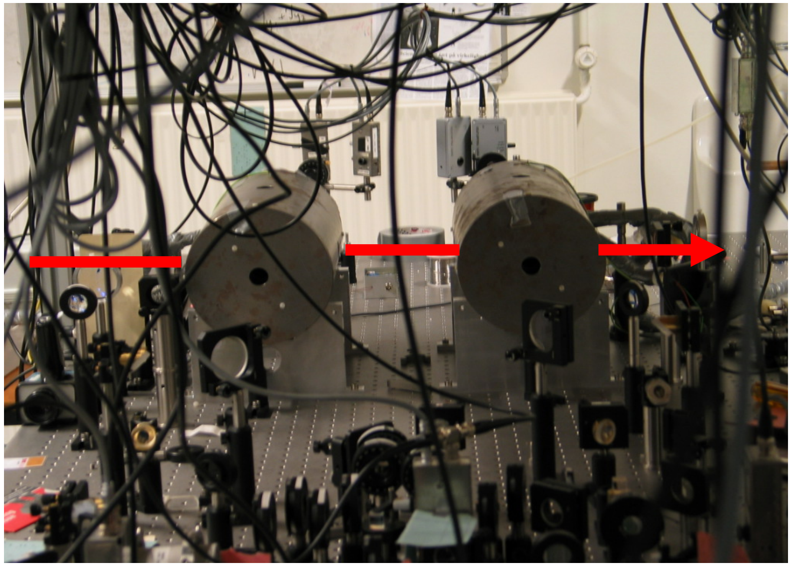
Niels Bohr Institute
**Copenhagen University**

# Quantum Atom Optics
## at room temperature

Eugene Polzik



## Ensemble approach

Our alternative program (1997 - ):

**Propagating light pulses + atomic ensembles**

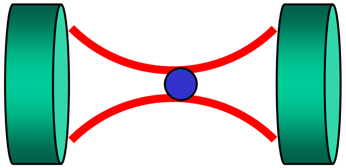
Energy levels with rf or microwave separation - no need for $\lambda^3$ confinement

*Collective = ensemble quantum variables*

*Ground state Hf or Zeeman sublevels*

$$e^{i\cdot\delta k\cdot r} = e^{i\cdot\delta\omega\cdot r} \longrightarrow 1$$

## *Cavity QED*



*Strong coupling to a single atom - qubit*

*Caltech – optical λ*

*Paris – microwave*

*MPQ – optical*

*MPQ, Innsruck – ions*

*Stanford - solid state*

…

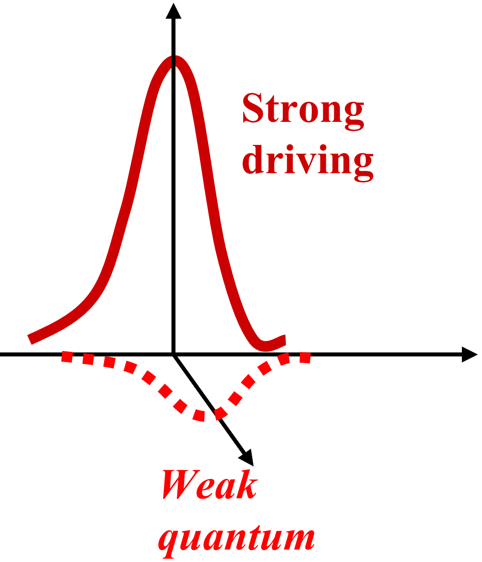
# Spin Squeezed Atoms

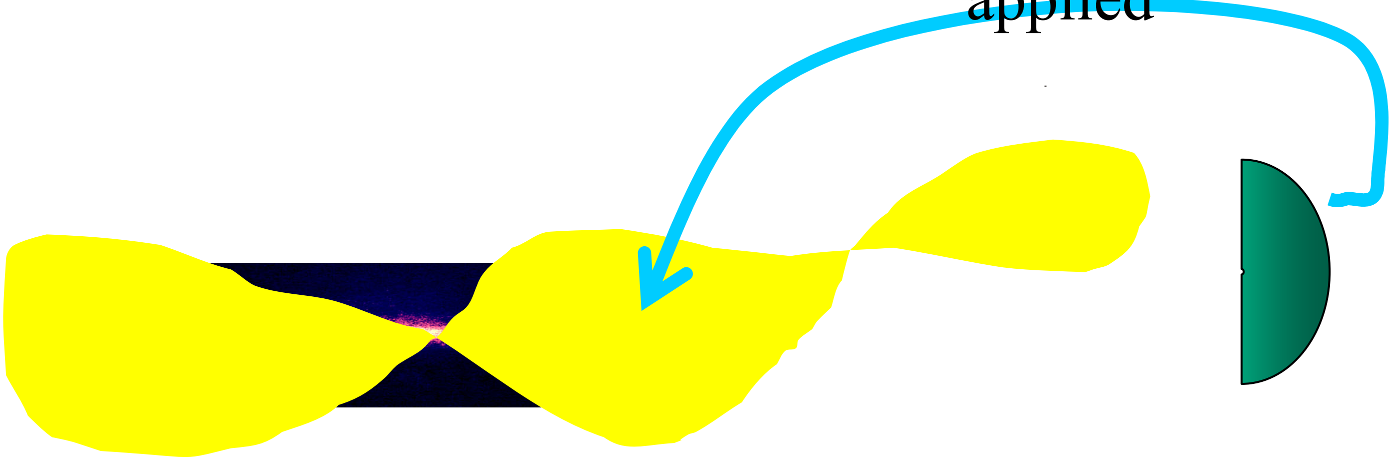
Very inefficient
lives only nseconds,
but a nice first try…

# Light-Matter quantum interface

Light pulse - consisting of two modes

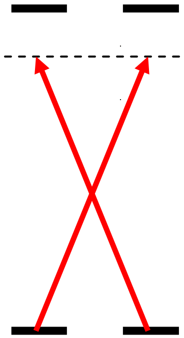
…and feedback applied





Passes through one… or more atomic samples

Projection measurement on light can be made…

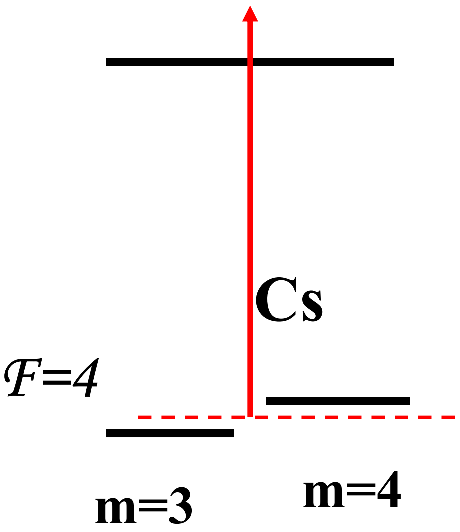


Dipole off-resonant interaction entangles light and atoms

J. Sherson, B. Julsgaard, and E.S. P.
to appear in *Advances of Atomic Molecular and Optical Physics*, 2006.
available on quant-ph

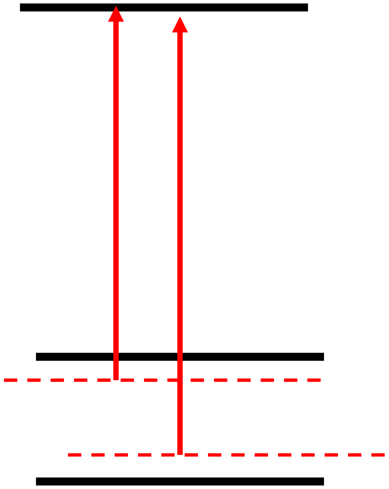
# *Examples of interfaces discussed in this talk*

**Thermal cloud**



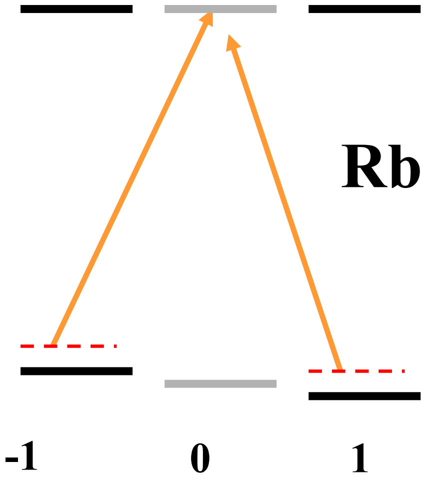
- Atomic entanglement
- Quantum memory

**Cold Cs sample**



- Quasi-spin squeezing
- Clock applications

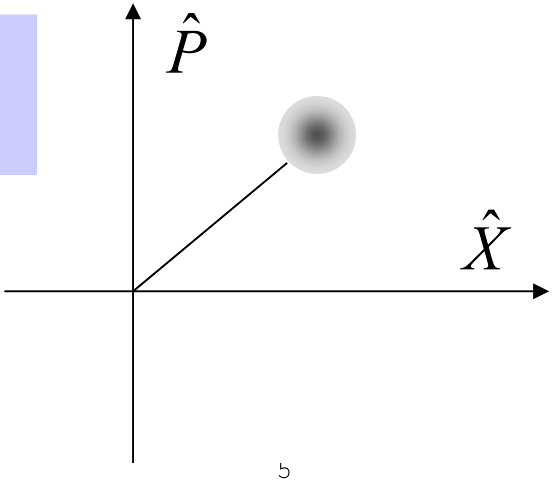
**BEC**



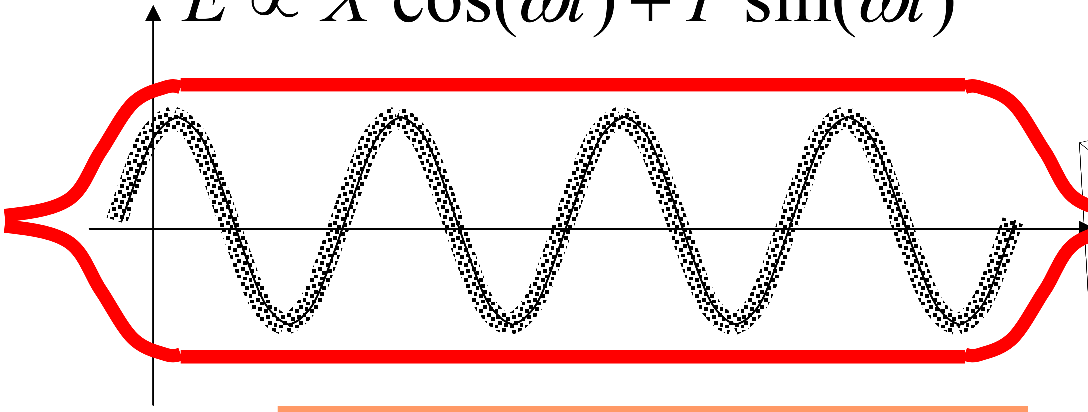
- Atomic cat state generation
- Least invasive quantum state, quantum correlations measurement

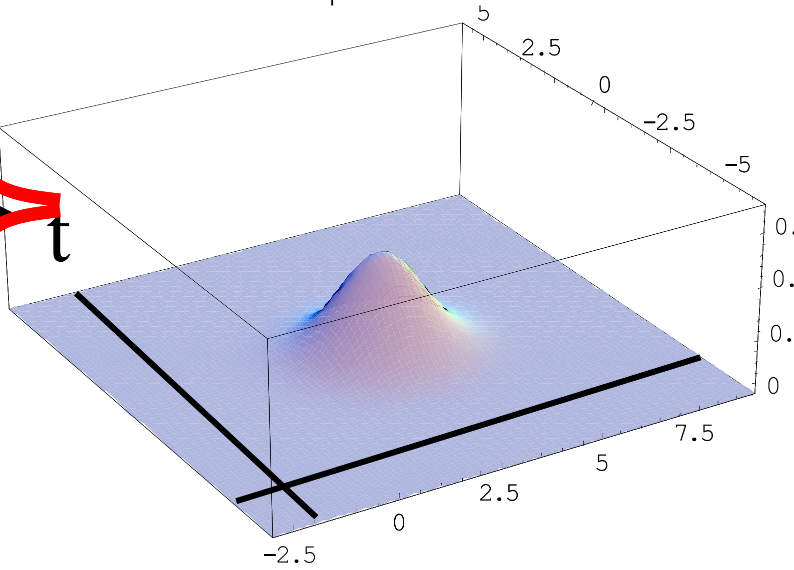
# Quantum variables for light: Coherent state

$$\left[\hat{X},\hat{P}\right]=i \qquad Var\left(\hat{X}\right)=Var\left(\hat{P}\right)=\tfrac{1}{2}$$



$$\hat{E}\propto\hat{X}\cos(\omega t)+\hat{P}\sin(\omega t)$$

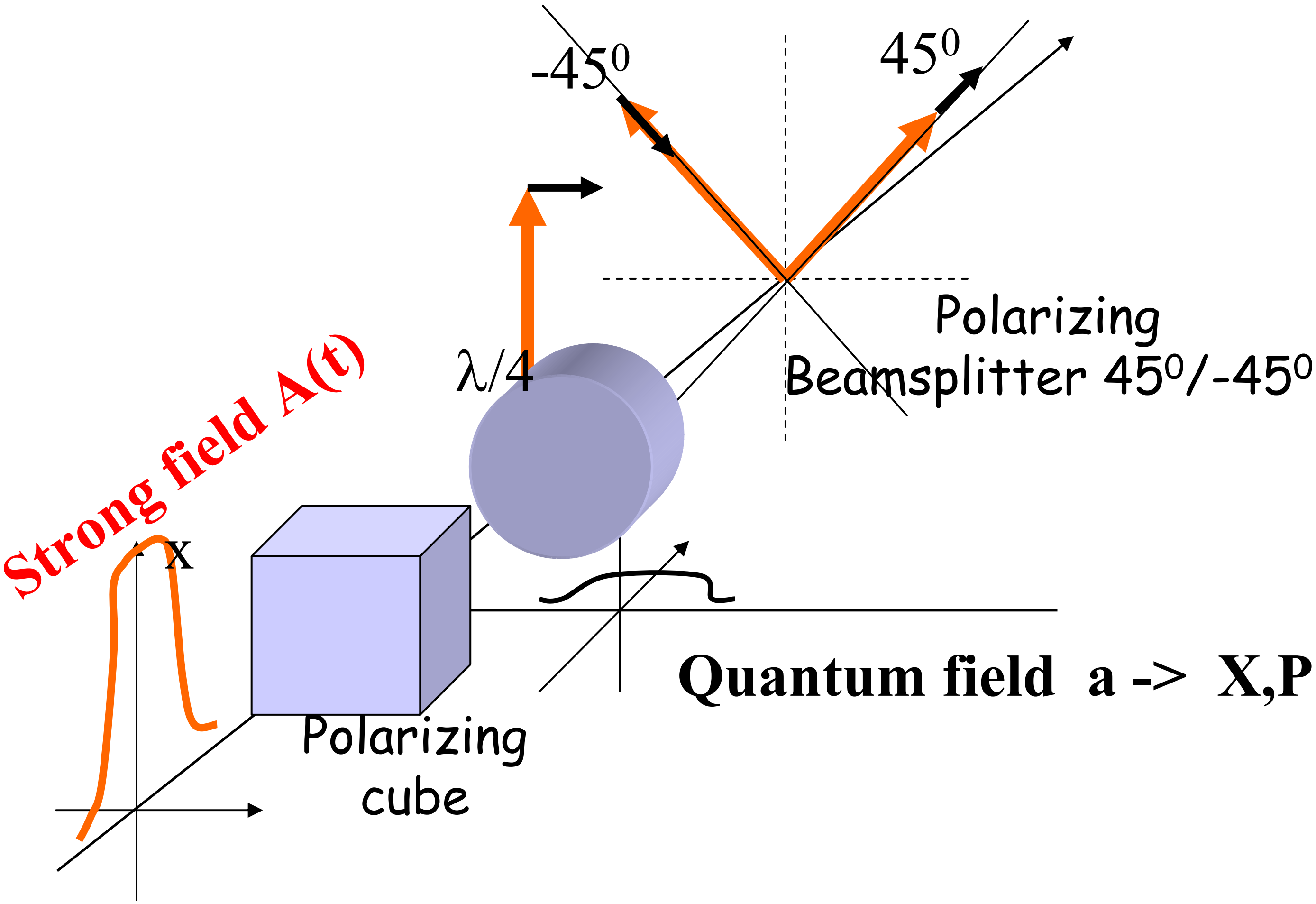




**Pulse:** $$\hat{X}_{\mathrm{L}}=\frac{1}{\sqrt{T}}\int_{0}^{T}(\hat{a}^{+}(t)+\hat{a}(t))dt$$

# Polarization homodyning - measure X (or P)

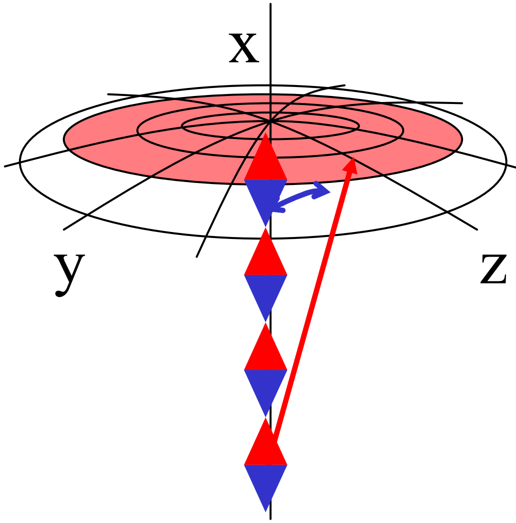
$$\hat{S}_2 = \tfrac{1}{4}[(A+\hat{a})^+(A+\hat{a})-(A-\hat{a})^+(A-\hat{a})] = \tfrac{1}{2}A(a^+ + a) = \tfrac{1}{\sqrt{2}}A\hat{X}$$



$$\hat{S}_3 = \tfrac{1}{\sqrt{2}}A\hat{P}$$

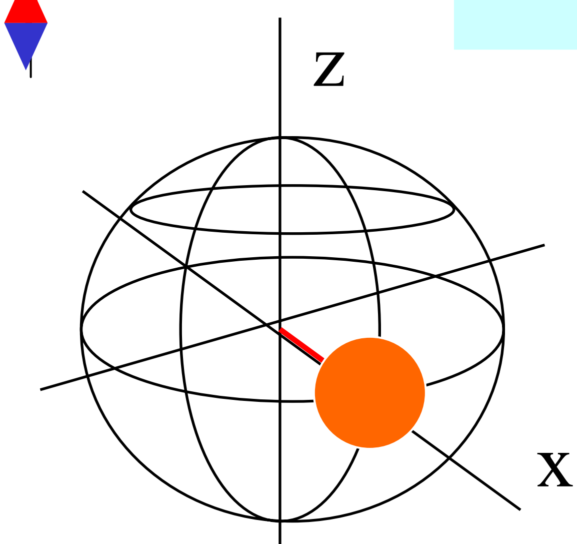
# Thermal ensemble of spin-1/2 atoms

# Complimentary quantum variables for an atomic ensemble:



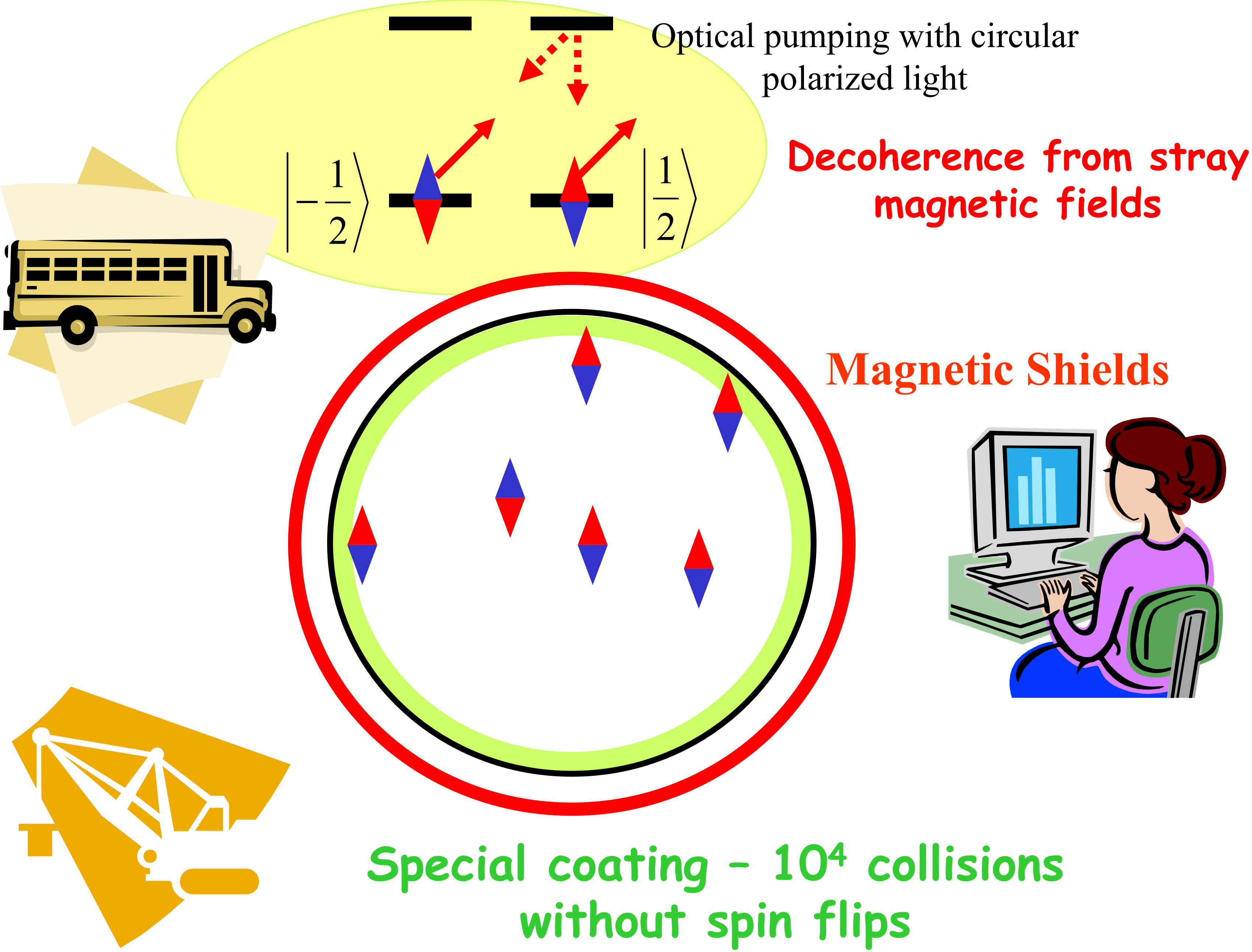
$$\left[\hat{J}_z, \hat{J}_y\right] = iJ_x \qquad \delta J_y \delta J_z \geq \tfrac{1}{2} J_x$$

$$\left[\hat{X}_A, \hat{P}_A\right] = i \qquad \hat{X}_A = \frac{\hat{J}_z}{\sqrt{J_x}},\ P_A = \frac{\hat{J}_y}{\sqrt{J_x}}$$



Coherent
Spin state

# Object – gas of spin polarized atoms at room temperature



$\left|-\frac{1}{2}\right\rangle$

$\left|\frac{1}{2}\right\rangle$

Optical pumping with circular polarized light

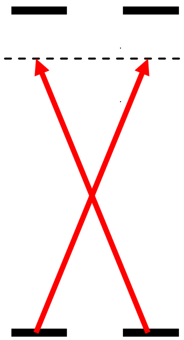
Decoherence from stray magnetic fields

Magnetic Shields

Special coating – $10^4$ collisions without spin flips

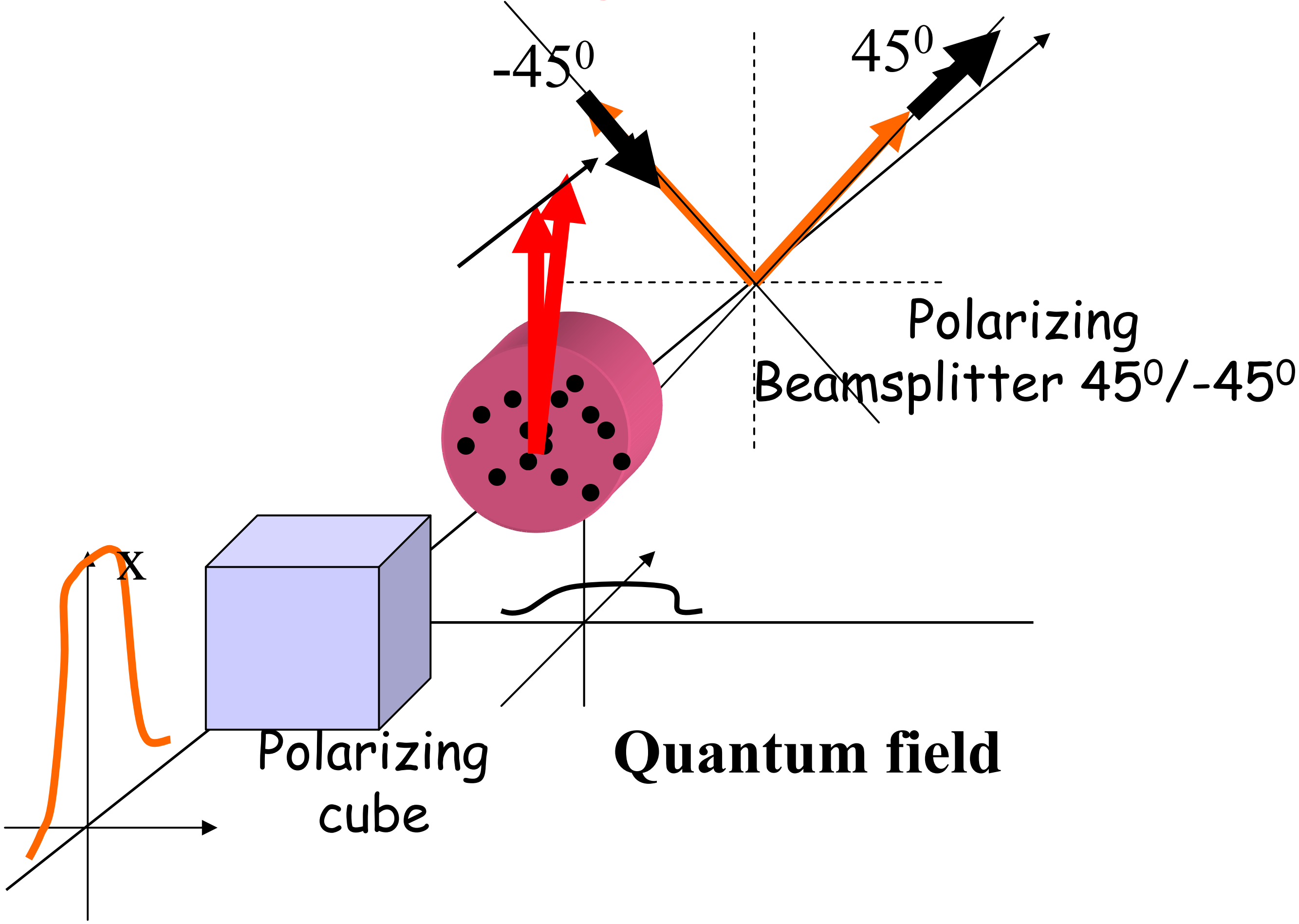
# Light to atoms coupling

***Dipole off-resonant interaction entangles light and atoms***

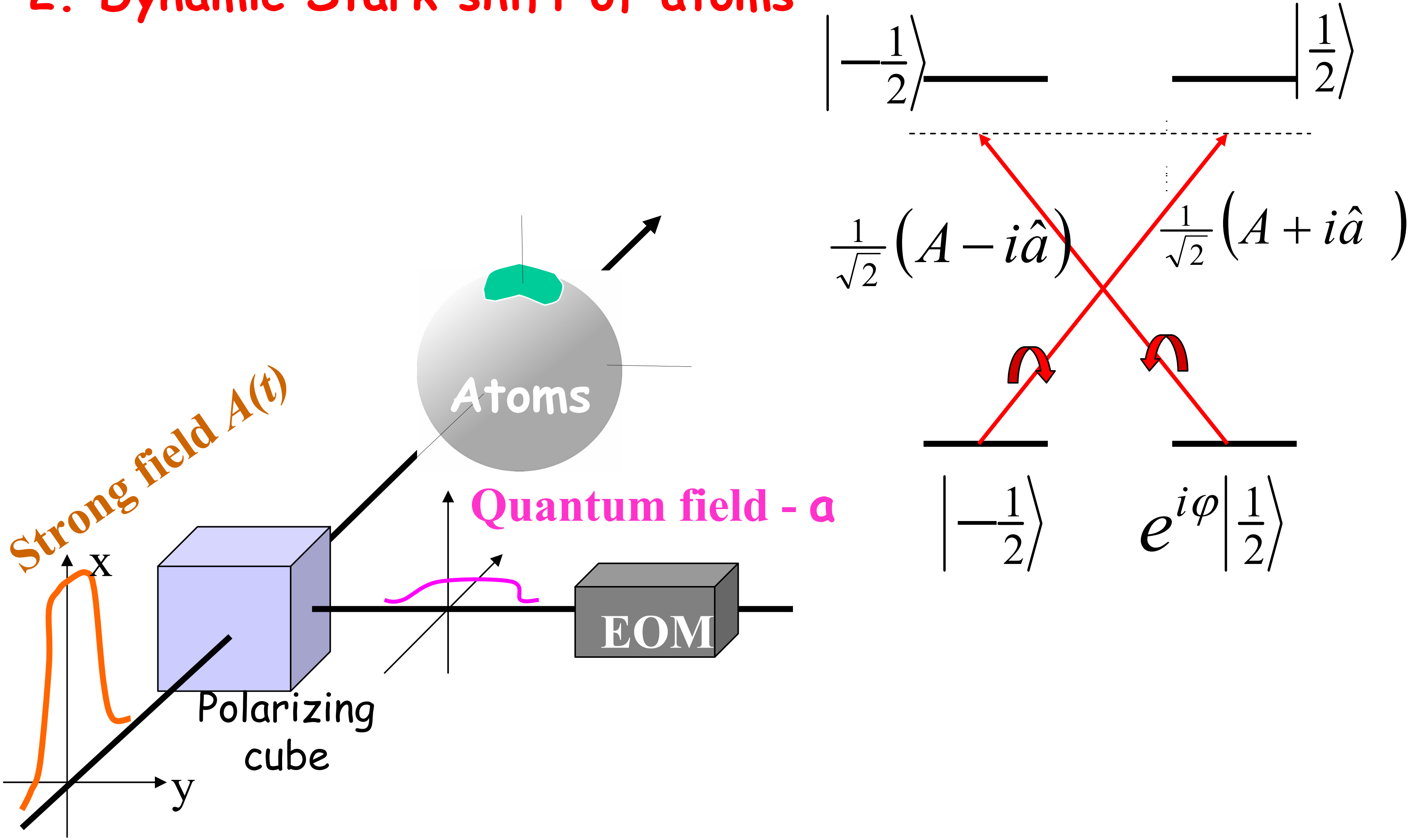


$$\hat{H} = a\hat{S}_3\hat{J}_z \propto \hat{P}_L\hat{X}_A$$

# Physics behind the Hamiltonian:
# 1. Polarization rotation of light



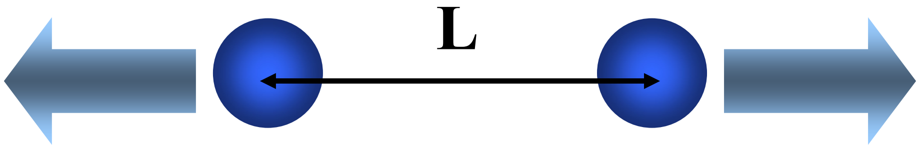
# Physics behind the Hamiltonian:
# 2. Dynamic Stark shift of atoms



# EPR state of two atomic clouds
# 2001

- *Einstein-Podolsky-Rosen paradox – entanglement; 1935*

2 particles entangled in position/momentum



$\hat{X}_1, \hat{P}_1$ $\quad\quad$ $\hat{X}_2, \hat{P}_2 = mV$

$$\hat{X}_1 - \hat{X}_2 = L \qquad \hat{P}_1 + \hat{P}_2 = 0$$

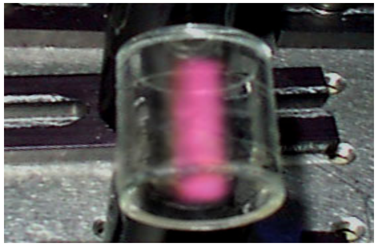
*Simon* (2000); *Duan, Giedke, Cirac, Zoller* (2000)

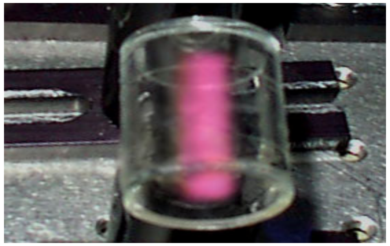
<u>Necessary and sufficient condition for entanglement</u>

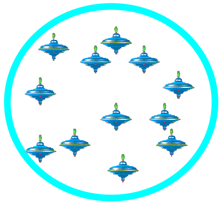
$$\delta(X_1 - X_2)^2 + \delta(P_1 + P_2)^2 < 2$$

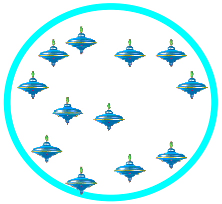
B. Julsgaard, A. Kozhekin and EP, ***Nature***, **413**, 400 (2001)

# *Experimental long-lived entanglement of two macroscopic objects.*

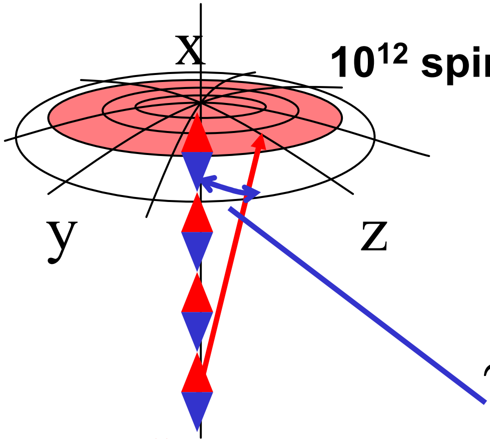




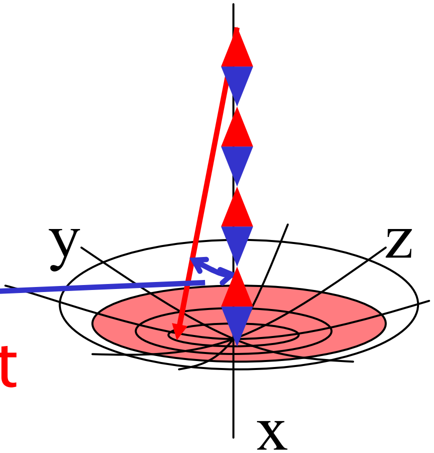




$10^{12}$ **spins in each ensemble**

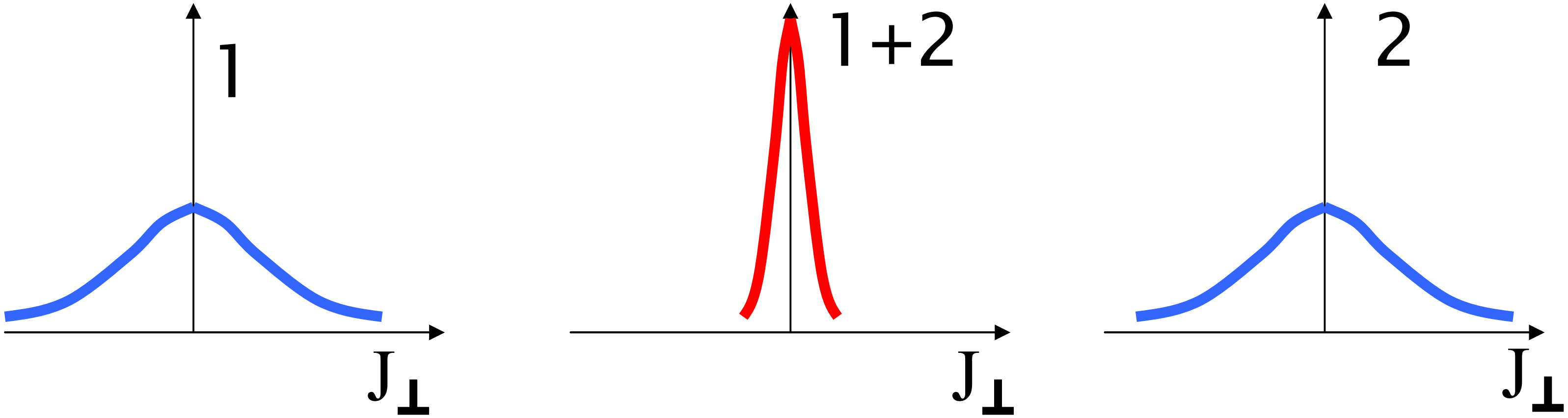


$\sim N^{-\frac{1}{2}}$

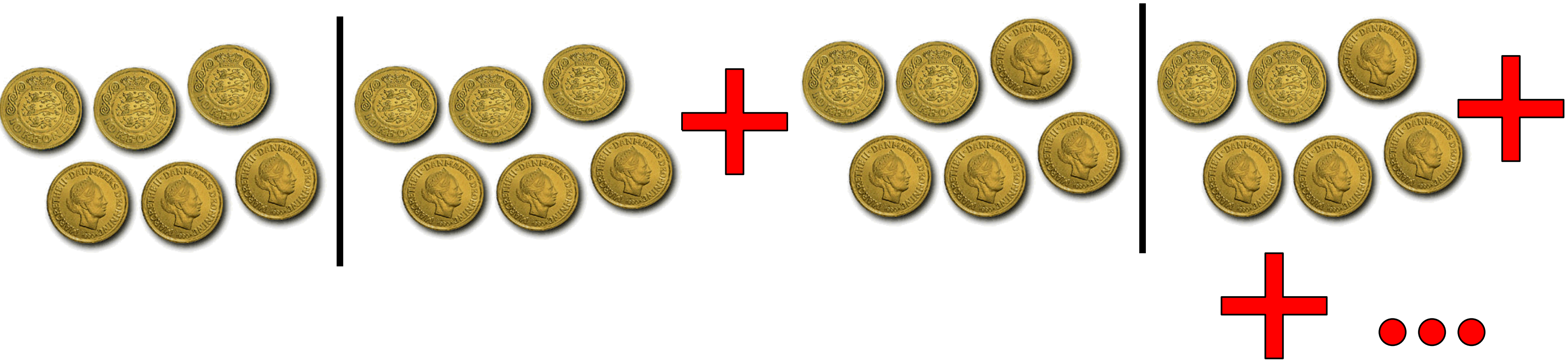


pins which are “more parallel” than that are entangled

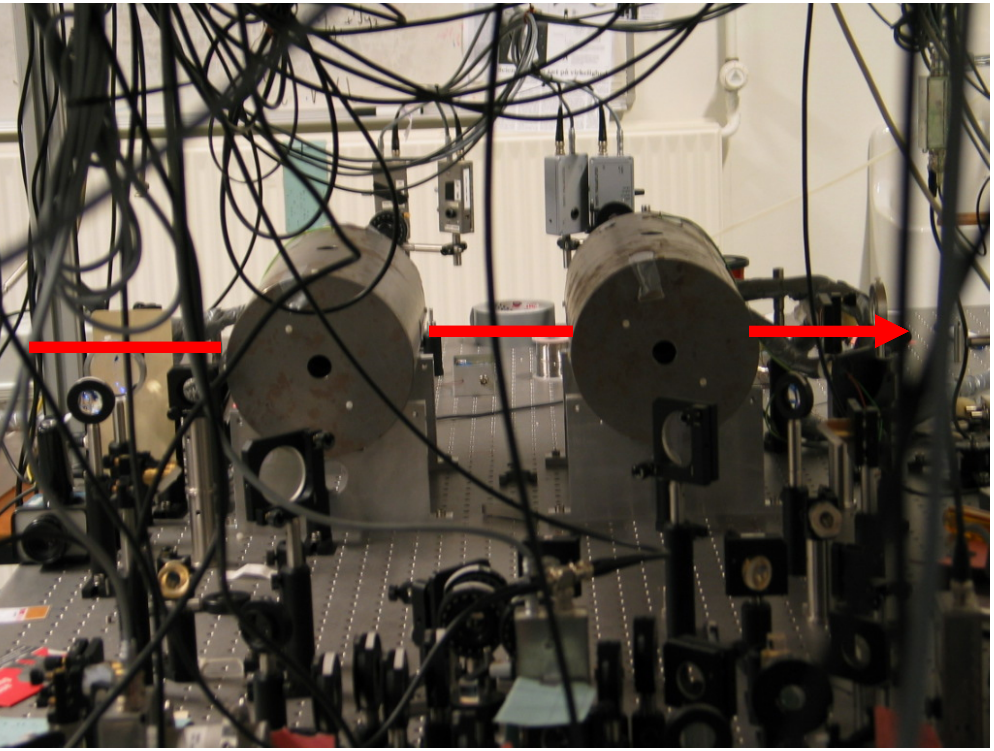
# Stern-Gerlach projection on any axis $\perp$ to x:

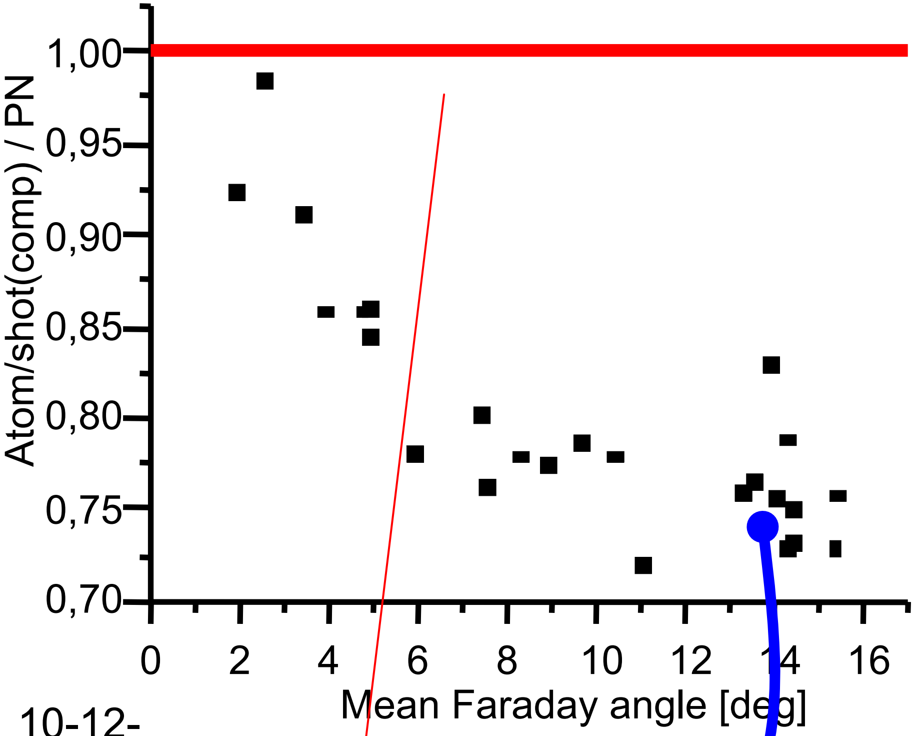


Along y,z: ideally no misbalance between heads and tails of the two ensembles, or, at least, less than random misbalance $\sqrt{N}$



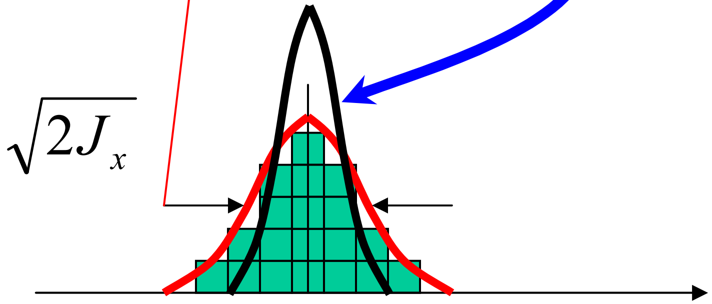
# Material objects deterministically entangled at 0.5 m distance





10-12-2003/noise.opj

Quantum uncertainty

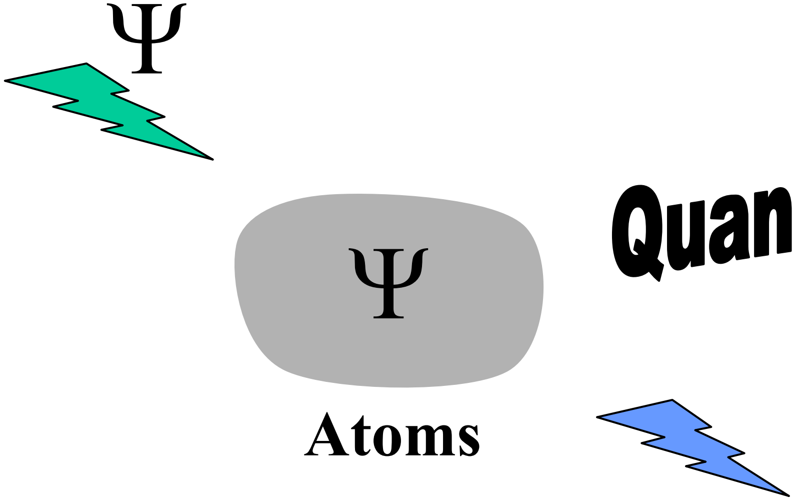


$$J_{z1} + J_{z2} \ \ or \ \ J_{y1} + J_{y2}$$

**Niels Bohr Institute**
**December 2003**

# Quantum Memory for Light
# 2004

# *What do we want to achieve?*



**Quantum memory for light**

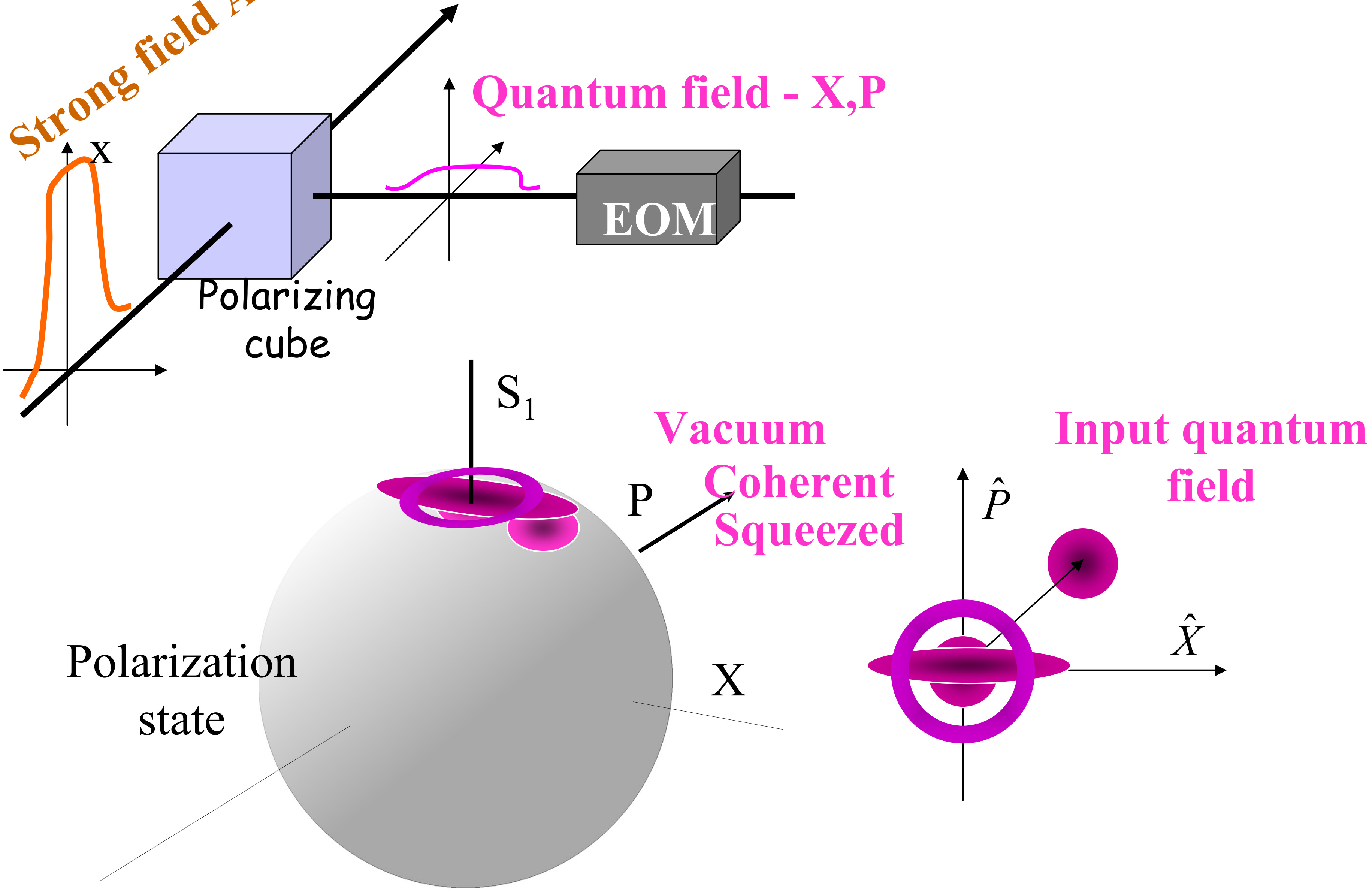
**Classical approach - measure and write**

**Problem:**

**Cannot measure an unknown state**

Example:
single polarized
photon

# Preparation of the input state of light



# Implementation: light-to-matter state transfer

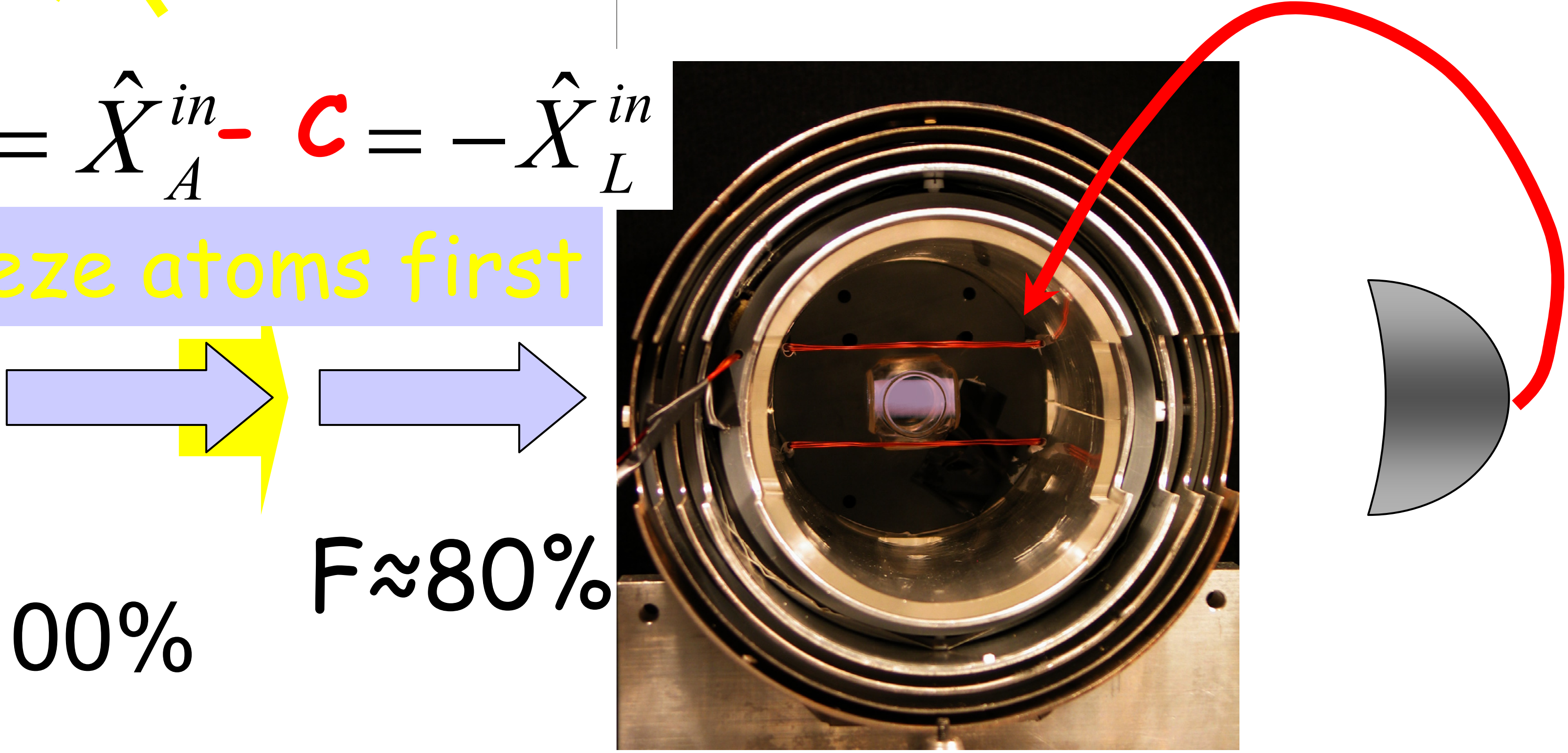
**No prior entanglement necessary**

$$\hat{H} = a\hat{S}_3\hat{J}_z \propto \hat{P}_L\hat{X}_A$$

$$\hat{P}_A^{mem} = \cancel{\hat{P}_A^{in}} + \hat{P}_L^{in} \qquad \hat{X}_L^{out} = \hat{X}_L^{in} + \hat{X}_A^{in} = c$$

$$\hat{X}_A^{mem} = \hat{X}_A^{in} - c = -\hat{X}_L^{in}$$

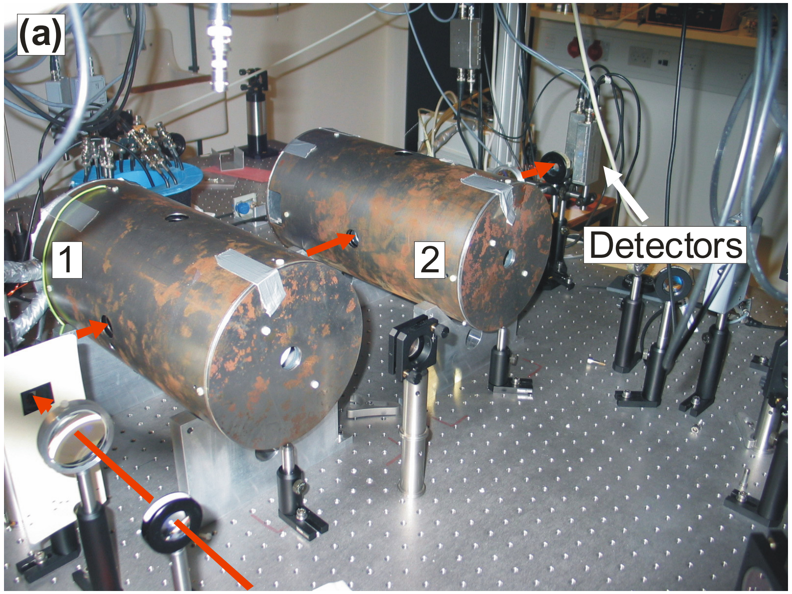
squeeze atoms first

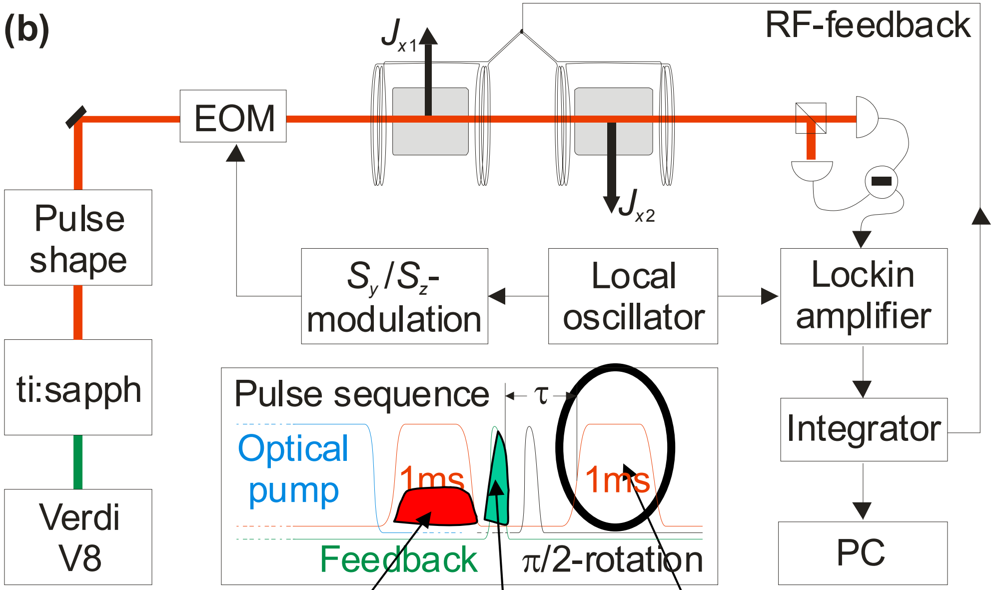


F≈80%

F→100%

B. Julsgaard, J. Sherson, J. Fiurášek , I. Cirac, and E. S. Polzik
*Nature*, **432**, 482 (2004); quant-ph/0410072.





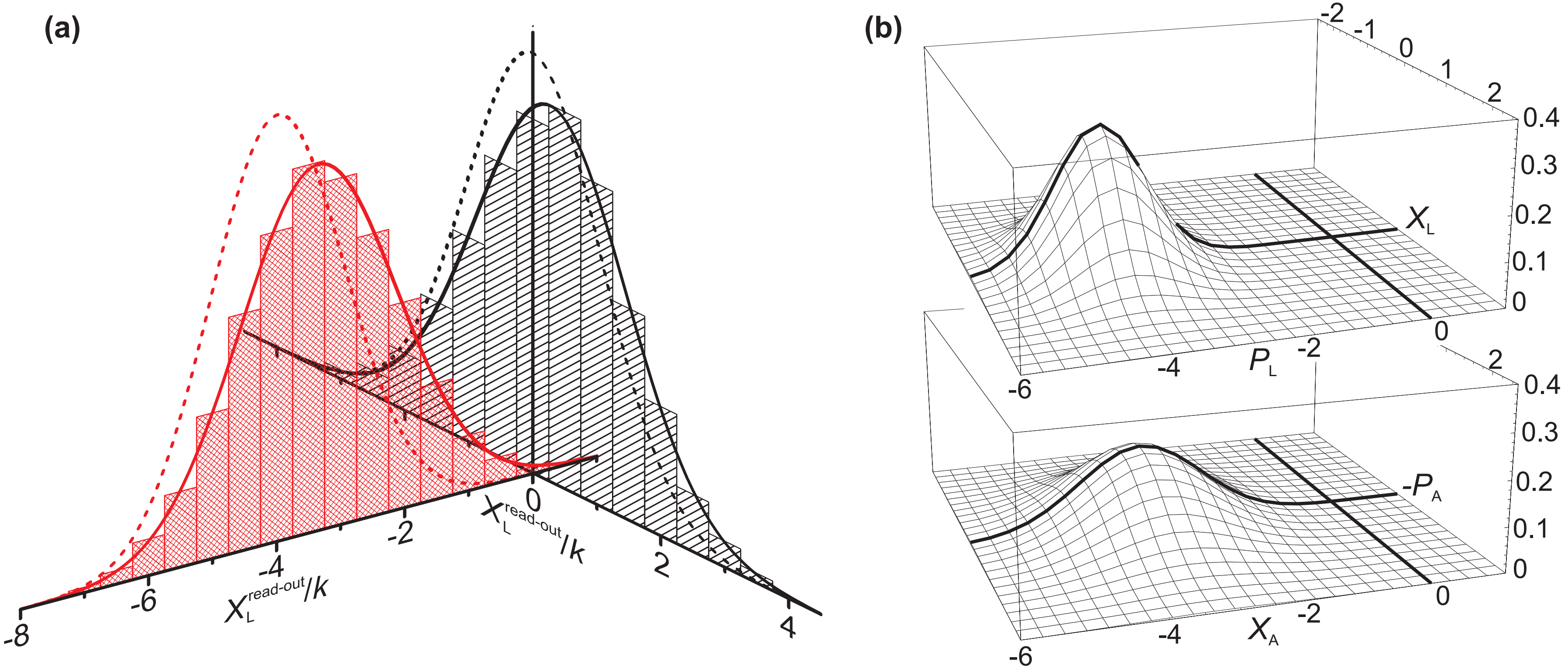
*Nature*, Nov. 25 (2004)
quant-ph/0410072.

Input pulse

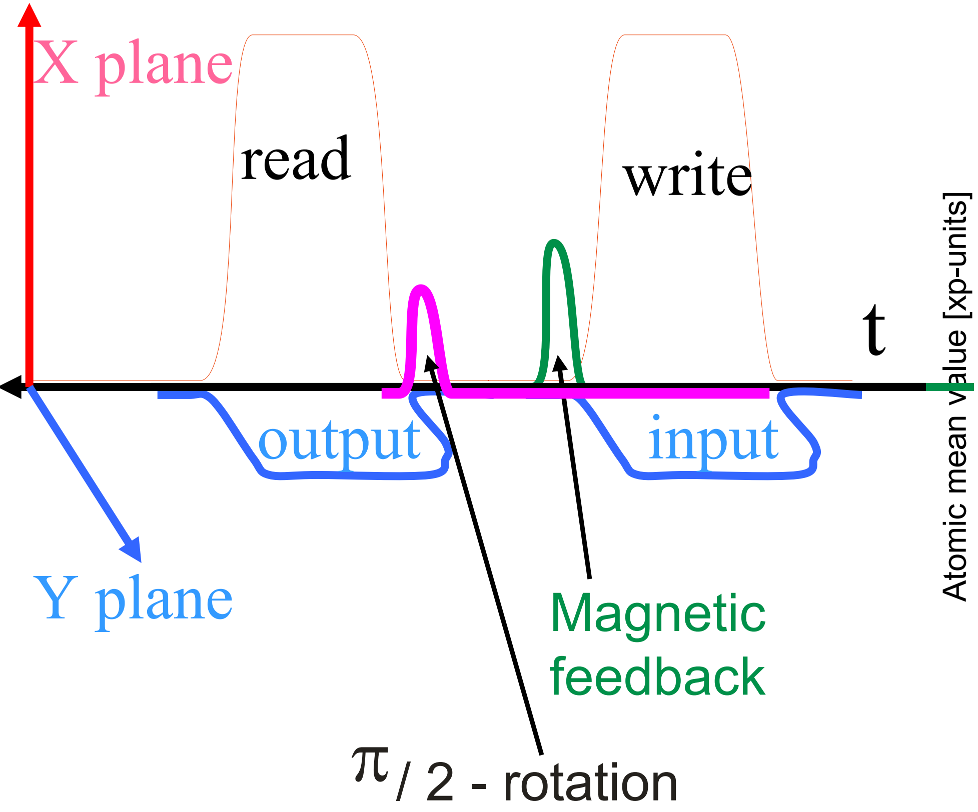
Magnetic feedback

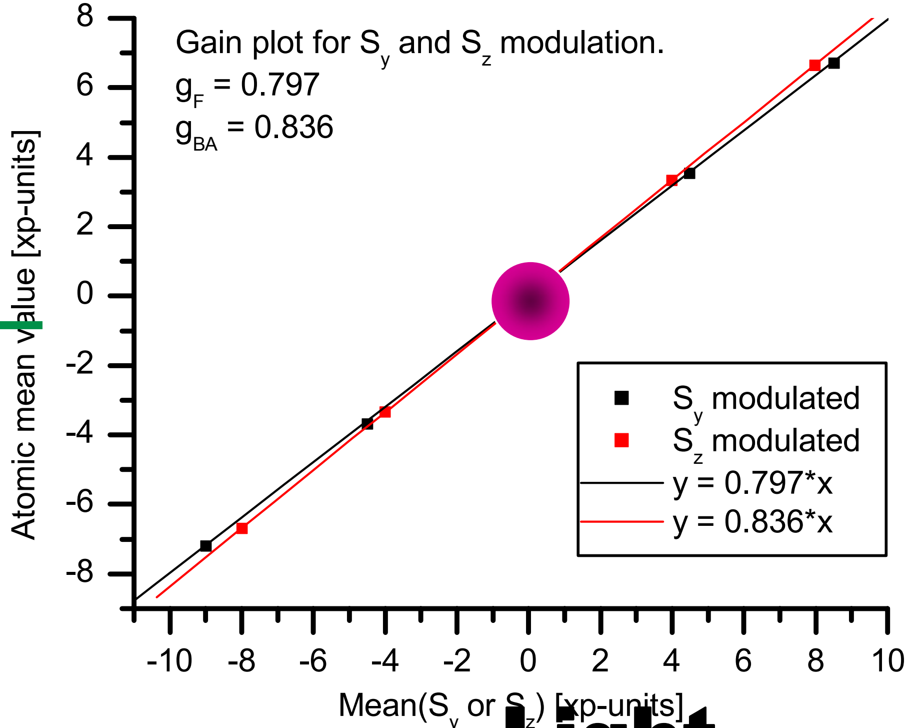
Readout pulse

# Quantum tomography of the collective atomic state

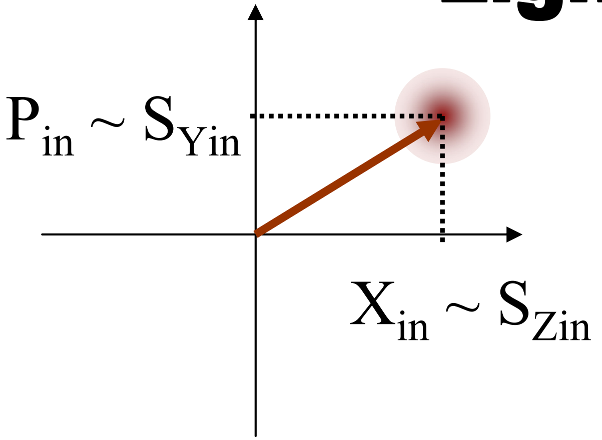


# **Stored state** versus **Input state**: mean amplitudes

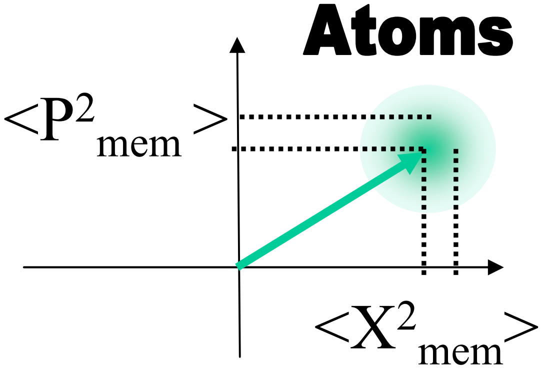


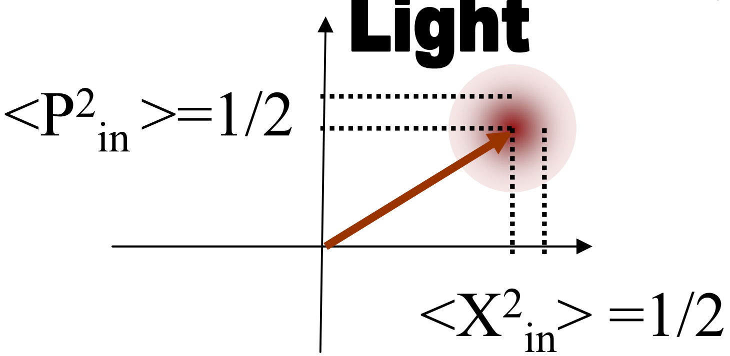


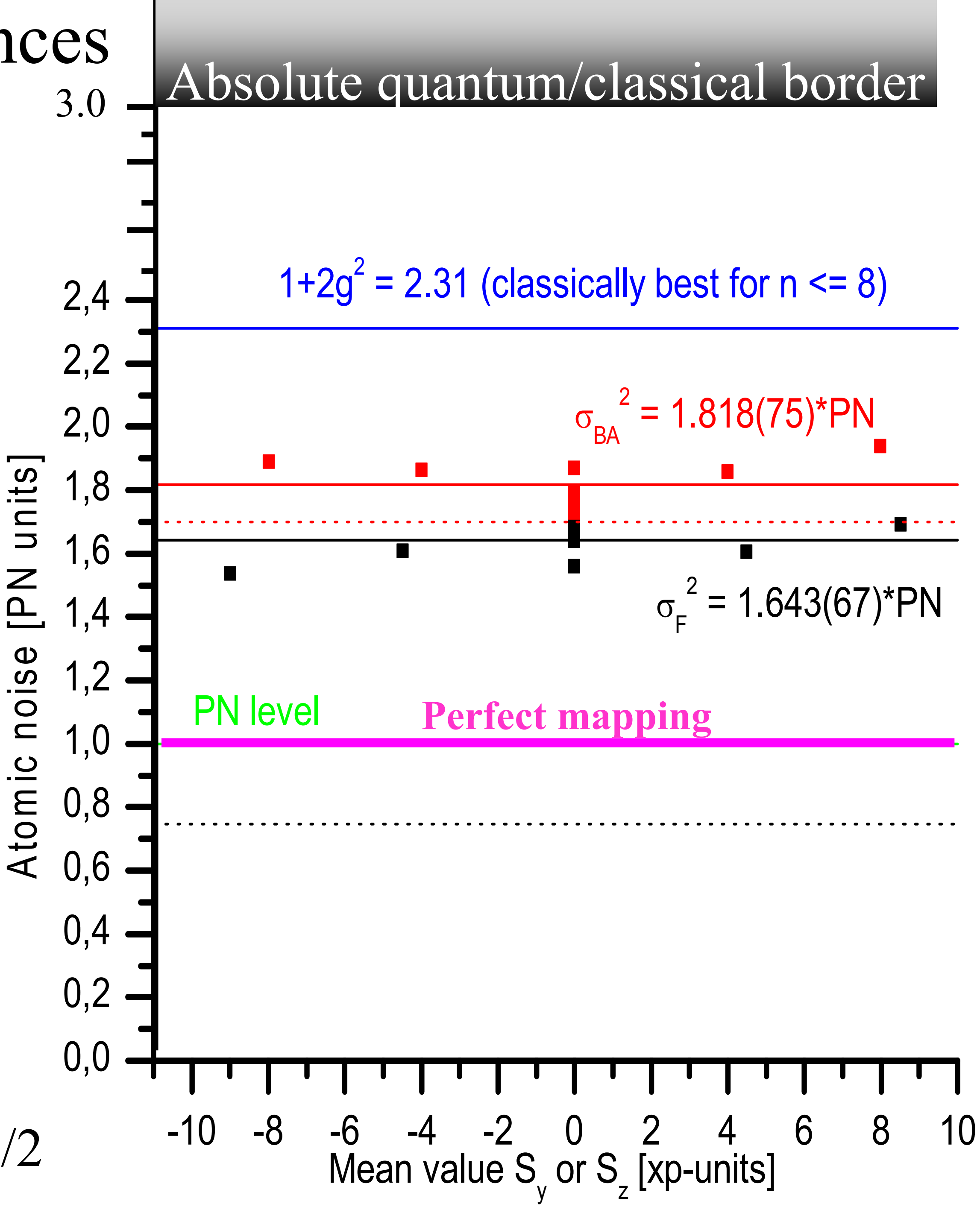
**Light**



# Stored state: variances





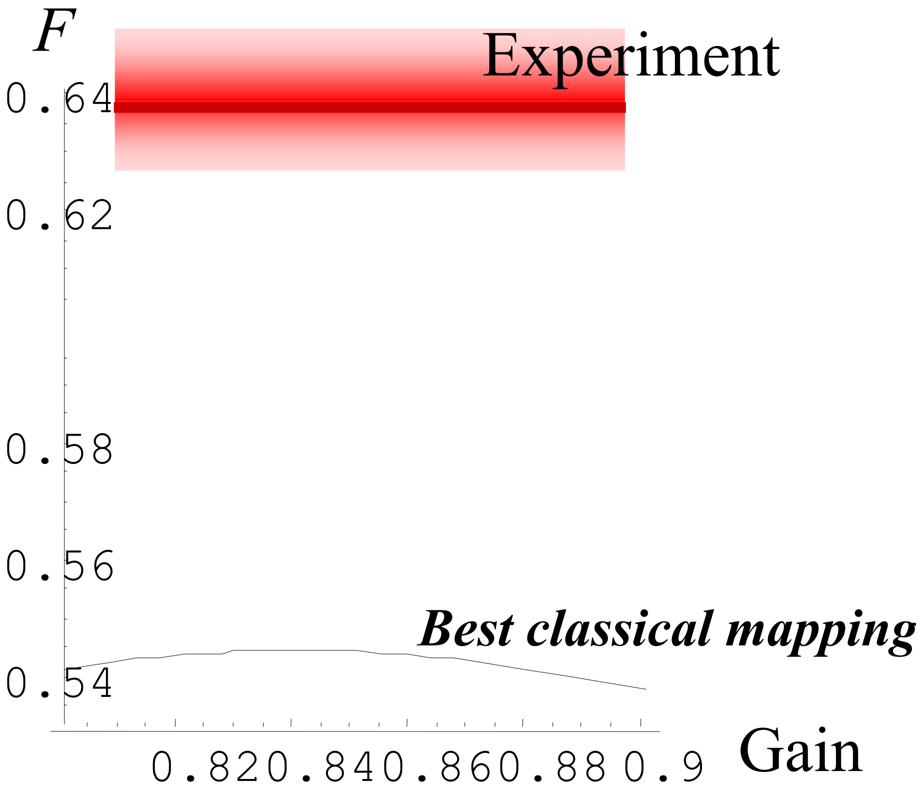


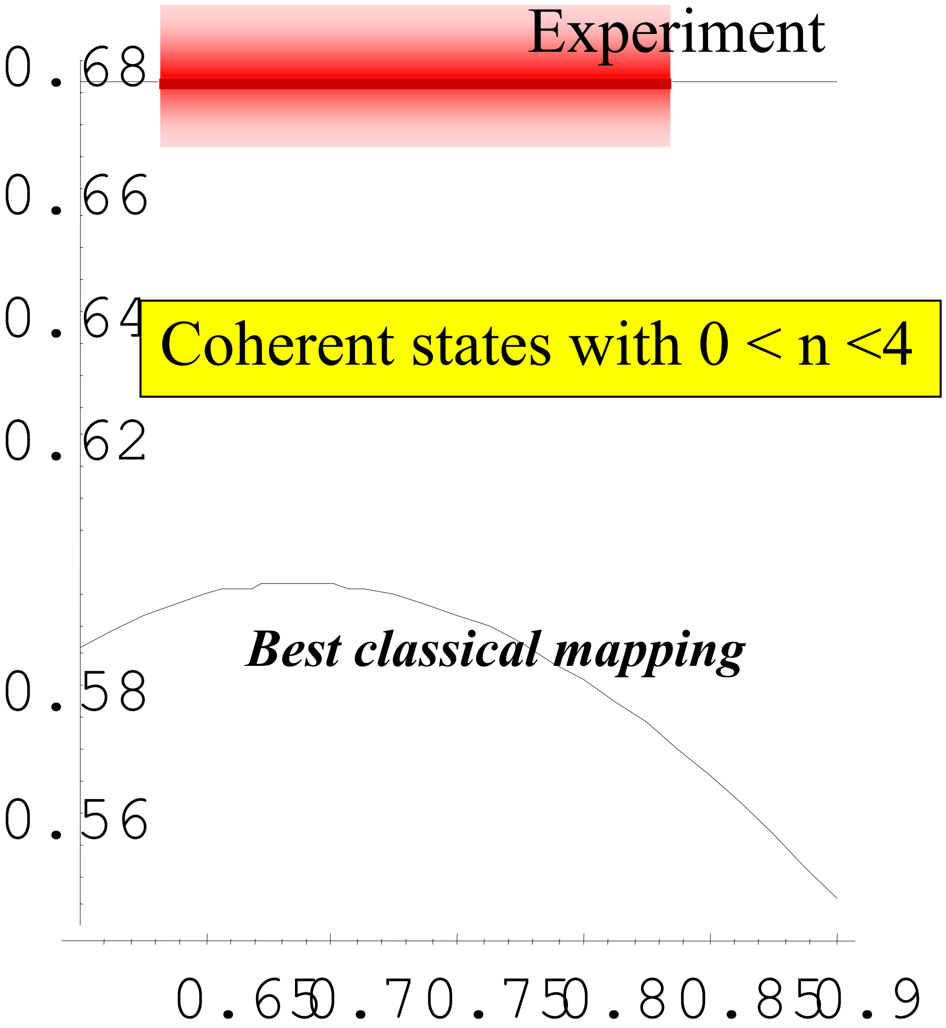
# Fidelity of quantum storage

$$F = \int P(|\Psi_{in}\rangle)\langle\Psi_{in}|\hat{\rho}_{out}|\Psi_{in}\rangle d|\Psi_{in}\rangle$$

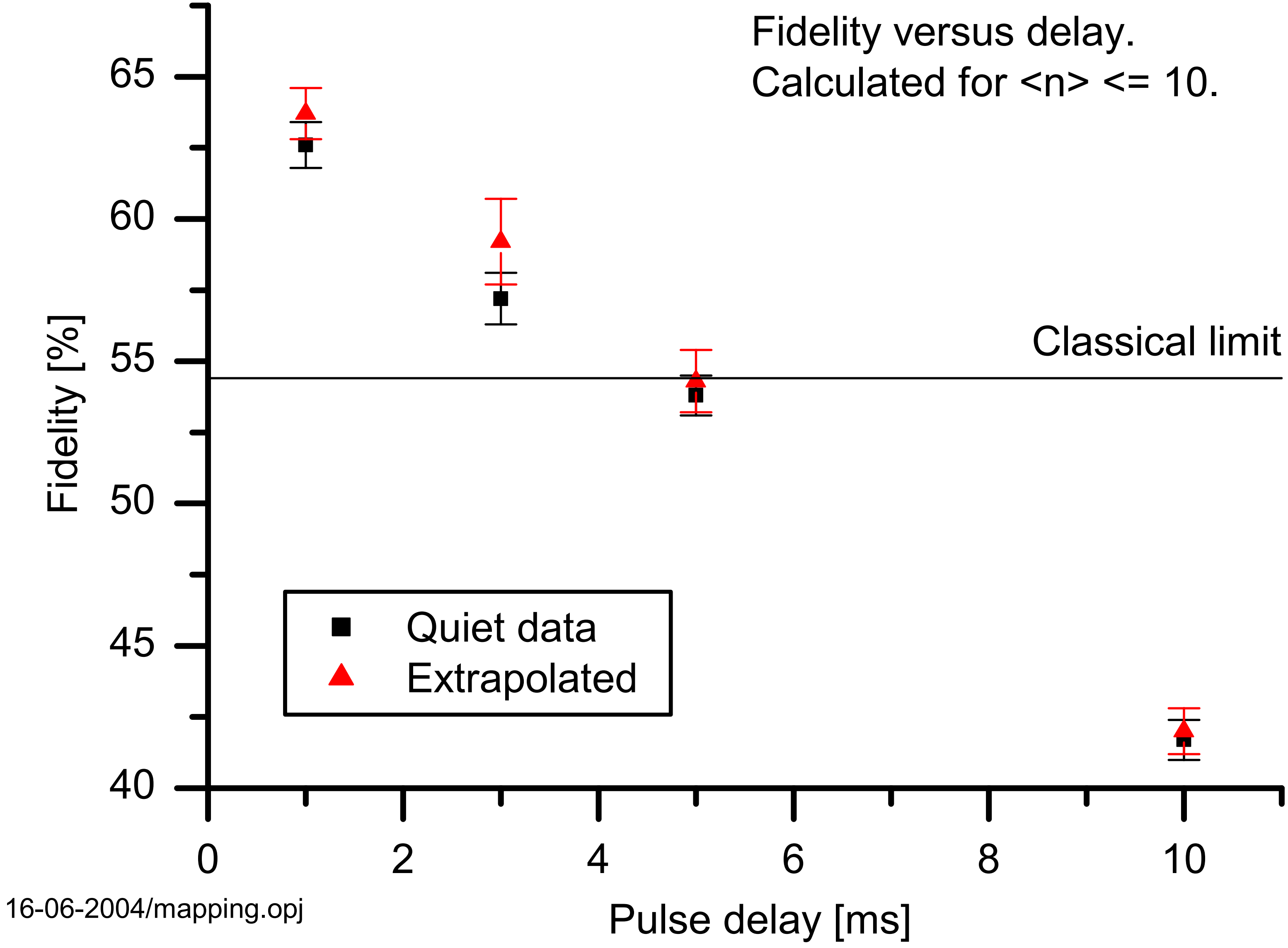
- State overlap averaged over the set of input states

Coherent states with 0 < n <8



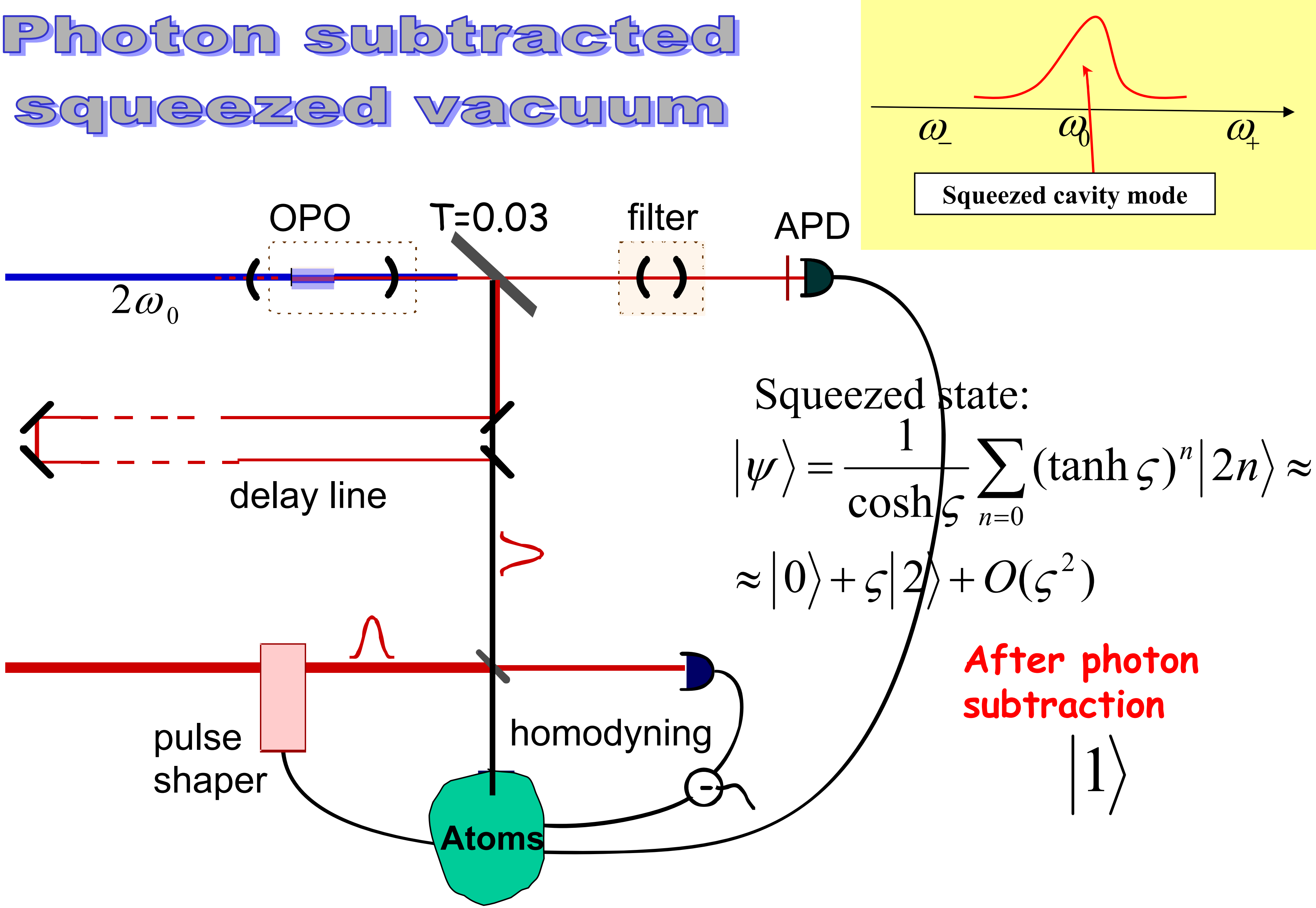

Coherent states with 0 < n <4

# Quantum memory lifetime



# Single photon state source for atomic memories 2006

# Photon subtracted squeezed vacuum



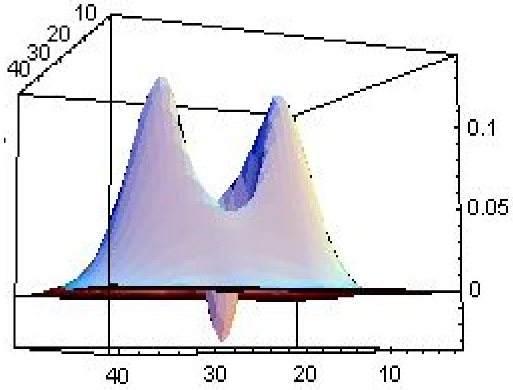
Squeezed state:

$$|\psi\rangle = \frac{1}{\cosh\varsigma}\sum_{n=0}(\tanh\varsigma)^n|2n\rangle \approx$$

$$\approx |0\rangle + \varsigma|2\rangle + O(\varsigma^2)$$

**After photon subtraction**

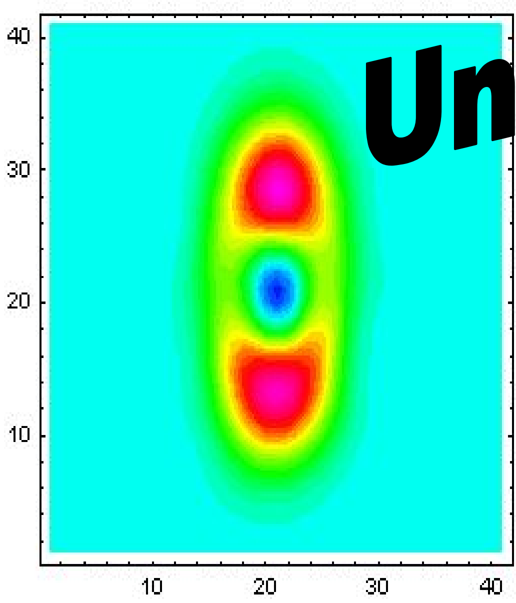
$$|1\rangle$$

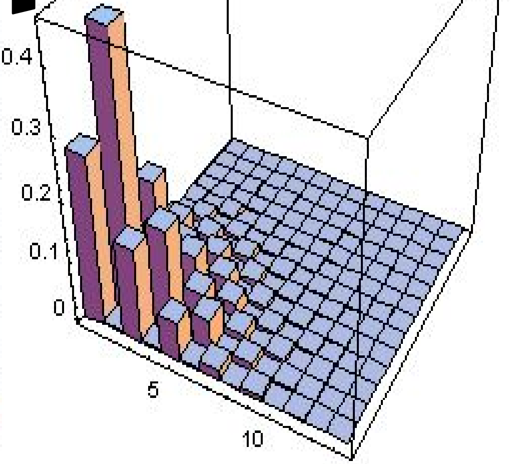


S:\Data\200602\20060208
C2cat_1_####_5.6-18-64-sym.txt

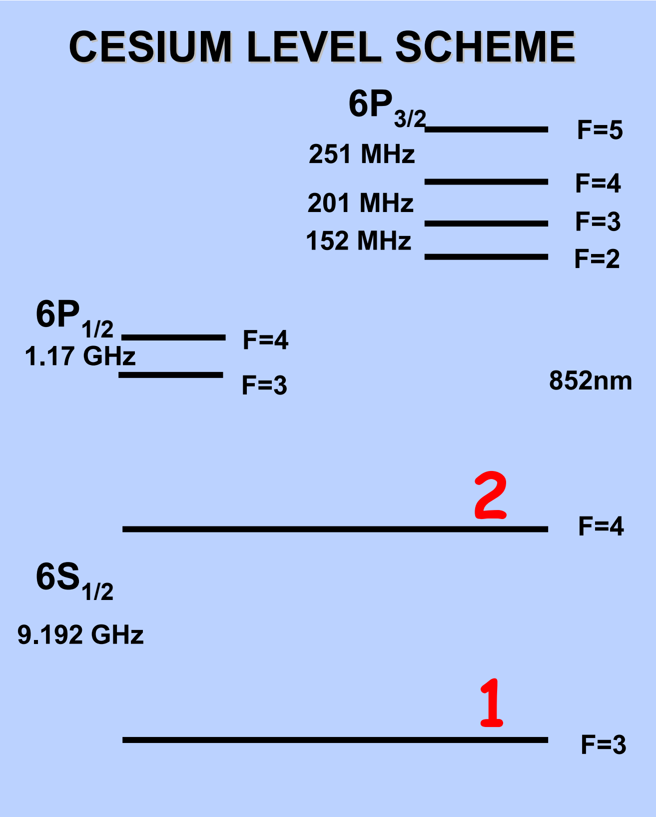
Mean of 7 traces, 85% compensation

Origin: -0.032 Maximum: 0.141





# Quantum interface with cold atoms



**CESIUM LEVEL SCHEME**

$6P_{3/2}$

251 MHz

201 MHz

152 MHz

F=5

F=4

F=3

F=2

$6P_{1/2}$

1.17 GHz

F=4

F=3

852nm

2

F=4

$6S_{1/2}$

9.192 GHz

1

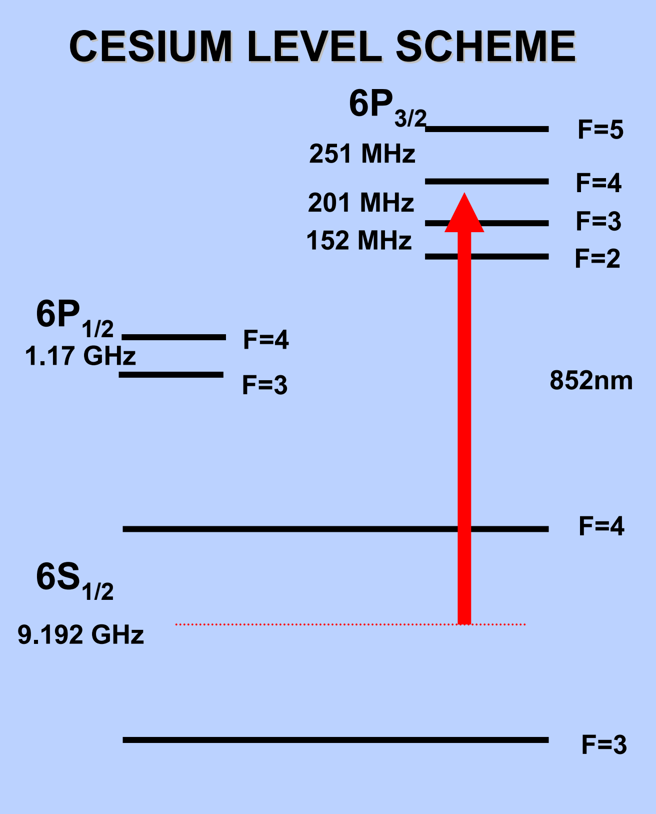
F=3

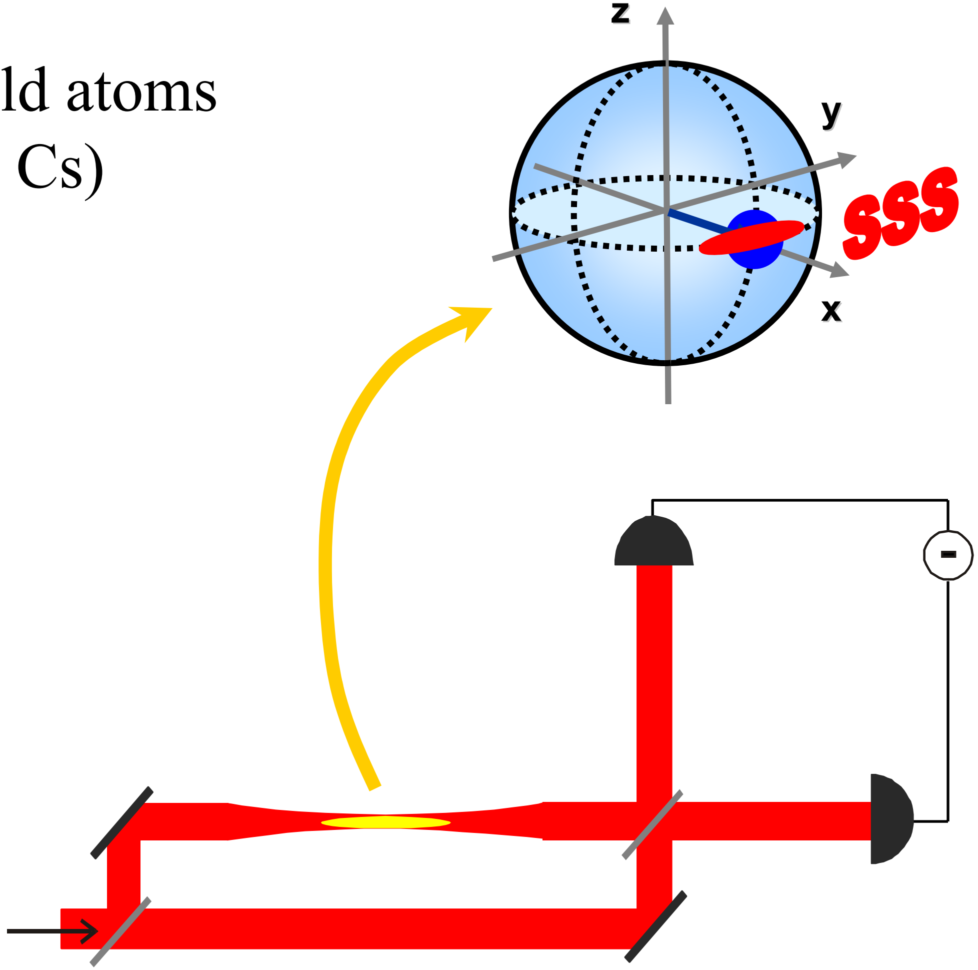
$$J_x = \frac{N_a}{L}\int_0^L (\sigma_{12} + \sigma_{21}^{+})dz$$

$$J_y = \frac{N_a}{L}\int_0^L (\sigma_{12} - \sigma_{21}^{+})dz$$

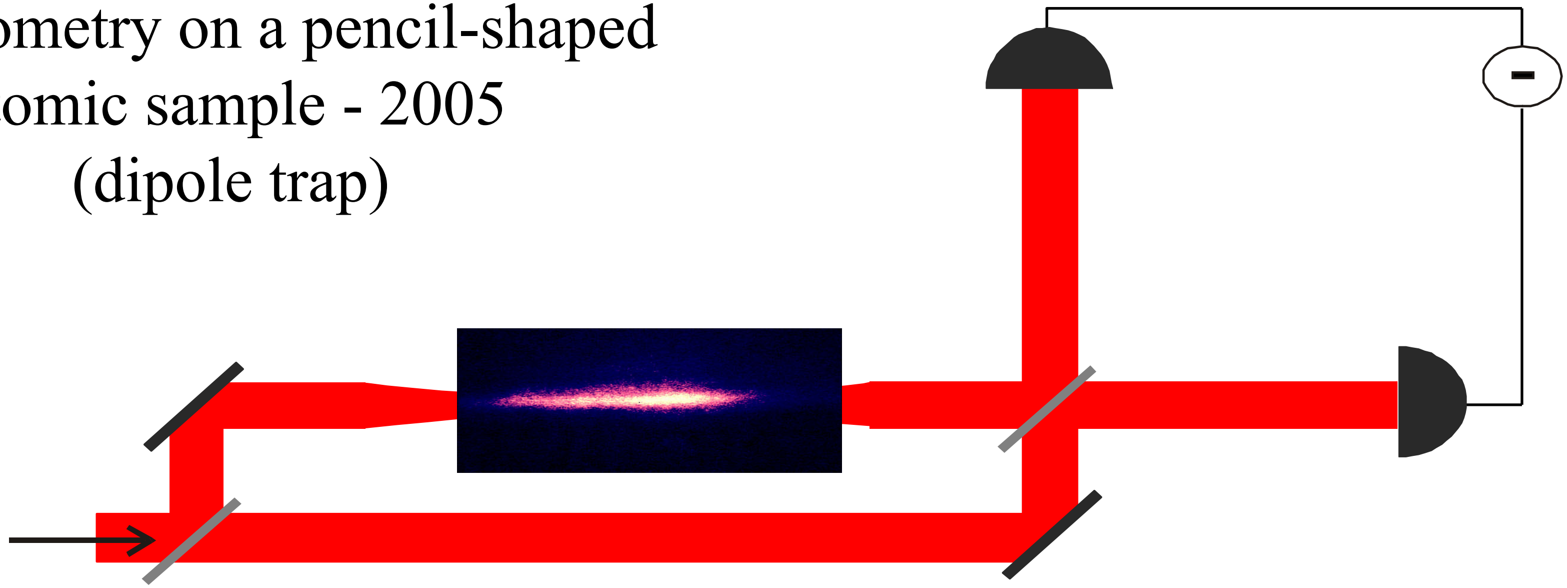
$$J_z = \frac{N_a}{L}\int_0^L (\sigma_{11} - \sigma_{22})dz$$

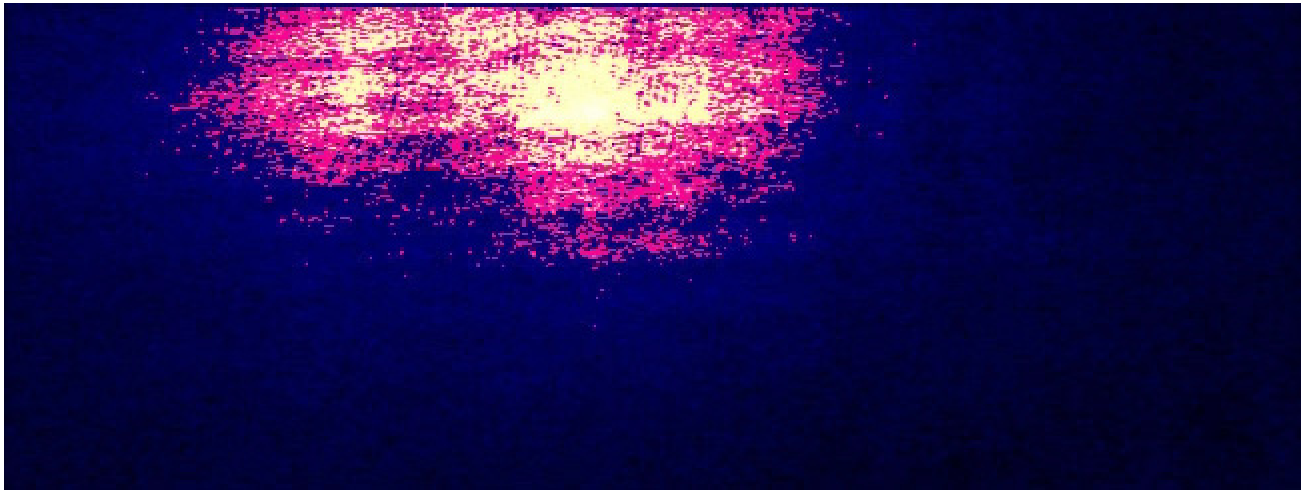
# Spin squeezing with cold atoms
# (clock transition in Cs)


CESIUM LEVEL SCHEME

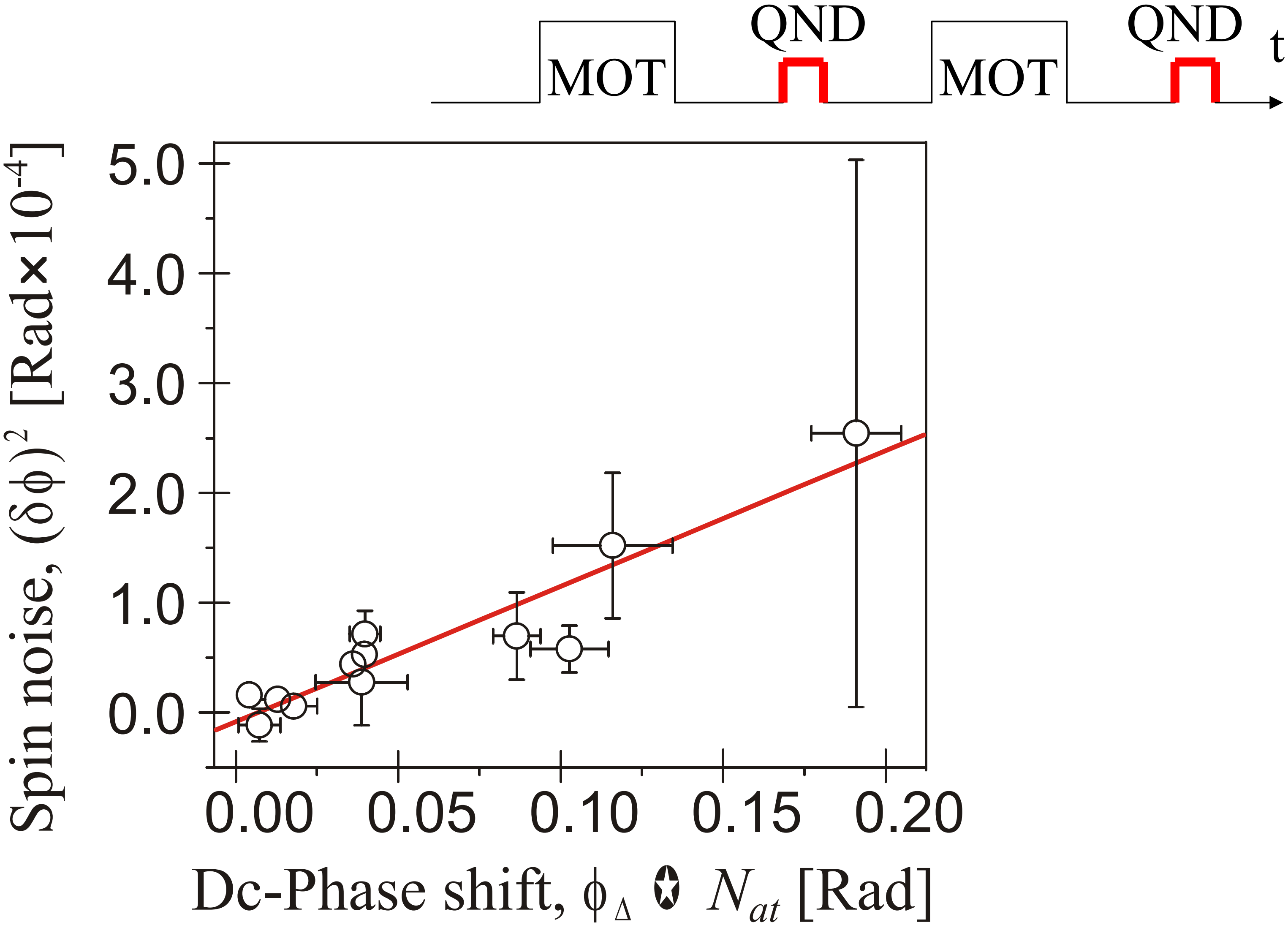


# Interferometry on a pencil-shaped atomic sample - 2005 (dipole trap)

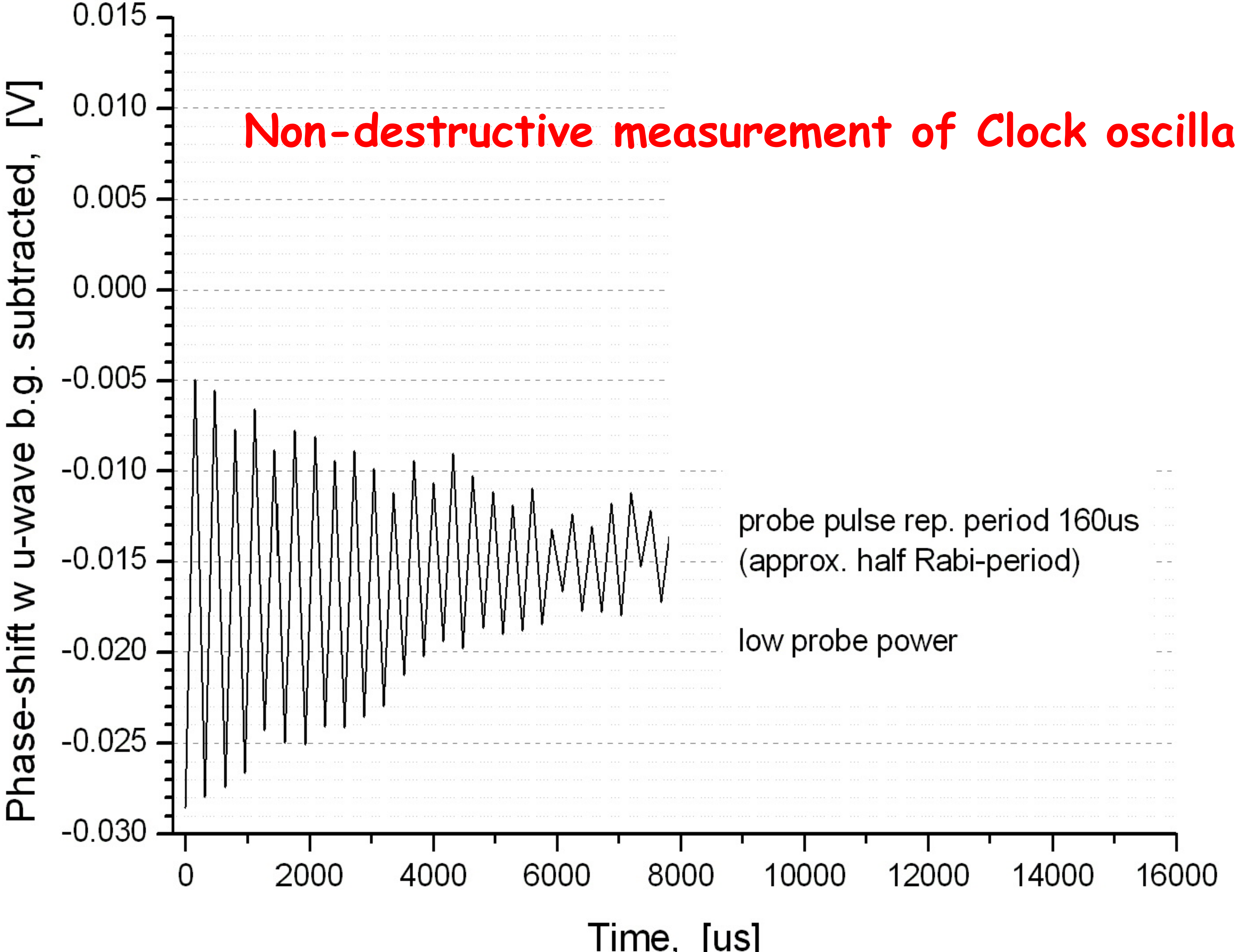




# Quantum noise limited sensitivity to number of atoms



# Non-destructive measurement of Clock oscillatio



probe pulse rep. period 160us
(approx. half Rabi-period)

low probe power