Raman-Induced Oscillation Between an Atomic and Molecular Gas

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BEC II

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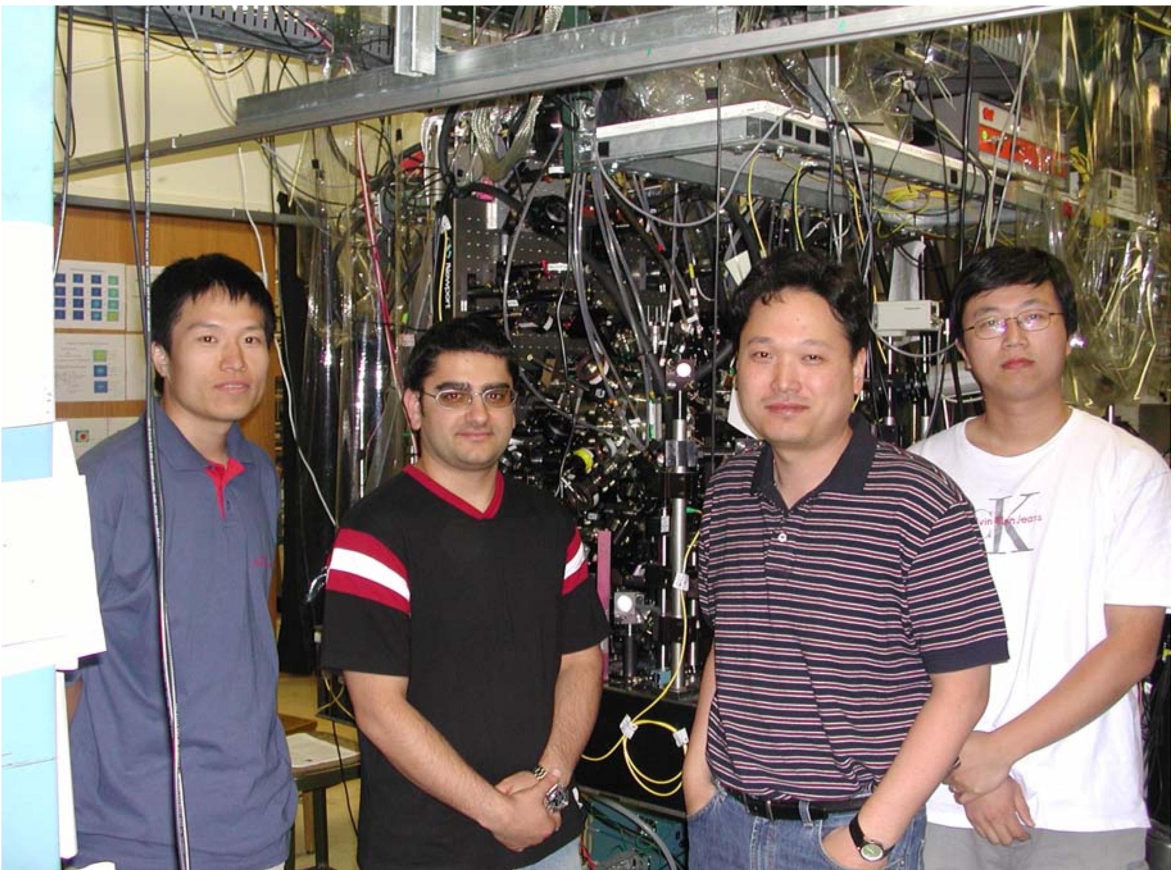


Zeeman-slowed ^{87}Rb beam

Dark MOT, molasses

Cloverleaf trap

RF-induced evaporation

BEC with up to 2×10^6 atoms

(F = 1, M= −1)

Outline

Feshbach Resonance and Raman Photoassociation in Bose Condensates.

Raman Photoassociation in a Mott Insulator.

- Resolved Contact Energy Shifts

  Can Determine Fraction of Sites with 1, 2, or 3 atoms.

  Can Determine Atom-Molecule Scattering Length.

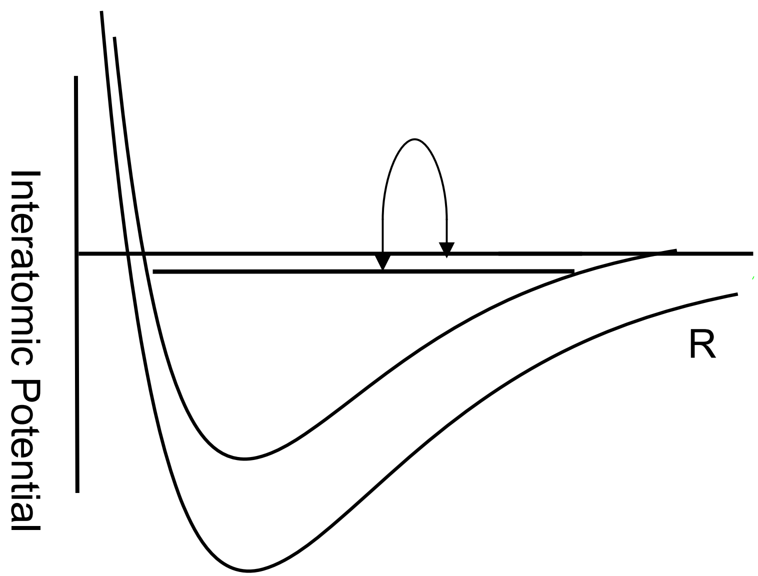
- Oscillating Atomic <-> Molecular gas!

Bragg spectroscopy of atoms in a 3D optical lattice

Coherent Atom-Molecule Coupling Mechanisms

- Feshbach Resonance

(JILA, MIT, Innsbruck, ENS, Rice, Munich,…)

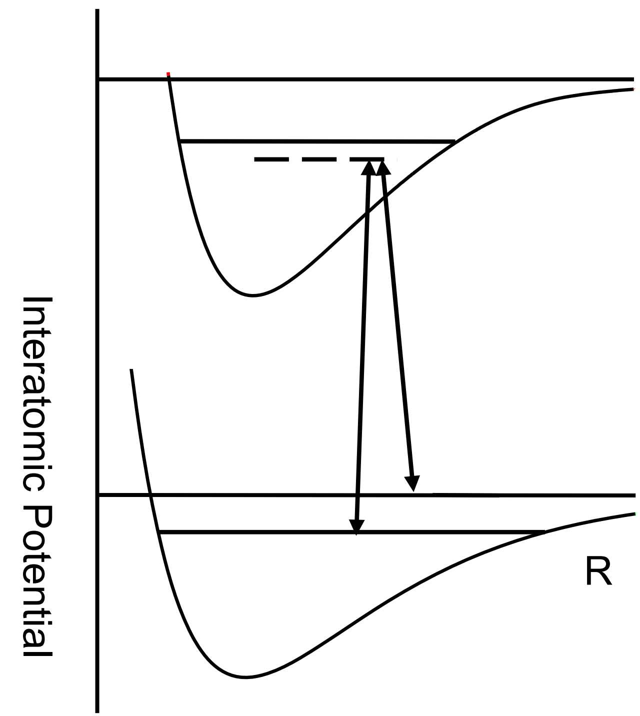


- Variation: Radio Frequency Coupling

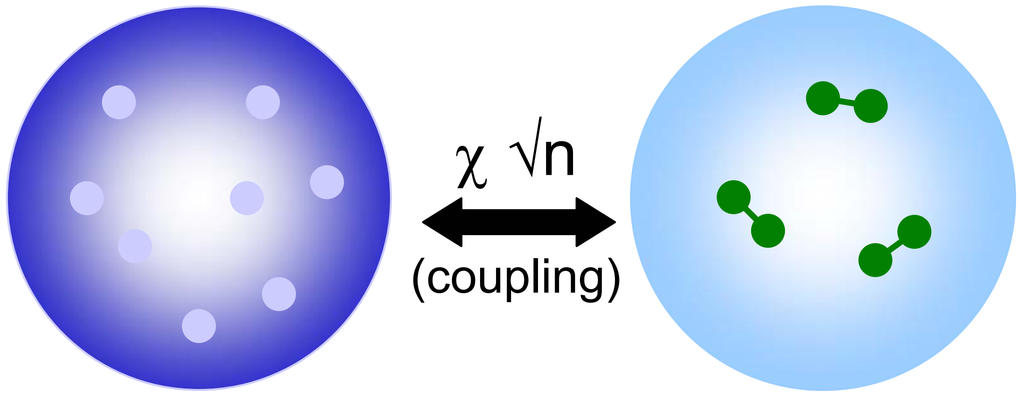
(JILA, MIT, Innsbruck, …)

- Raman Photoassociation

(Texas, Rice, Munich,…)



Coherent Atom-Molecule Coupling In a Bose Condensate



φ : atom field $\quad\quad$ ψ: molecule field

$$H \sim \chi\, \varphi^2\, \psi^+ + \text{h.c.}$$

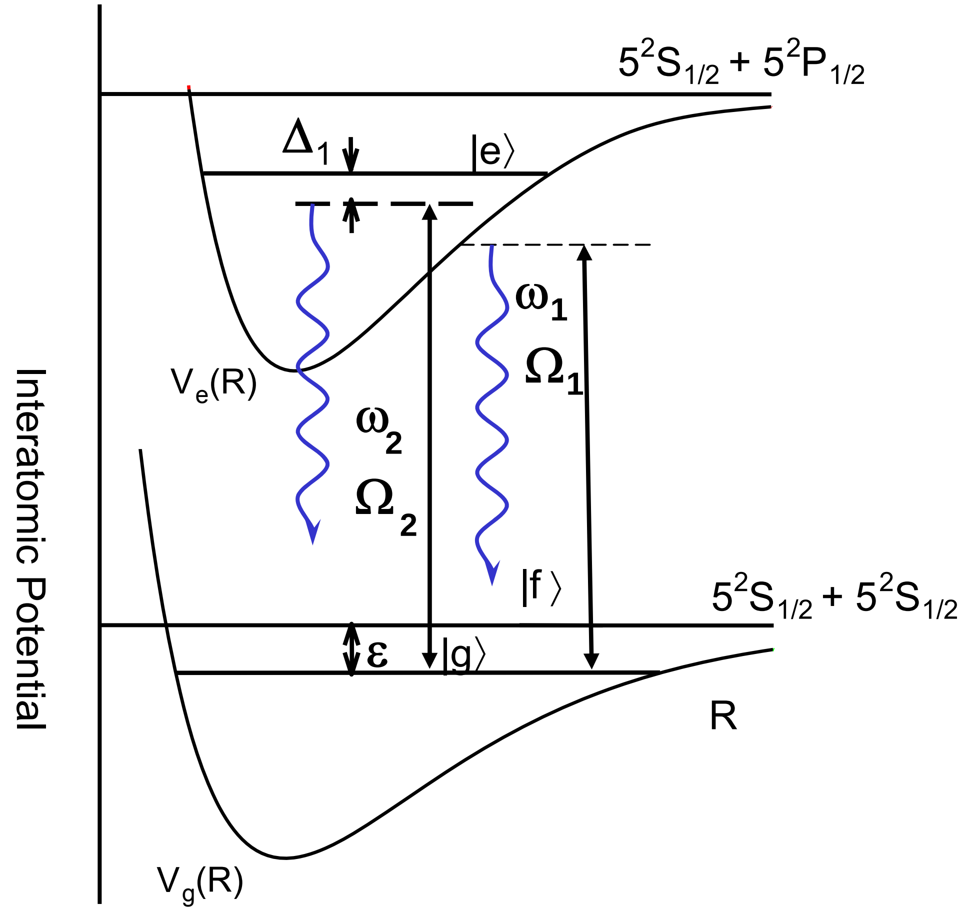
- Analogous to frequency doubling and parametric downconversion
- Pairing fields play a role ~ spontaneous down conversion
- Can in principle produce macroscopic coherent oscillation
- Theory: Drummond, Holland, Timmermanns, Burnett, …

Molecule Losses

$\Gamma_M = \Gamma_L + K_{inel} n_a$

Γ_L= Rate of spontaneous laser light scattering

(Can be calculated)



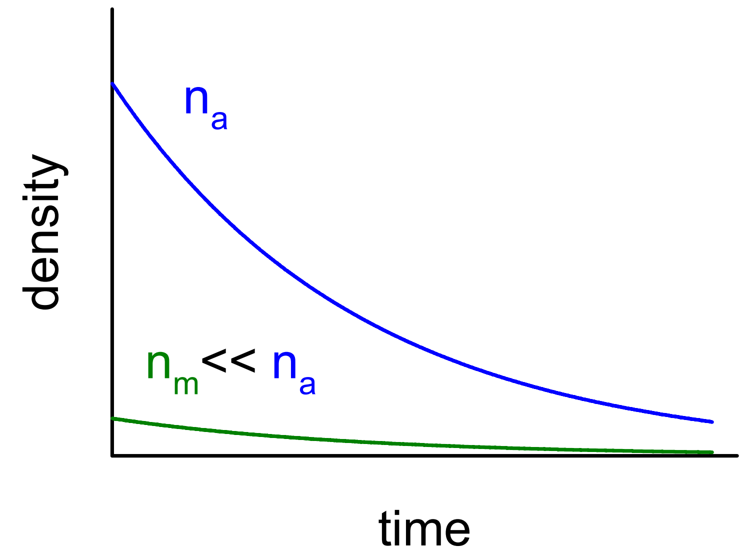
$K_{inel} n_a$ = Rate of inelastic collisions with atoms

(not calculable, generically expect $K_{inel} \sim 10^{-11}$ cm^3/s)

$\chi \sqrt{n} \ll \Gamma_M$

rate equation dynamics

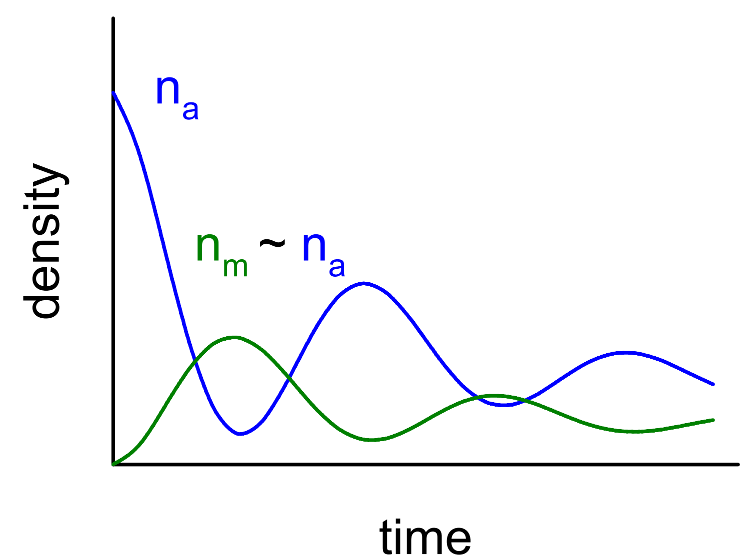
atom loss rate : $\chi^2 n / \Gamma_M$



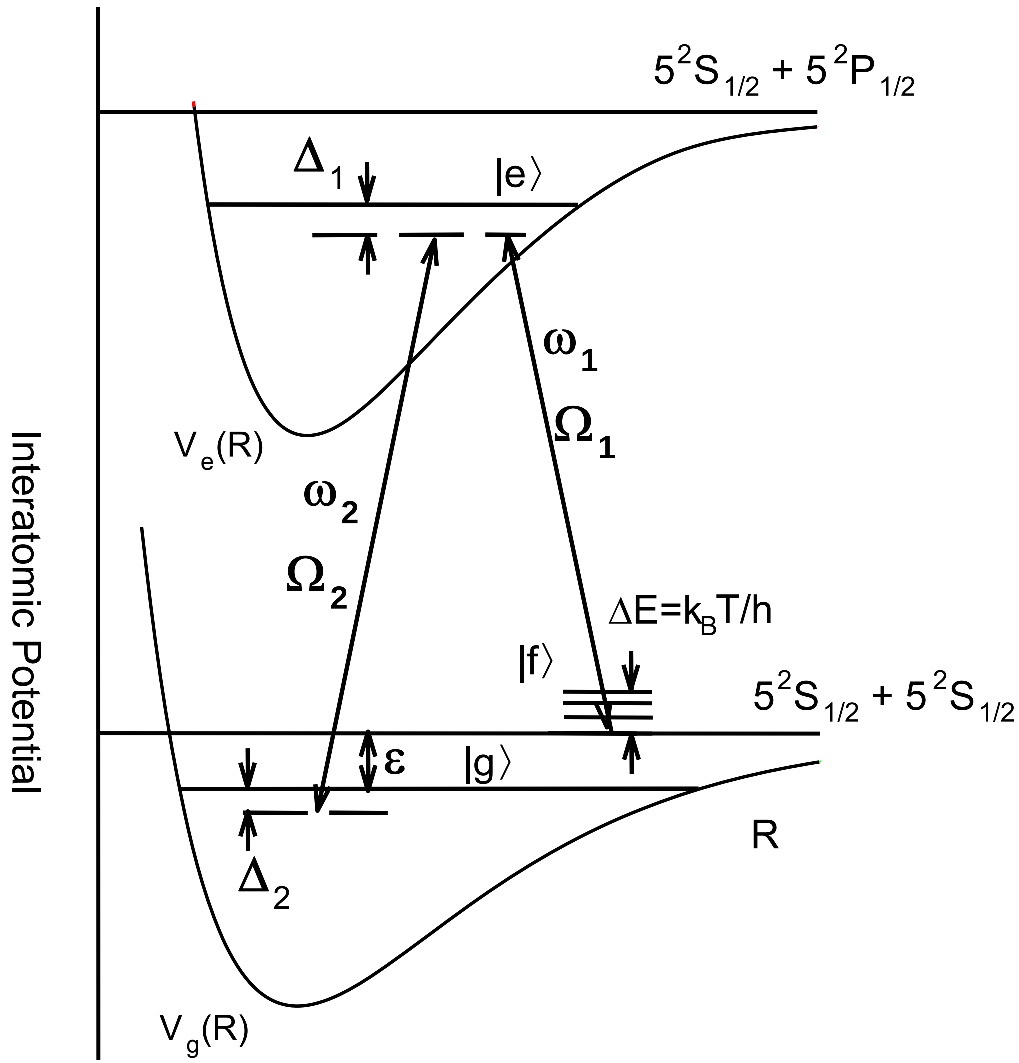
$\chi \sqrt{n} \gg \Gamma_M$

Coherently coupled
matter waves

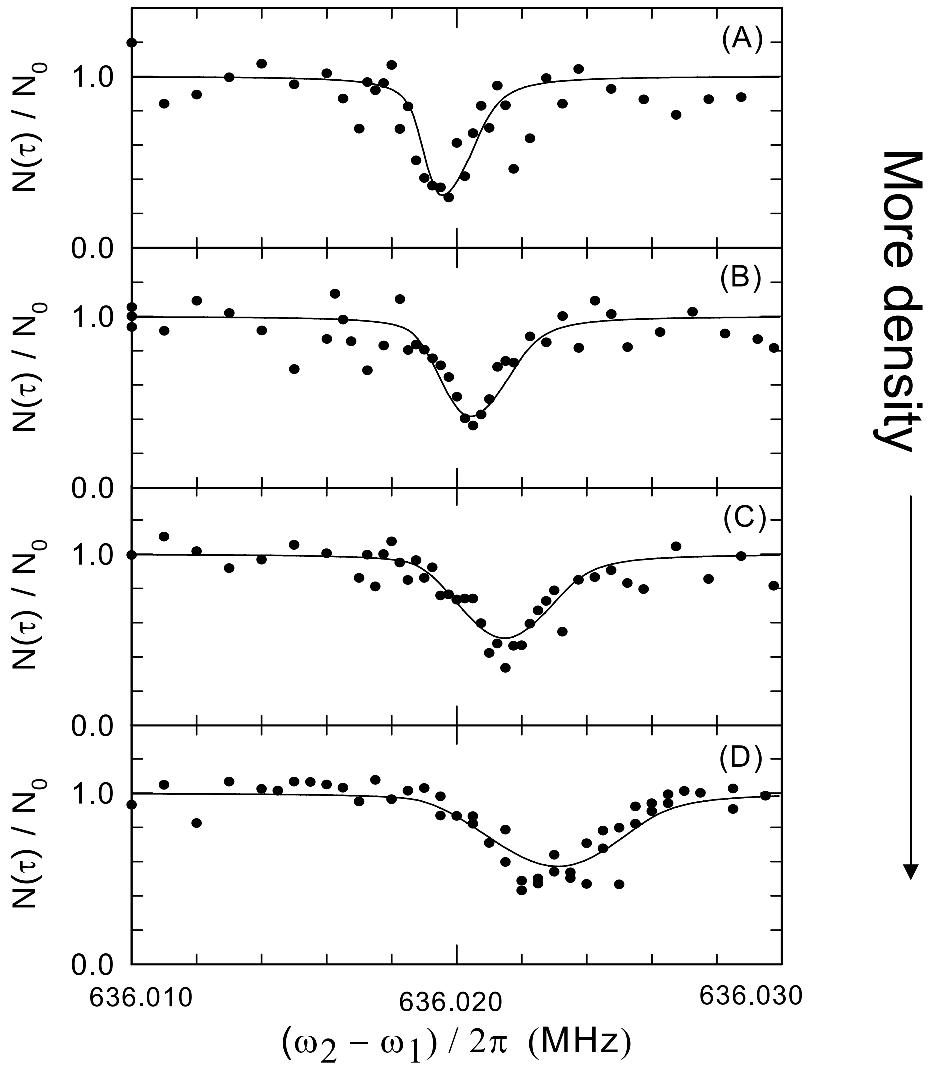
Collective atom-molecular
Rabi oscillation, STIRAP,…



Stimulated Raman Photoassociation



Stimulated Raman resonances in an ^{87}Rb Bose condensate



Linewidth < 2 kHz!

Increased linewidth with increased atomic density

Shift in line center with increased atomic density

Fit with photoassociation rate theory of Bohn and Julienne

Results

(Wynar, et al., Science **287**, 1016 (2000))

$\varepsilon_0/2\pi$ = 636.0094 ± 0.0012 MHz

a_{ma} = -180 ± 150 a_0

$K_{inel} < 8 \times 10^{-11}$ cm^3/s

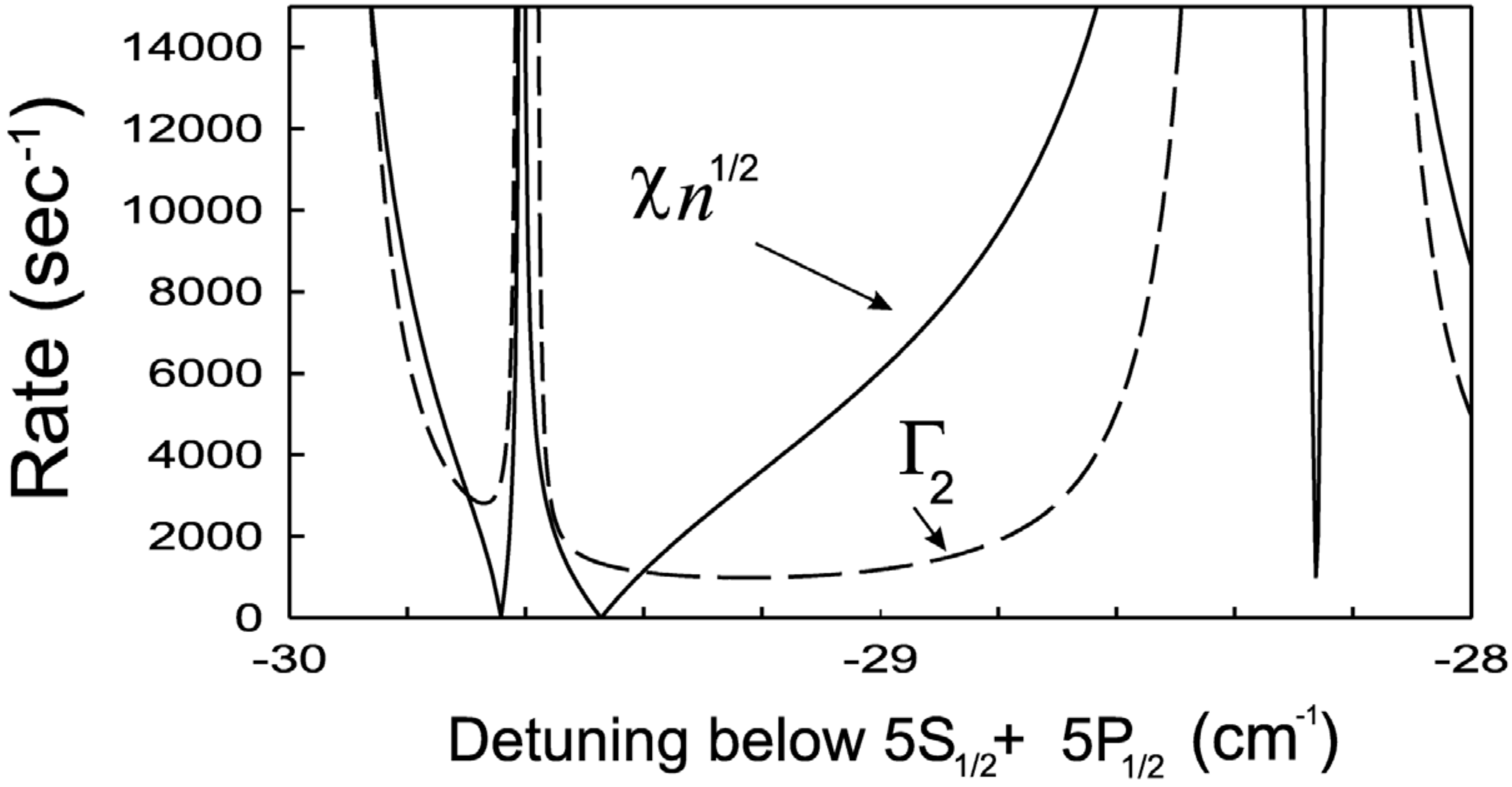
1,000 more accurate molecular binding energy than previously

First measurement of a molecule-condensate interaction

Mean field interactions account for shift and most of the broadening (no definite, nonzero K_{inel})

Calculated Coupling Rate and Spontaneous Photon Loss Rate for Rb_2

[Assumes $K_{inel} << 10^{-11}$ cm^3/s]

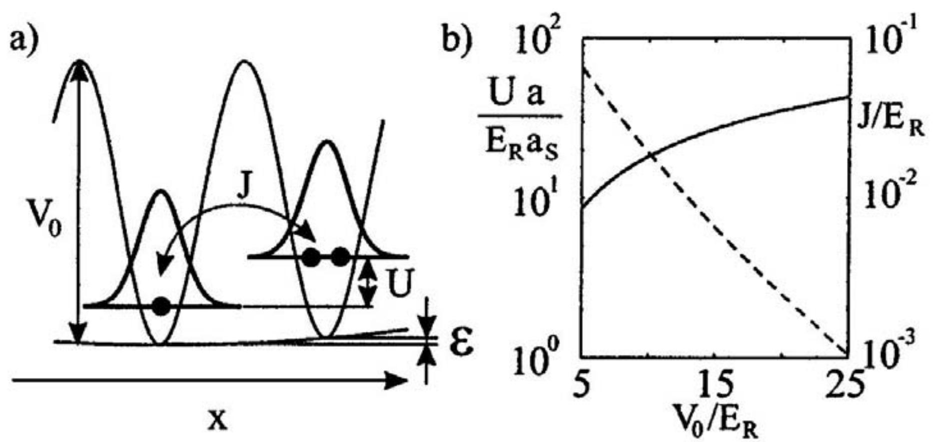


Experiments: Tried, limited evidence of collective coherent behavior

Bose-Hubbard Model

First Studied: M. Fisher et al., PRB **40**, 546 (1989)

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



Zero temperature lattice model in 1, 2 or 3 dimensions

Hopping matrix element between adjacent lattice sites J

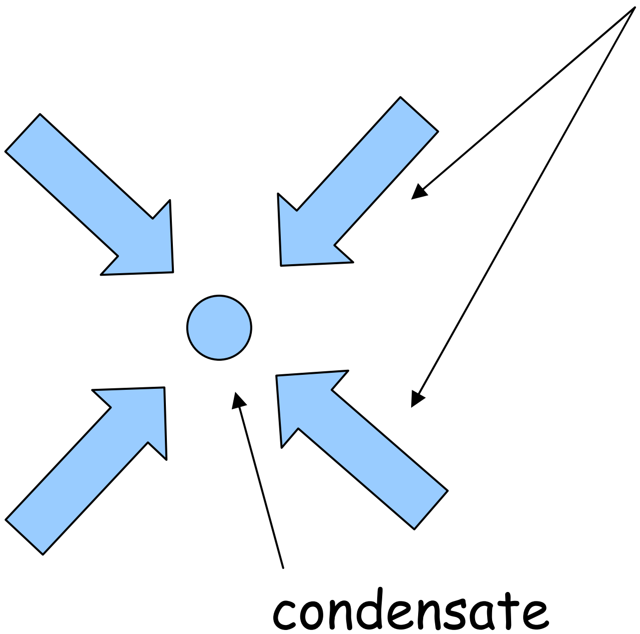
Onsite repulsive contact interaction between bosons U

Assume particles remain in lowest band (U << splitting between bands)

*Optical lattice loaded with dilute gas condensate provides ideal realization of Bose-Hubbard mode*l: D. Jaksch et al., Phys. Rev. Lett. **81**, 3108-3111 (1998).

Transition first observed: M. Greiner et al., Nature **415**, 39 (2002)

Optical Lattice



six laser beams produce three orthogonal standing wave fields

λ = 830 nm, P up to 200 mW per beam

Beam waist $\cong$ 200-300 μm

Dipole potential $V(x) \sim \alpha(\omega)\, I(x)$

$V = V_0(\sin^2(kx) + \sin^2(ky) + \sin^2(kz))$

V_0 up to 30 E_R

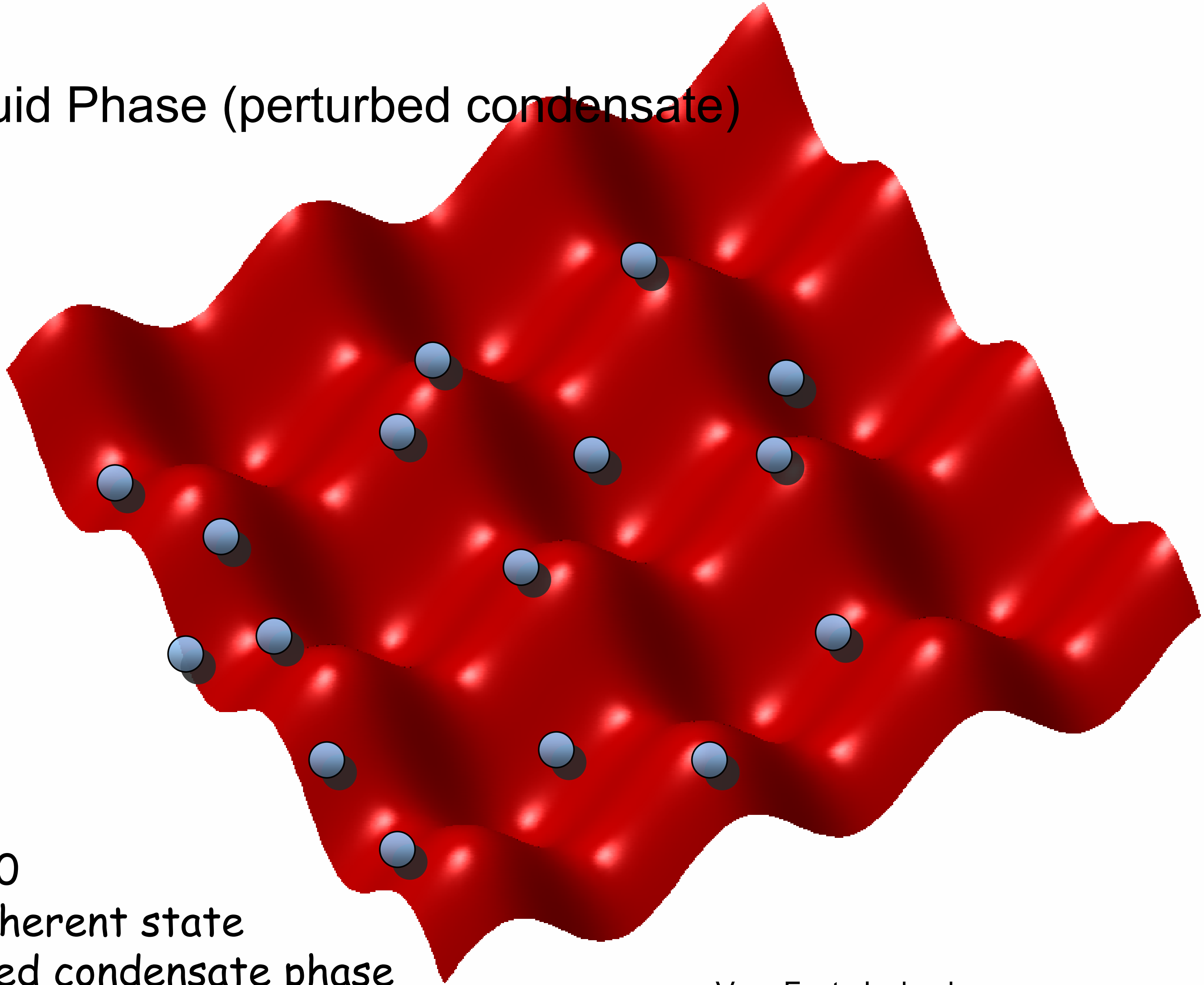
$E_R = k_B \times 150$ nK $= h \times 3.2$ kHz

Phase transition occurs with $V_{0c} \approx$ 12-14 E_r

For $V_0 > V_{0c}$, $h\nu_L \gg U \gg J$ ν_L = vibration frequency

For $V_0 = 20\, E_R$ $\nu_L \approx 30$ kHz $U/h \approx 2$ kHz $J/h \approx 8$ Hz

Superfluid Phase (perturbed condensate)



$\phi_i = \langle b_i \rangle \neq 0$

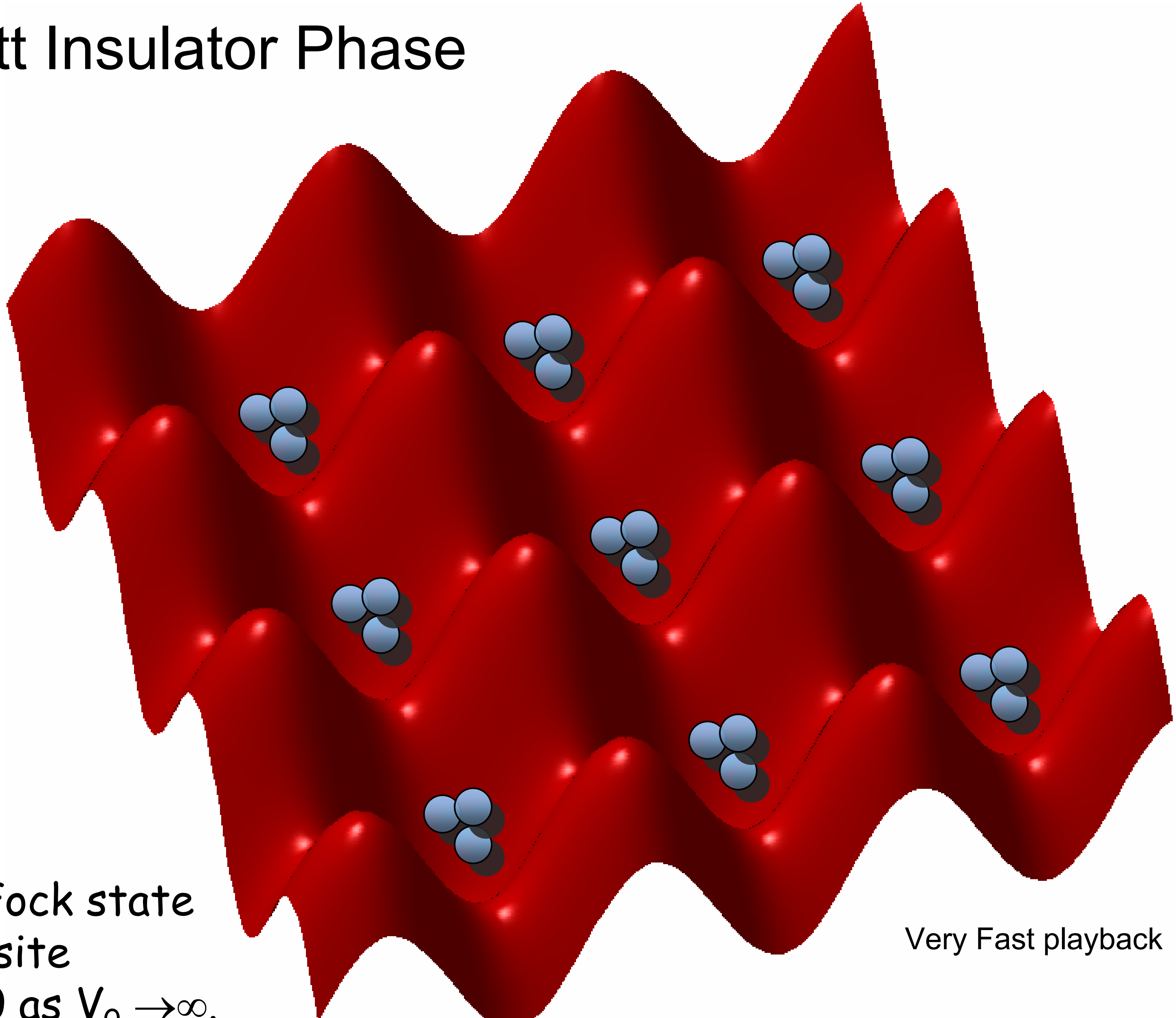
Approx. coherent state

Well defined condensate phase

Uncertain particle number

Very Fast playback

Mott Insulator Phase

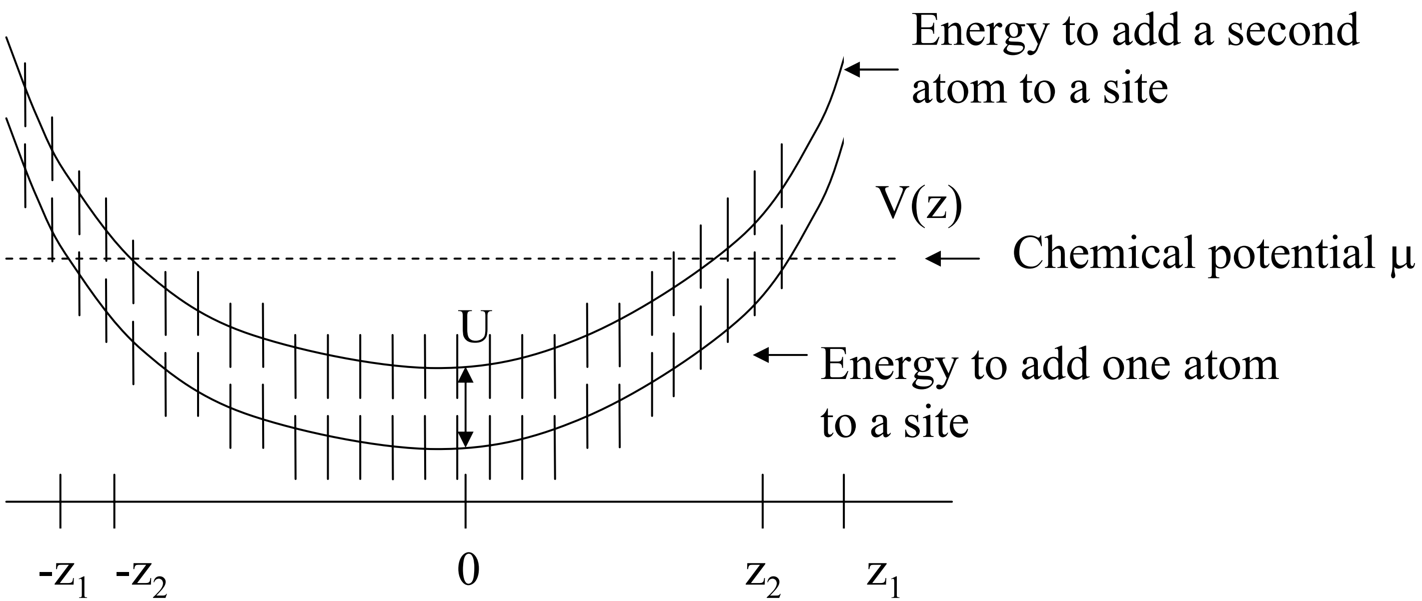


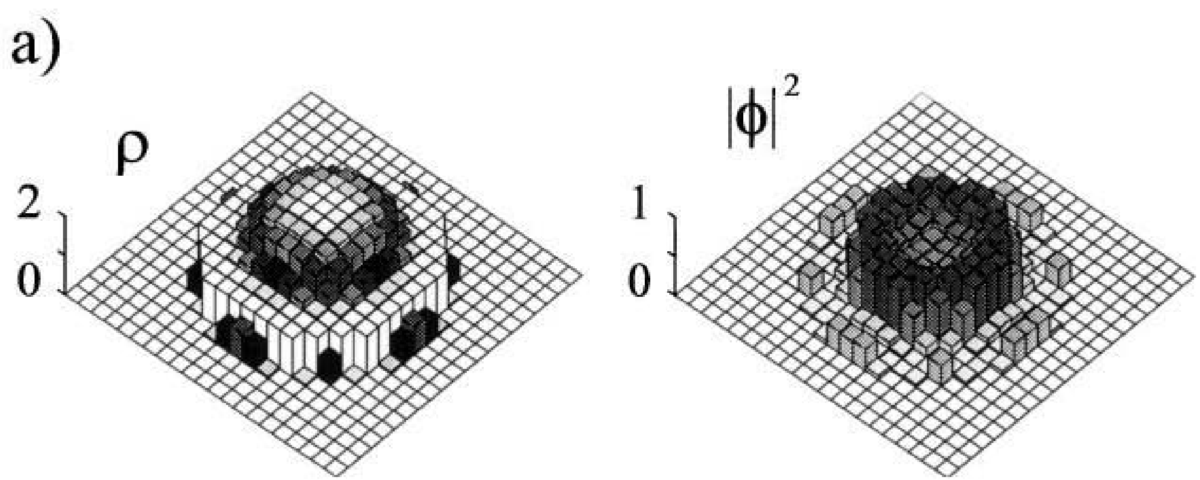
Aprox. Fock state at each site

$\langle b_i \rangle \to 0$ as $V_0 \to \infty$.

Very Fast playback

Effect of Trap Potential

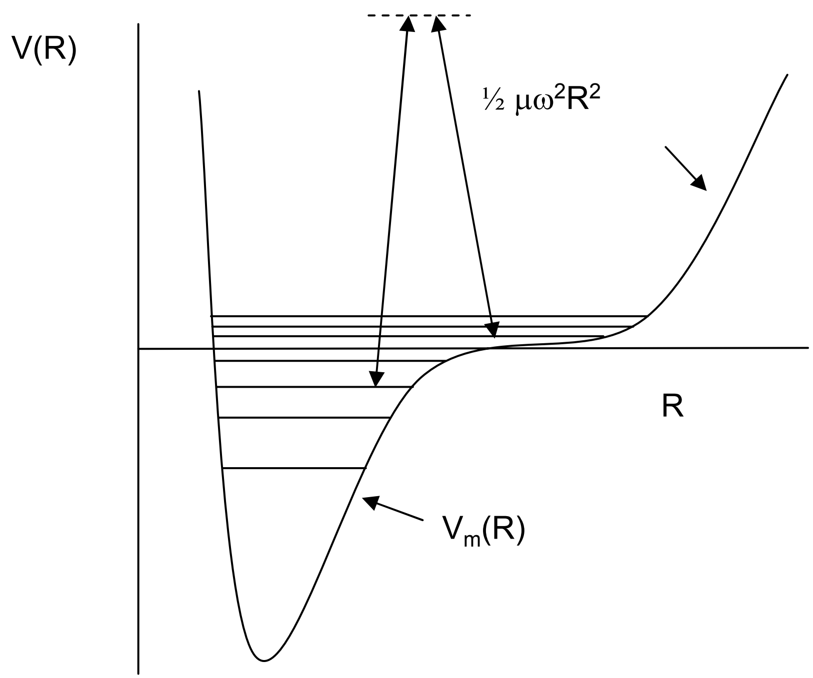




Calculation of Jaksch et al., Phys Rev. Lett. **81**, 3111 (1998)

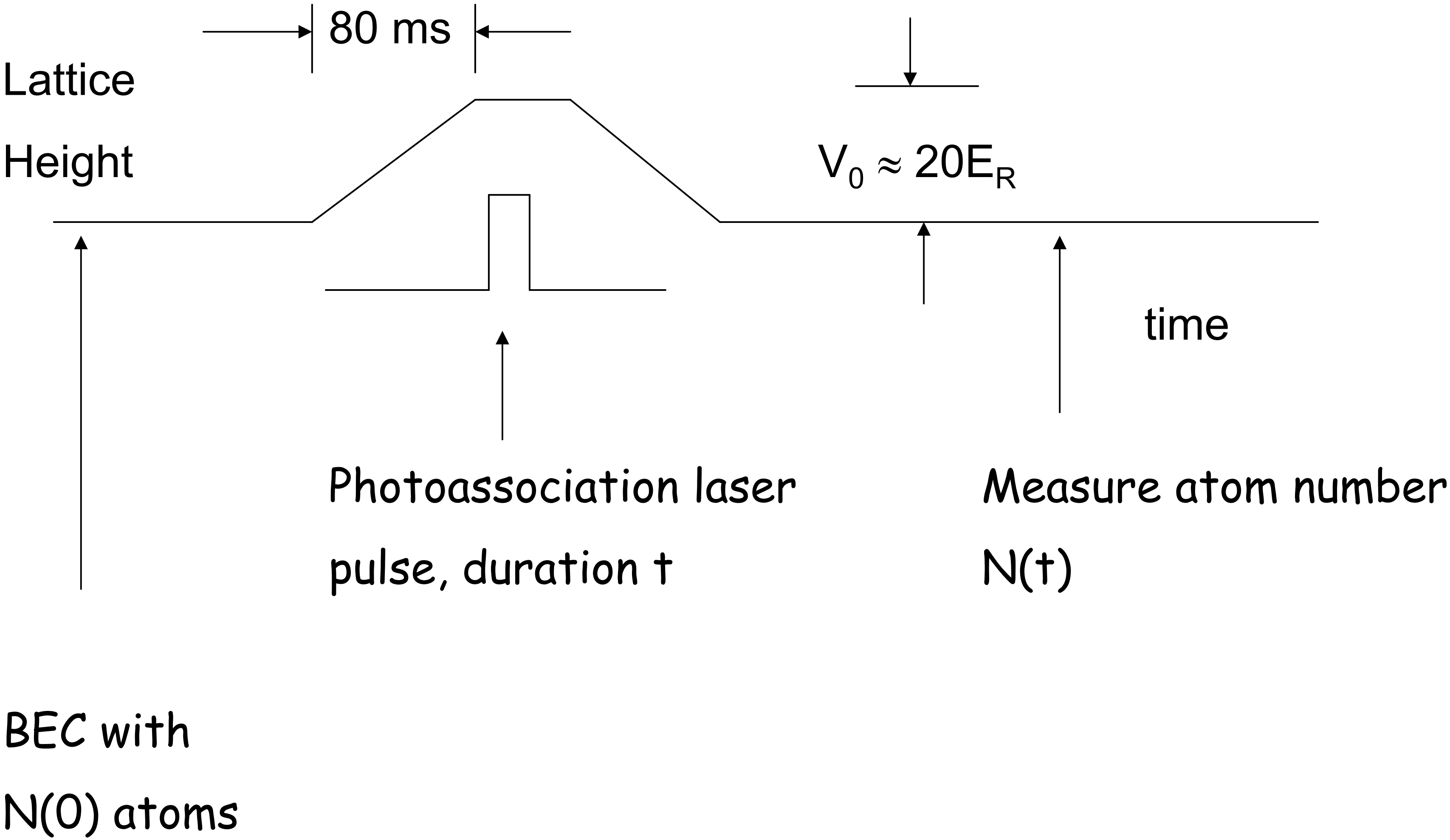
Raman photoassociation of two atoms in an optical lattice site

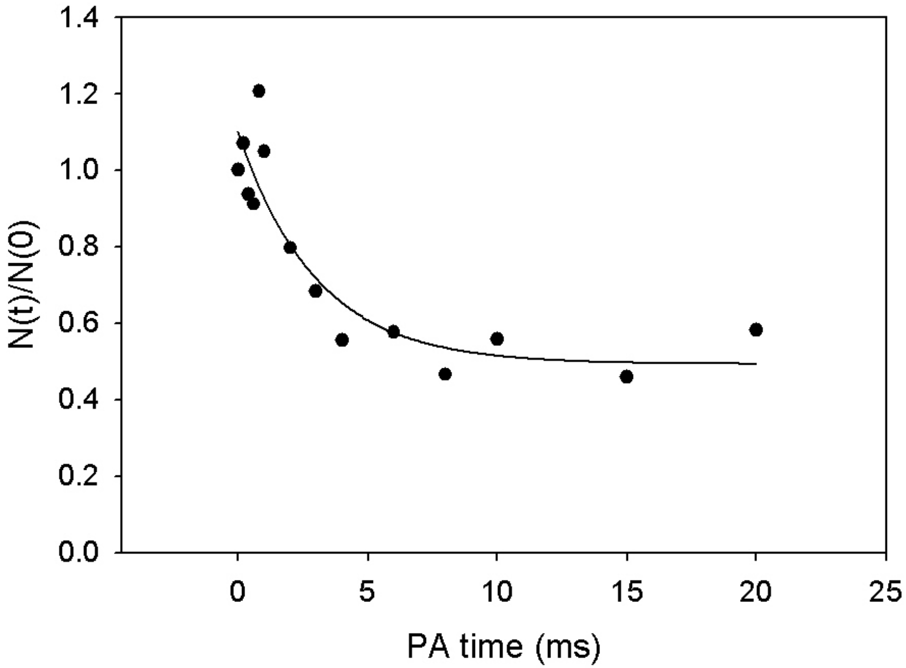
Proposal: D. Jaksch *et al*., Phys. Rev. Lett. **89**, 040402 (2002)



- Continuum → discrete levels of atoms in lattice site
- $\omega/2\pi \approx 30$ kHz = lattice vibration frequency
- Enhanced free-bound coupling
- Eliminates inelastic collisions

Photoassociation in a Mott Insulator





Single Color Photoassociation

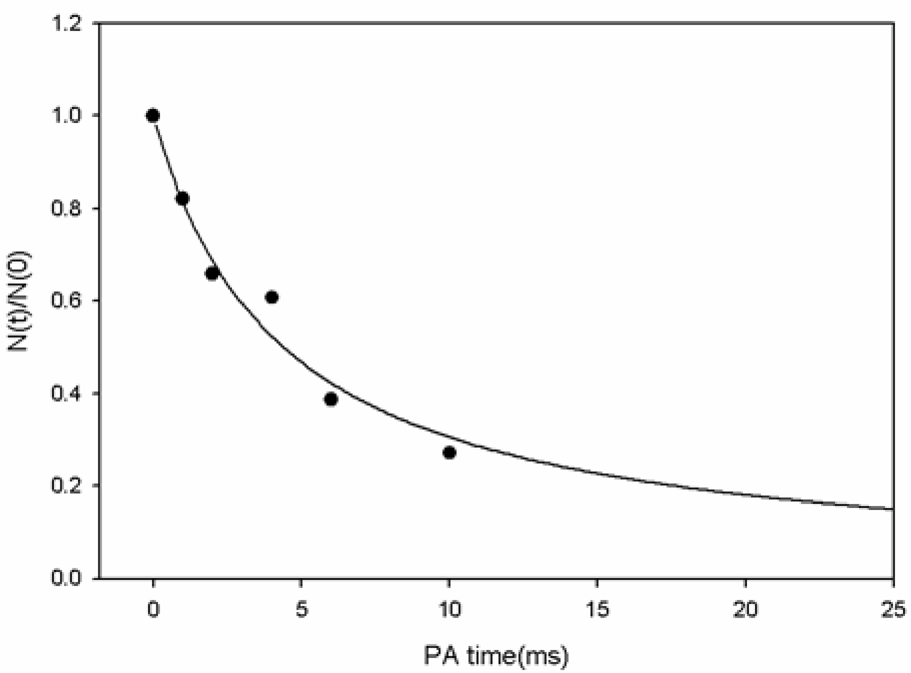
Optical Lattice On

$V_0 = 22\ E_R$

$N(t)/N(0) = A\exp(-t/\tau_1) + B\exp(-t/\tau_2)$

$\tau_1 = 1.56$ ms $\tau_2 = 82.6$ ms

→ 40% of atoms in multiply occupied sites, remainder in singly occupied sites.



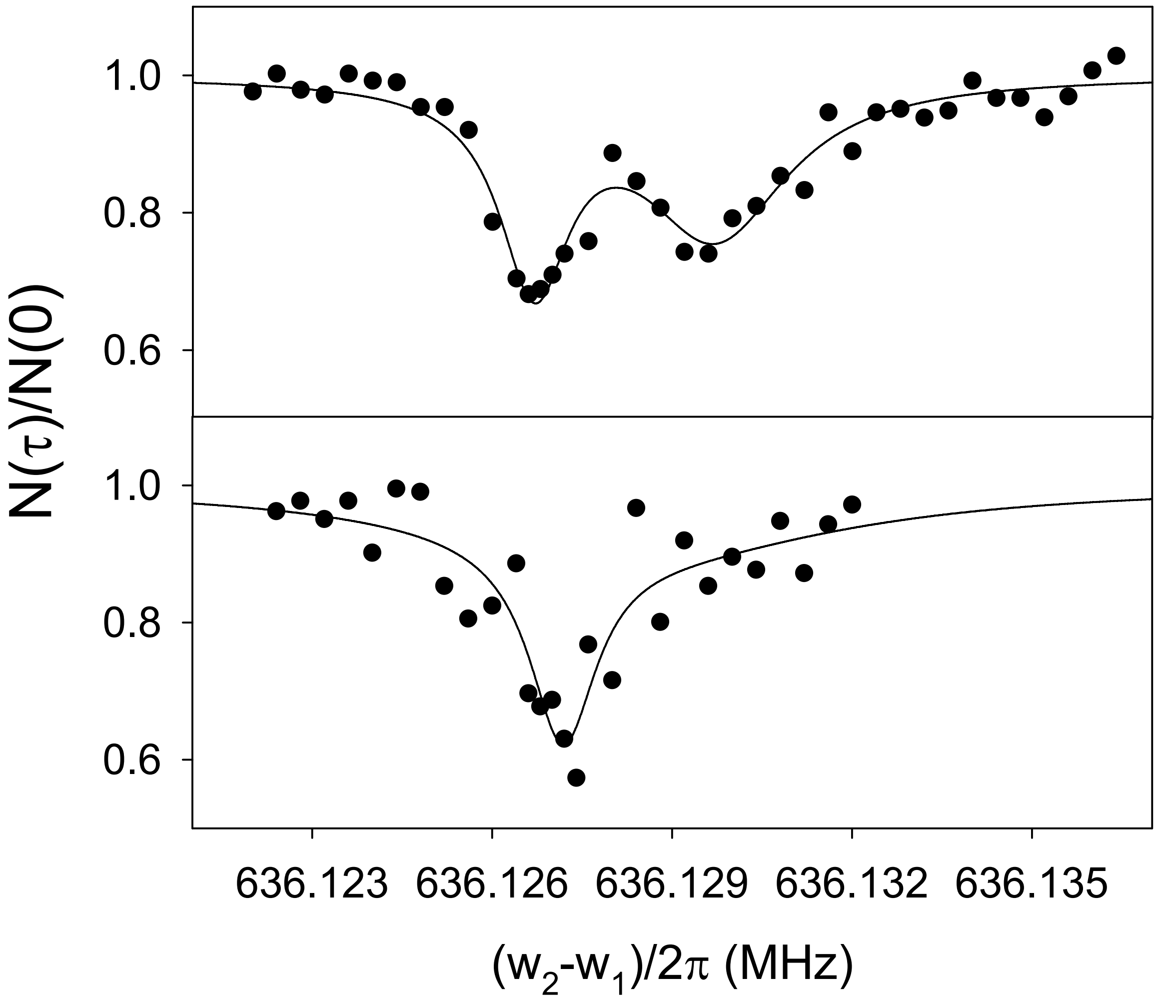
Optical Lattice Off

$N(t)/N(0) = 1/(1+t/\tau)$

$\tau = 4.39$ ms

PA = probe of short range correlations in a gas

Raman Frequency Scan

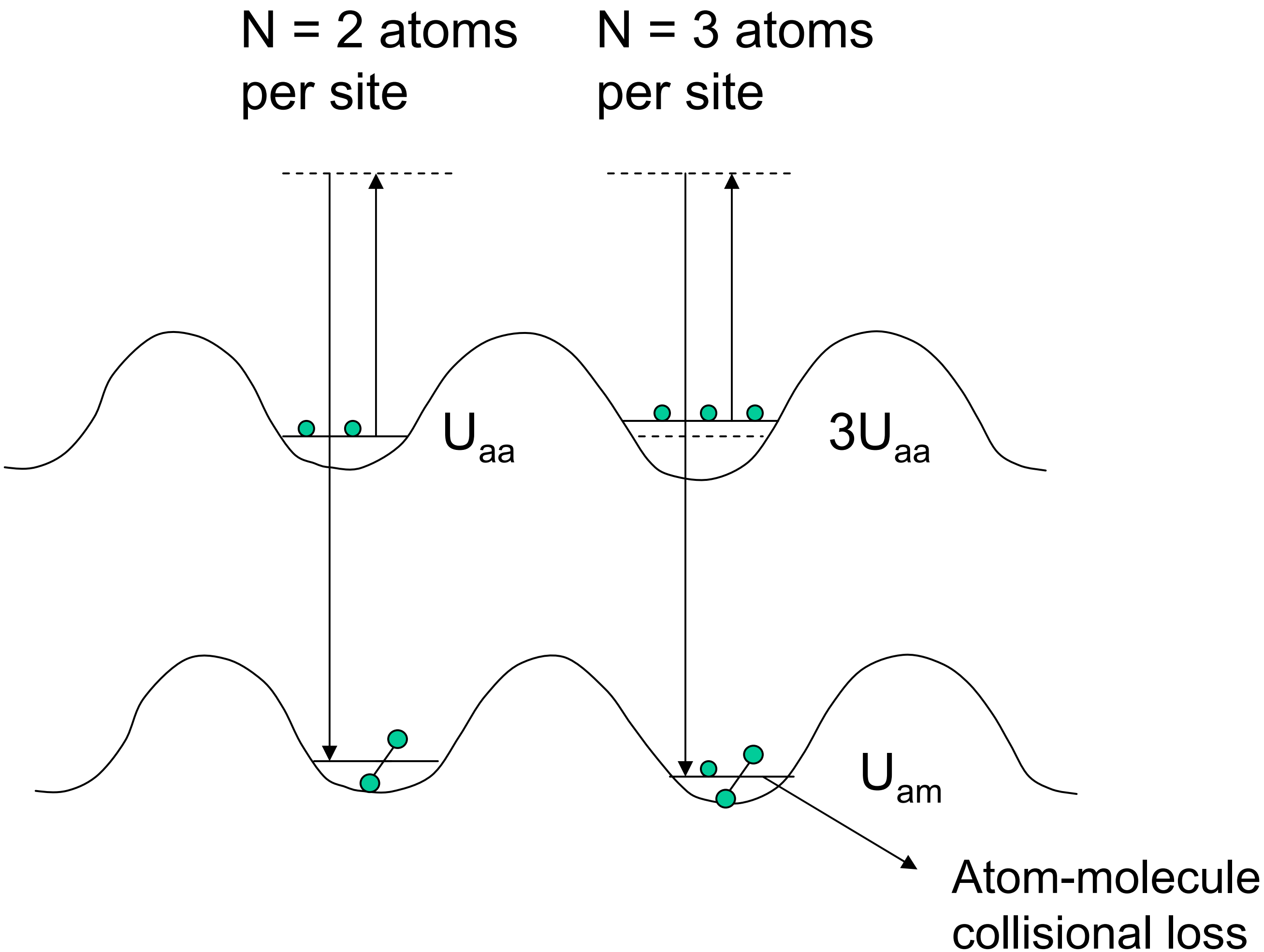


N(0) ≈0.5 million

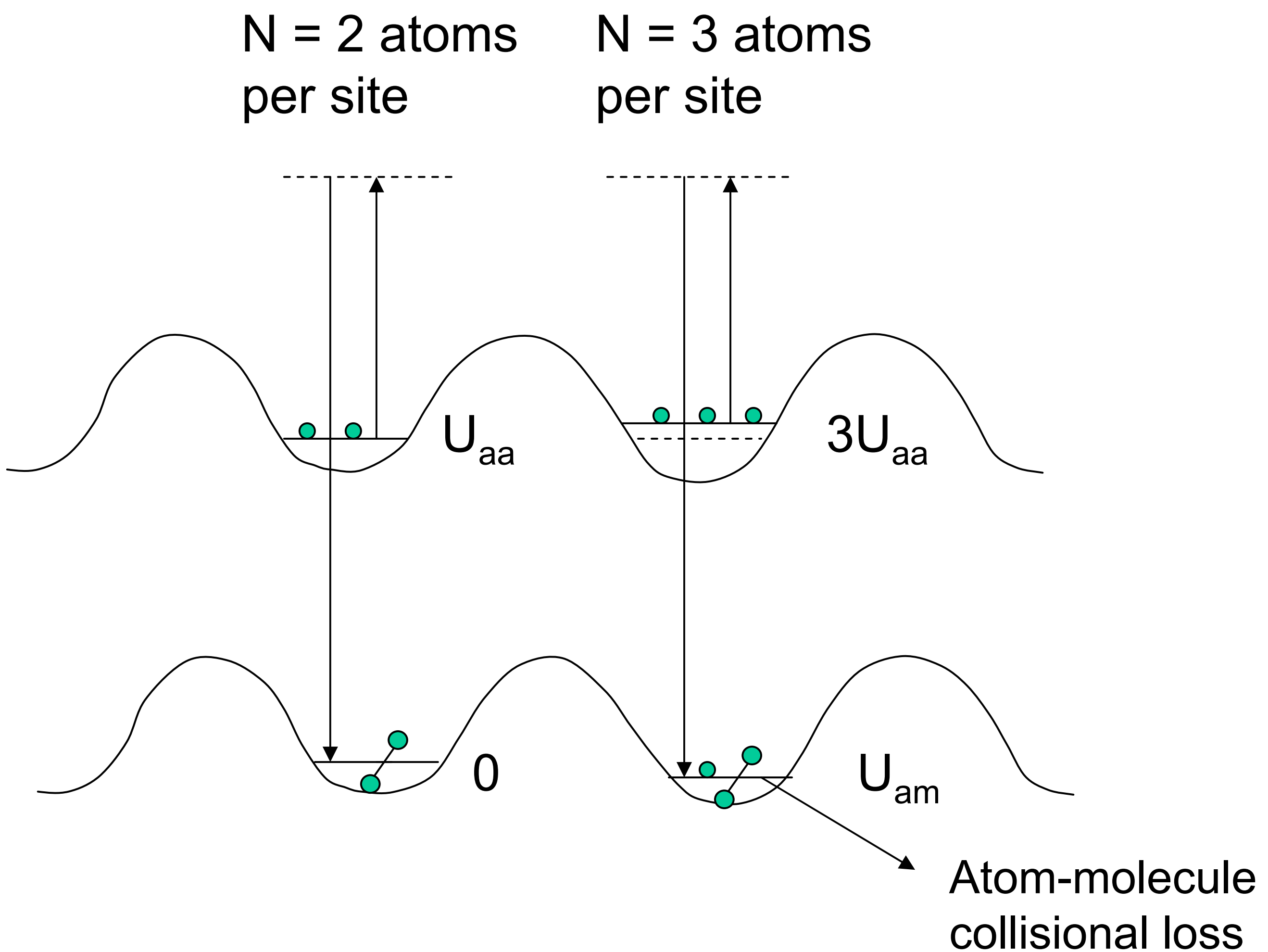
N=2 per site ≈ 30%
N=3 per site ≈ 23%

N(0) ≈ 0.25 million

N=2 per site ≈ 33%



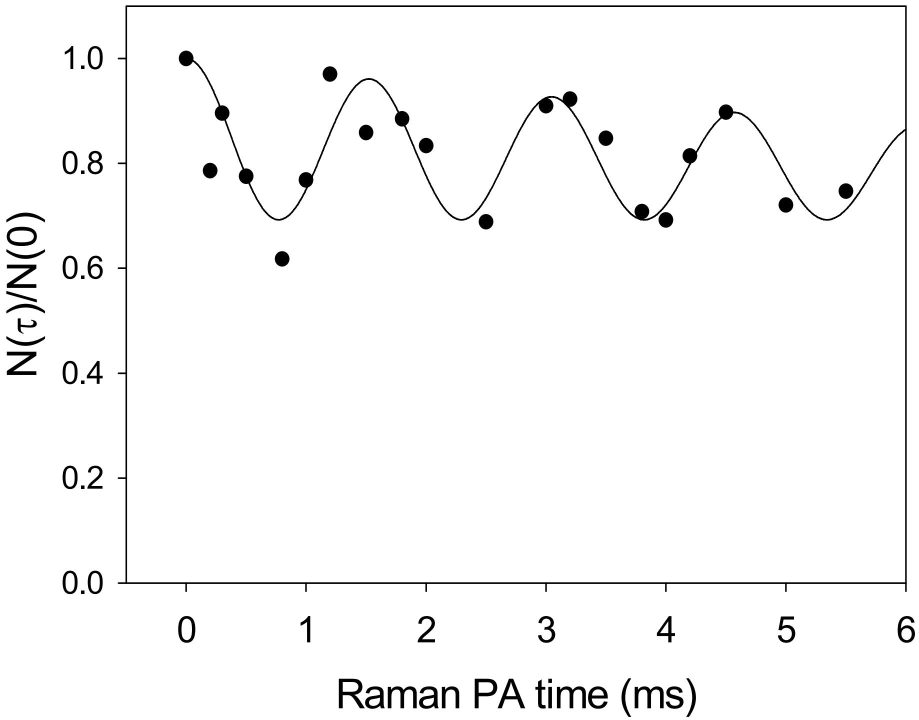
N = 2 atoms
per site
N = 3 atoms
per site
U_{aa}
$3U_{aa}$
U_{am}
Atom-molecule
collisional loss



Measured shift → Measured U_{aa} → $a_{am} = -5 \pm 20\ a_0$

Greater width of N=3 peak: inelastic collision loss, greater power broadening. Estimate that $K_{inel} \sim$ few $\times 10^{-11}$ cm^3/s

Number of atoms vs. PA time, on Raman resonance with N = 2 peak

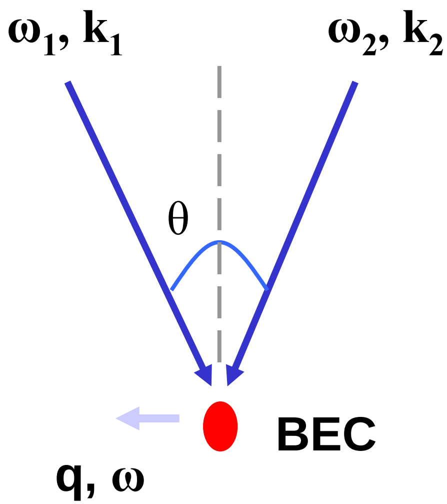


N(0)~0.28 million atoms

Central core of gas oscillates between an atomic and a molecular quantum gas!

Ultimate control of atomic pairs – *all* degrees of freedom exactly controlled

Bragg spectroscopy



- Two far-detuned laser beams imposed on the gas sample
- Stimulated absorption of one photon from one laser beam and stimulated emission into the other laser beam
- Frequency difference determined by two acousto-optical modulators

Momentum transfer

$$\hbar \boldsymbol{q} = \hbar \boldsymbol{k}_2 - \hbar \boldsymbol{k}_1$$

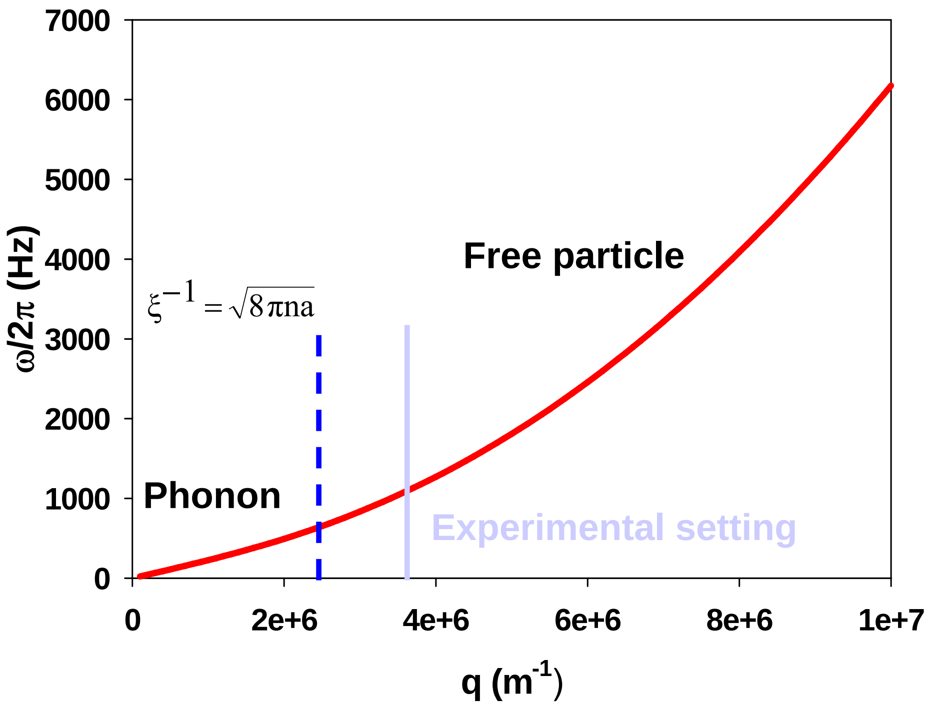
ω(q) – response of quantum gas to perturbation

Energy transfer

$$\hbar \omega = \hbar \omega_2 - \hbar \omega_1$$

Stenger *et al.*, PRL 82, 4569

Dispersion relation $\omega(q)$



ξ is healing length

Steinhauer *et al*., PRL 88, 120407

For a weakly interacting quantum gas system

$$\hbar\omega(q) = \sqrt{\frac{\hbar^2 q^2}{2m}\left(2\mu + \frac{\hbar^2 q^2}{2m}\right)}$$

μ is chemical potential; m is atomic mass

For small q, collective excitations

$$\hbar\omega(q) = \hbar c q$$

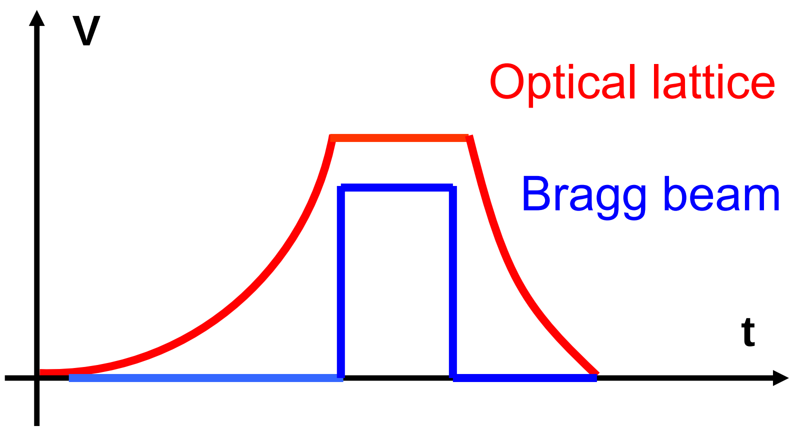
$c = \sqrt{\frac{\mu}{m}}$, speed of sound

For large q, single-particle excitations

$$\hbar\omega(q) = \frac{\hbar^2 q^2}{2m} + \mu$$

Bragg spectroscopy of Superfluid in 3-D Lattice

- Temperature increase due to the excitations
- Measure the gas temperature with TOF imaging

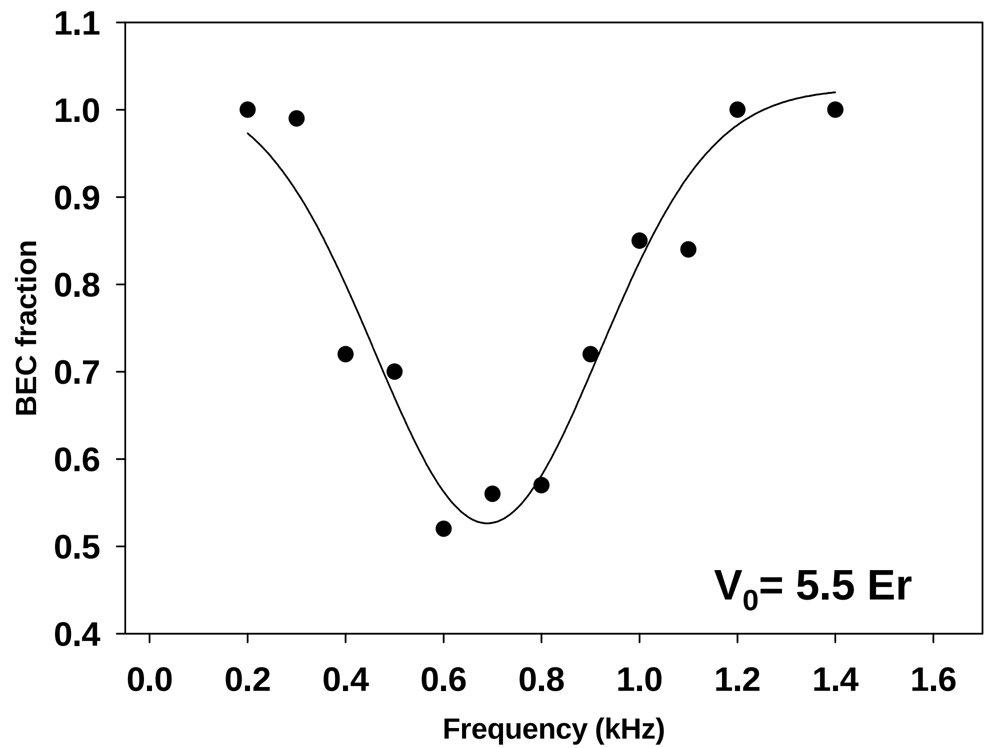


- **Two photon excitation rate ~500 Hz**

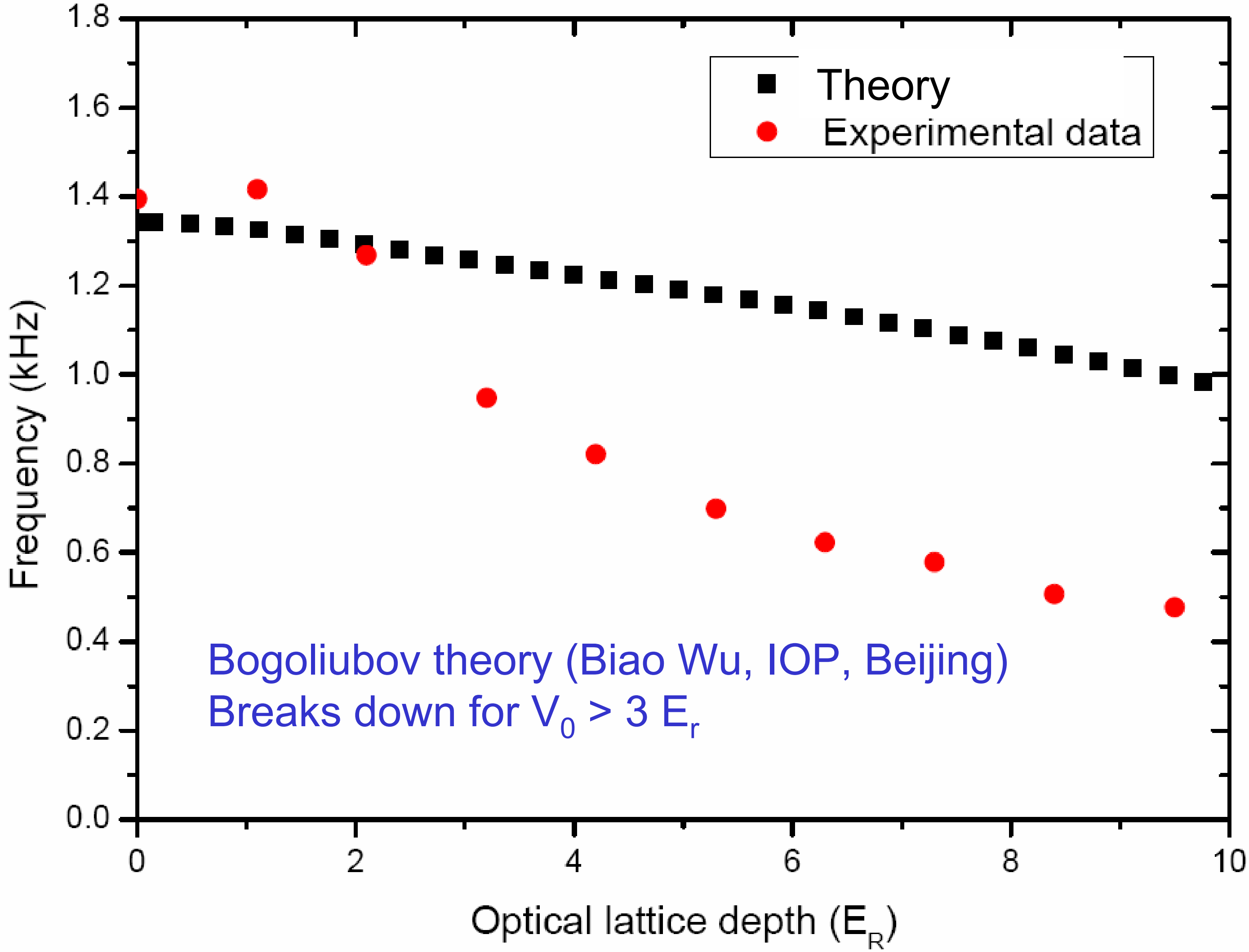
$$\Omega_R = \frac{\Gamma^2}{4\Delta} \frac{I}{I_{sat}}$$

Γ is natural linewidth; Δ is frequency detuning (430 GHz);
I is laser intensity (~100 mW/cm^2); I_{sat} is saturation intensity.

- **Pulse duration 3 - 20 ms**

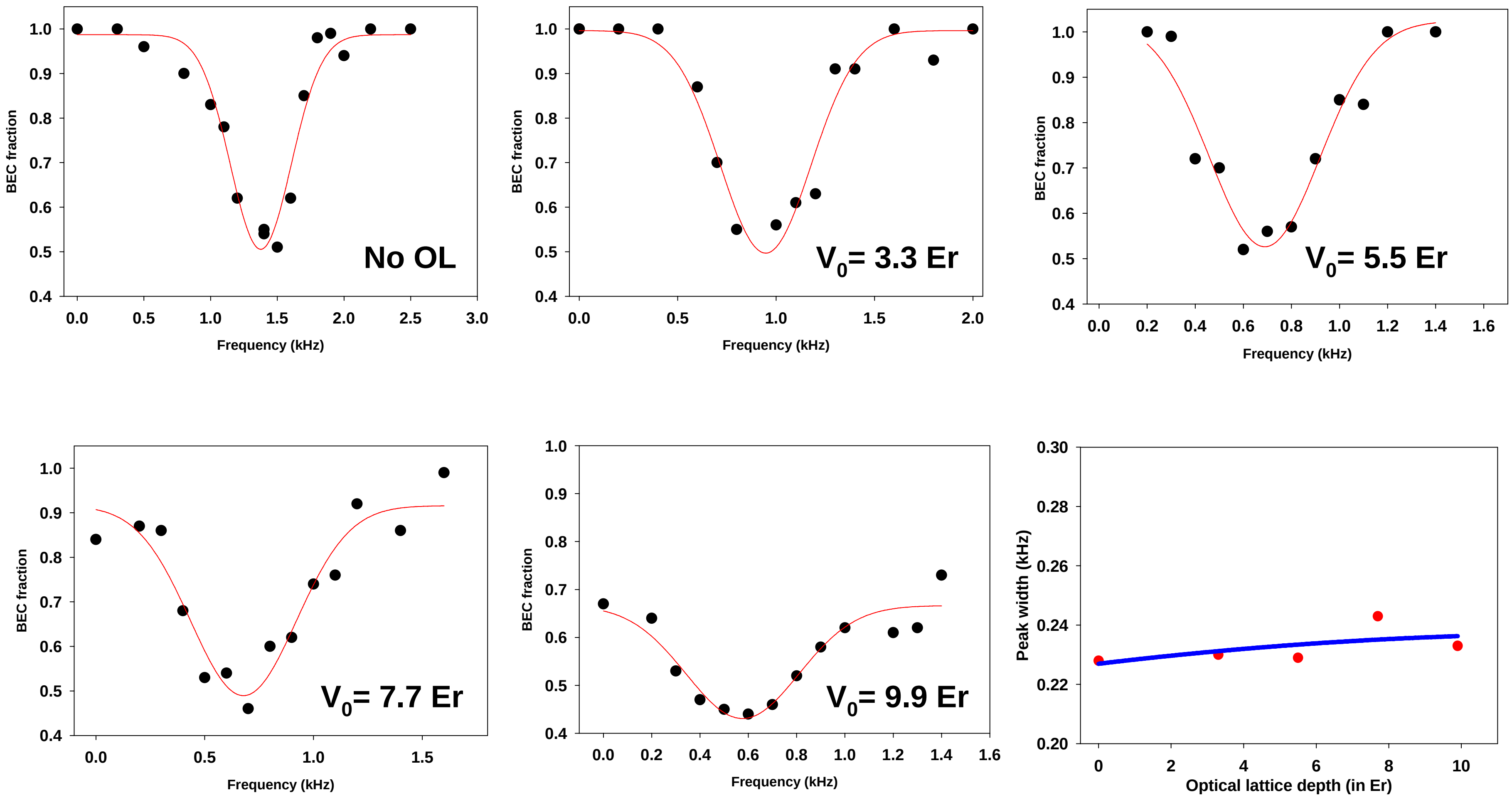


Gaussian fitting: resonant frequency is taken as the center value of the fitting



As optical lattice depth increases, μ^* increases due to tighter confinement, m^* increases due to the decreased band width

Excitation spectra at different optical lattice depths



Conclusion

Photoassociation in Mott insulator provides measure of singly, doubly, and triply occupied lattice sites – confirm large fraction of multiply occupied sites.

Resolved spectrum determines atom-molecule interactions

Oscillating atomic <-> molecular gas!

Bragg spectra in lattice show breakdown of Bogoliubov theory at surpisingly low lattice depths.