Heisenberg Spectroscopy in an Optical Lattice

Mark Kasevich

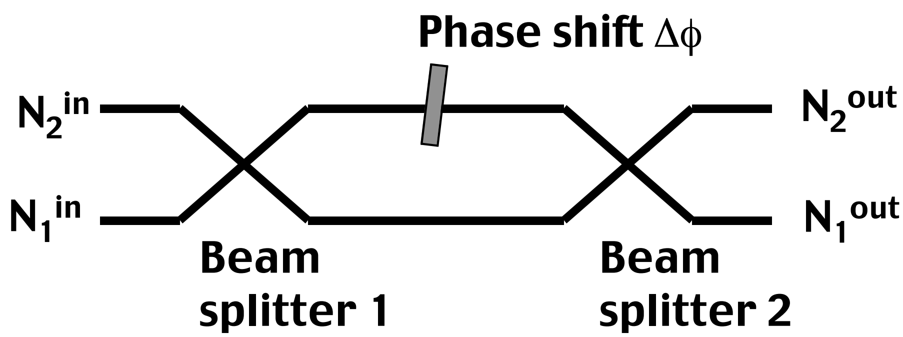
Yale University

Stefanie Dettmer
Matt Fenselau
Ari Tuchman

Mark Kasevich
Yale University
mark.kasevich@yale.edu

Interferometry with Squeezed States

Generic scheme (closely related to proposal by Holland and Burnett, 1993):



- Fock states at input ports
- Number measurements at output ports

Capable of resolving phase shifts at Heisenberg limit ($\Delta\phi \sim 1/N$)

Implementation in lattice system:

State preparation = Insulator transition

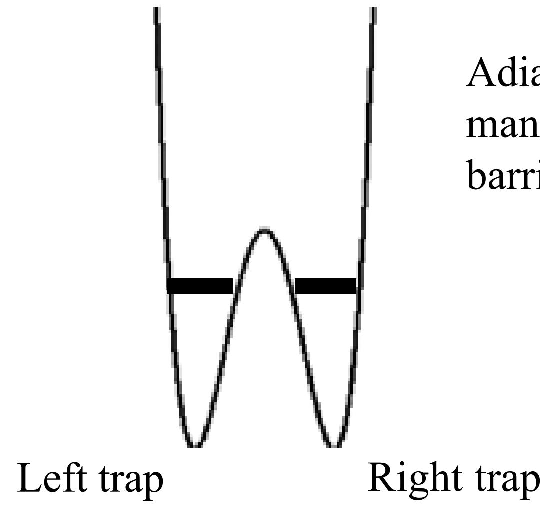
Beam-splitter = Sudden change in lattice parameters

Phase-shift = Sudden change in external potential

Readout = Interference of atoms released from lattice

Mark Kasevich
Yale University
mark.kasevich@yale.edu

Double-well System



Adiabatically manipulate tunnel barrier height

Hamiltonian

$$H = -\gamma \underbrace{(a_L^+ a_R + a_R^+ a_L)}_{\text{tunneling}} - g\beta/2\underbrace{[(a_L^+ a_L)^2 + (a_R^+ a_R)^2]}_{\text{mean field}}$$

What is the many-body ground state of this system (assume N atoms are partitioned between the two traps)?

Literature

A. Imamoglu, M. Lewenstein, and L. You, 1997.
J. Javanainen, 1998.
R. Spekkens and J. Sipe, 1999.
A. Smerzi and S. Raghavan, 1999.

Mark Kasevich
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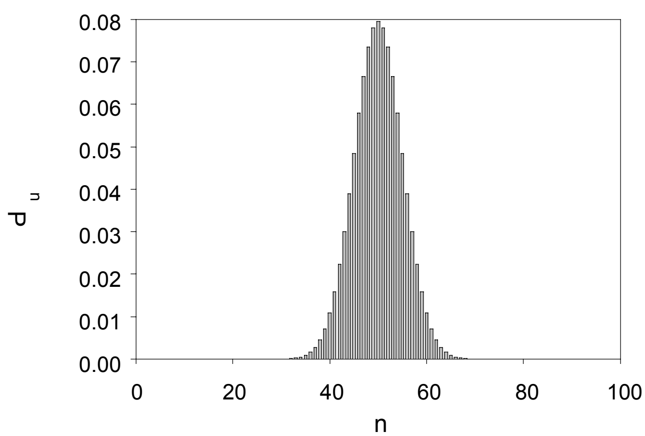
Ground States

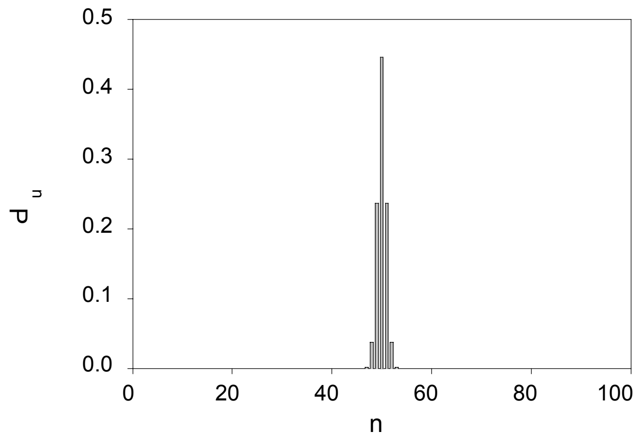
Assume $|\psi\rangle = \Sigma c_n |n, N\text{-}n\rangle$

Left trap   Right trap



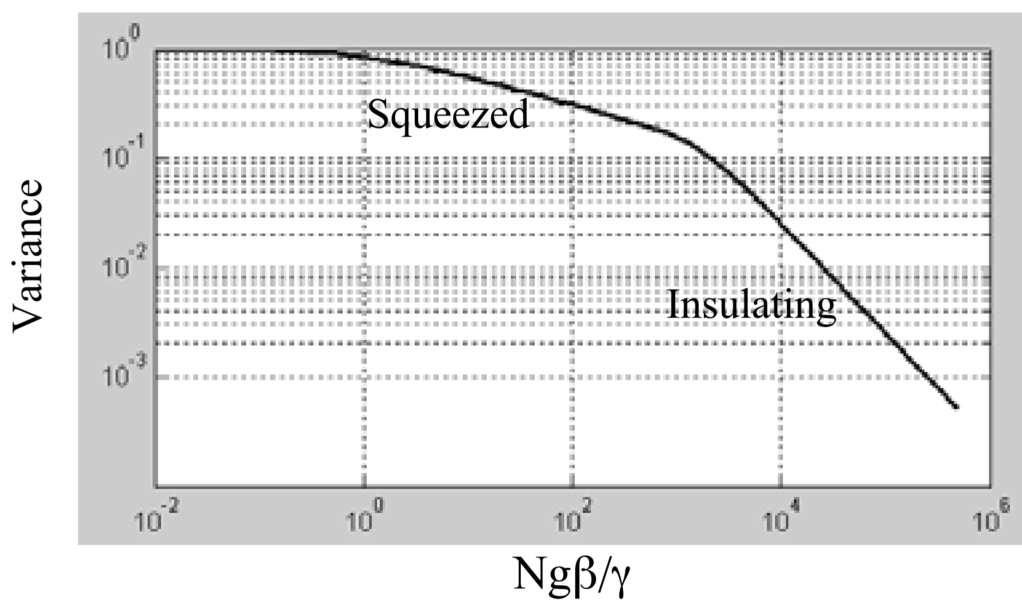
$Ng\beta/\gamma = 0$
(non-interacting)

$|\psi\rangle \sim \{(a_L^{+} + a_R^{+})/\sqrt{2}\}^N |vac\rangle$



$Ng\beta/\gamma = 100$

For $Ng\beta/\gamma \rightarrow$:,
$\rangle \sim \{a_L^{+}\}^{N/2} \{a_R^{+}\}^{N/2} |vac\rangle$



Mark Kasevich
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Lattice Potential

Find ground state for harmonic + lattice potential

Use variational method to find ground-state:

Ansatz,

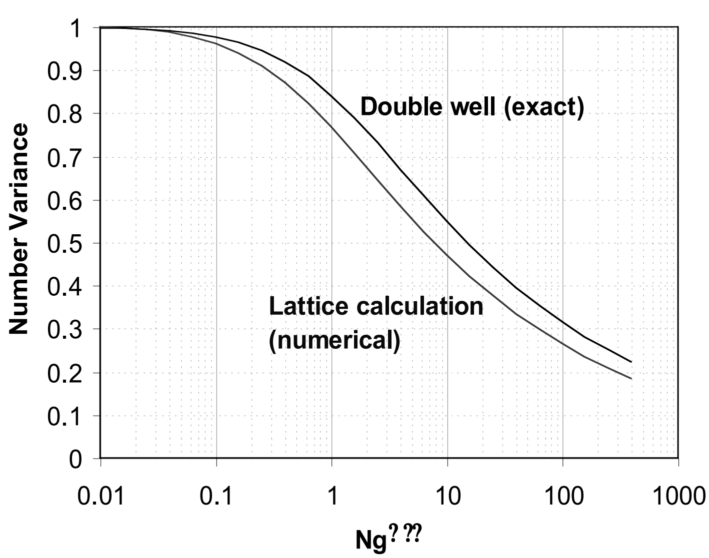
$|\psi\rangle = \Pi_\iota |\phi_i\rangle$ (*i* indexes lattice site)

where,

$|\phi_i\rangle \sim \Sigma \exp -\{(n-n_0)^{2/}\sigma_\iota^{2}\} |n\rangle$

Vary n_0, σ

Example solution:



30 lattice sites

~50 atoms/site (center)

Mark Kasevich
Yale University
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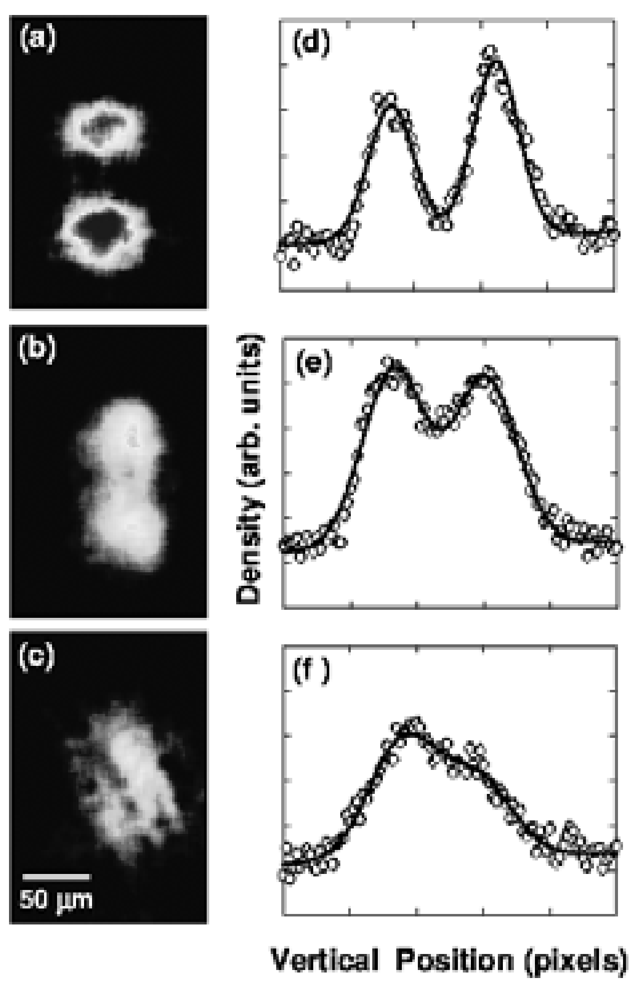
Experiment

- Adiabatically (with respect to many-atom ground state) ramp lattice intensity to form squeezed states (200 msec).
- Switch off harmonic trap, hold for short time (2 msec) in gravitational potential (lattice beams vertically oriented).
- Release atoms from lattice. Observe interference of atoms released from lattice.

7 E_r lattice depth

18 E_r lattice depth

44 E_r lattice depth



Mark Kasevich
Yale University
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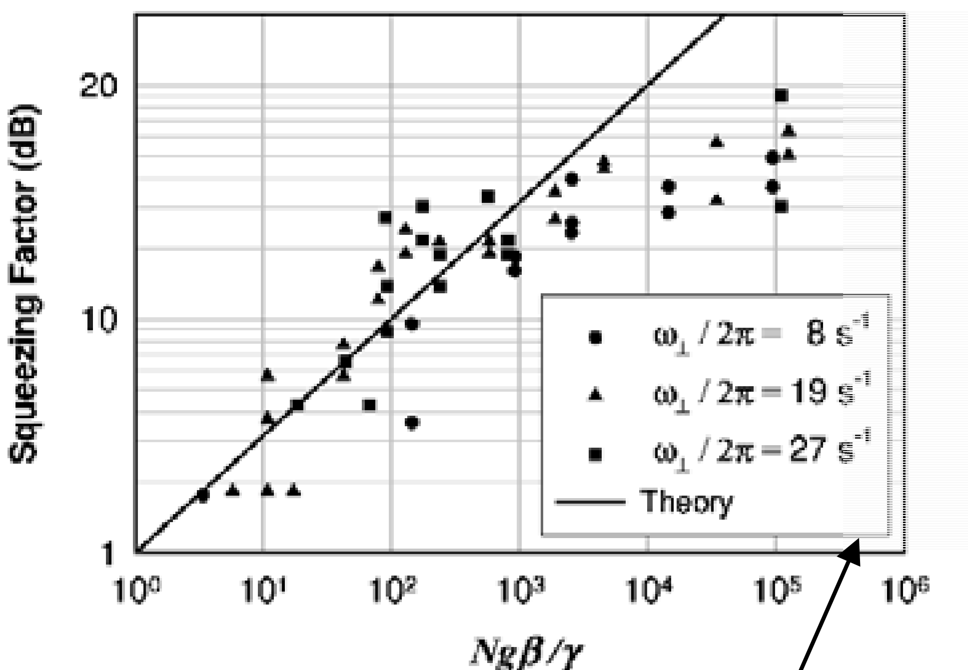
Squeezing Factor

Analyze interference patterns to extract phase variance at each lattice site

- compare measured with modeled signals



Insulating regime (accessed in most recent experiments)

Mark Kasevich
Yale University
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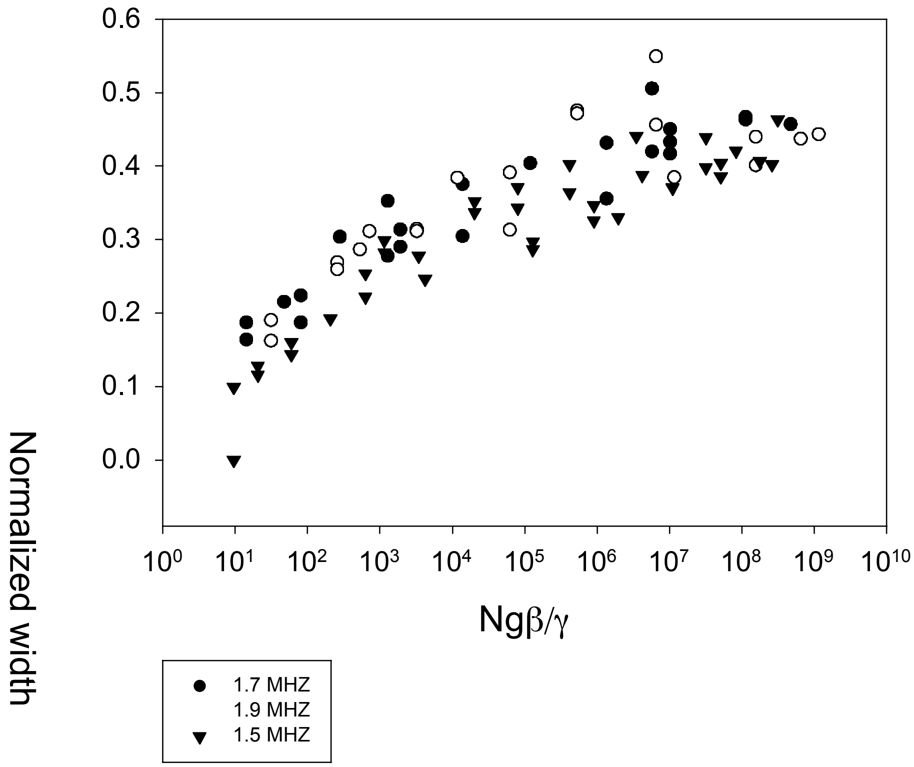
Temperature Dependence



Observed dephasing is independent of temperature of condensate.

Mark Kasevich
Yale University
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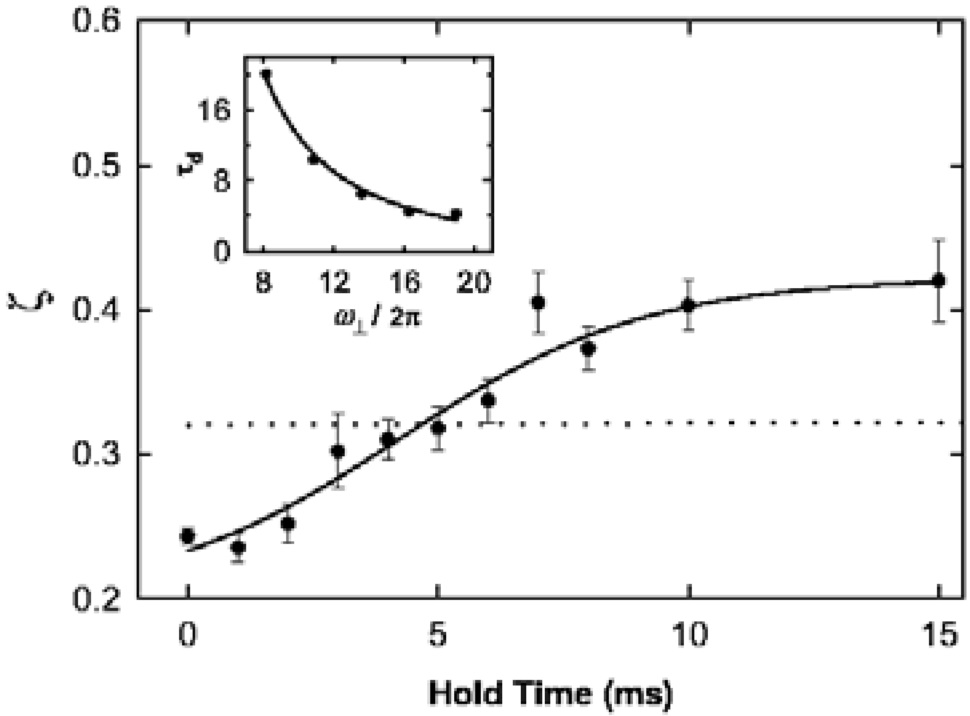
Non-adiabatic Lattice Step

- Suddenly raise lattice to deep level
- Hold for fixed time
- Investigate interference pattern



Mark Kasevich
Yale University
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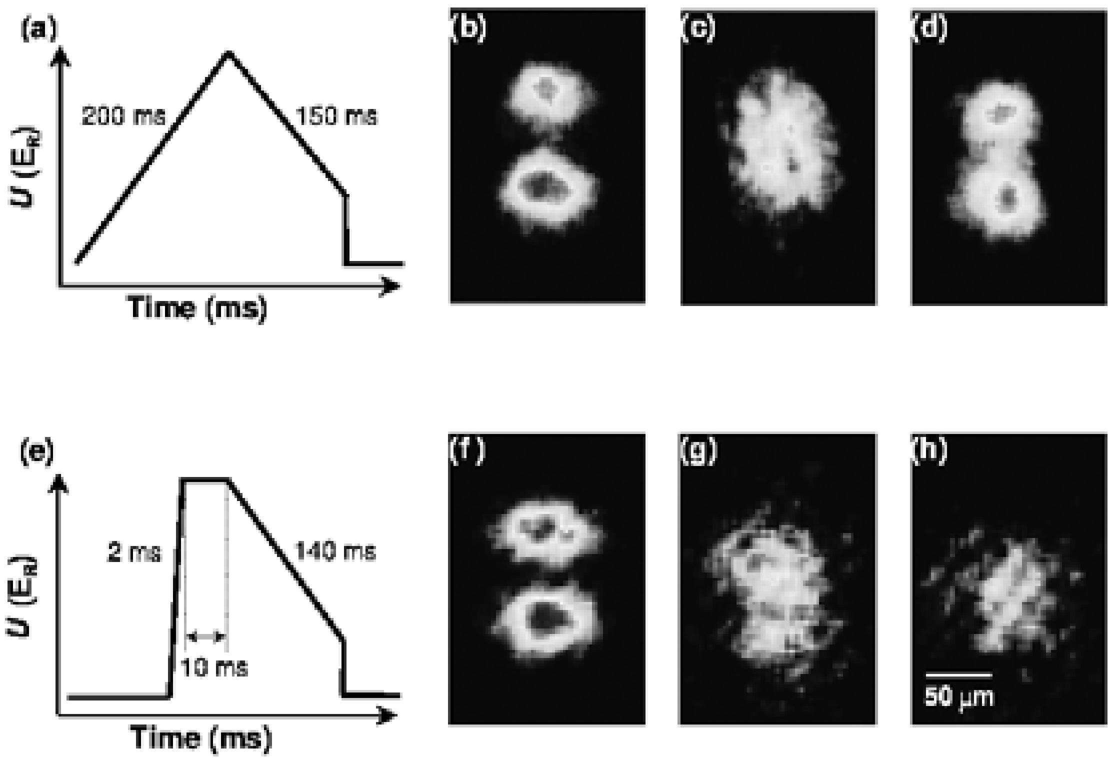
Adiabatic State Manipulation

- Slowly ramp lattice up to produce squeezed state.
- Slowly ramp lattice down to recover coherent state.
- Compare with response to fast initial ramp.



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Yale University
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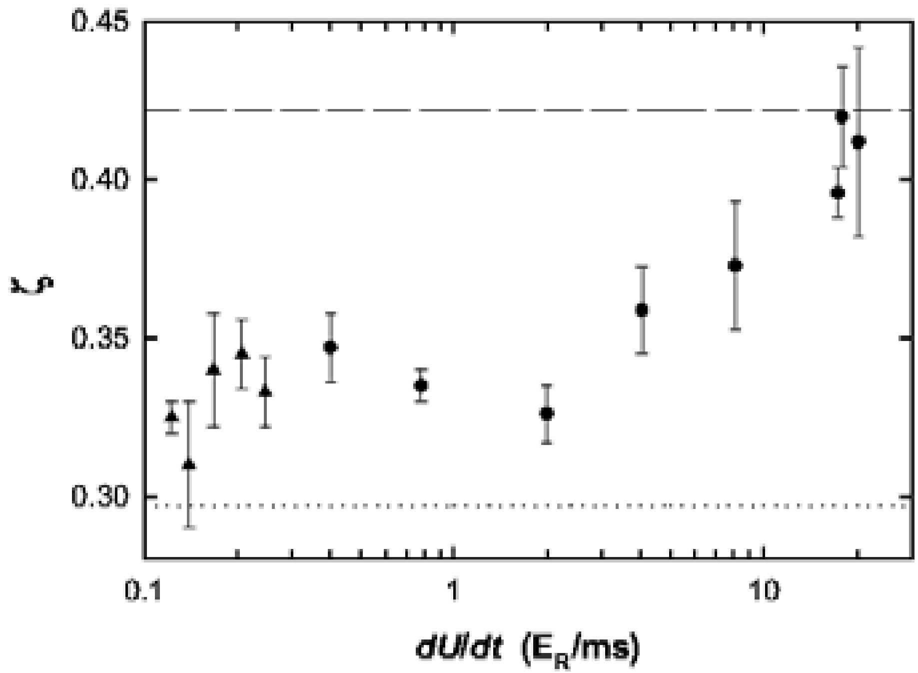
Time Scale for Adiabaticity

Change ramp time to investigate transition between adiabatic and non-adiabatic behavior.



Mark Kasevich
Yale University
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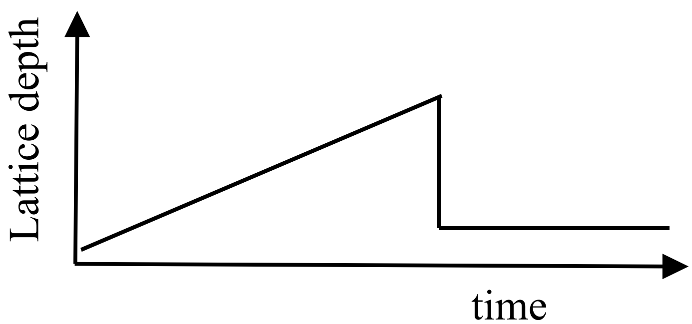
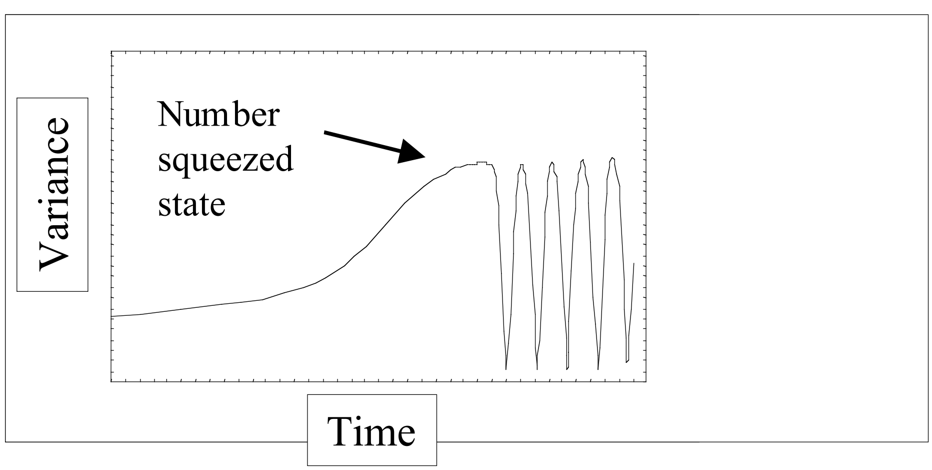
Lattice Dynamics

- Adiabatically ramp lattice depth to prepare number squeezed states
- Suddenly drop lattice depth to allow tunneling
- (Drop slow compared to vibration frequency in well)



Time dependent variational estimate
for phase variance per lattice well



Experimental signature: breathing in interference contrast

Mark Kasevich
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Time-dependent Variational Calculation

Wavefunction parameterized in terms of mean and variance of atom number and phase for each lattice site:

$$\Psi_k = \Psi_k(\phi_k, n_k, \sigma_{\phi,k}, \sigma_{n,k})$$

Lattice wavefunction: $$\Psi = \prod_{k=1}^{N} \Psi_k$$

Time dependent equations for variational parameters:

$$\dot{\phi}_k(t) = 4n_k(t) - 2[n_{k-1}(t) + n_{k+1}(t)]$$

$$\dot{n}_k(t) = \Gamma \sin[\phi_{k-1}(t) - \phi_k(t)] e^{-[\sigma^2_{\phi,k}(t) + \sigma^2_{\phi,k-1}(t)]/2}$$
$$-\Gamma \sin[\phi_k(t) - \phi_{k+1}(t)] e^{-[\sigma^2_{\phi,k}(t) + \sigma^2_{\phi,k+1}(t)]/2}$$

$$\dot{\sigma}_{\phi,k}(t) = 4\sigma_{\phi,k}(t)\delta_k(t)$$

$$\dot{\delta}_k(t) = -4\delta_k^2(t) + \frac{1}{\sigma^4_{\phi,k}(t)}$$
$$-\Gamma \cos[\phi_{k-1}(t) - \phi_k(t)] e^{-[\sigma^2_{\phi,k}(t) + \sigma^2_{\phi,k-1}(t)]/2}$$
$$-\Gamma \cos[\phi_k(t) - \phi_{k+1}(t)] e^{-[\sigma^2_{\phi,k}(t) + \sigma^2_{\phi,k+1}(t)]/2}$$

where $\delta_k = \delta_k(\sigma_{n,k}, \sigma_{\phi,k})$

$\Gamma \sim$ (Tunneling energy / mean field energy)

Model allows for calculation of time evolution of quantum state. Valid for $\sigma_\phi < 1$ rad.

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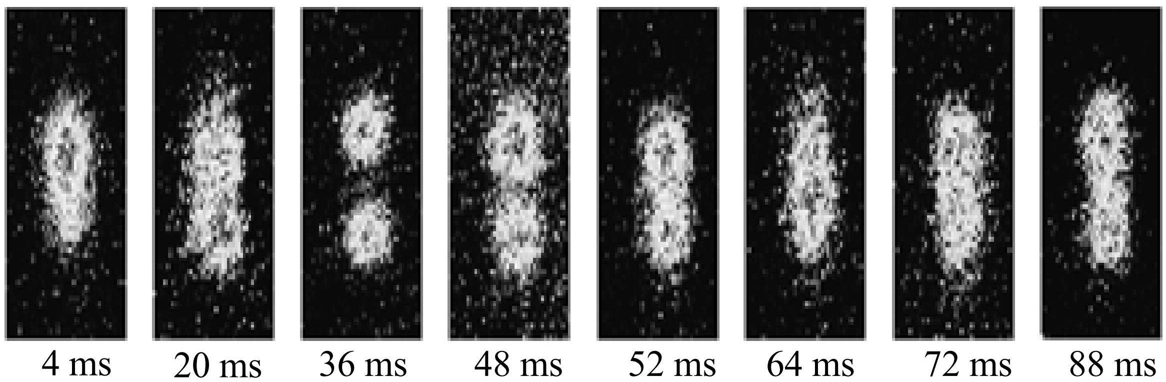
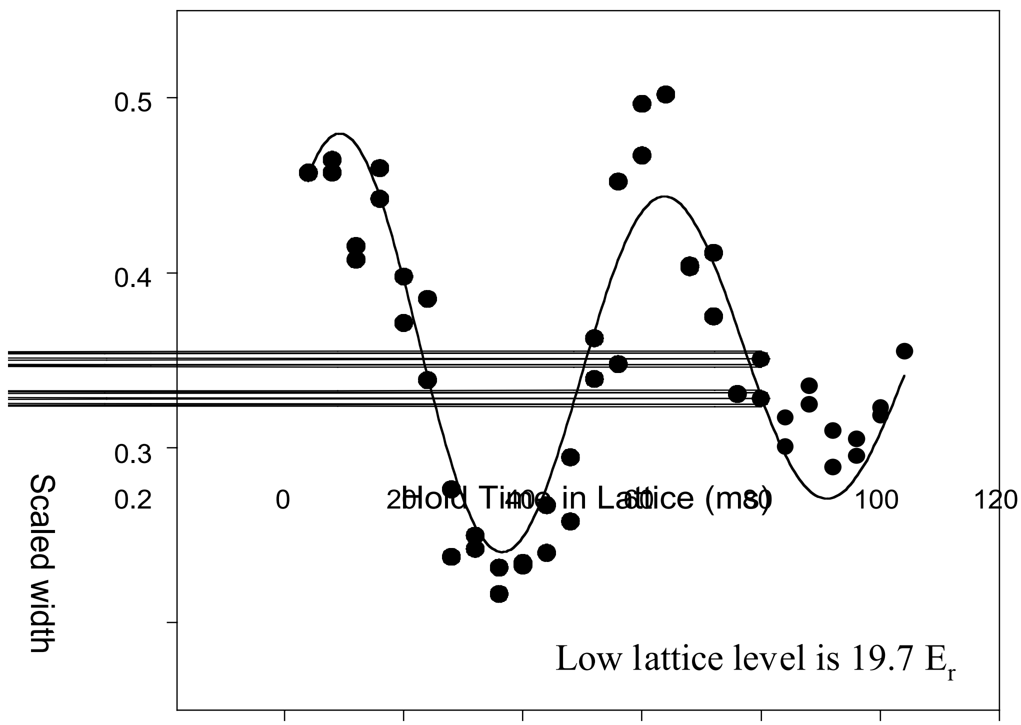
Observed State Oscillations





Mark Kasevich
Yale University
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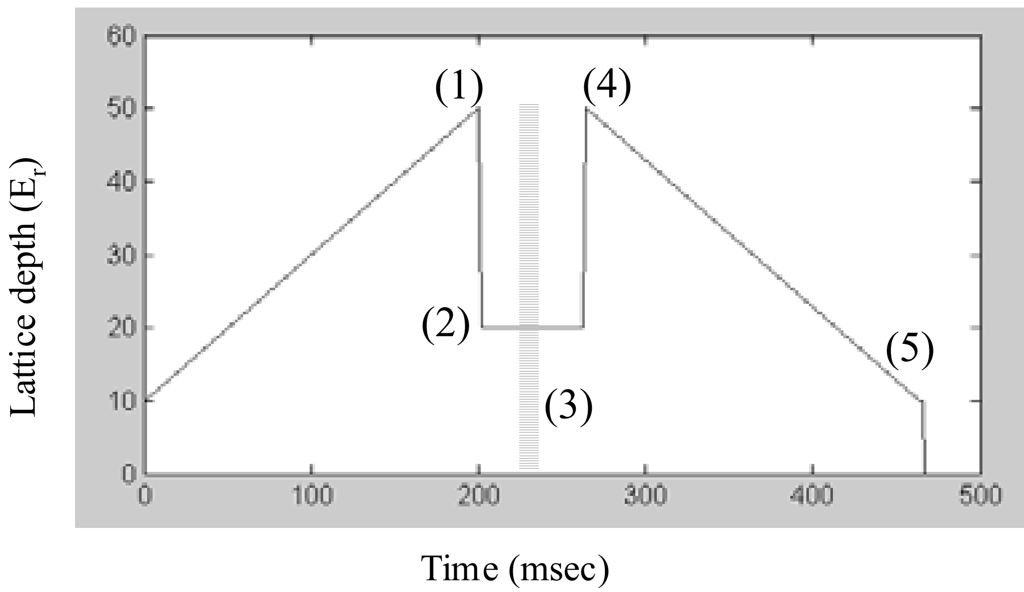
Interferometry Sequence



Interferometry sequence:

- Create array of Fock states
- Begin first beamsplitter (induce state oscillation to phase squeezed states)
- Apply gravity-induced phase stamp (suddenly turn off harmonic potential)
- End second beamsplitter
- Begin read-out sequence
- Release atoms from lattice

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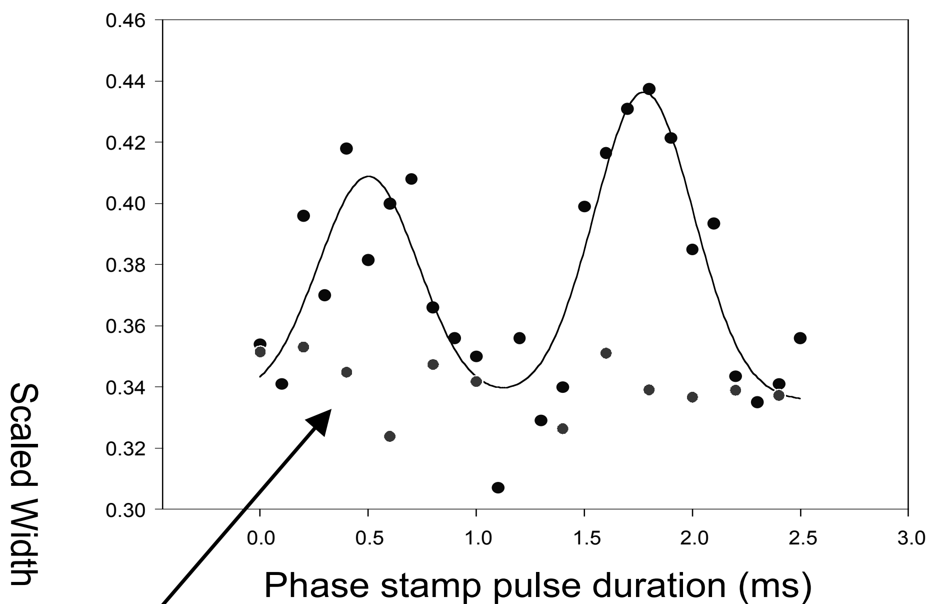
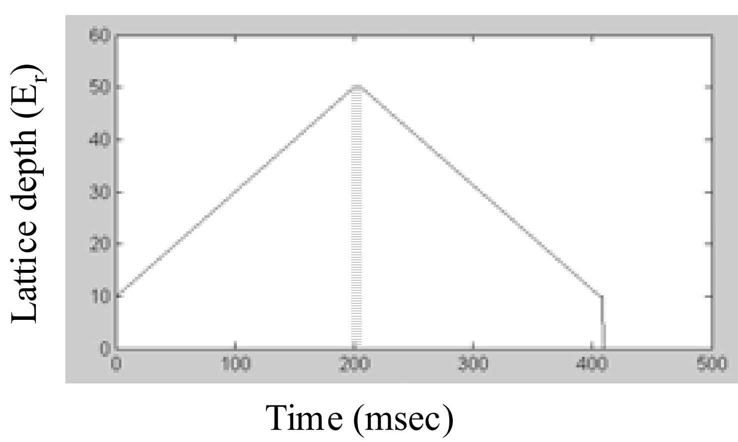
Results



Phase stamp
on Fock state

Fock state response:



No contrast oscillation is observed vs. size of phase stamp.

Independently verifies state preparation.