Storage of a single photon in a Bose-Einstein condensate

December 13, 2006

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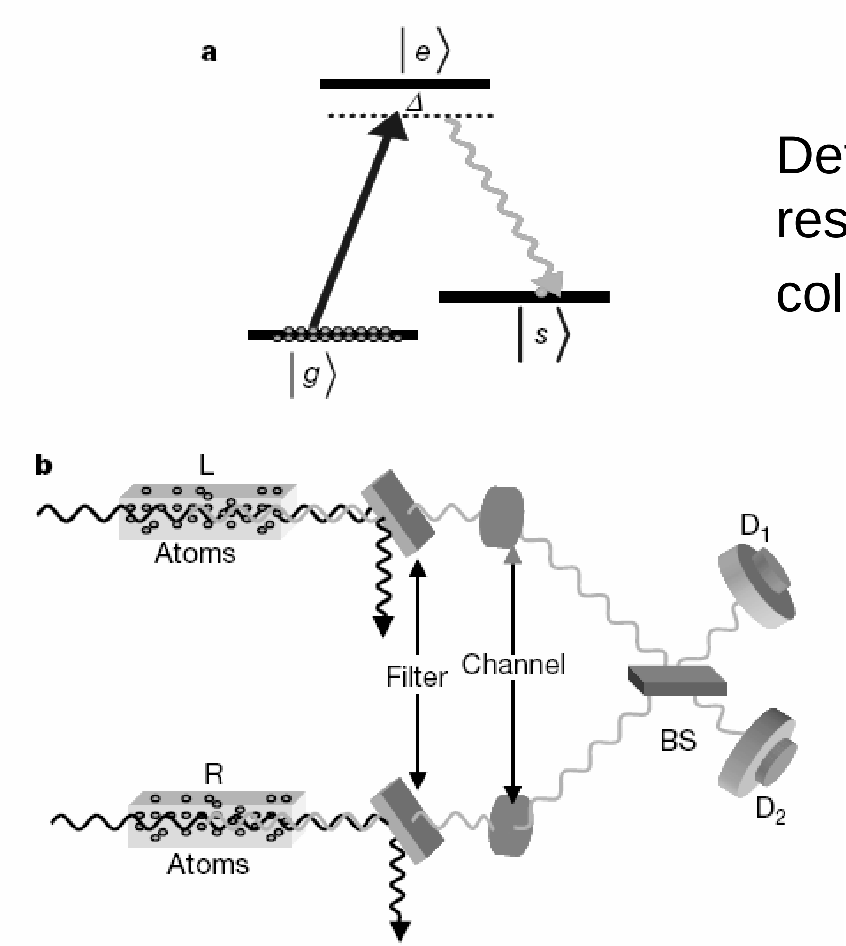
Motivation: DLCZ protocol

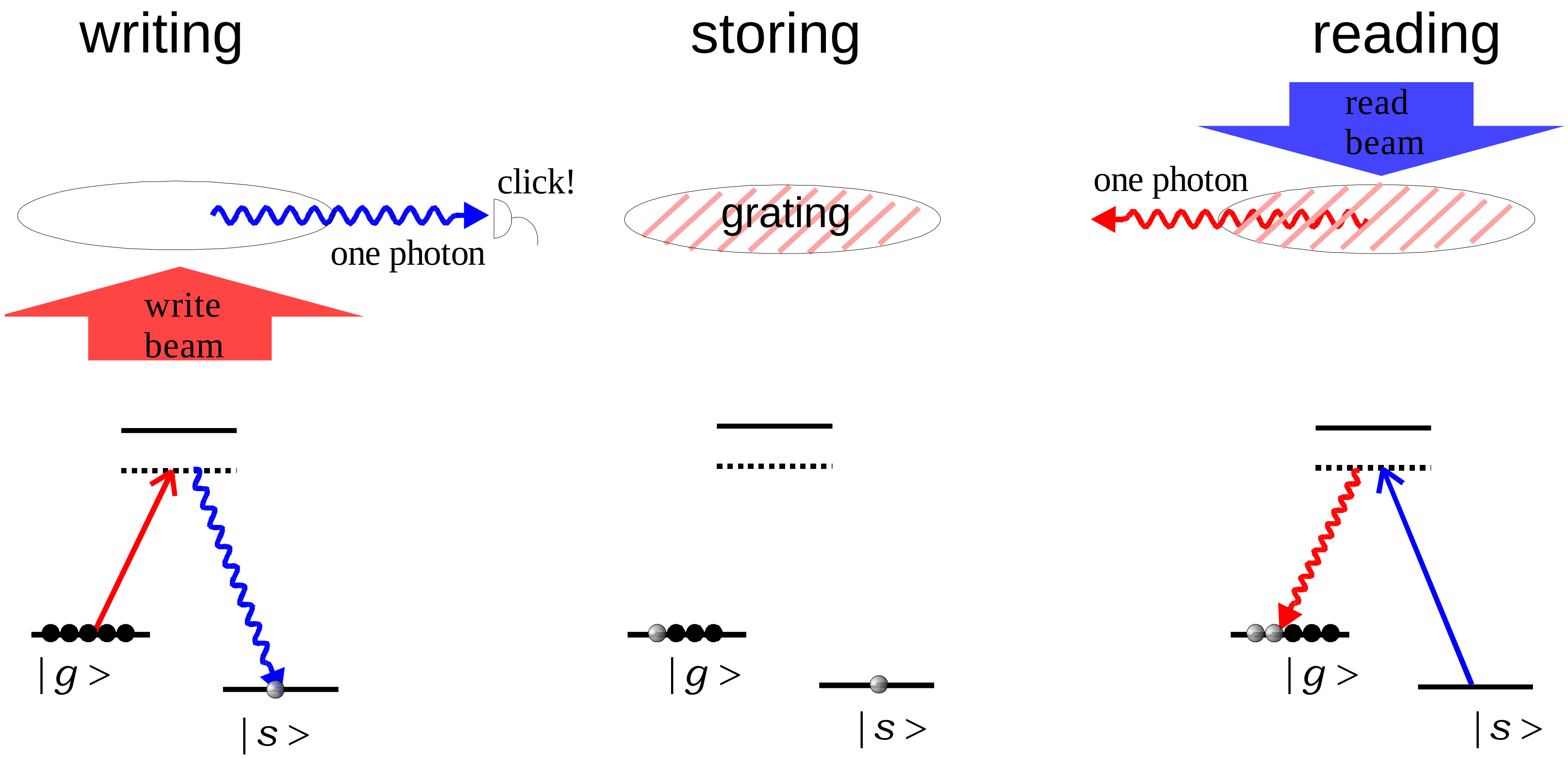


Detection of a forward-scattered photon results in the excitation of the symmetric collective mode defined by

$$S^{+} \equiv \frac{1}{\sqrt{N}} \sum_{i=1}^{N} | s >_i < g |$$

L.-M. Duan, M. D. Lukin, J. I. Cirac,and P. Zoller, Nature. **414**, 413 (2001)

Writing, storing, and reading of a single photon



Efficient retrieval of a single excitation stored in an atomic ensemble

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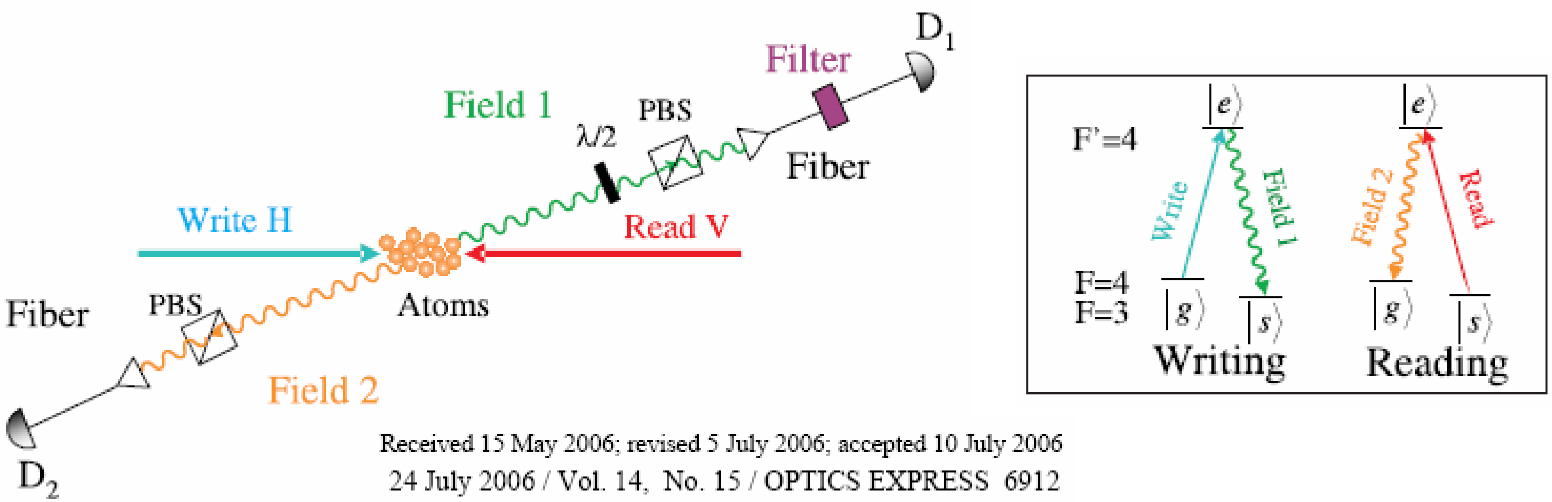
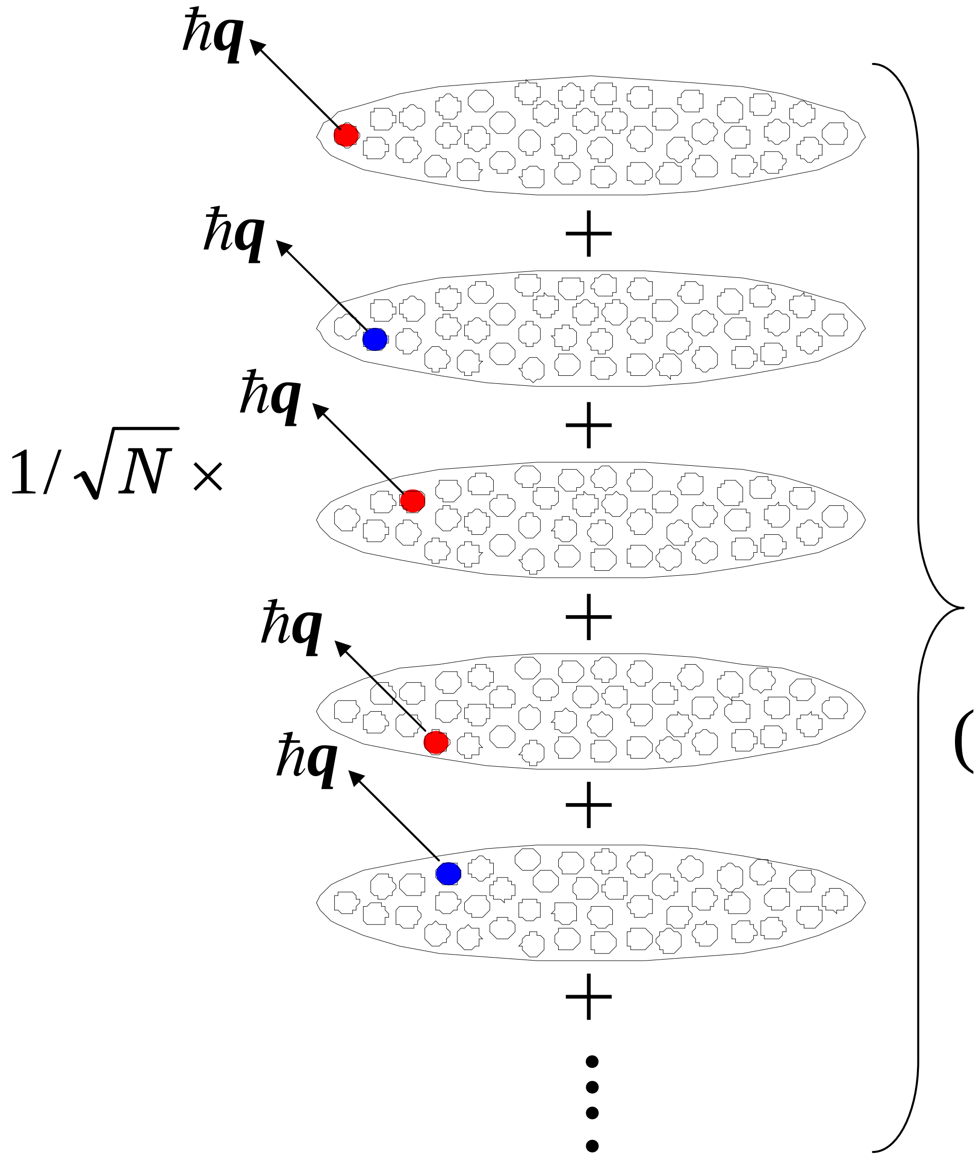
Abstract: We report significant improvements in the retrieval efficiency of a single excitation stored in an atomic ensemble and in the subsequent generation of strongly correlated pairs of photons. A 50% probability of transforming the stored excitation into one photon in a well-defined spatio-temporal mode at the output of the ensemble is demonstrated. These improvements are illustrated by the generation of high-quality heralded single photons with a suppression of the two-photon component below 1% of the value for a coherent state. A broad characterization of our system is performed for different parameters in order to provide input for the future design of realistic quantum networks.

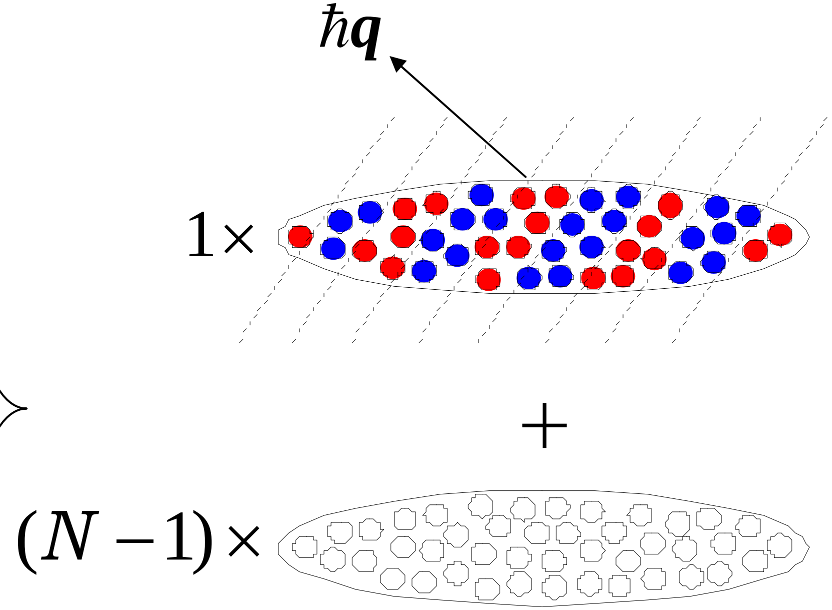


Received 15 May 2006; revised 5 July 2006; accepted 10 July 2006
24 July 2006 / Vol. 14, No. 15 / OPTICS EXPRESS 6912

The origin of a grating
(Indiscernability of the atoms)



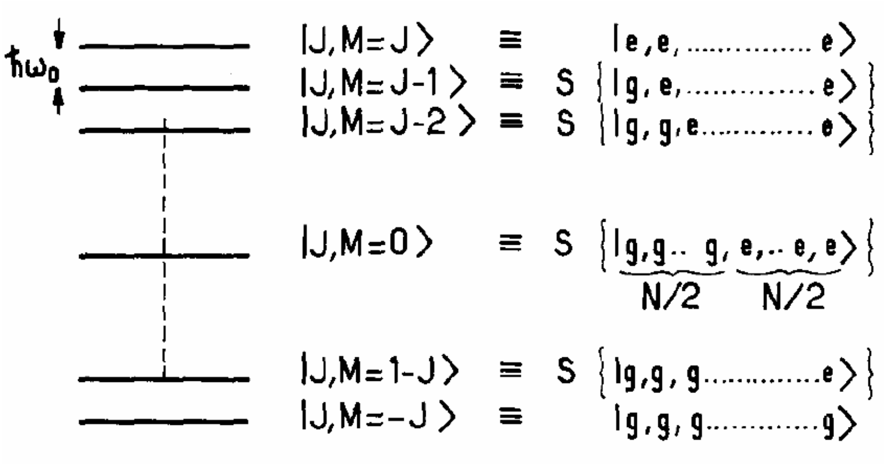
One atom is excited to the collective atomic mode defined by S^{+}



$$S^{+}|0_a> \equiv \frac{1}{\sqrt{N}}\sum_{i=1}^{N}|g_1, g_2, \cdots, s_i, \cdots, g_{N_a}>$$

Collective mode = Dicke state

N-atom system ⇔ N spin-1/2 system with the total spin J = N/2
(assumption: *Indiscernability* of the atoms with respect to photon emission)



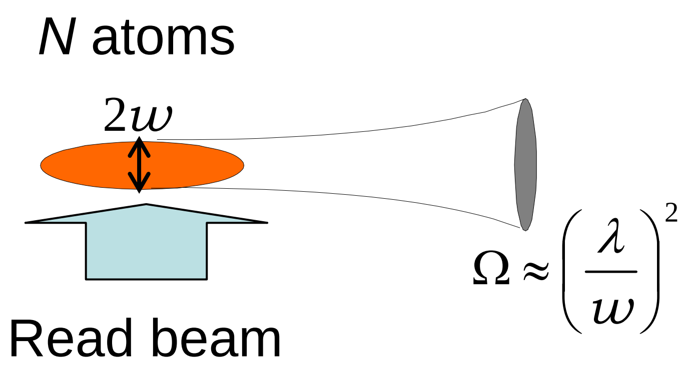
Spontaneous emission rate of the N-atom system:

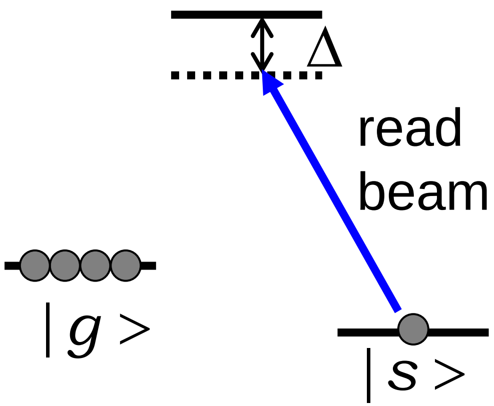
$$\Gamma_N = \Gamma\langle J,M\,|\,J_+J_-\,|\,J,M\rangle$$
$$= \Gamma(J+M)(J-M+1)$$
$$= \Gamma N_e(N_g+1)$$

Bosonic stimulation
(Superradiant emission)

R. H. Dicke, Phys. Rev. **93**, 99 (1954)
M. Gross and S. Haroche, Phys. Rep. **93**, 301 (1982)

Raman scattering rate for a cigar-shaped atomic ensemble





Single-atom Raman scattering rate

$$R = \Gamma \frac{\Omega_p^2}{4\Delta^2}$$

N_a-atom Raman scattering rate

$$R_N = f(\theta) R \langle J, M | J_+ J_- | J, M \rangle \Omega$$
$$= f(\theta) R N_s (N_g + 1) \Omega$$

Mode field pattern

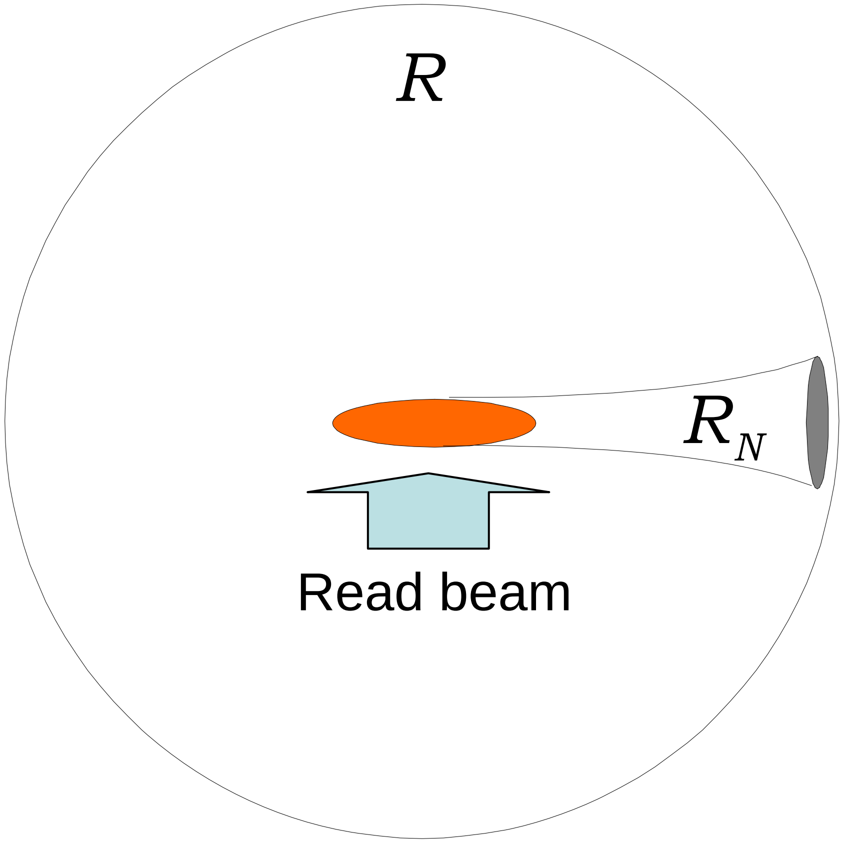
Phase matching solid angle

For the reading ($N_g = N$-1, N_s = 1)

$$R_N = \boxed{N} f(\theta) R \, \Omega$$

Collective enhancement

Spontaneous scattering vs. Collective scattering



The ratio between spontaneous and collective Raman scattering rates:

$$\frac{R_N}{R} = N\eta$$: cooperativity parameter

$$\eta \equiv f(\theta)\Omega$$: single-atom optical depth

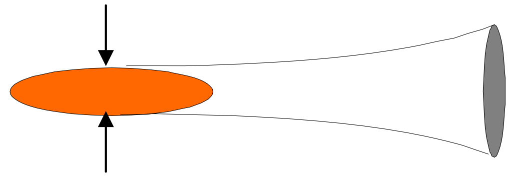
$$\Omega \approx \left(\frac{\lambda}{w}\right)^2 \quad f(\theta) = \begin{cases} \dfrac{3\sin^2\theta}{8\pi} & (\pi\text{–pol.}) \\ \dfrac{3(1+\cos^2\theta)}{16\pi} & (\sigma\text{-pol.}) \end{cases}$$

The probability that an atom in the collective mode emits a photon into the solid angle Ω

$$P_s = \frac{N\eta}{1+N\eta}$$

Cooperativity parameter of Bose condensates

Typical size of a Bose condensate: d = 10 μm



$$\Omega \approx \left(\frac{\lambda}{d}\right)^2 \approx 10^{-3}$$

Typical number of atoms in a Bose condensate: $N = 10^6$

Cooperativity parameter for a typical Bose condensate:

$$N\eta \approx N\Omega \approx 10^3$$

Probability of successful retrieval of a single photon:

$$P_s = \frac{N\eta}{1+N\eta} \approx 99.9\%$$

BEC is ideal for storage of a single photon!

cf.) Cooperativity parameter and Purcell factor for cavities

The rate for an excited atom in the cavity to emit a photon into the cavity mode

$$R = \frac{2\pi}{\hbar^2} |< g,1|\hbar g_0(a\sigma^+ + a^+\sigma)|e,0>|^2 \; \delta(\omega - \omega_A)$$

$$= 2\pi g_0^2 \frac{k/\pi}{\kappa^2 + \delta^2} \xrightarrow{\delta=0} \frac{2g_o^2}{\kappa} \qquad \frac{k/\pi}{\kappa^2+\delta^2}$$

Normalized Cavity line shape

$$\left(g_0 \equiv \sqrt{\frac{d_{eg}^2\omega}{2\varepsilon_0\hbar V}}, \quad d_{eg} \equiv < e|-e\hat{x}|g>, \quad 2\kappa = \frac{1}{\tau_c} = \frac{\pi c}{lF}, \quad V = \frac{\pi}{4} w_0^2 \cdot l \right)$$

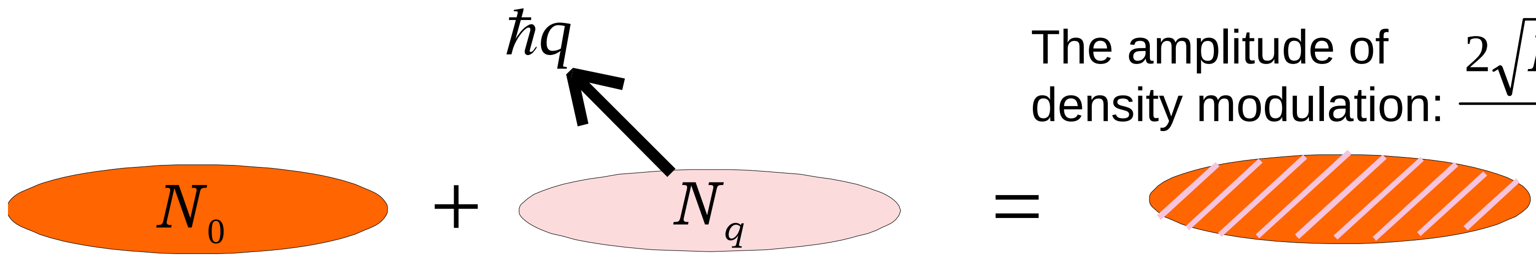
The ratio between R and spontaneous emission rate Γ (Puecell factor)

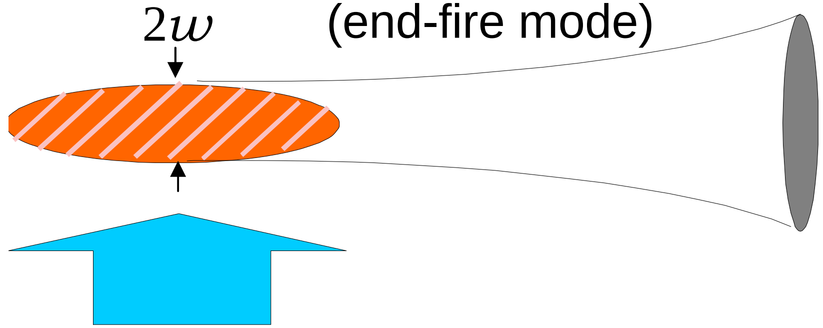
$$\boxed{\frac{R}{\Gamma} = \frac{2g_0^2}{\kappa\Gamma} = 2C = \frac{3\lambda^3}{4\pi^2}\left(\frac{Q}{V}\right)} \qquad \left(Q \equiv \frac{\omega}{\Delta\omega} = \frac{2l}{\lambda} F \right)$$

Cooperativity parameter: $\boxed{C \equiv \frac{g_0^2}{\kappa\Gamma} = \frac{12F}{\pi w_0^2 k^2} = \frac{F}{2\pi}\frac{\sigma_{\text{atom}}}{A}}$ $\left(\sigma_{\text{atom}} = 6\pi\lambda\!\!\!^{-2}, \; A = \frac{\pi}{4} w_0^2 \right)$

Relation between cooperativity parameter and superradiance

The amplitude of density modulation: $\dfrac{2\sqrt{N_0 N_q}}{V}$





Phase-matching solid angle

$$\Omega \approx \left(\frac{\lambda}{\omega}\right)^2$$

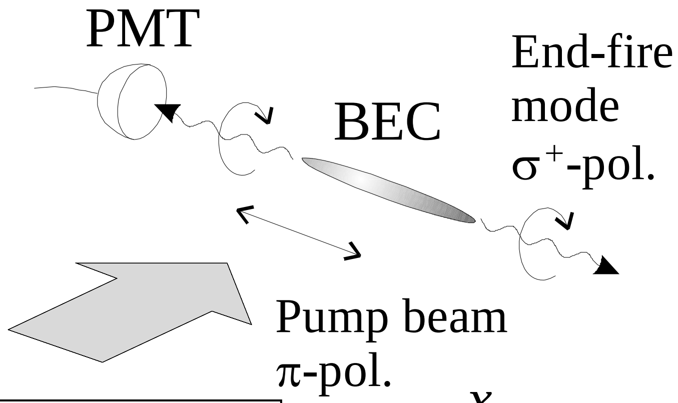
Power in the end-fire mode

$$P = \hbar\omega \frac{\sin^2\theta}{8\pi/3} R N_0 N_q \Omega \;\Rightarrow\; \frac{\dot{N}_q}{N_q} = R \boxed{\frac{\sin^2\theta}{8\pi/3} N_0 \Omega}$$

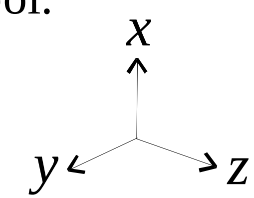
R : single-atom Rayleigh scattering rate

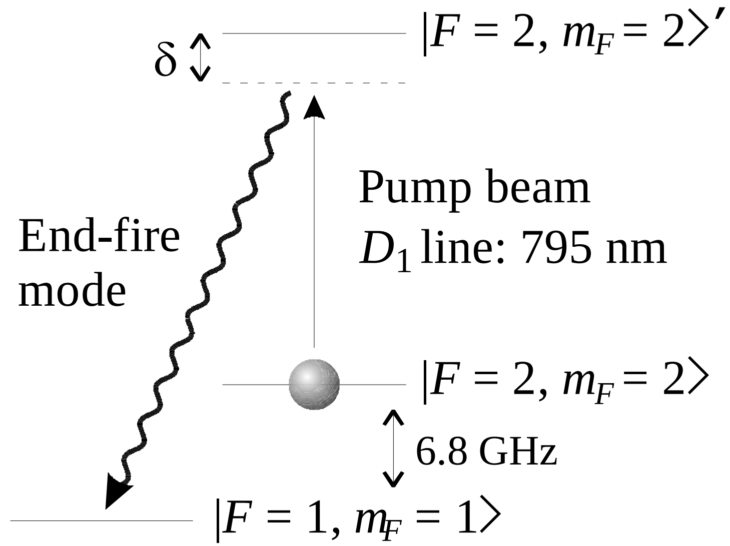
Cooperativity parameter

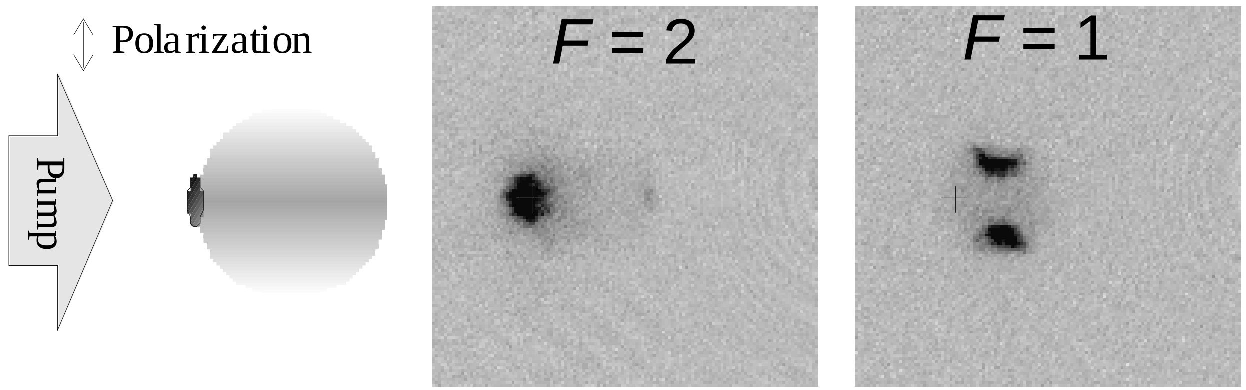
Superradiant Raman scattering in a Bose condensate



Detuning: -2.6 GHz
Intensity: 40 mW/cm^2
Pulse duration: 100 μs

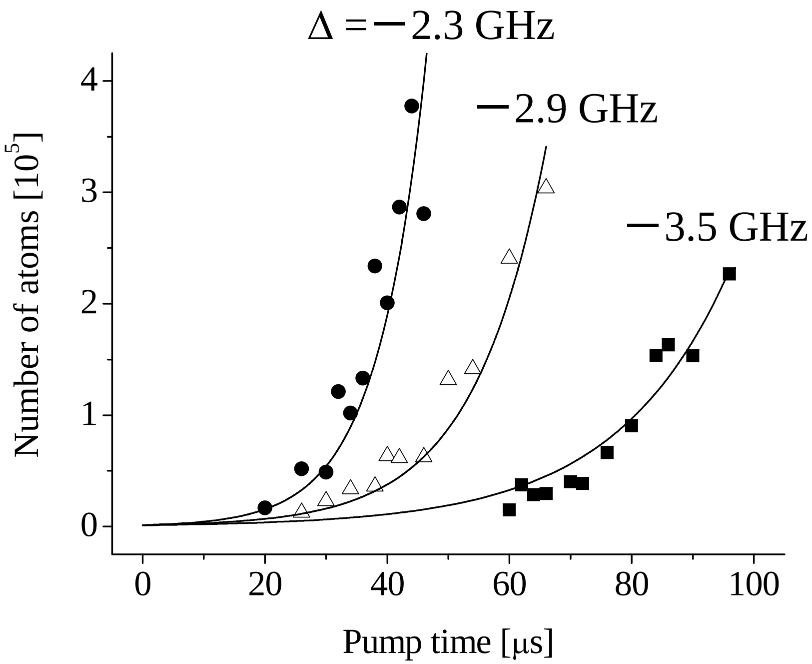


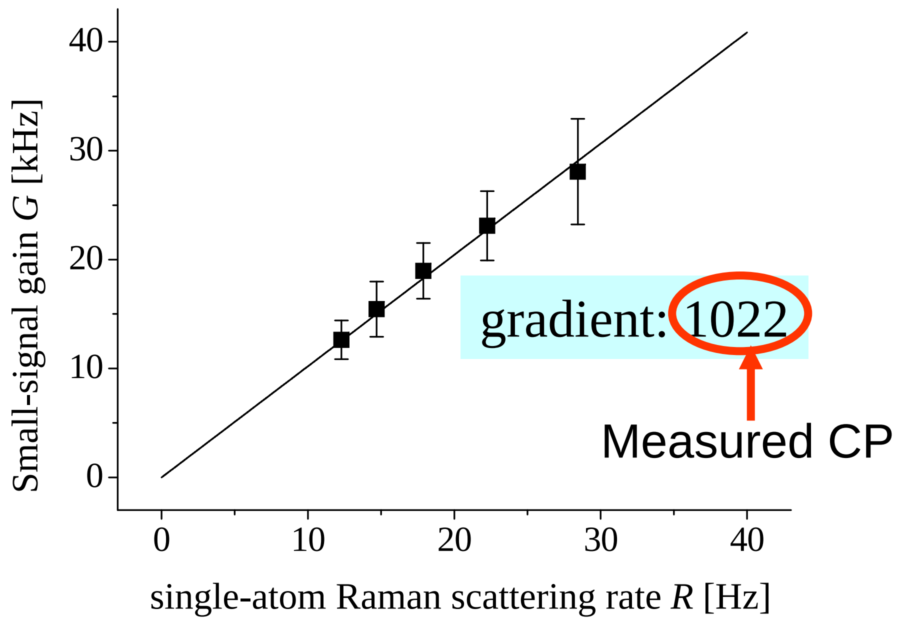




Y. Yoshikawa, T. Sugiura, Y. T., and T. Kuga, PRA **69** 041603 (2004)

Measurement of the cooperativity parameter(CP) of a Bose condensate





$$\dot{N}_q \approx \frac{3}{8\pi} R N_0 N_q \Omega \xrightarrow{N_0 << N_q} N_q \approx e^{Gt}$$

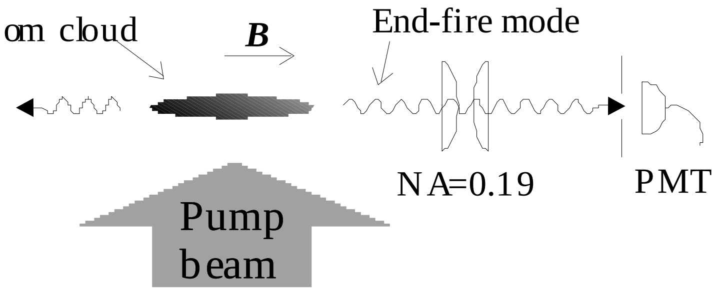
R: single-atom Raman scattering rate

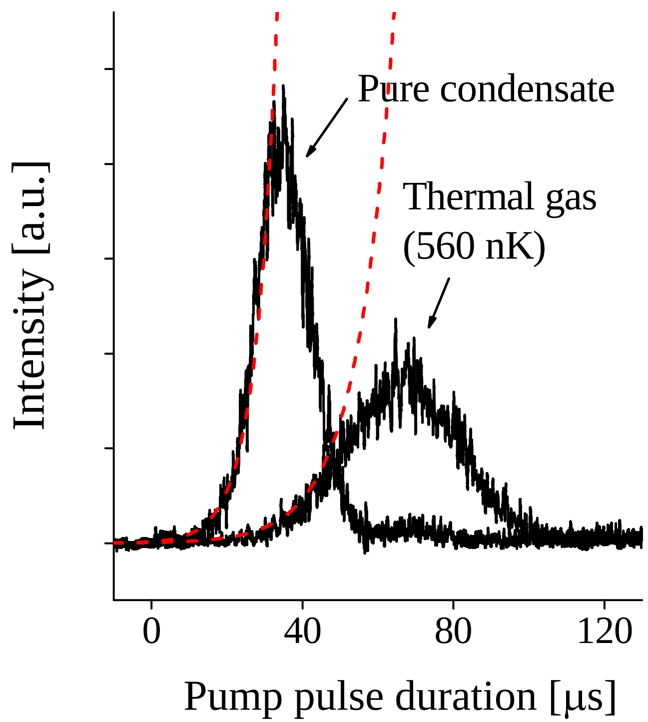
Small-signal gain:

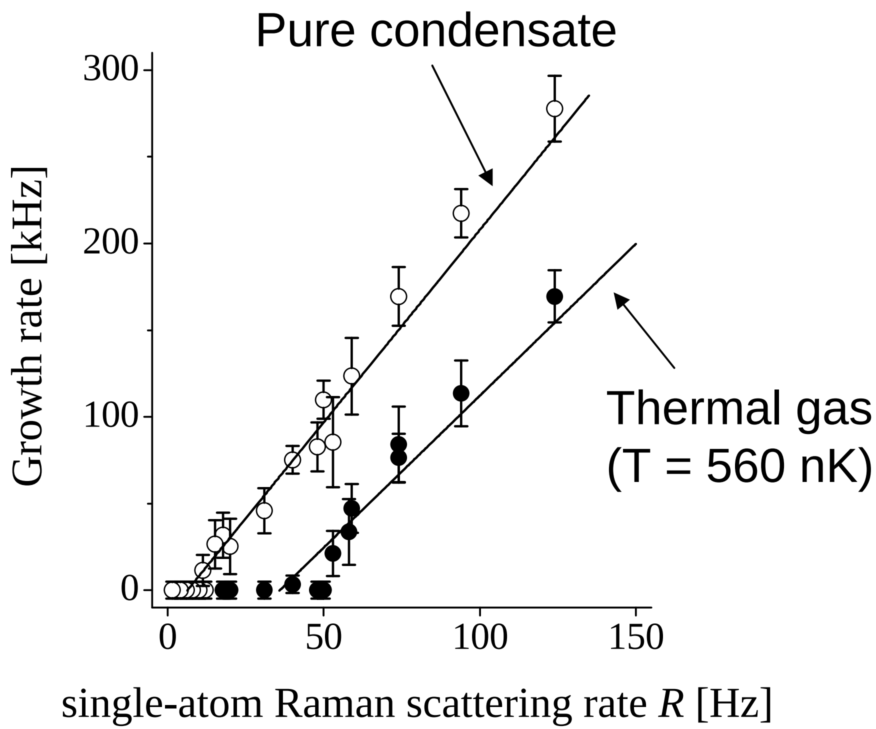
$$G = \frac{3}{8\pi} N_0 \Omega R = 890 R$$

Calculated CP

Superradiance in a Thermal gas







Y. Yoshikawa, Y. T. and T. Kuga, PRL **94** 083602 (2005)

What determines the coherence time?

a) The endfire mode

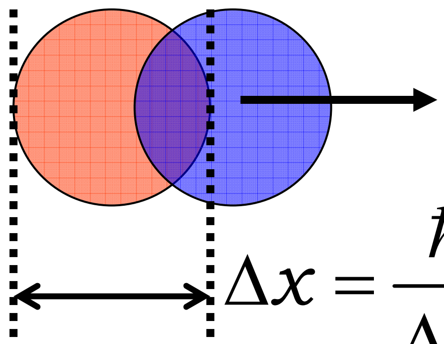
Doppler width:

$$\Delta\omega_{\mathrm{D}} = q\bar{\upsilon} \qquad \left(\bar{\upsilon} = \sqrt{\frac{k_{\mathrm{B}}T}{m}}\right)$$

RMS velocity

$$\boxed{\tau_{\mathrm{c}} = \frac{1}{\Delta\omega_{\mathrm{D}}} = \frac{1}{q\bar{\upsilon}}}$$

b) matter wave grating
(overlap of the wave packets)



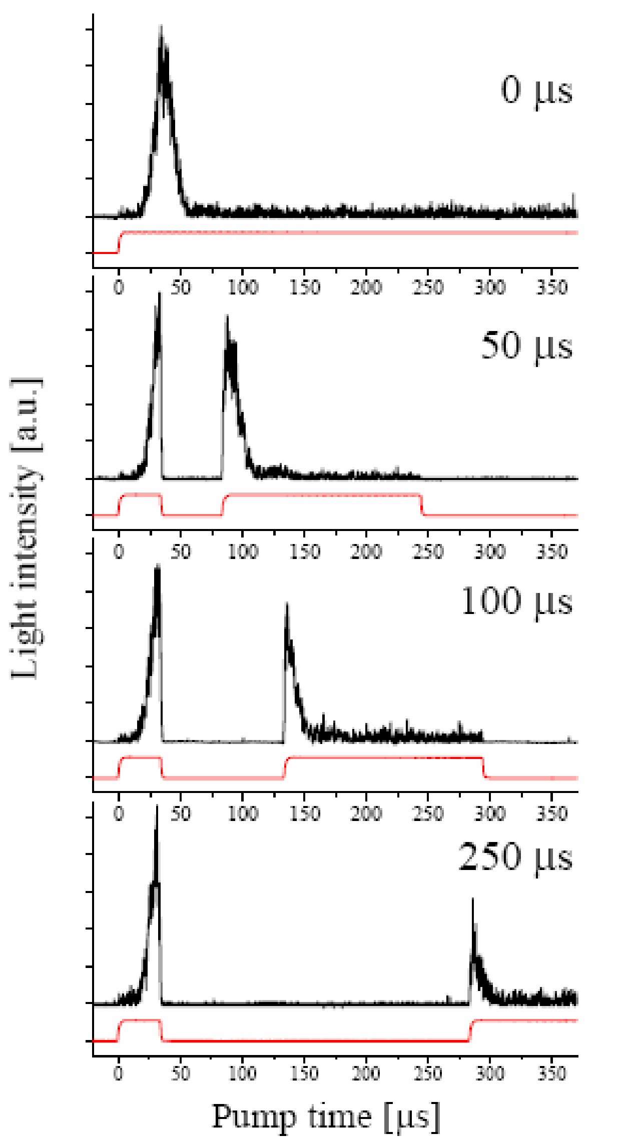
$$\upsilon = \frac{\hbar q}{m}$$

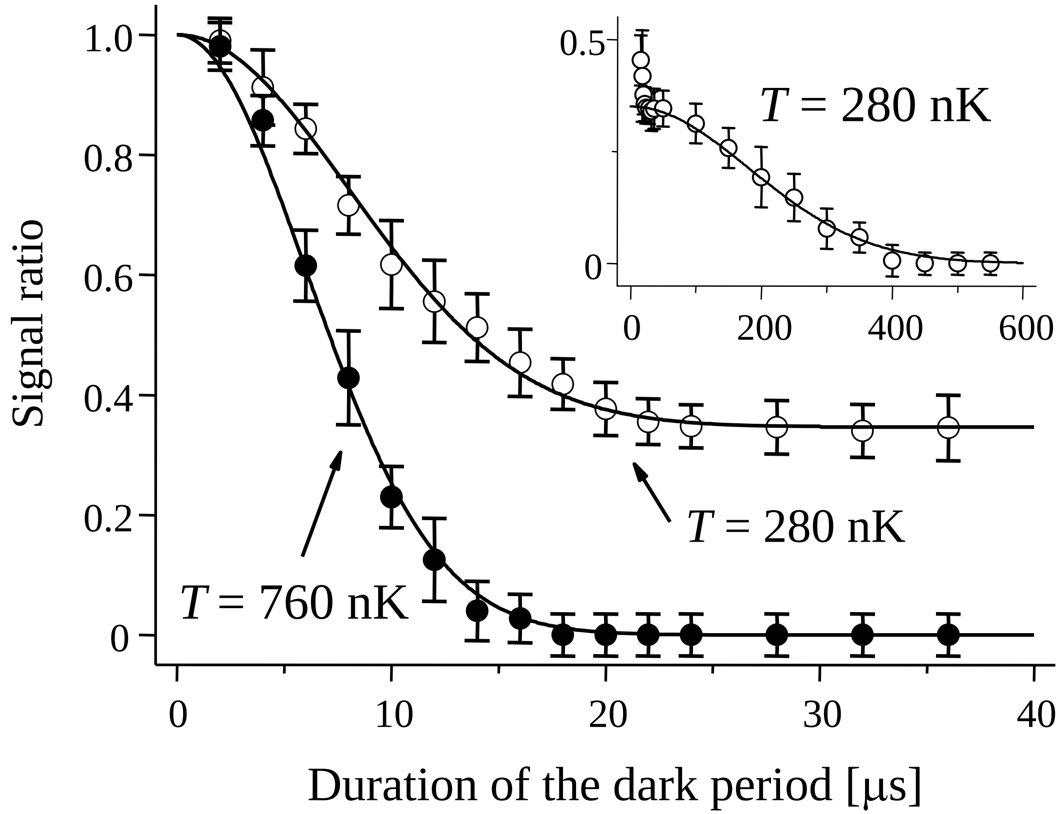
$$\Delta x = \frac{\hbar}{\Delta p} = \frac{\hbar}{m\bar{\upsilon}}$$

$$\boxed{\tau_{\mathrm{c}} = \frac{\Delta x}{\upsilon} = \frac{1}{q\bar{\upsilon}}}$$

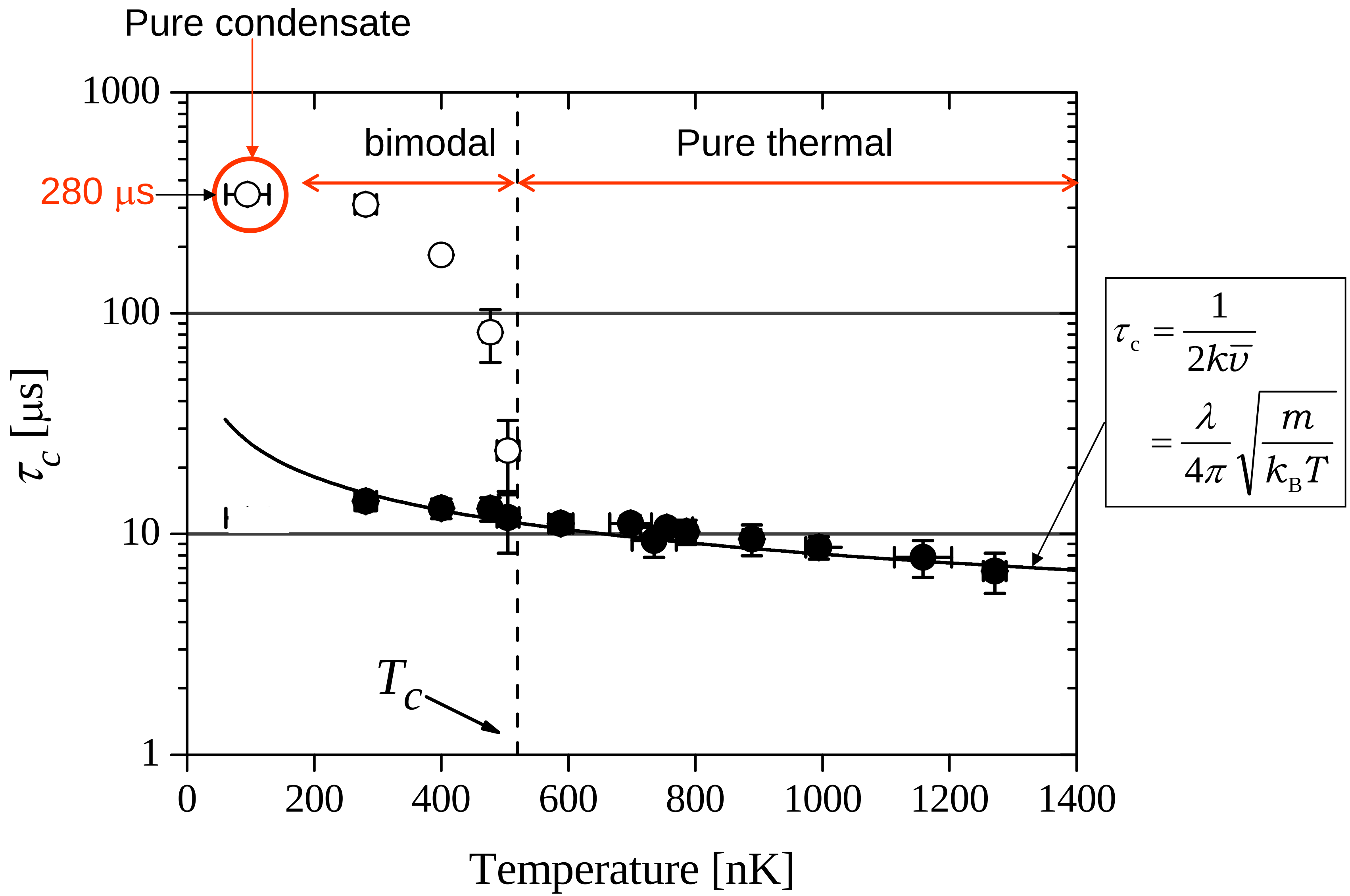
Coherence time is given by the inverse of the Doppler width

Storage (coherence) time measurement





Storage time vs. temperature



Merits of using a BEC for single photon storage

- Large cooperativity parameter ($\sim 10^3$) (nearly 100% conversion efficiency)

- Long storage (coherence) time ($\sim 300 \mu s$)

  (could be extended by Lamb-Dicke effect)

- Arbitrary angle between the pump and the signal light (possibility of simultaneous storage of many photons)