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Danish Quantum Optics Center University of Aarhus

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Light-Atoms Quantum Interface for Continuous Variables

Eugene Polzik

QUICOV

University of Aarhus

Content

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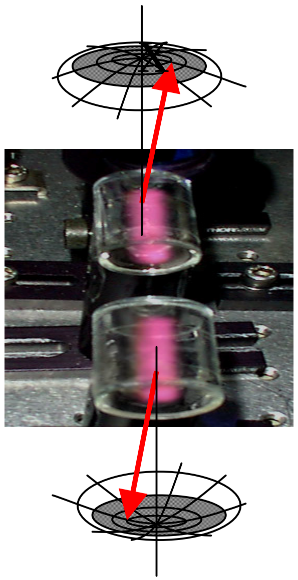
- Continuous variables for polarized light and oriented atoms
- Hamiltonian of light-atoms interaction
- Light-atoms interface via measurement induced back action: interface with and without teleportation
- Experiment with vacuum and squeezed vacuum input – recording a single quadrature

Experiment: recording in the ground state coherence (τ=1.5msec)
Schori, Julsgaard, Sorensen,Polzik
Phys. Rev. Lett. **89**, 057903, July 29, 2002
quant-ph/0203023

Theory - interspecies teleportation
Kuzmich, Polzik
Phys.Rev.Lett. ***85****, 5639 (2000)*

Recording w/out teleportation
Kuzmich, Polzik to appear in
"QI with continuous variables"
ed. Braunstein, Pati. Kluwer

Related work
Julsgaard, Kozhekin, Polzik
Nature **413**, 400 (2001).

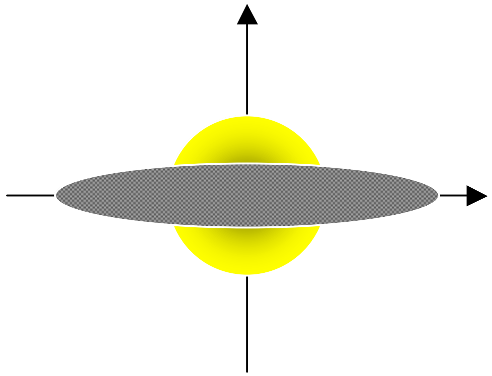


Continuous variables - light

Quadratures of light

$$X = \frac{1}{\sqrt{2}}(a^+ + a), P = \frac{i}{\sqrt{2}}(a^+ - a)$$

$$\left[\hat{X}, \hat{P}\right] = i$$

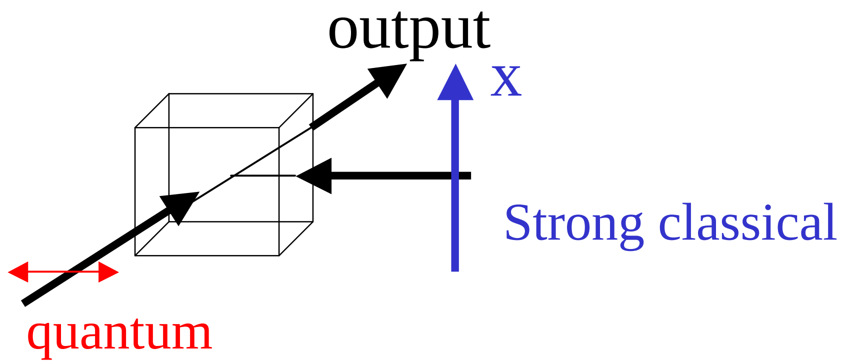


Can states of light like that be faithfully recorded in atoms?

Can such states be distinguished in the read out from atoms?

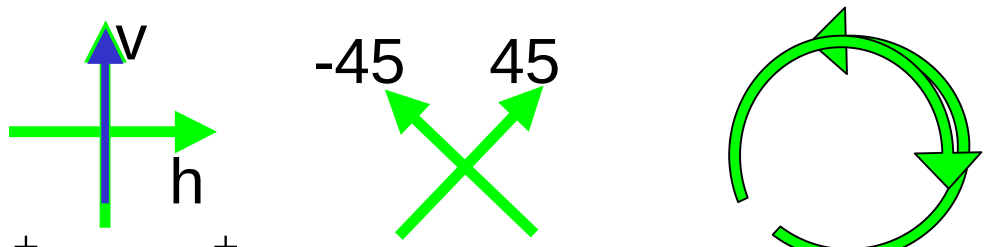
NB: the states are not orthogonal

Continuous variables – polarization states



Output polarization –
Stokes parameters

$$\left[\hat{S}_z, \hat{S}_y\right] = iS_x$$

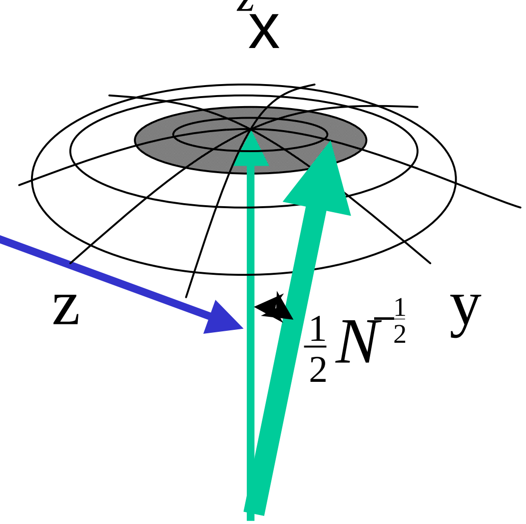


$$S_x = a_v^+ a_v - a_h^+ a_h$$

S_y

S_z

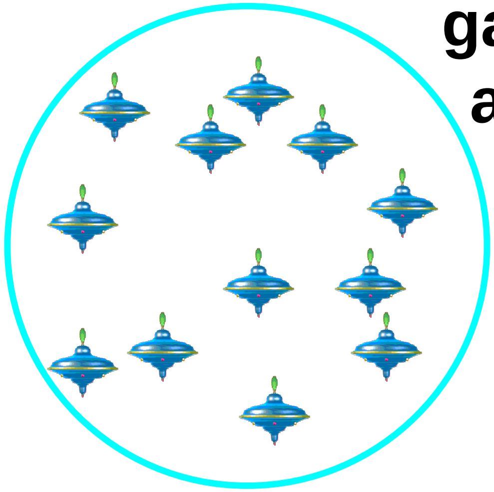
Large = classical

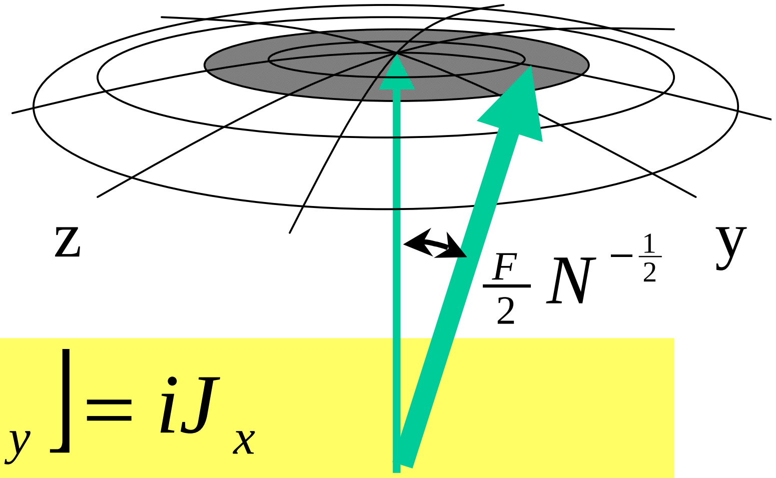


$$\hat{X} = \hat{S}_z \big/ \sqrt{S_x}, \quad P = \hat{S}_y \big/ \sqrt{S_x}$$

Macroscopic spin ensemble –
coherent spin state

gas sample at room T





$$\left[J_z, J_y\right] = iJ_x$$

$$\delta J_z^2 = \delta J_y^2 = \tfrac{1}{2} J_x = \tfrac{F}{2} N$$

X

State preparation (optical pumping)

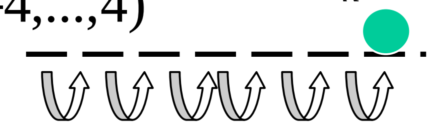
Cesium

$6P_{3/2}$

$$J_x = N \sum m\rho_{mm}$$

$m = (-4,\ldots,4)$

$6S_{1/2}, F=4$

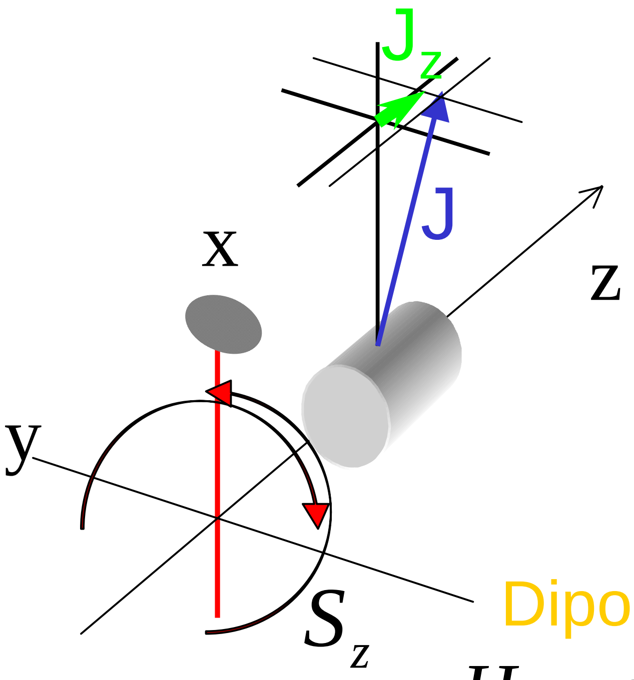


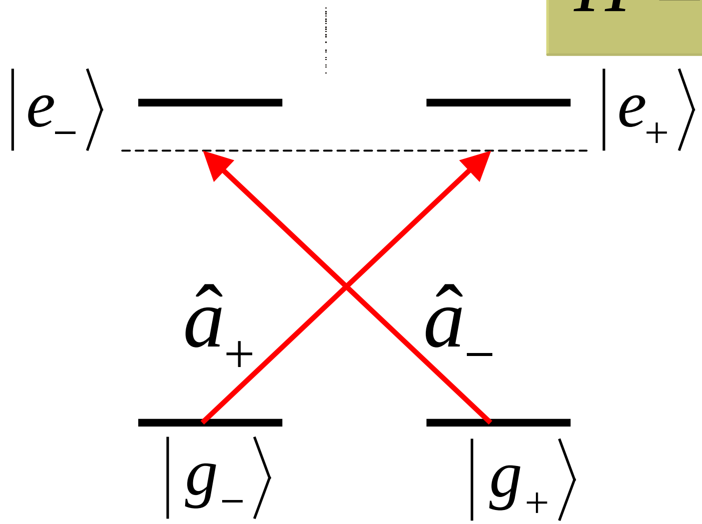
Coherences determine J_z, J_y

Light / Atom - Interaction

Hamiltonian:

$$H = aS_z J_z$$





Dipole interaction Hamiltonian:

$$H \propto dE \propto a_+ |g_-\rangle\langle e_+| + a_- |g_+\rangle\langle e_-| + h.c.$$

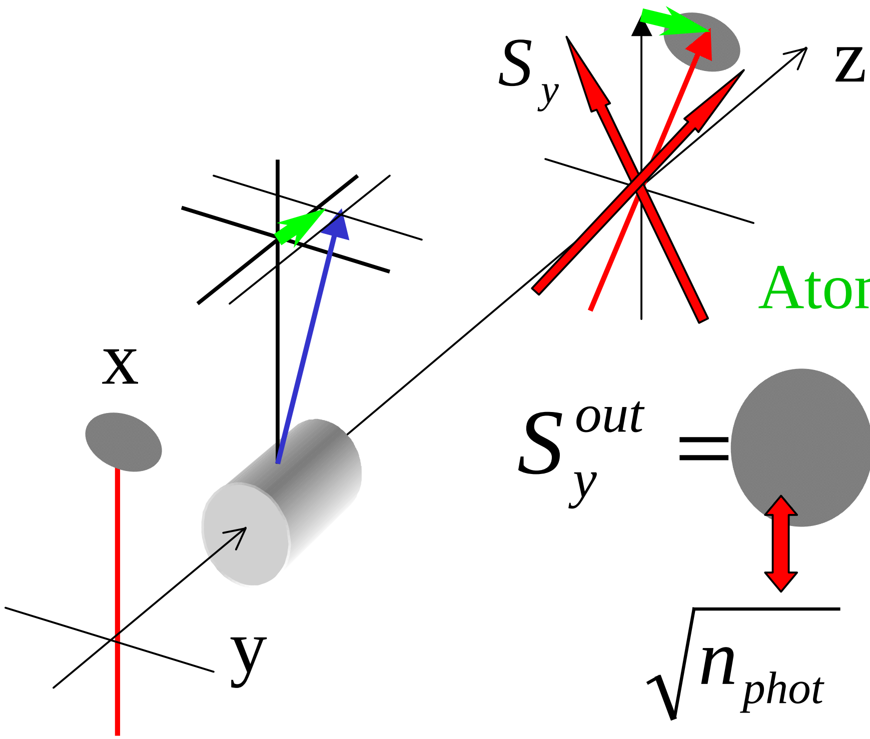
Off-resonant, perturbative:

$$H \propto a_+^+ a_+ |g_-\rangle\langle g_-| + a_-^+ a_- |g_+\rangle\langle g_+| =$$

$$= \tfrac{1}{2}(a_+^+ a_+ - a_-^+ a_-)(|g_-\rangle\langle g_-| - |g_+\rangle\langle g_+|) + \tfrac{1}{2} n_{phot} N_{atom} =$$

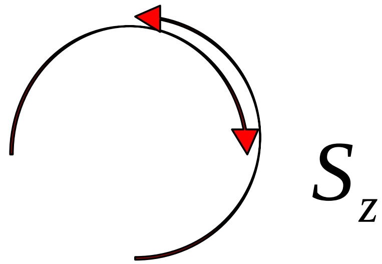
$$= \tfrac{1}{2} S_z J_z + \cancel{\tfrac{1}{2} n_{phot} N_{atom}}$$

Light / Atom - Interaction



Hamiltonian:

$$H = aS_z J_z$$



Faraday effect:

Atomic spins rotate polarization of light

$$S_y^{out} = \qquad + \kappa J_z$$

$$\sqrt{n_{phot}} \qquad \sqrt{N_{atom}}$$

$K=1$

$$\hat{X}^{out}_{light} = \hat{X}^{in}_{light} + \hat{P}^{in}_{atoms}$$

$$\kappa = \tfrac{1}{2} n_{phot} \frac{\sigma}{A} \frac{\gamma}{\Delta}$$

Figure of merit

$$\boxed{\left(\frac{\kappa J_z}{S_y^{in}}\right)^2 \approx \alpha_\Delta s_\Delta \frac{\Delta^2}{\gamma^2} \gamma \tau_{pulse} = \alpha_0 s_\Delta \gamma \tau_{pulse} = \alpha_0 \eta}$$

Probe depumping parameter:

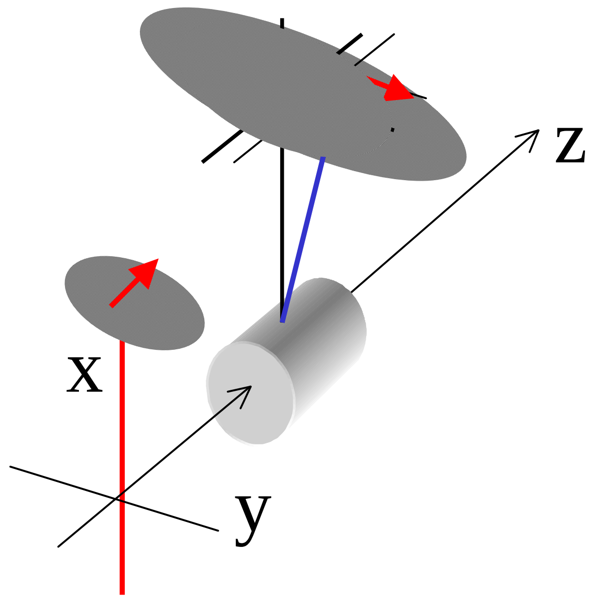
$$\eta << 1$$

Light / Atom - Interaction

Back action of light on atoms:

Light rotates spins of atoms

$$J_y^{out} = J_y^{in} + kS_z$$



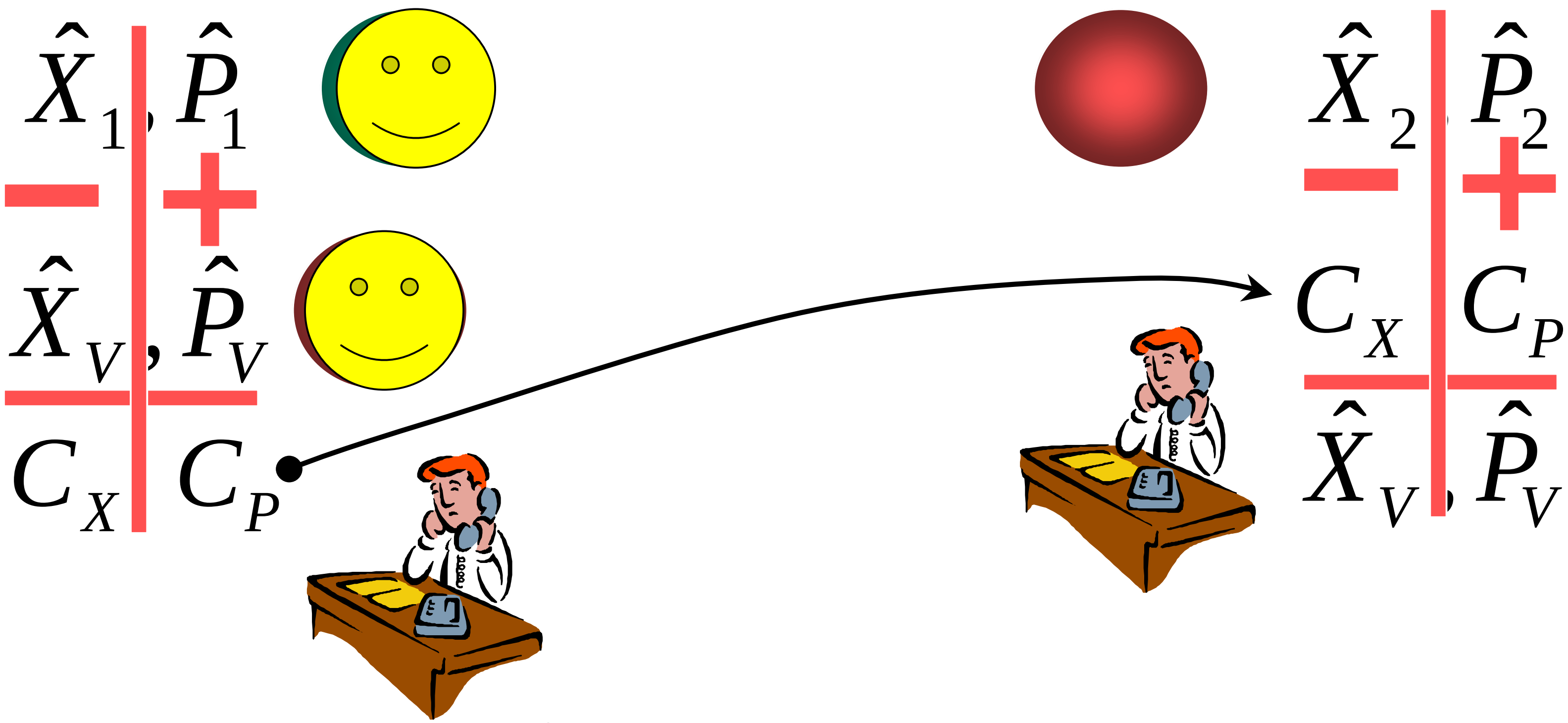
$$k = 1$$

$$\hat{X}_{atoms}^{out} = \hat{X}_{atoms}^{in} + \hat{P}_{light}^{in}$$

Teleportation principle (continuous variables)

$$[X,P]=i,[X_1-X_2,P_1+P_2]=0$$

L.Vaidman



Demonstrated experimentally for light variables by Furusawa, Sørensen, Fuchs, Braunstein Kimble, Polzik. *Science 1998*

Einstein-Podolsky-Rosen entangled state

$$X_1-X_2=0, P_1+P_2=0$$

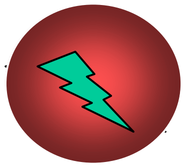
Light-to-Atoms Teleportation

J_{Z1}, J_{Y1}

J_{Z2}, J_{Y2}

$-\quad +$

$S_{ZV}\quad S_{YV}$

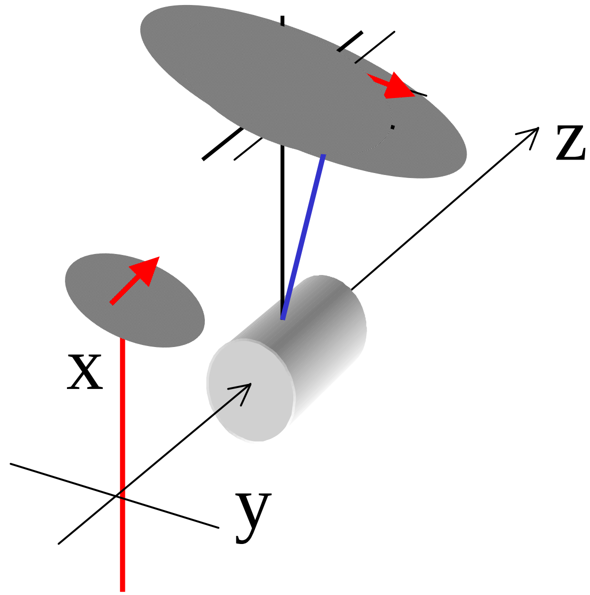


$$J_y^{out} = J_y^{in} + kS_z$$

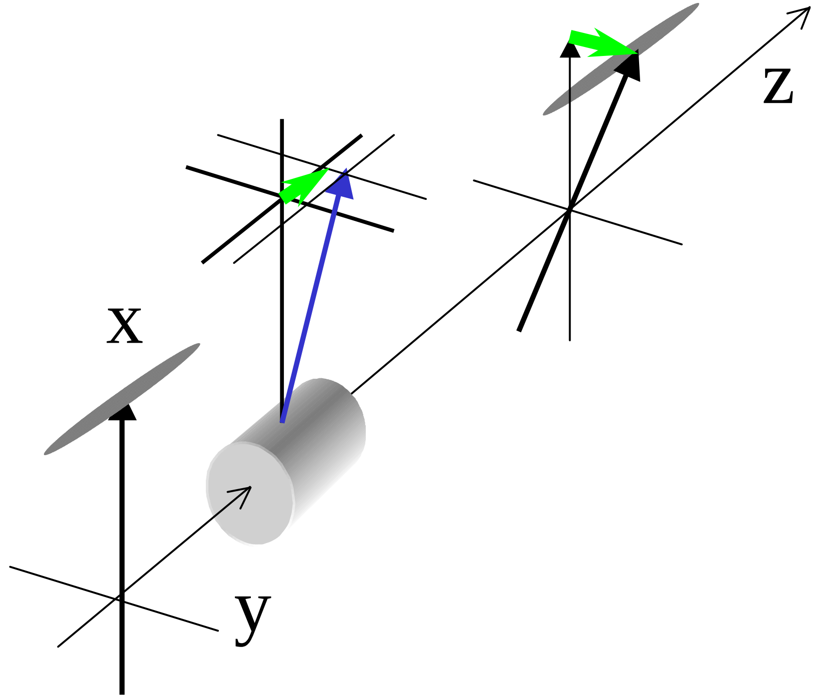
$$S_y^{out} = S_y^{in} + kJ_z$$

k=1

$$\hat{X}_{light}^{out} = \hat{X}_{light}^{in} + \hat{P}_{atoms}^{in}$$



Quantum memory read-out: single pulse



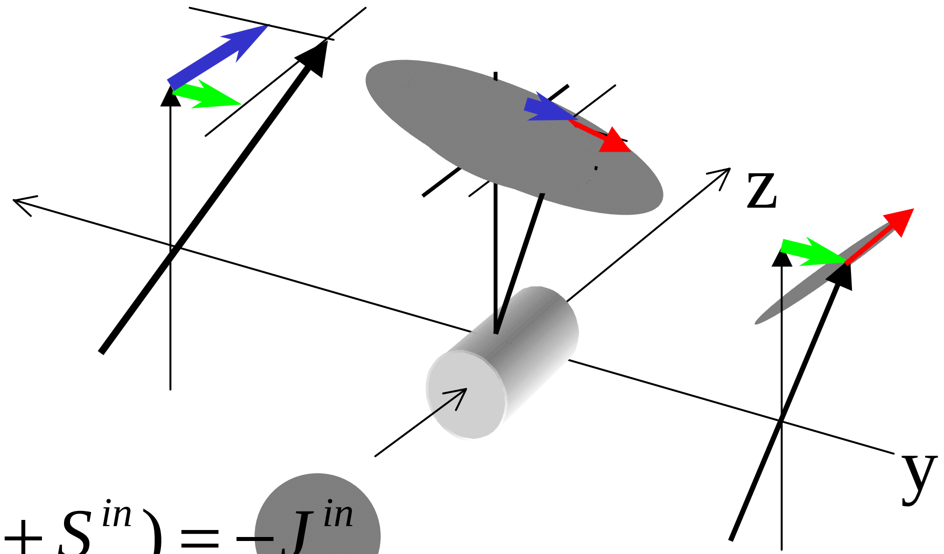
Step 1

$$S_y^{out} = S_y^{in} + \tfrac{1}{2} a n J_z = S_y^{in} + J_z^{in},$$

$$J_y^{out} = J_y^{in} + \tfrac{1}{2} a N S_z = J_y^{in} + S_z$$

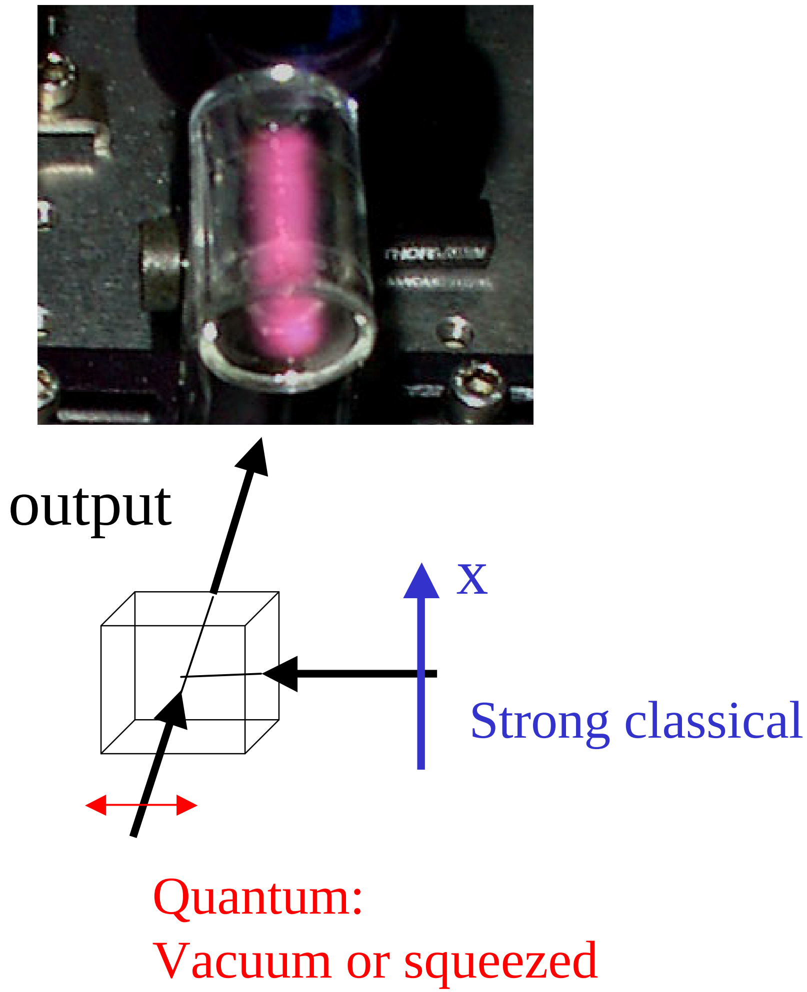
Step 2

Exchange y and z components:
pass light through λ/4 plate and
probe along spin-y axis

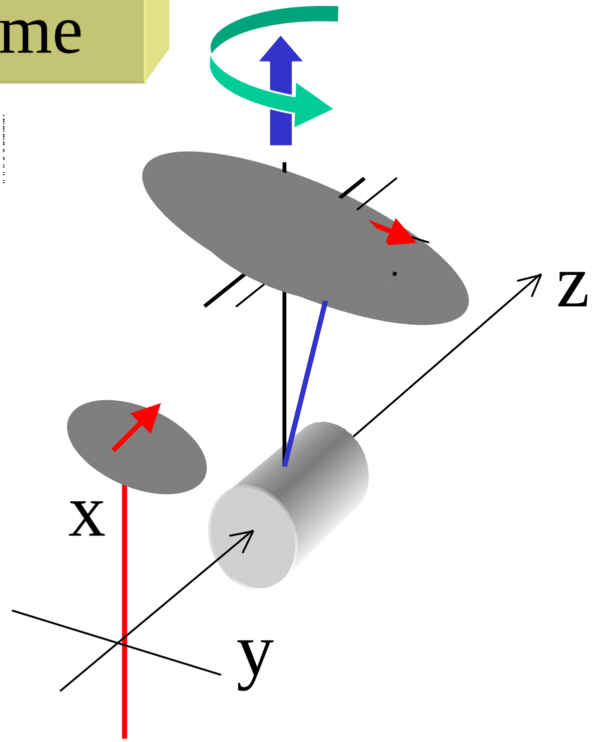


$$S_z^{out-2} = S_y^{in} + J_z^{in} \approx J_z^{in},$$

$$S_y^{out-2} = S_z^{out} - J_y^{out} = S_z^{in} - (J_y^{in} + S_z^{in}) = -J_y^{in}$$


output
x
Strong classical
Quantum:
Vacuum or squeezed

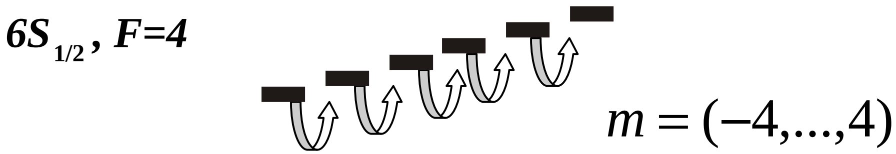
Light / Atom – Interaction, rotating frame



•To record a frequency component Ω of light we apply magnetic field **B** to atoms:

$$\dot{\hat{J}}_z(t) = \Omega \hat{J}_y(t) - \Gamma \hat{J}_z(t) + \hat{f}_z(t)$$

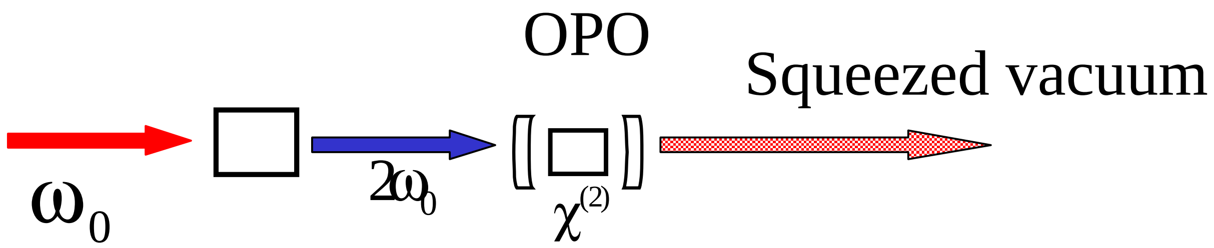
$$\dot{\hat{J}}_y(t) = -\Omega \hat{J}_z(t) - \Gamma \hat{J}_y(t) + k \quad + \hat{f}_y(t)$$



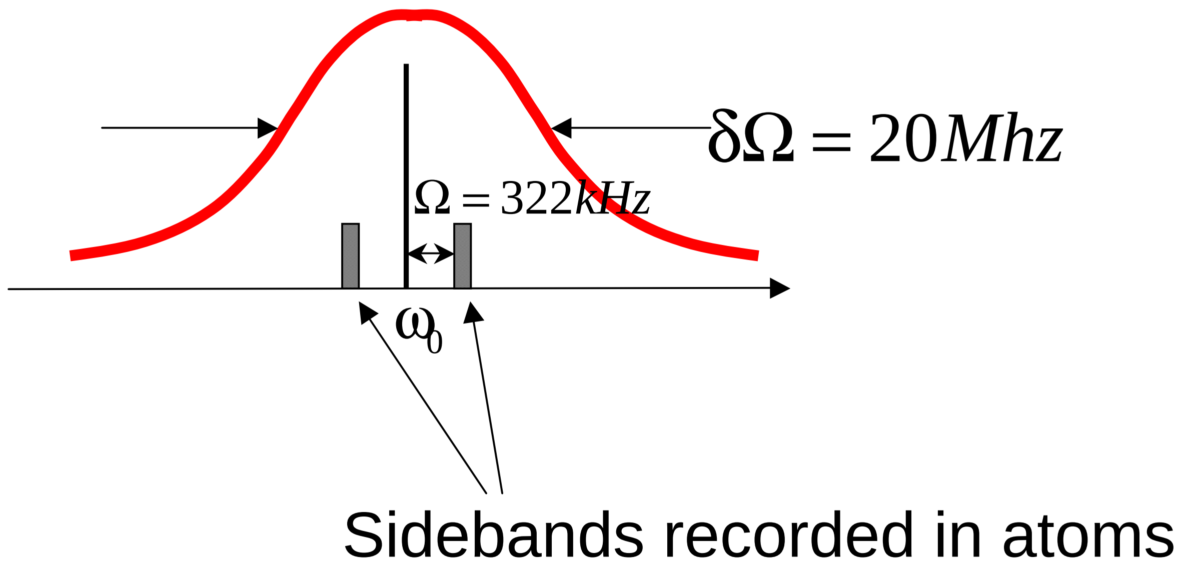
Measurement on light reads out atomic state which contains the memory term centered around Zeeman frequency Ω

$$\hat{S}_y^{out}(t) = \hat{S}_y^{in}(t) + k\hat{J}_z(t)$$

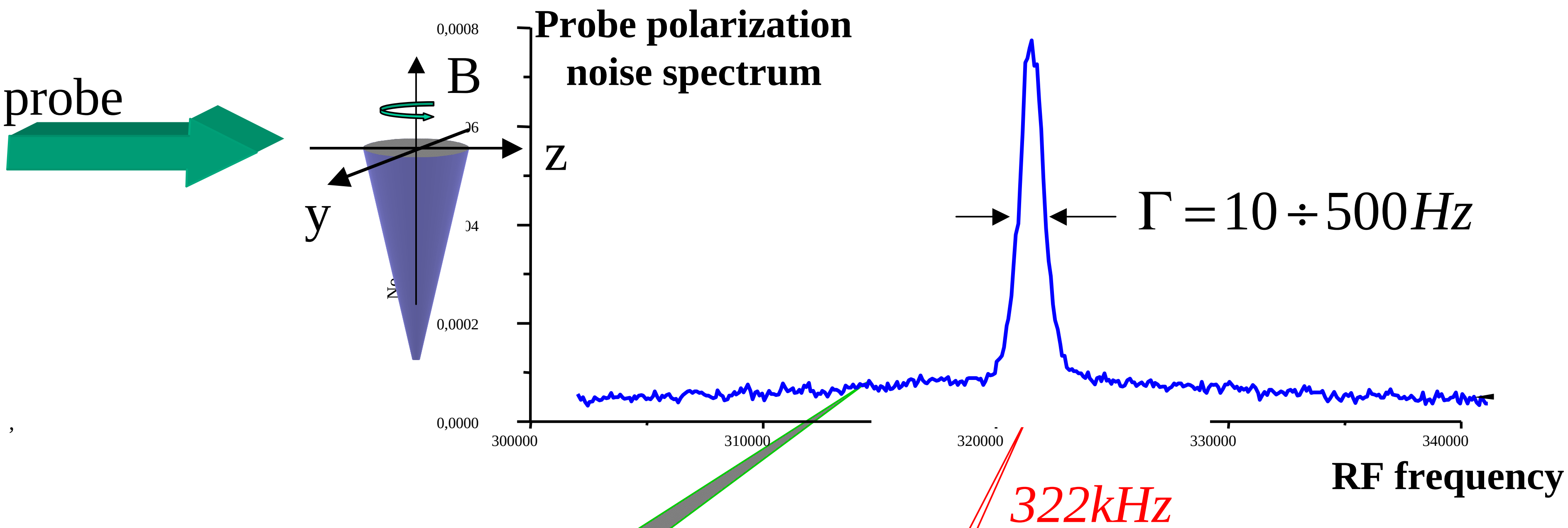
Source of light



Spectrum



Detecting quantum fluctuations of the spin

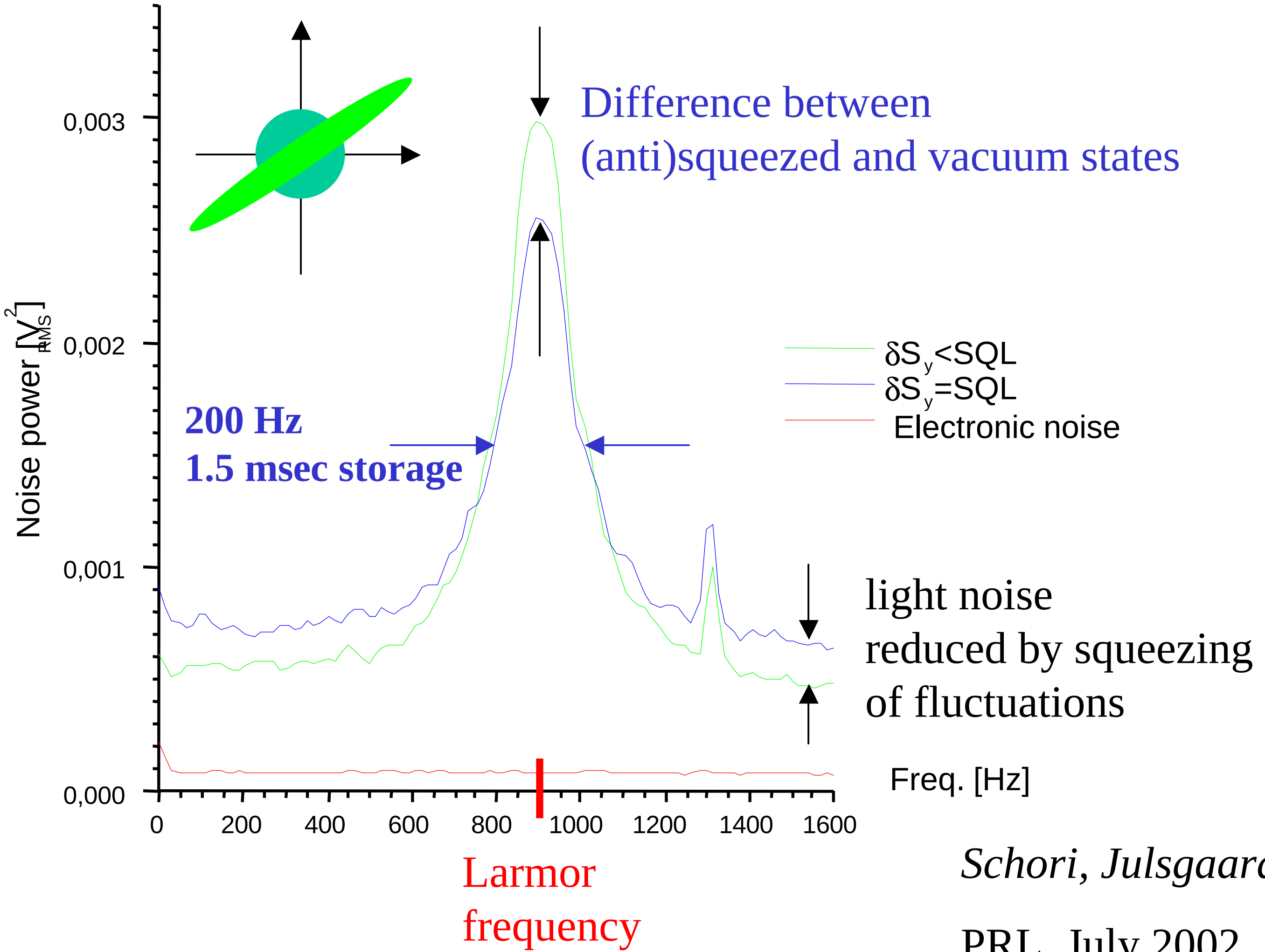


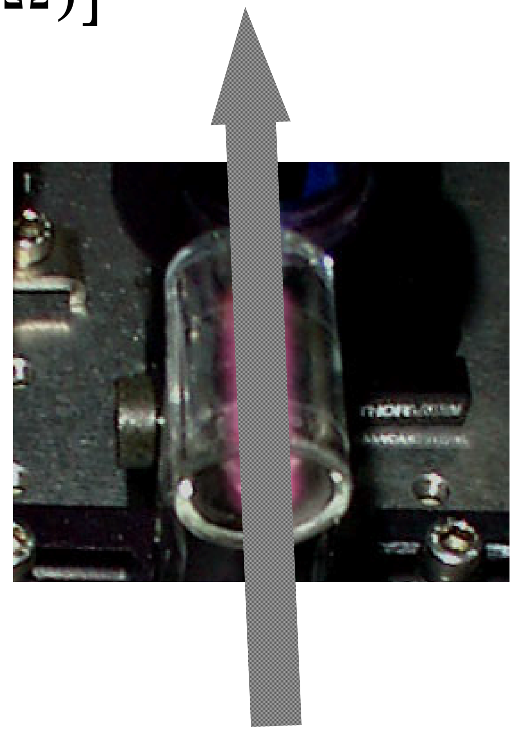
$$\hat{S}_y^{out}(\Omega) = \boxed{X\hat{S}_y^{in}(\Omega)} + \frac{a\Gamma}{\Gamma^2 + (\Omega - \Omega_L)^2}\left[\hat{J}_{z1} + bP\hat{S}_z^{in}(\Omega)\right]$$

$$X \times P = 1$$

(Partial) recording of quantum state of light in long-lived spins

$$\hat{S}_y^{out}(\Omega) = X\hat{S}_y^{in}(\Omega) + \frac{a\Gamma}{\Gamma^2 + (\Omega - \Omega_L)^2}\left[\hat{J}_{z1} + bP\hat{S}_z^{in}(\Omega)\right]$$

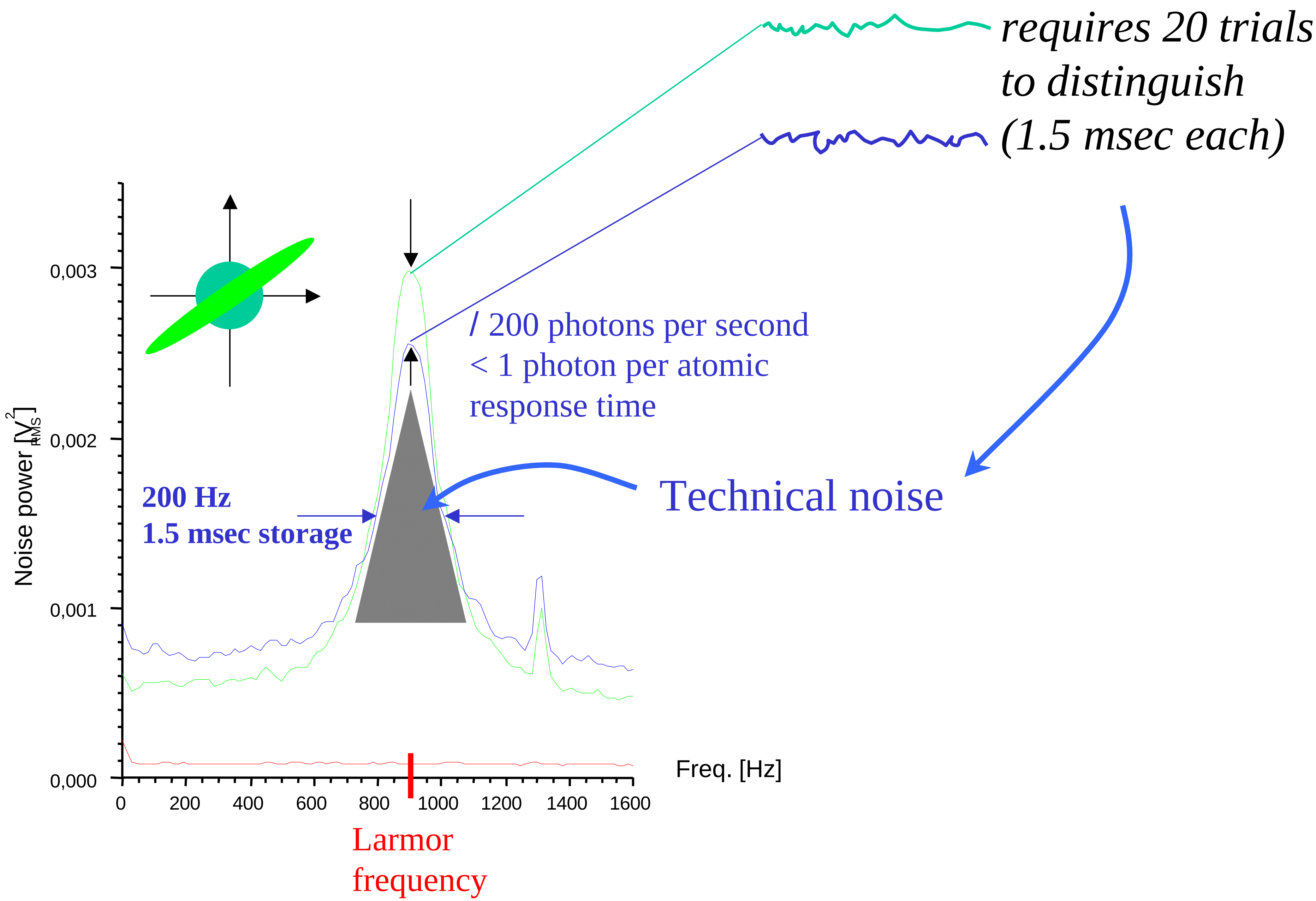




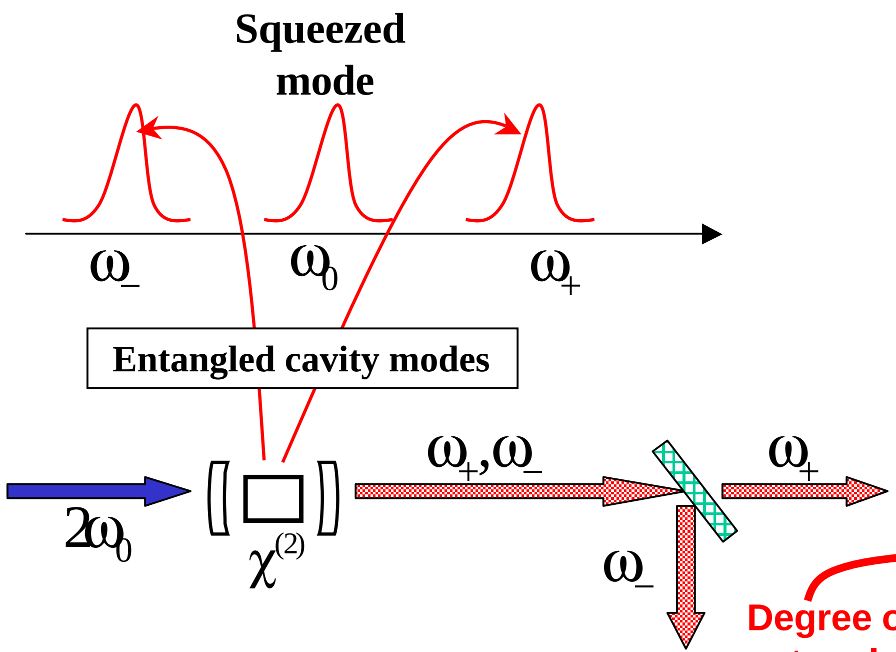
Light with
Controlled
X and P –
controlled
quantum state

Schori, Julsgaard, Sorensen, Polzik

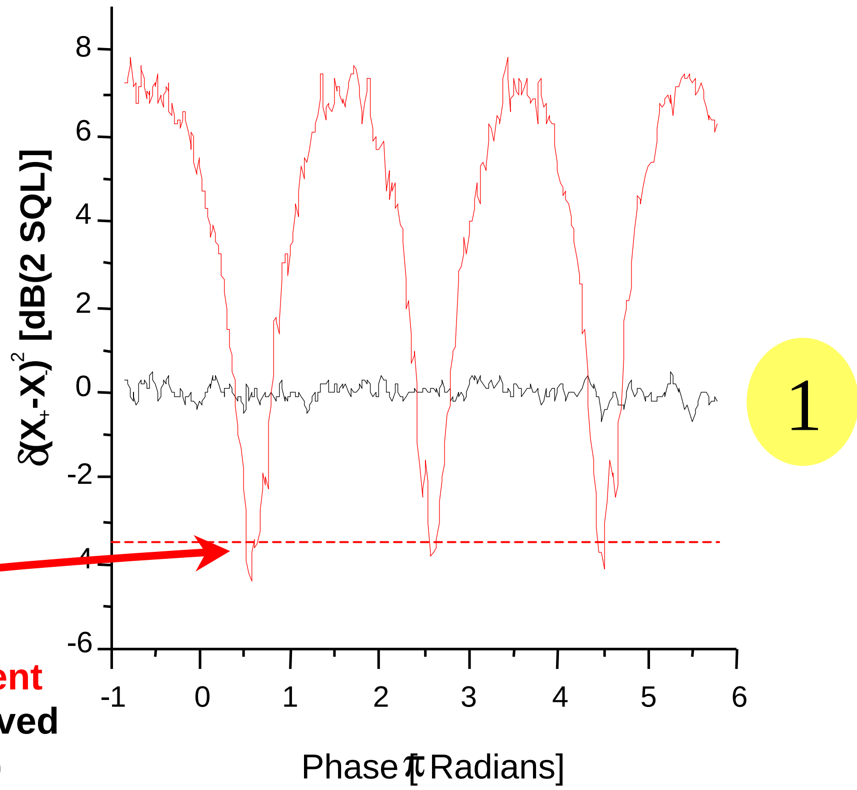
PRL, July 2002, quant-ph/0203023


requires 20 trials
to distinguish
(1.5 msec each)
/ 200 photons per second
< 1 photon per atomic
response time
Technical noise
200 Hz
1.5 msec storage
Noise power [V^2_{RMS}]
0,003
0,002
0,001
0,000
0
200
400
600
800
1000
1200
1400
1600
Freq. [Hz]
Larmor
frequency

Narrowband tunable squeezed/entangled beams



Degree of entanglement
0.6 – observed
(1- perfect)



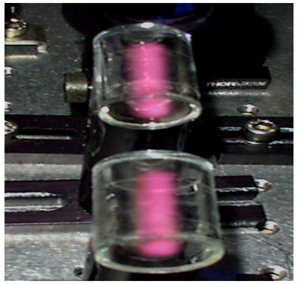
Sorensen, Schori, Polzik

To appear in PRA, quant-ph/0205015

$$\langle (X_1 - X_2)^2 \rangle + \langle (P_1 + P_2)^2 \rangle < 2$$

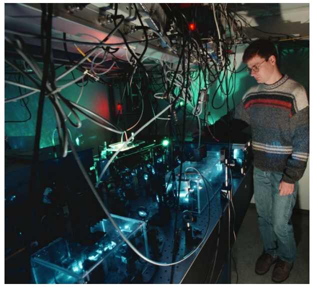
$$\text{OR} \begin{cases} \langle (P_1 + P_2)^2 \rangle < 1 \\ \langle (X_1 - X_2)^2 \rangle < 1 \end{cases}$$

Quantum communication protocols with entangled atomic samples and tunable EPR light



Entangled atomic samples

***Nature* 413**, 400 (2001).



Entangled tunable light source

To appear in PRA, quant-ph/0205015

Protocols:

Quantum memory   Atomic teleportation

Scalability – an array of dipole traps or solid state implementation – quantum holograms

Requirements:

- Long-lived 2 or more level state of a single particle
- The ability to optically pump the system into one of these states
- Dipole coupling to light
- Optically dense medium

Example: pencil-shaped cold cesium sample

50 microns by 500 microns

10^5 atoms, 10^5 photons per pulse

Experiment: recording in the ground state coherence (τ=1.5msec)
Schori, Julsgaard, Sorensen,Polzik
Phys. Rev. Lett. **89**, 057903 (2002),
quant-ph/0203023

Related work – entangled atomic ensembles
Julsgaard, Kozhekin, Polzik
Nature **413**, 400 (2001).

Theory - interspecies teleportation
Kuzmich, Polzik
Phys.Rev.Lett. ***85****, 5639 (2000)*

Earlier work: shot term recording in an excited atomic state (**τ=32 **nsec)
Kuzmich, Mølmer,Polzik. Phys.Rev.Lett., ***79****, 4782 (1997)*
Hald, Sorensen, Schori, Polzik. Phys.Rev.Lett., ***83****, 1319 (1999)*