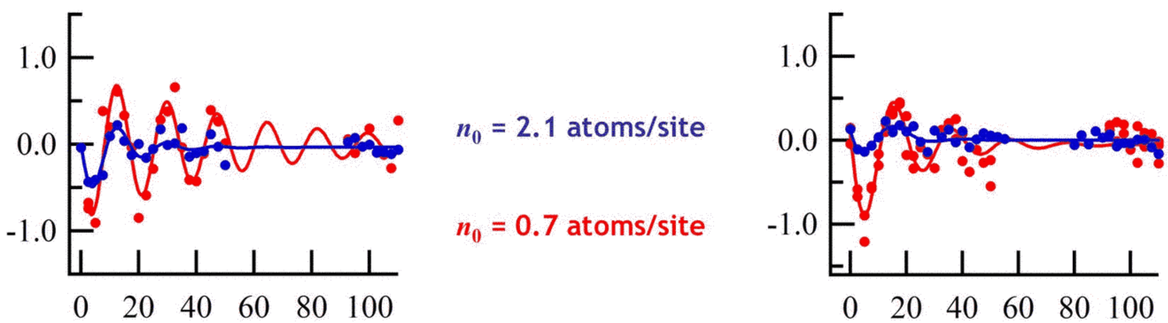
Transport in 1D Lattice



"Depletion" is may be substantial

"Depletion" is weaky dependent on V_0 (V_0<2)

Other Hints



Lower density → less damping

Initial indications damping is largely temperature independent

Questions

Should thermal "depletion" and quantum "depletion" damp equivalently?

How do we explain temperature dependence?

Should we expect smooth transition to the insulating state for inhomogeneous system?

What role in general does the inhomogeneities play?

How long until we get the moved experiment back up & running?

People

Current Postdocs/
Graduate Students

K. O'Hara
C. Fertig
J. Huckans

Former Posdocs/
Visitors

B. Laburthe-Tolra

M. Anderlini
S. Rolston

Lasercooling Group

K. Helmerson P. Lett T. Porto W. Phillips

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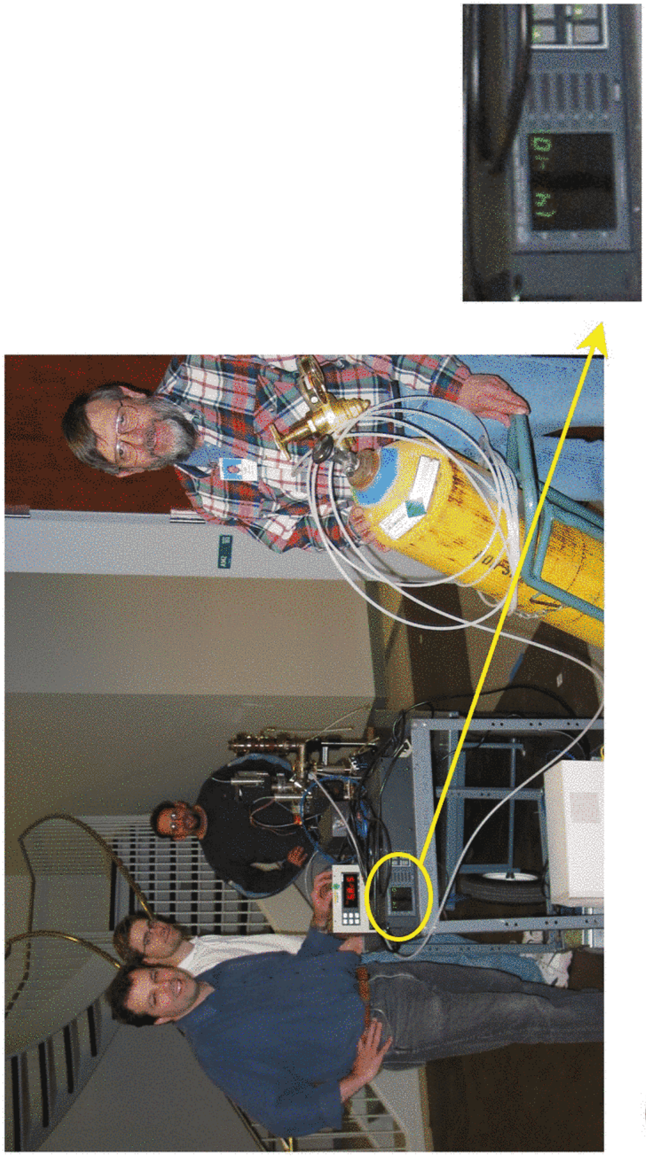
Experiment In Motion



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