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Spontaneous Emission of Matter Waves from a Tunable Open Quantum System

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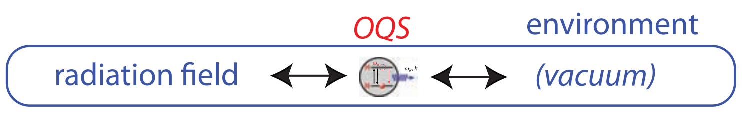
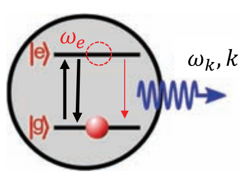
Introduction

QED/Quantum optics & Open quantum systems



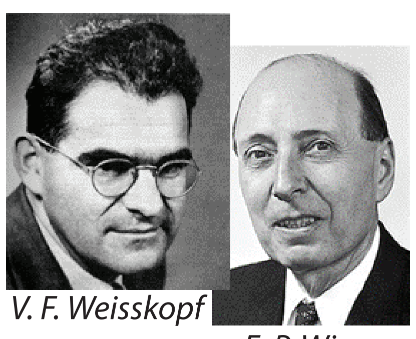
P.A.M. Dirac



Dirac's radiation theory (1927)

$$\hat{H} = \hbar\omega_{eg}|e\rangle\langle e| + \sum_k \hbar\omega_k \hat{b}_k^\dagger \hat{b}_k + i\sum_k (\boldsymbol{d}_{eg}\cdot\boldsymbol{\mathcal{E}}_k)\, \hat{b}_k^\dagger |g\rangle\langle e|\, e^{-i\Delta_k t} + h.c.$$

$\mathcal{E}_k = \sqrt{\frac{\hbar\omega_k}{2\varepsilon_0 V}}$ zero-point field; $\Delta_k = \omega_k - \omega_e$ detuning



V. F. Weisskopf — E. P. Wigner

W-W model for spont. em. (1930)

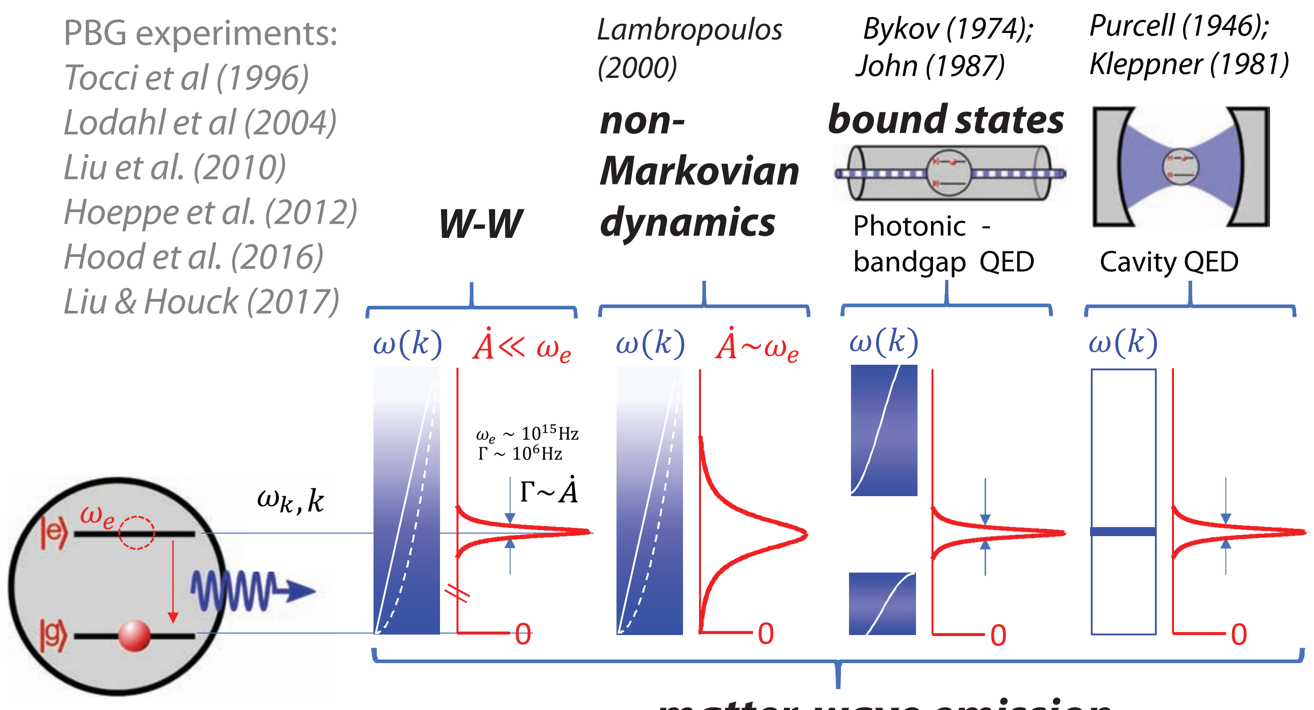
$$|\psi(t)\rangle = A(t)e^{-i\omega_e t}|e,0\rangle + \sum_k B_k(t)\, e^{-i\omega_k t}|g,1_k\rangle$$

$$\dot{A}(t) = -\sum_k |g_k|^2 \int_0^t dt' e^{i(\omega_k-\omega_e)(t-t')} A(t')$$

WW approximation ("slow" evol.)

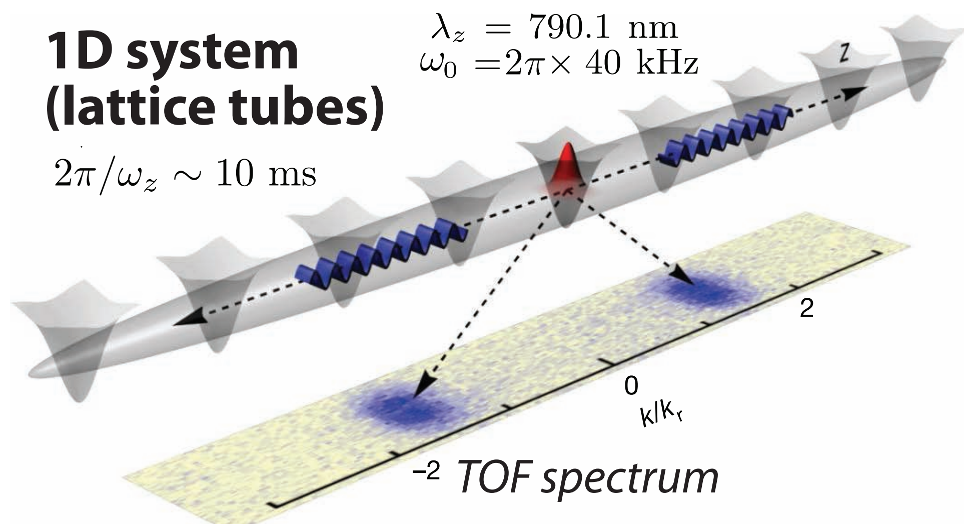
$$\frac{\Gamma}{2} + i\times\Delta_L \longrightarrow \Gamma \sim \frac{2\pi}{\hbar}|d_{ge}\mathcal{E}_e|^2 \varrho(\hbar\omega_e)$$

Going beyond the assumptions of the W-W model



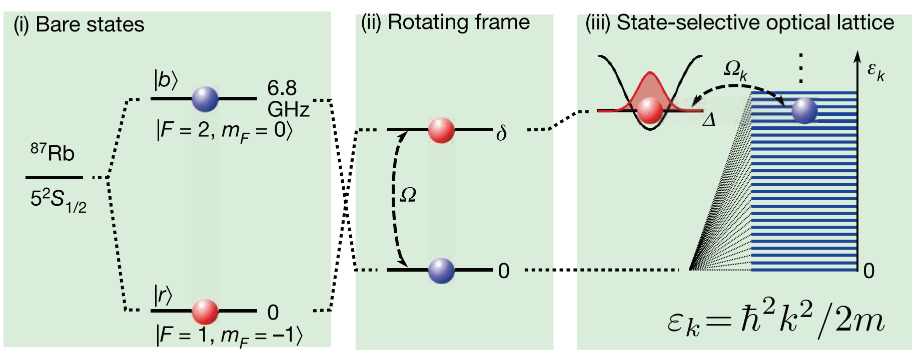
de Vega, Porras & Cirac (2008, 2011); Stewart et al. (2017)
González-Tudela & Cirac (2017/18)

Matter-Wave Emission



- Emitter array (mostly empty) in lattice with state-selectivity along z
- prepared via thinned-out Mott insulator with <n> < 0.5

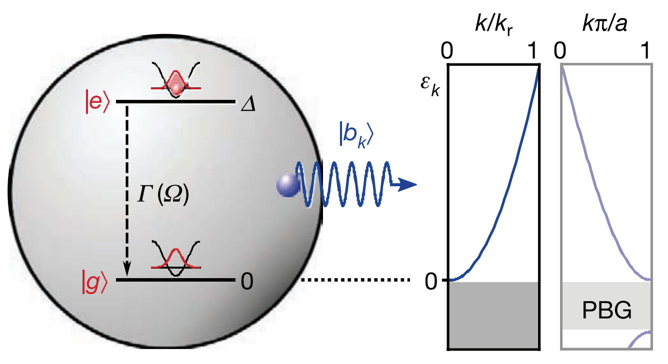
- μwave-driven trans. between trapped (red) and untrapped (blue) HF ground states of ^{87}Rb



$$\hat{H} = \sum_{k,j} \hbar g_k e^{i(\Delta_k t - kz_j)} |g_j\rangle\langle e_j|\, \hat{b}_k^\dagger + \mathrm{H.c.}$$

$g_k = \Omega\langle k|\psi_e\rangle/2$, $\Delta_k = \Delta - \varepsilon_k/\hbar$, $\Delta = \delta + \omega_0/2$, $\varepsilon_k = \hbar^2 k^2/2m$

extended Weisskopf-Wigner model



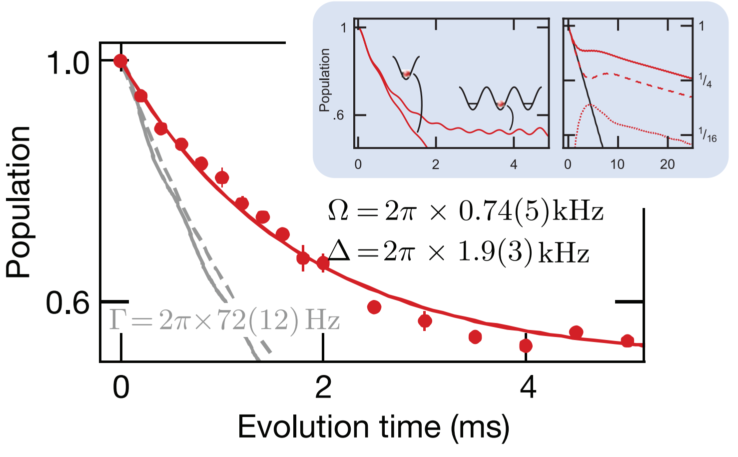
each lattice site forms an elementary emitter of atomic matter waves, with tunable excitation energy Δ and vacuum coupling Ω

ansatz for single emitter

$$|\Psi\rangle = A(t)\,|e,\,0_k\rangle + \sum_k B_k(t)\,|g,\,1_k\rangle$$

Markovian Regime $\Omega/\Delta \ll 1$

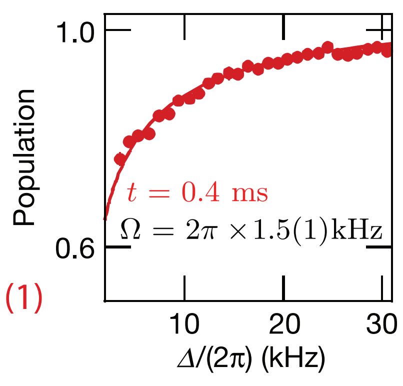
(quasi-)Markovian regime $(\Omega/\Delta)^2 \ll 1$



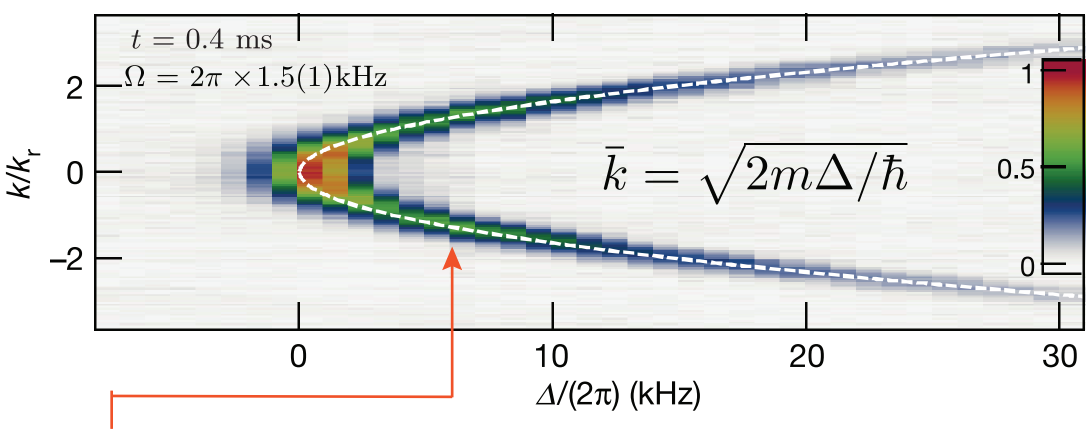
- Exponential decay to ~50%; ***numerical model*** suggests *atom reabsorption* by neighboring empty wells (radiation trapping in optically thick medium)

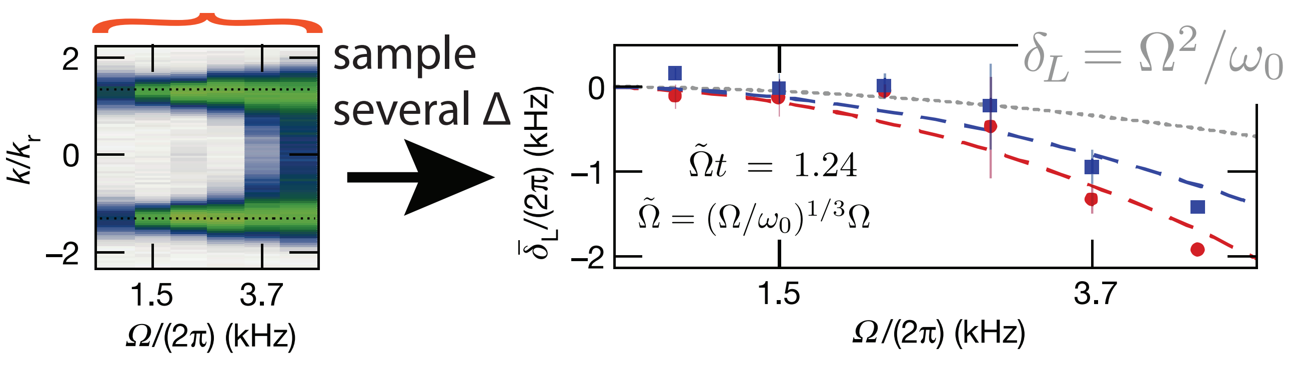
- Detuning dependence of decay matches Markovian expectation for isolated emitter

$$\Gamma = \Omega_0^2/\sqrt{\omega_0\Delta} \quad \times 0.61(1)$$



- Matter-wave emission spectrum follows parabolic dispersion (spectrum includes non-Markovian data)



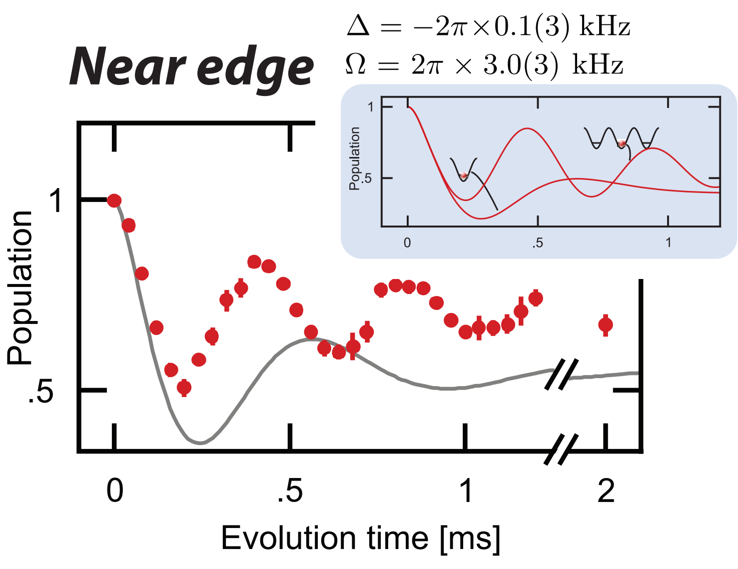


- Observe Lamb-like shift from measuring kinetic energy ~<k²> as a function of Ω.

by factor ~3 too large (but no collective enhancement)

Non-Markovian Regime

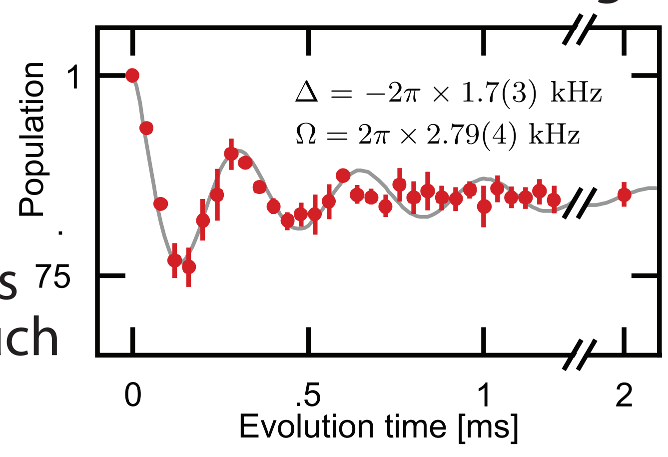
Near edge



- Long-lived oscillations signal non-Markovian behavior (radiation backflow); ***numerical model*** again suggests coupling to neighboring empty wells

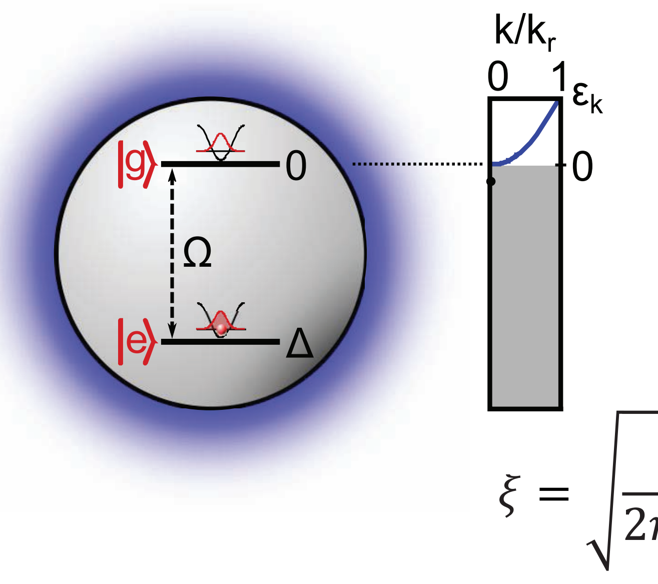
- Observe clear oscillations as expected from ***analytical treatment*** for single emitter
- matter waves cannot propagate; neighboring wells don't influence evolution much

Below edge



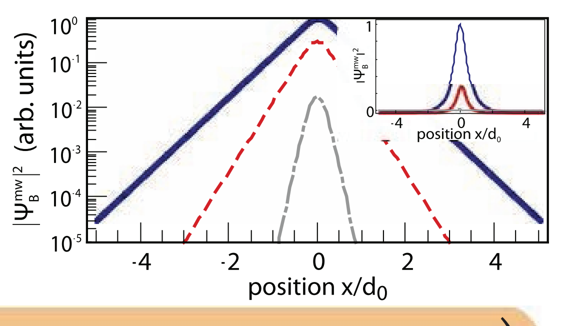
Bound state

Stewart et al. (PRA, 2017)



- Emitter is "dressed" by a coherent cloud of matter waves (evanescent wave)
- Matter waves in the gap "reflect" back to emitter

$$\xi = \sqrt{\frac{\hbar}{2m|\omega_B|}}$$



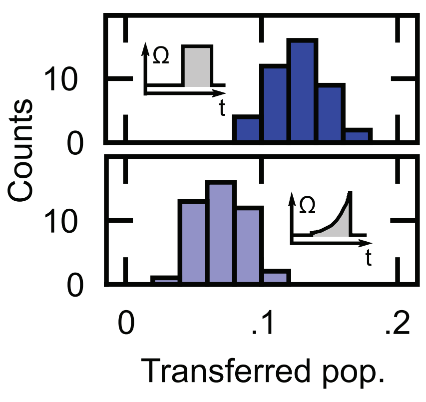
$$|\psi_B\rangle = c_B\left(|e,0_\omega\rangle - \int_0^\infty \frac{g^*(\omega)}{\omega-\omega_B}\,\rho(\omega)|g,1_\omega\rangle\,\mathrm{d}\omega\right)$$

$$\omega_B \approx \frac{\Delta}{2} - \frac{1}{2}\sqrt{\Delta^2 + \Xi\,\Omega^2}$$

Probing the Bound State

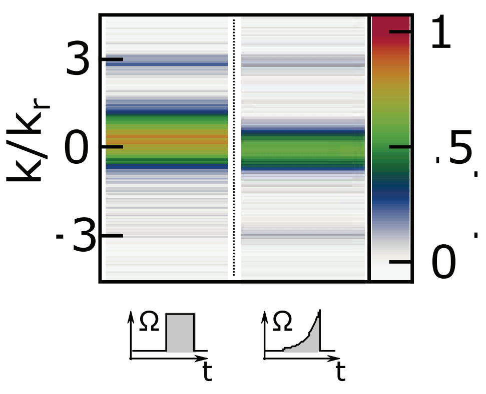
$\Delta = -2\pi\times 2.2(3)$ kHz $\quad \Omega = 2\pi\times 2.79(4)$ kHz $\quad t = 2.6$ ms

Adiabatic vs. sudden coupling reveals bound contribution

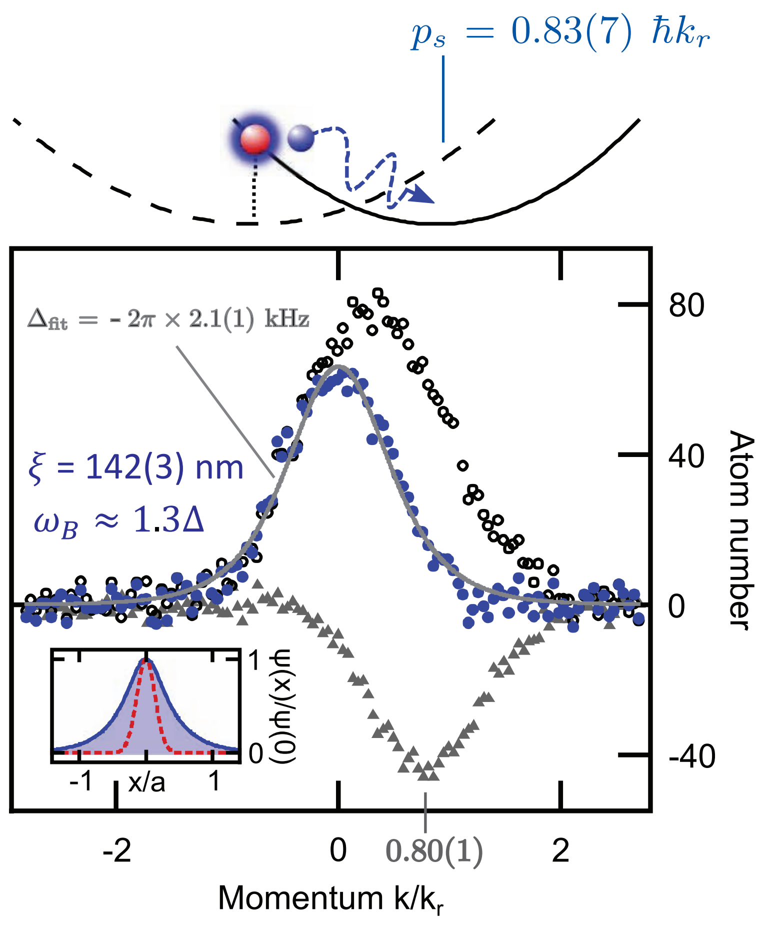


- More atoms transferred for non-adiabatic pulse

- Momentum distributions look qualitatively different



- Gravitational sag shifts trap
- Non-adiabatically released (free) atoms are accelerated toward trap minimum
- Population that remains is bound-state cloud
- Compare bound portion to (Fourier transform of) result from analytical model



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