Interference effects in the cavity-assisted laser cooling of single atoms and atomic ensembles

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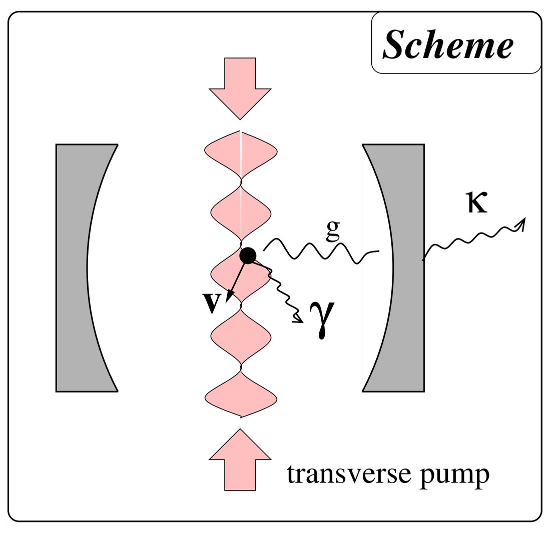
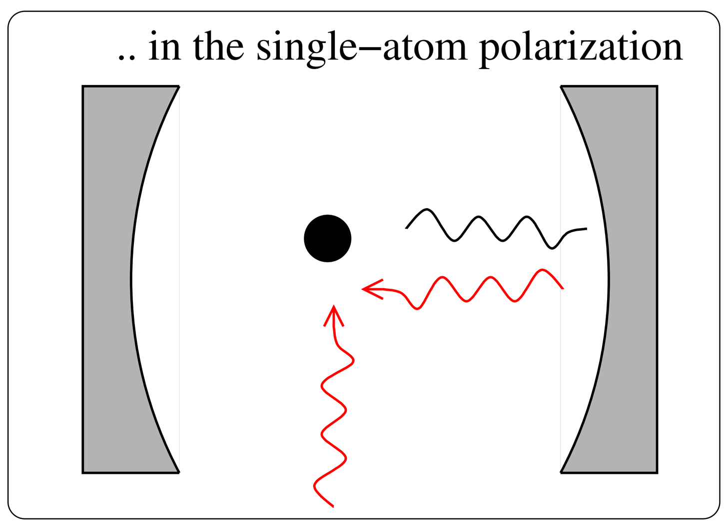
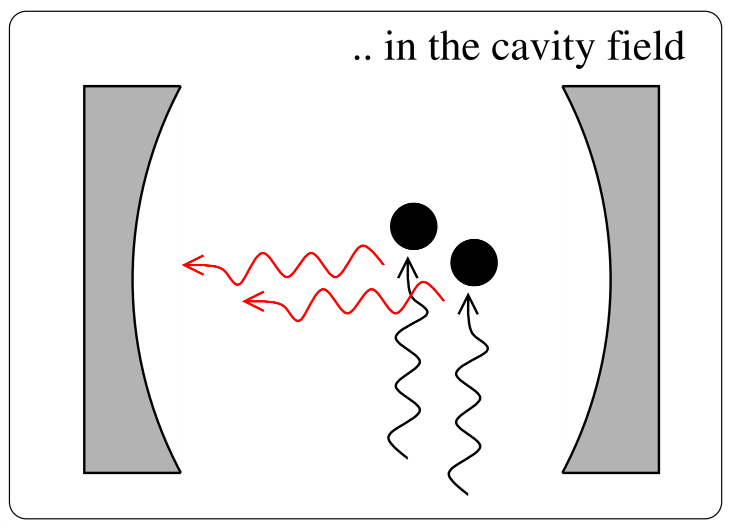
1 Laser-driven atoms in a cavity



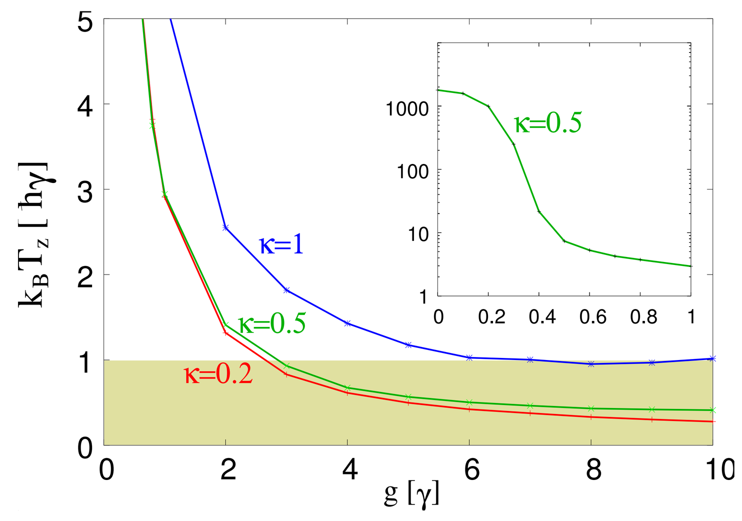
- Strong coupling: $g \sim \gamma$
- High-Q cavity: $\kappa = 0.5\gamma$
- Far detuned pump: $\Delta_A = -350\gamma$
- Near-resonant mode $\Delta_C = -0.6\gamma$

2 Interference effects





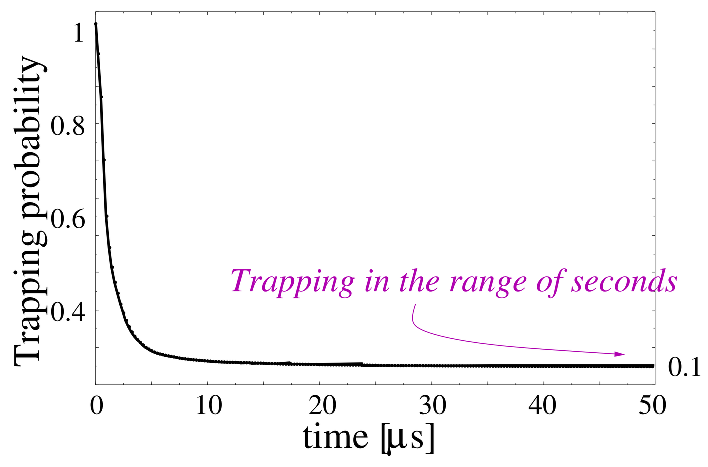
3 Temperature strongly depends on coupling g



$g = 0 \rightarrow \gamma$: $\Delta T_z \sim 3$ orders of magnitude

sub-Doppler regime $\longrightarrow$ very long trapping times

4 Trapping probability



Trapping probability decays as a sum of two exponentials (atoms are initially at Doppler-temperature).

5 Anomalous Doppler effect

Velocity-dependent interference in the atomic polarization.

$$\langle\sigma\rangle = \frac{\eta_t}{i\Delta_A - \gamma + \frac{g^2}{i\Delta_C - \kappa} - ikv_z\left(1 - \frac{g^2}{(i\Delta_C-\kappa)^2}\right)}$$

$$= \frac{\eta_t + g\left\langle a^{(0)}\right\rangle}{i(\Delta_A - kv_z) + \gamma} + \frac{v_z g \left\langle a^{(1)}\right\rangle}{i\Delta_A + \gamma}$$

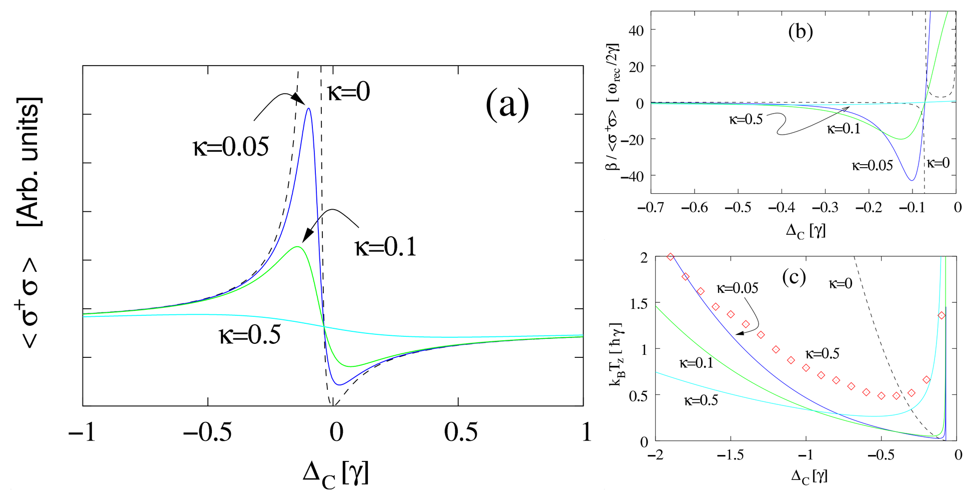
$$= \textit{adiabatic} + \textit{nonadiabatic}$$

$$(g/\kappa)^2 = \begin{cases} 100 & \text{(MPQ)} \\ 20 & \text{(Caltech)} \end{cases}$$

Ultra-sensitivity to atomic motion
$\longrightarrow$ large friction at low velocities

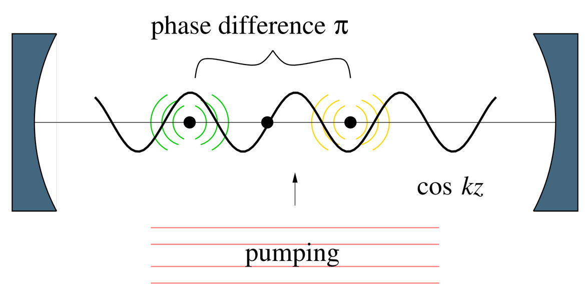
6 Polariton cooling

Resonance at $\Delta_A \Delta_C \approx g^2$ & width $\approx \kappa + (\gamma - \kappa) g^2/\Delta_A^2$

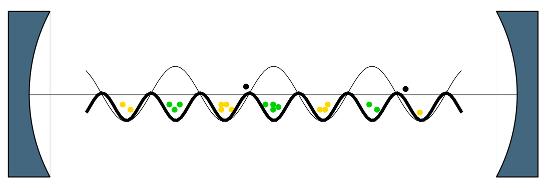


Reference: P. Domokos, A. Vukics, H. Ritsch, Phys. Rev. Lett. 92, 103601 (2004).

7 Scattering into the cavity mode

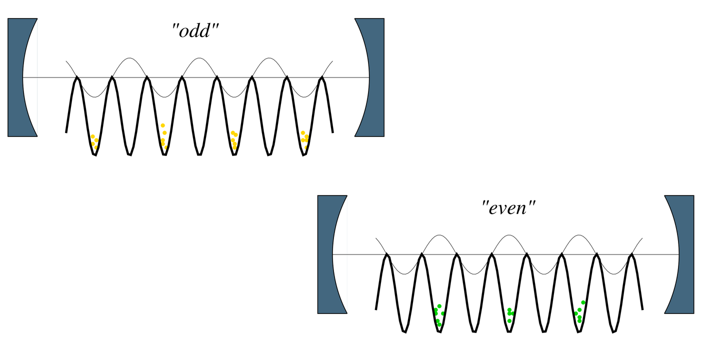


Destructive interference for uniform distribution. Finite number of atoms (fluctuations) ⇒ shallow trapping sites are at the antinodes for red detuning.



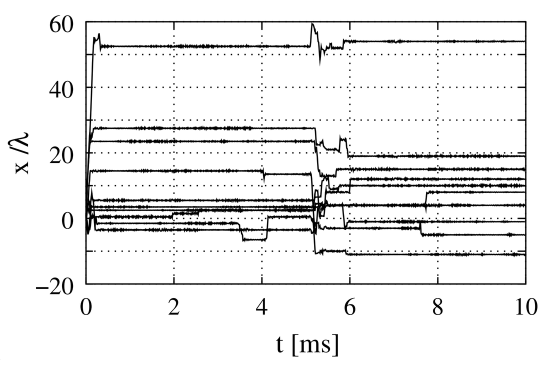
Localisation with a periodicity $\lambda/2$ occurs?

8 Self-organization



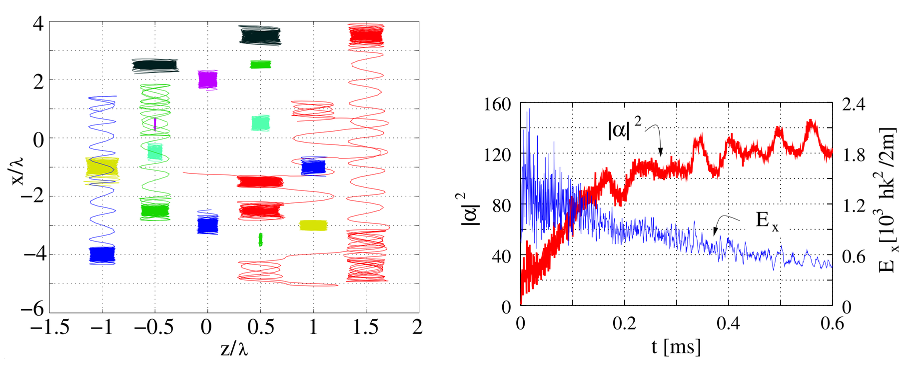
The atoms self-organize into one of the two possible patterns with λ periodicity. They fall into deep potential wells, the energy is dissipated by cavity cooling mechanism.

9 One-dimensional motion



N=10, $(g,\ \kappa,\ \gamma)$=(50, 10, 20)/μs, $\Delta_A = -500\gamma$, $\eta = 1000/\mu s$ (mean photon number about 7), M=85 (Rb).

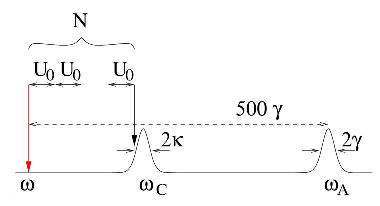
10 Three-dimensional motion

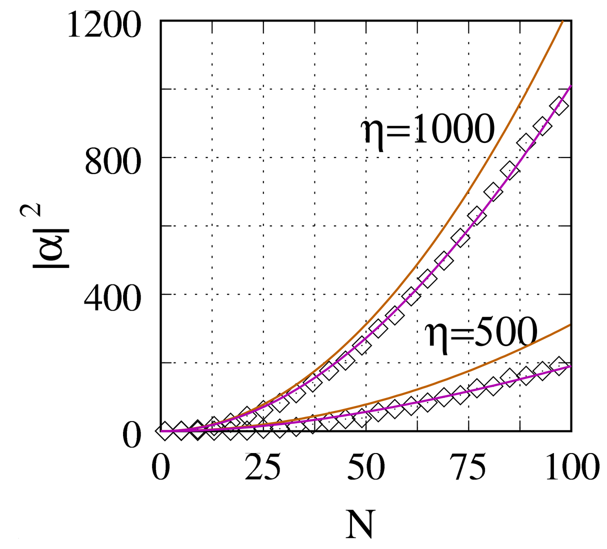


N=20, $(g,\ \kappa,\ \gamma)$=(30, 10, 20)/μs, $\Delta_A = -100\gamma$, $\eta = 2500$.

11 Superradiance

$\Delta_C - NU_0 = \kappa$
$\kappa = \gamma/2$
$U_0 = \gamma/80$
Saturation < 0.06



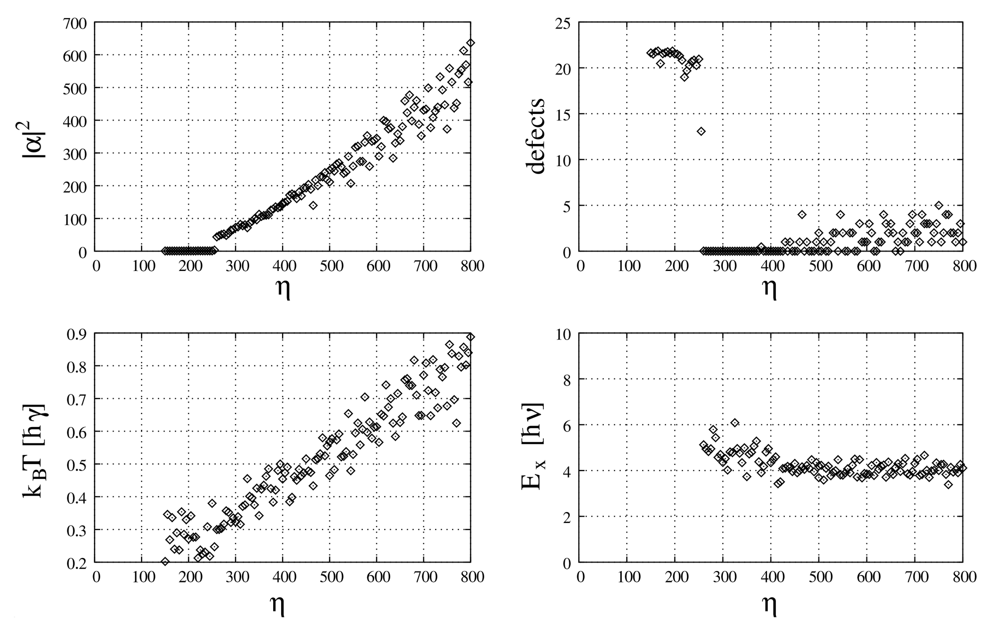


$$\overline{\mid\alpha\mid^2} = N^2 \frac{\mid\eta_{\rm eff}\mid^2}{\kappa^2} \frac{(1 - k^2\overline{x^2})}{1 + \left[1 + (U_0 N/\kappa) k^2 \overline{x^2}\right]^2}$$

$\overline{x^2} = 0$

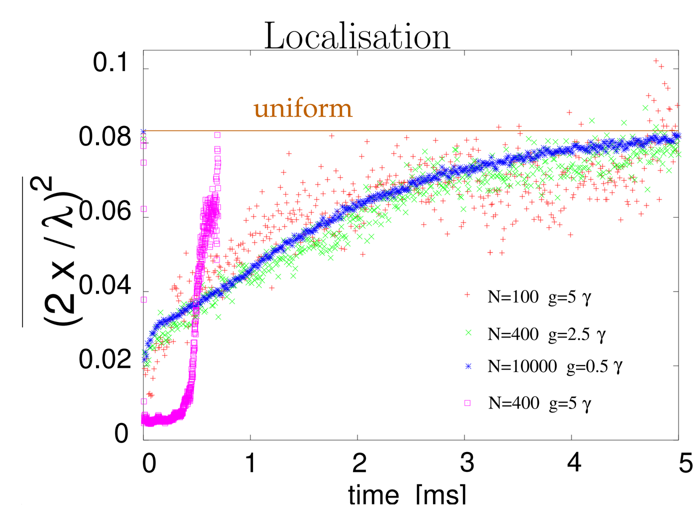
$k^2\overline{x^2} = 0.14 \quad (\eta = 500),\ k^2\overline{x^2} = 0.06 \quad (\eta = 1000)$

12 Threshold and temperatures



N=50, $(g,\ \kappa,\ \gamma)$=(100, 10, 20)/μs, saturation < 0.1

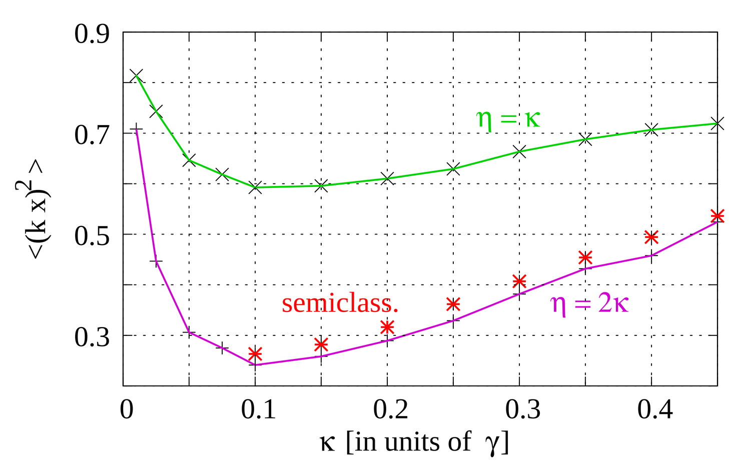
13 Scaling for large ensemble

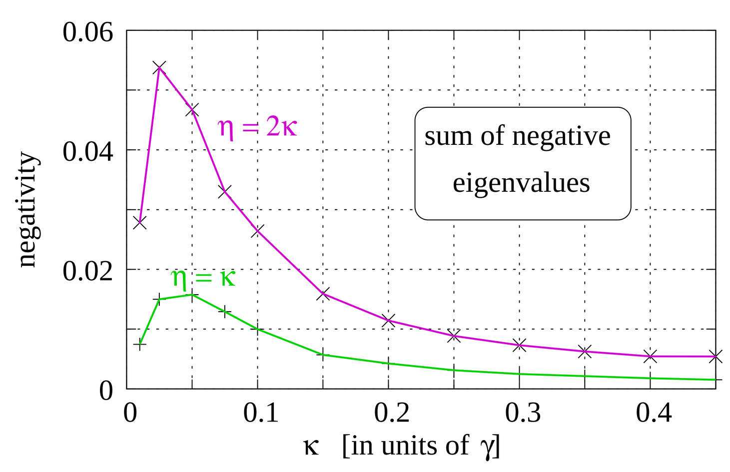


Pattern formation is independent of Ng^2.

Reference: P. Domokos and H. Ritsch, Phys. Rev. Lett. 89, 253003 (2002).

14 Quantum Monte Carlo wavefunction simulations of cavity cooling





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