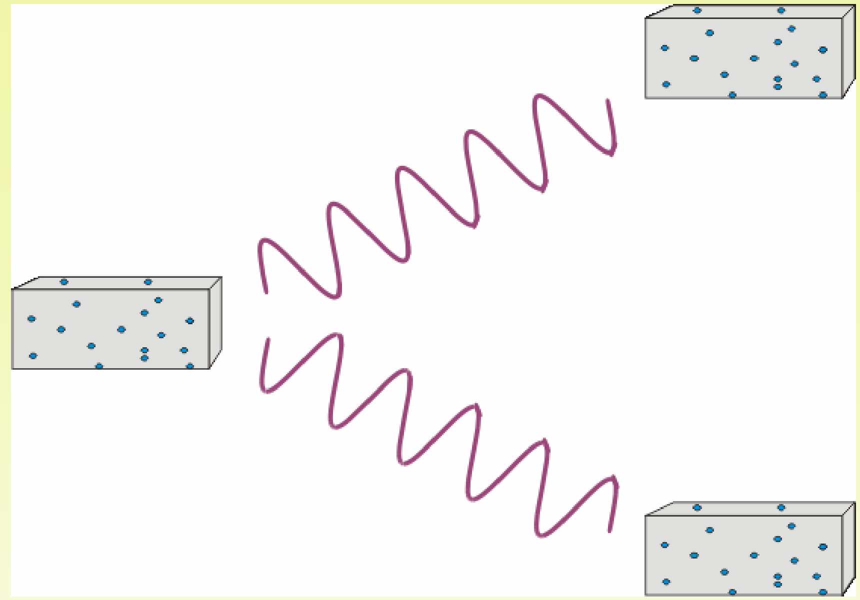
Les Houches, Feb. 2005

Atom-Field Quantum State Manipulation and Storage

Aurélien Dantan, Vincent Josse, Nicolas Treps,
Alberto Bramati, Michel Pinard, Elisabeth Giacobino

Quantum Optics Group,
Laboratoire Kastler Brossel,
Univ. Pierre et Marie Curie, ENS, Paris

Quantum info &
communication
→ atom-field networks
[Duan et al.]



Continuous variables

quantum state ~ noise

high flux

efficient detection

collective coupling ($\propto N$)

- Non-classical state generation with cold atoms
- Atomic quantum memory
- Atomic teleportation

Optical variables

Monomode field

$$E = \mathcal{E}_0 \left[\; X \cos(\omega t) + Y \sin(\omega t) \; \right]$$

X, Y quadrature operators

$$\begin{cases} X = (A^+ + A) \\ Y = i\,(A^+ - A) \end{cases}$$

"amplitude"

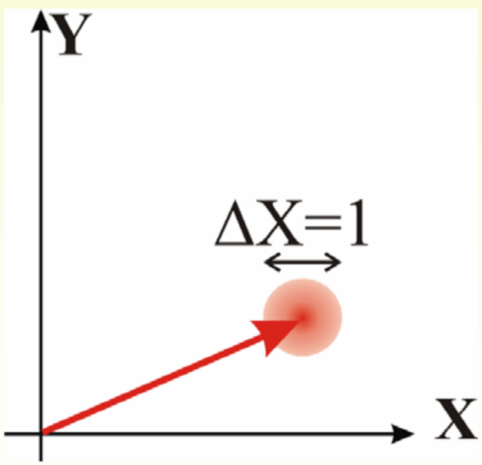
"phase"

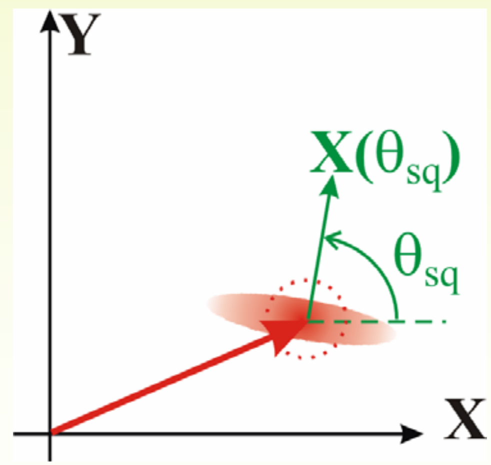
Quantum noise

$$[X, Y] = 2i$$

Heisenberg inequalities

$$\Delta X \, \Delta Y \geq 1$$

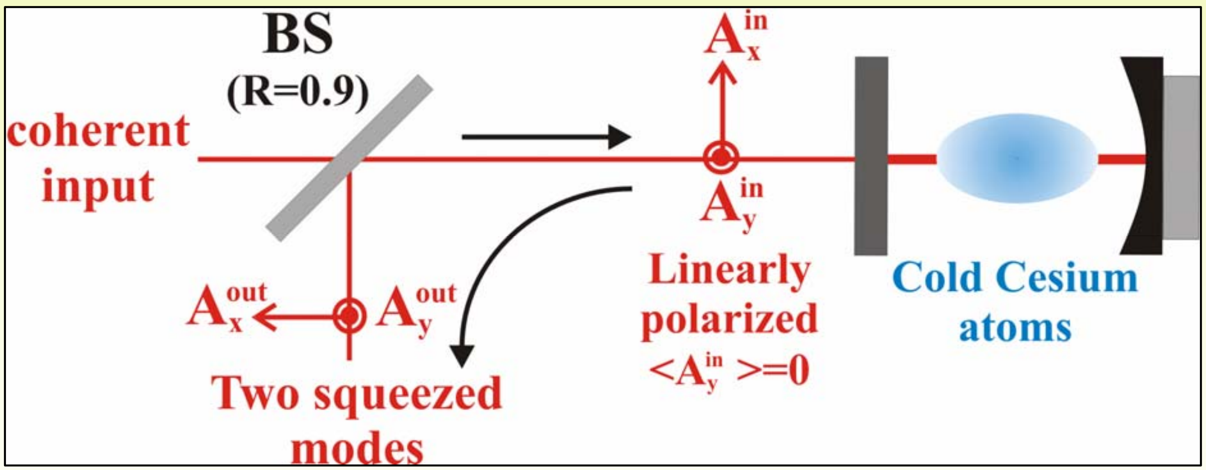




Coherent state $\Delta X = \Delta Y = 1$

Squeezed state $\Delta X_{\theta_{sq}} < 1$

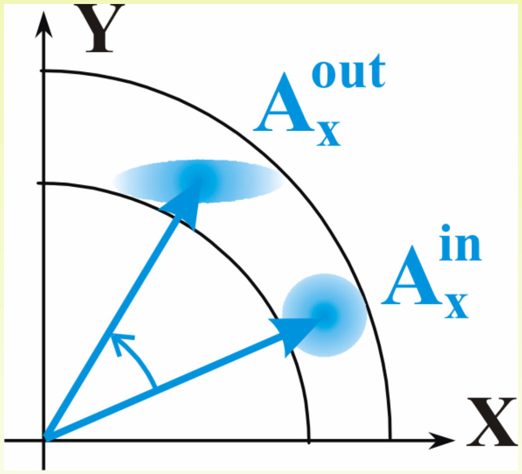
Squeezed state generation with cold atoms

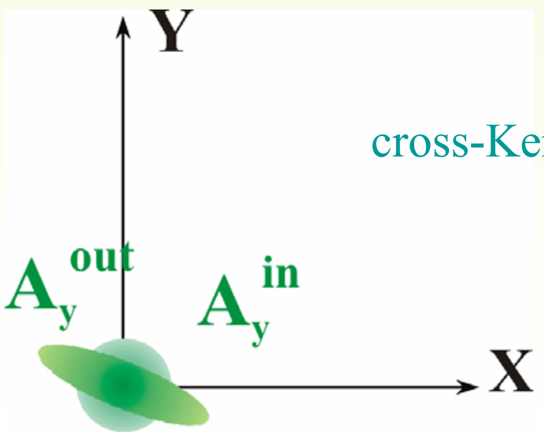


$T_{MOT} \sim 1mK$
D_2 line @ 852nm
$\Delta = 45$ MHz
Cavity bandwidth = 5MHz
$N_{atomes} = 10^6\text{-}10^7$

Squeezed state generation with cold atoms

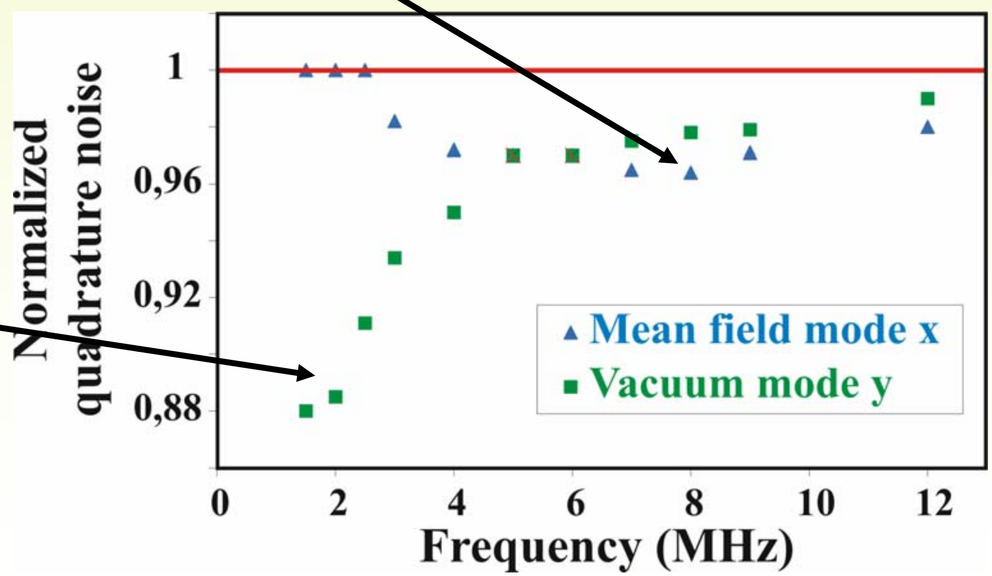
Kerr medium : $n = n_0 - n_2 I$





Kerr effect

cross-Kerr effect

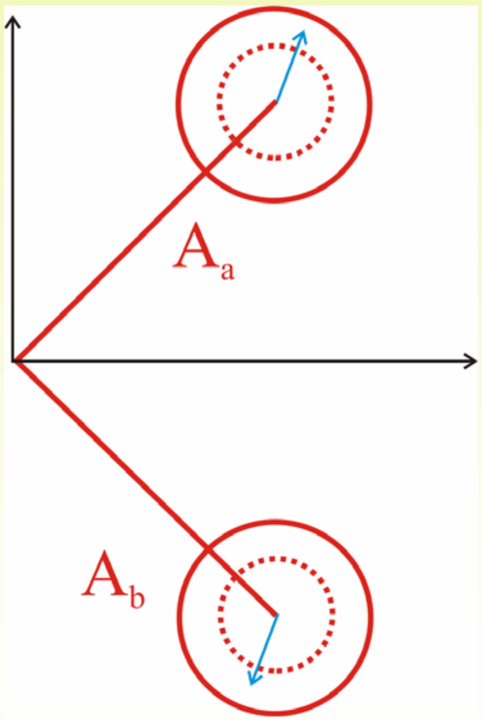


V. Josse *et al.* PRL 91, 103601 (2003)

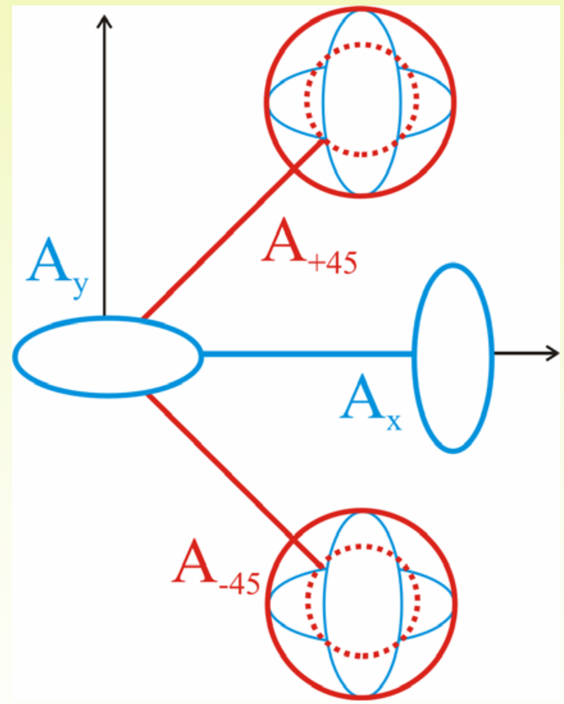
CV entanglement

Inseparability criterion for *a, b* orthogonal Gaussian states

$$I_{a,b}(\theta) = \frac{1}{2}\left\{\Delta^2(X_a + X_b)(\theta) + \Delta^2(Y_a - Y_b)(\theta)\right\} < 2$$



$$A_{\pm 45} = \frac{A_x \pm A_y}{\sqrt{2}}$$



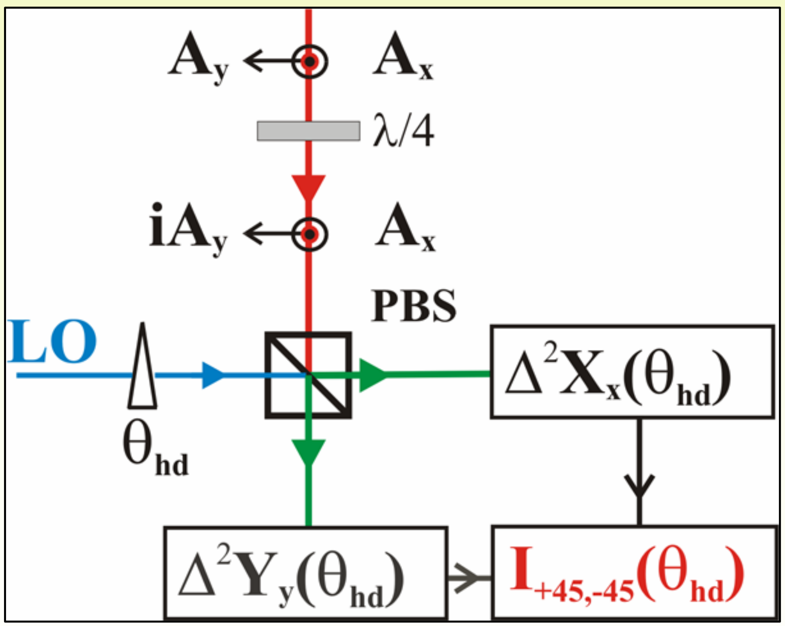
$$I_{+45,-45}(\theta_{sq}) = \Delta^2 X_x(\theta_{sq}) + \Delta^2 Y_y(\theta_{sq}) < 2$$

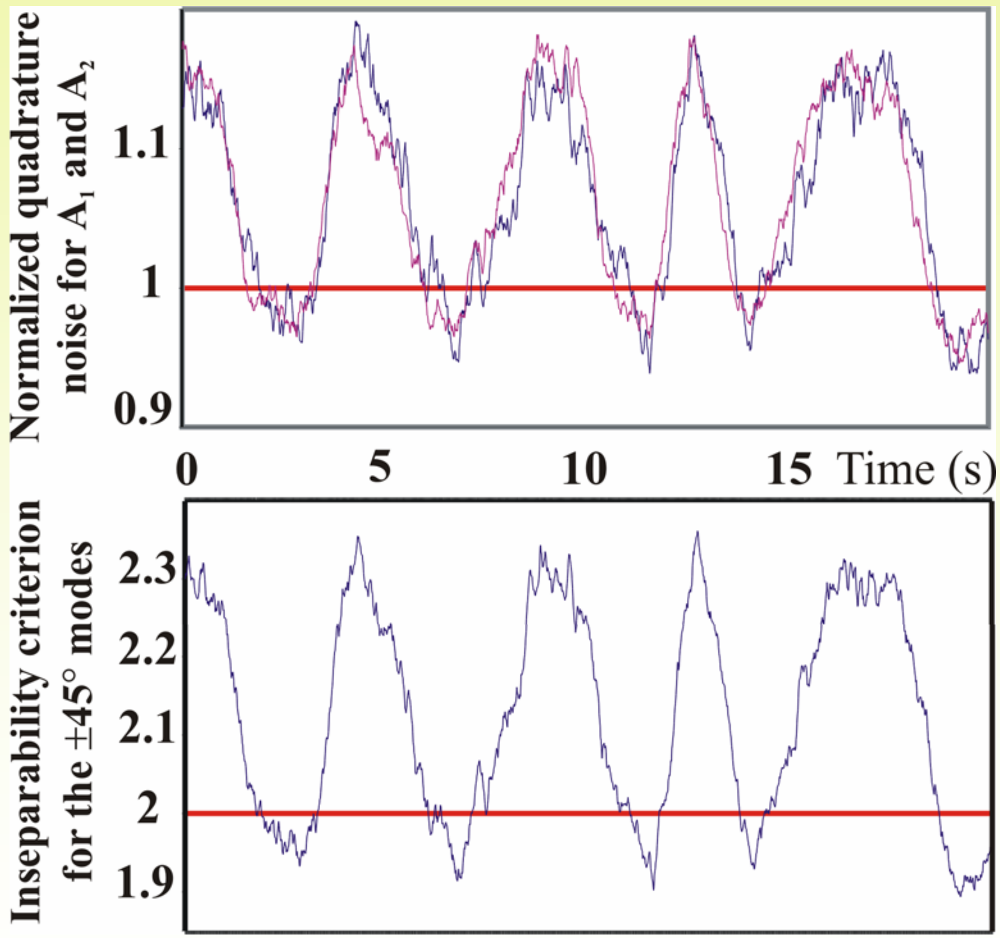
Entanglement = sum of squeezings

Inseparability criterion measurement

$$I_{+45,-45}(\theta) = \Delta^2 X_x(\theta) + \Delta^2 Y_y(\theta)$$

Direct measurement
→ 2 homodyne detections





V. Josse *et al.* PRL 92, 123601 (2004)

Non-classical state generation

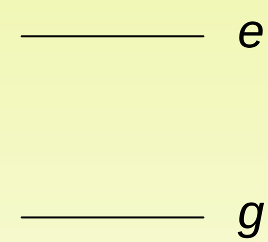
- $\chi^{(2)}$: OPO, OPA
- $\chi^{(3)}$: Kerr effect in fibers, atoms

→ Efficient, broad bandwidth, tunable…

→ *Storage ?*

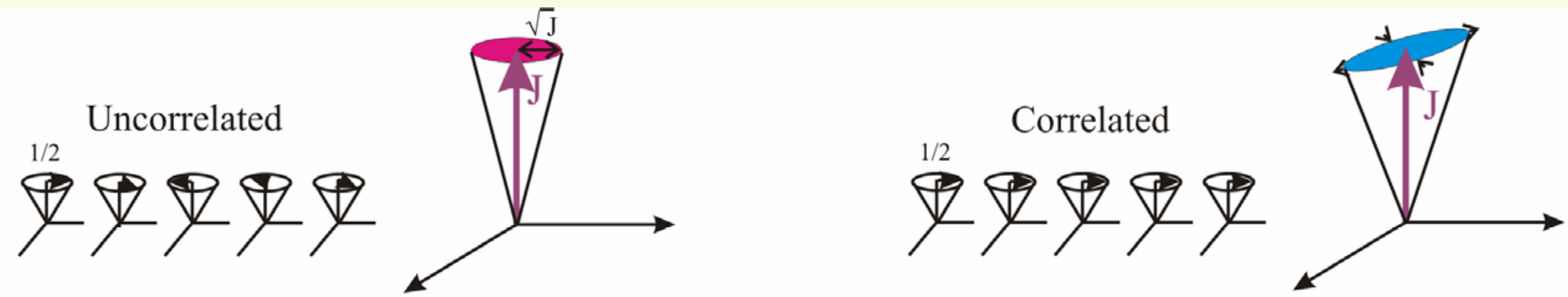
Atomic variables

- N 2-level atoms ≡ N spins ½



- Collective operators $J_x = \sum_{i=1}^{N} J_x^i = \sum_{i=1}^{N} \left(|e\rangle_i \langle g|_i + |g\rangle_i \langle e|_i \right) / 2$

- Heisenberg inequalities $[J_x, J_y] = iJ_z \Rightarrow \boxed{\Delta J_x^2 \, \Delta J_y^2 \geq \left| \langle J_z \rangle \right|^2 / 4}$



Coherent spin state $\Delta J_\perp^2 = \frac{N}{4}$

Spin-squeezed state $\Delta J_\perp^2 < \frac{N}{4}$

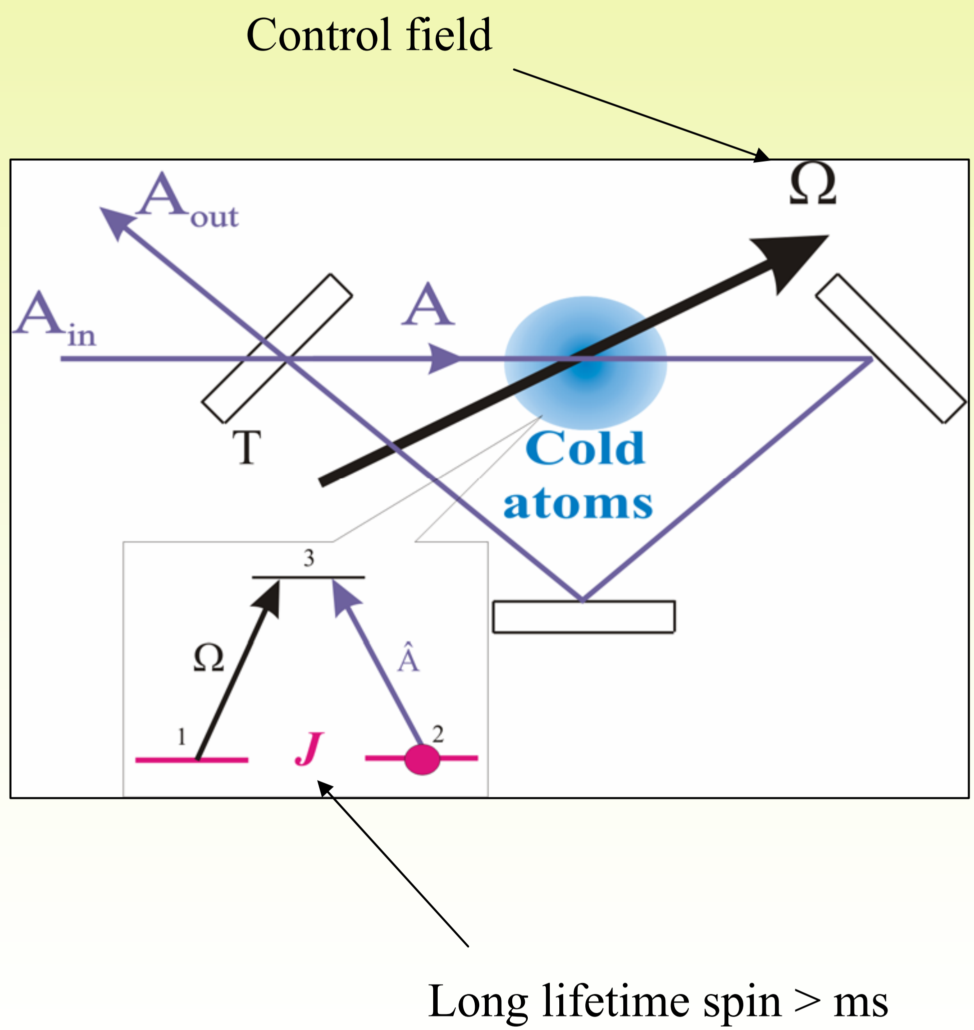
Atomic quantum memory

Principle :

• transfer of the field quantum state A^{in} to the atoms → ***« writing»***

• ***« storage »***

• ***« readout »*** of the atomic state



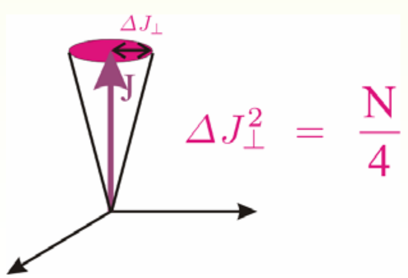
Atomic quantum memory

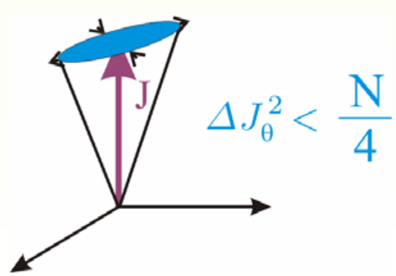
- A^{in} broadband squeezed vacuum state

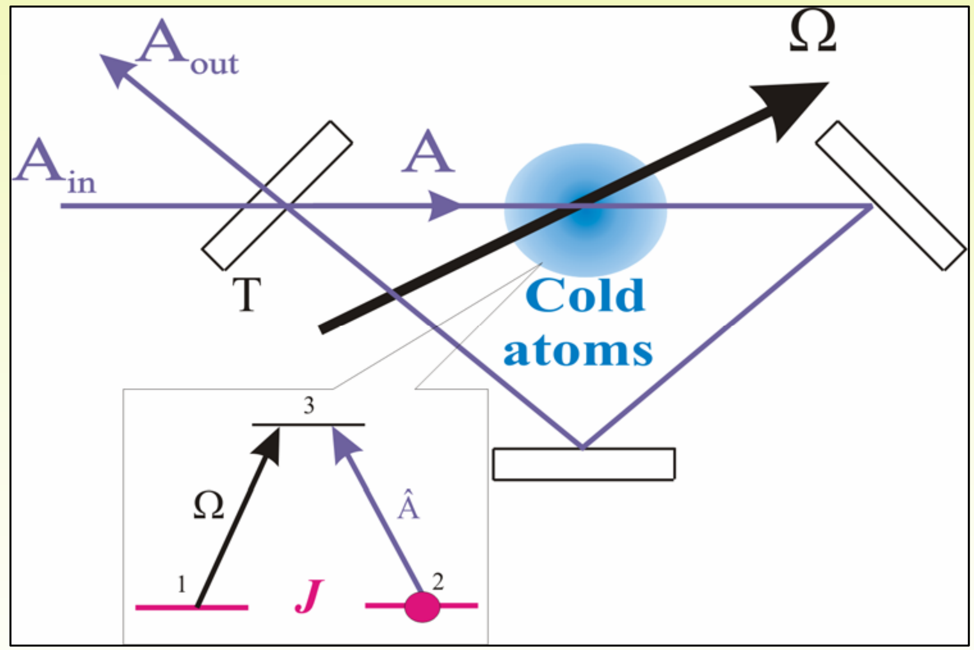
  $\langle A^{in} \rangle = 0 \Rightarrow \langle J_z \rangle = N/2$

- Atomic coherence ≡ harmonic oscillator

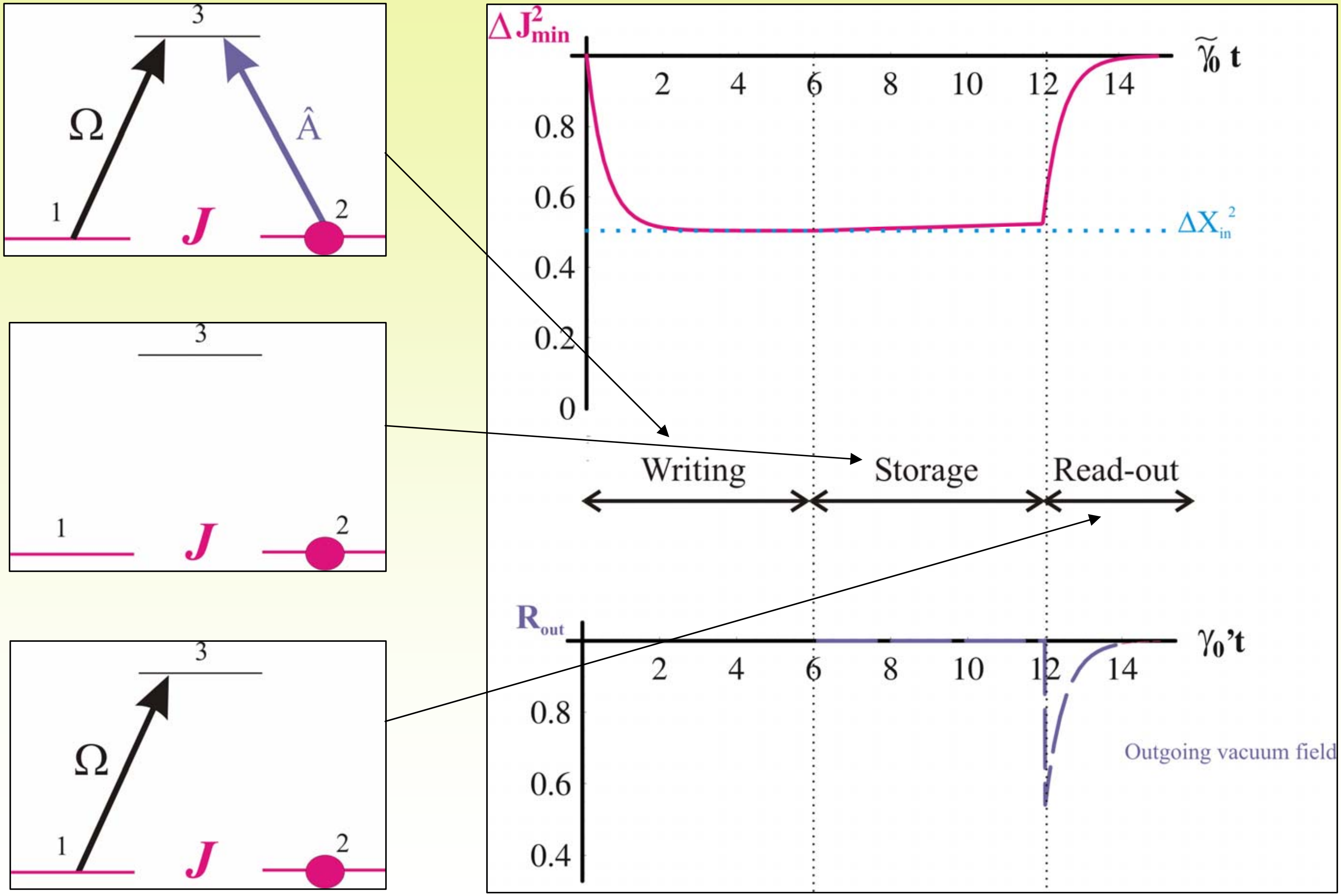
  $\Delta J_x \, \Delta J_y \geq N/4$



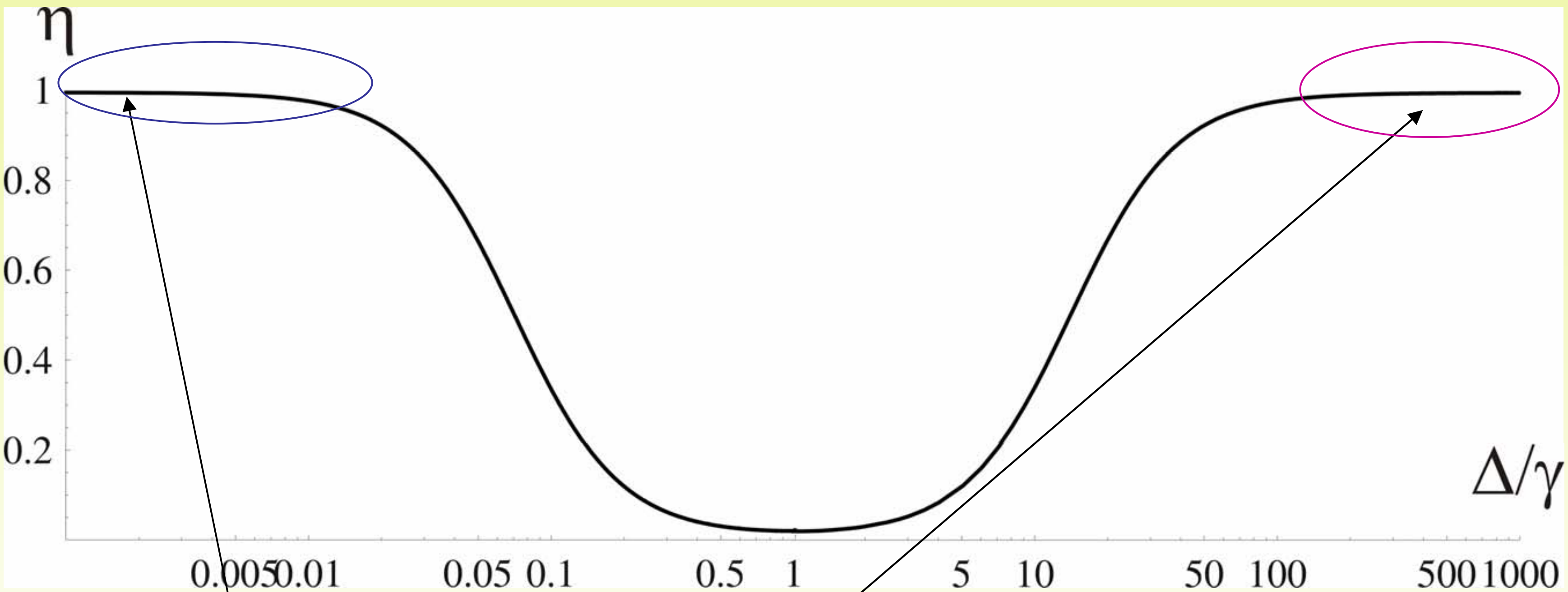




Quantum memory



Quantum memory : efficiency



Optimal transfer for δ = 0

- EIT (Δ = 0) « slow light » (Hau, Lukin, Kuzmich)

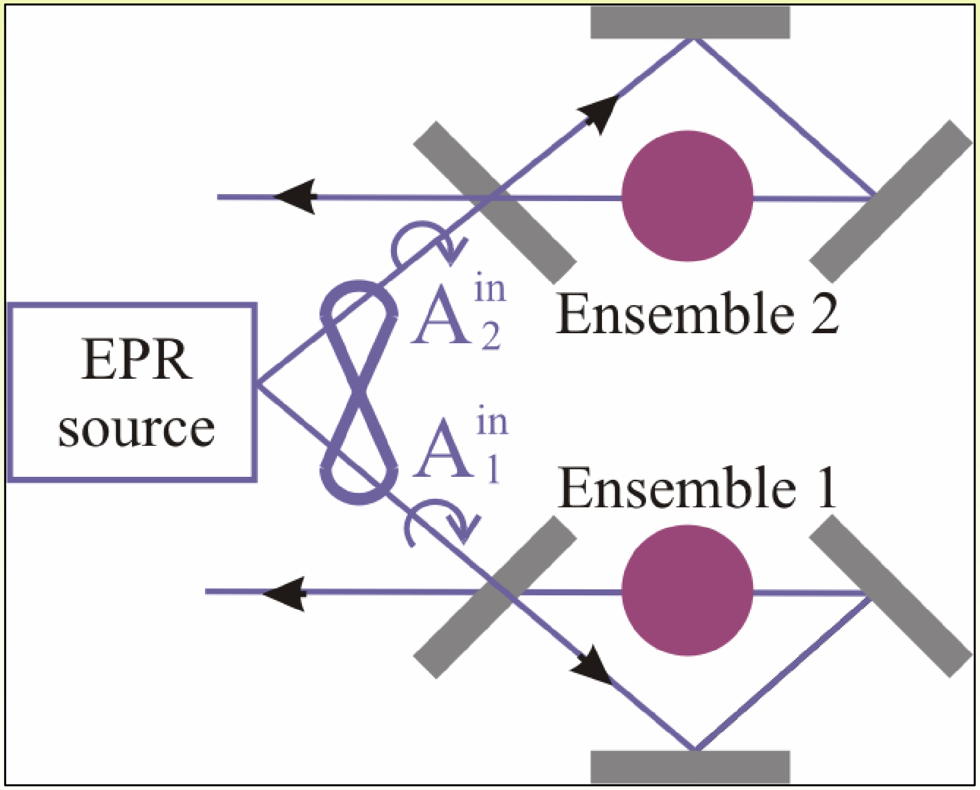
- Raman (Δ >> γ) Polzik

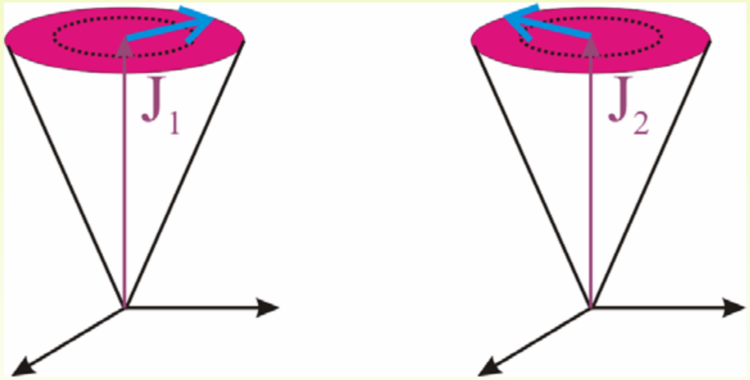
Efficiency

$$\eta = \frac{atomic\ squeezing}{field\ squeezing} \approx 100\%$$

A. Dantan *et al.* PRA 69, 43810 (2004)

Storage of entanglement



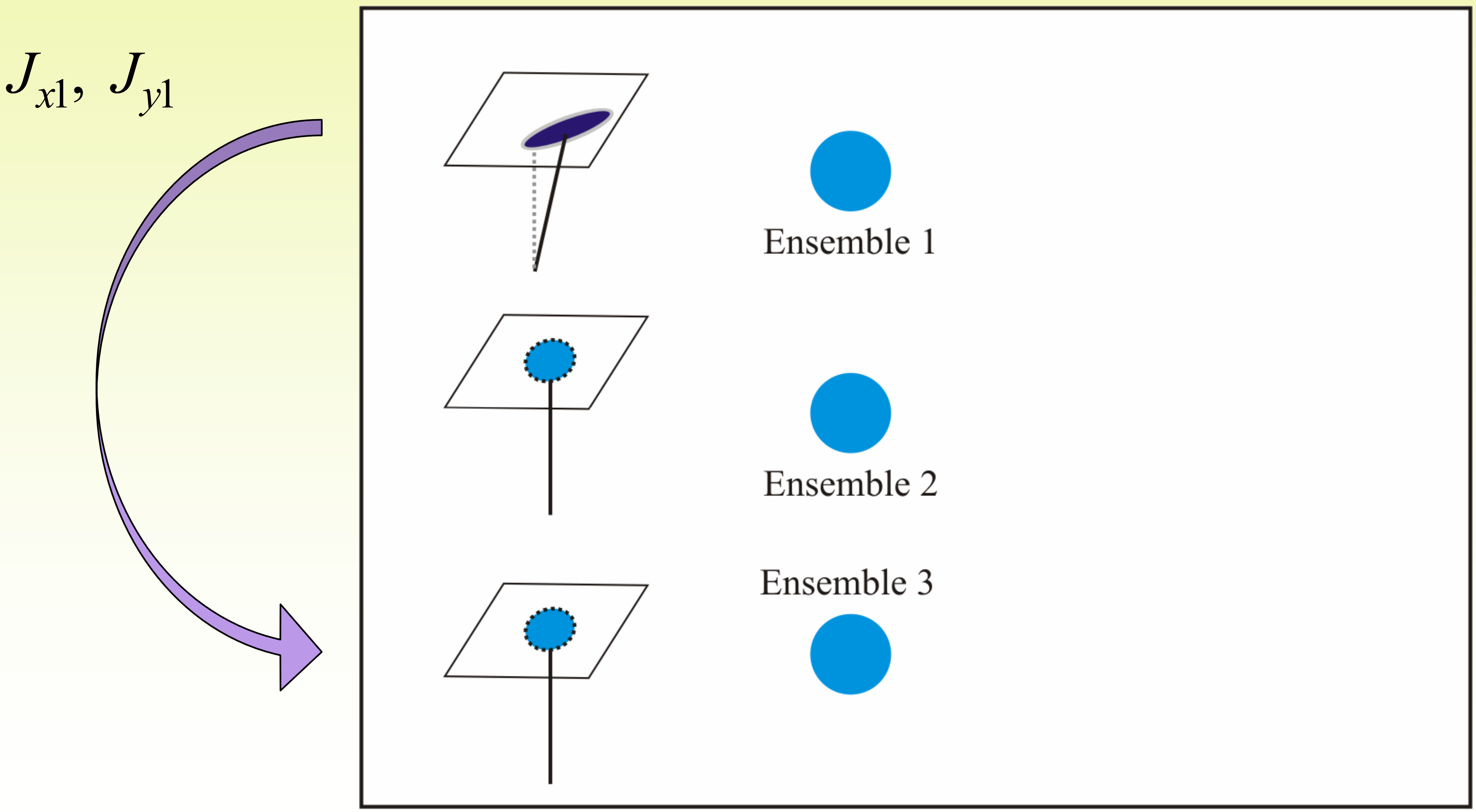


→ Efficient transfer ~ 100%

A. Dantan *et al.* Europhys. Lett. 67, 881 (2004)

Atomic teleportation

<u>Goal</u> : teleportation of ensemble 1 quantum state to ensemble 3

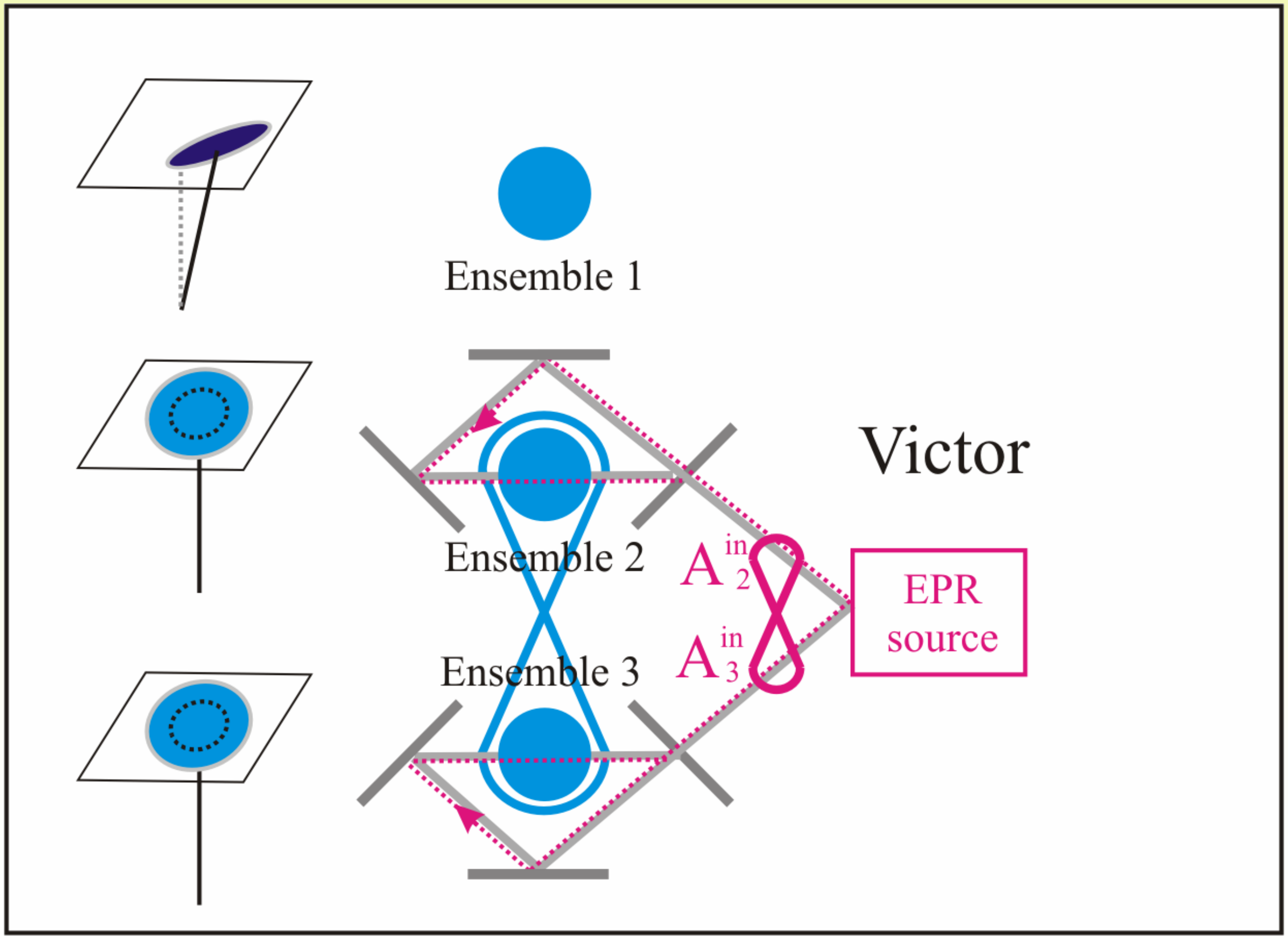


Atomic teleportation

1) Preparation : Victor

$$J_{x2} \sim J_{x3},$$

$$J_{y2} \sim -J_{y3}$$

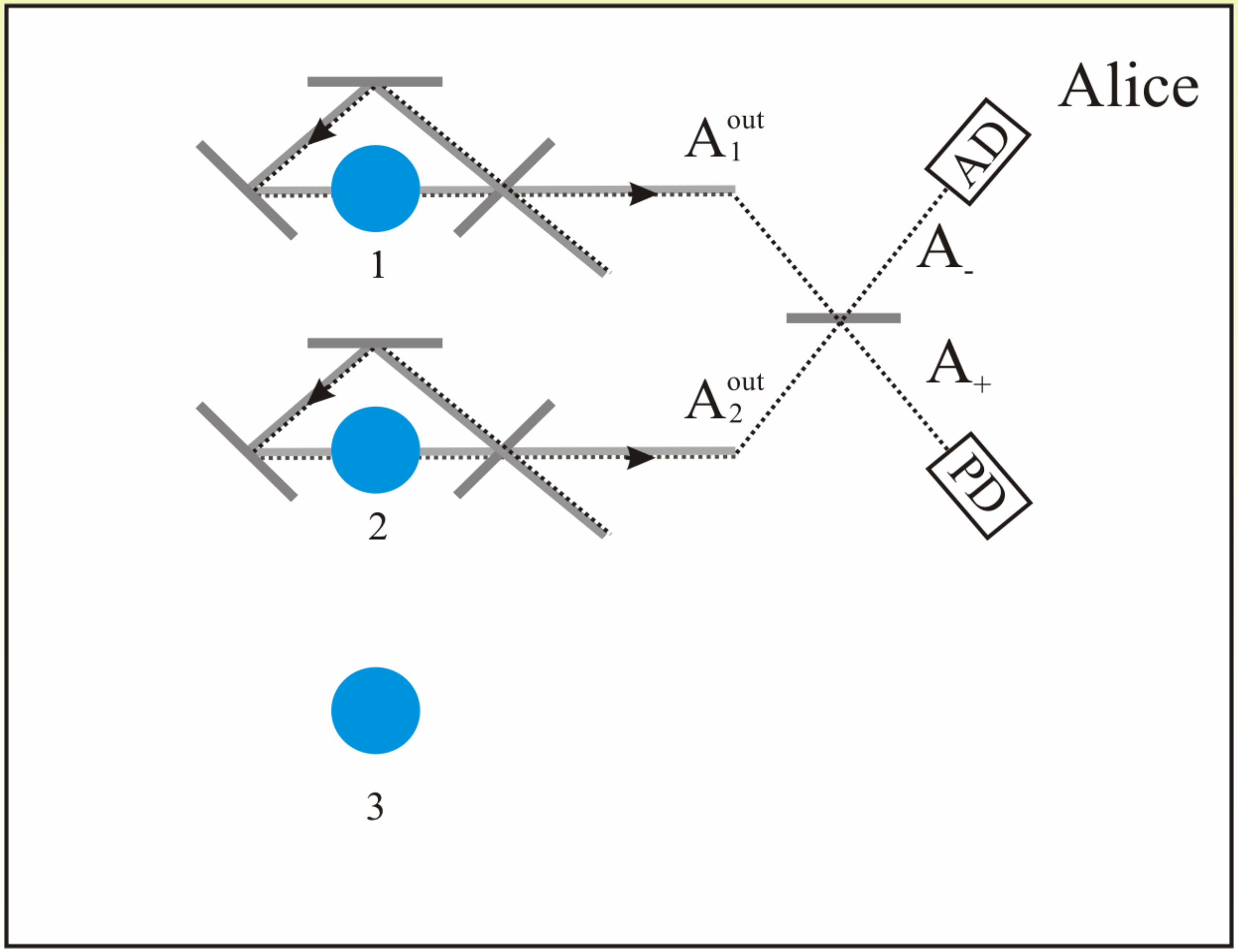


Atomic teleportation

2) Joint measurements : Alice

$$X_{-} \sim J_{x1} - J_{x2}$$

$$Y_{+} \sim J_{y1} + J_{y2}$$



Atomic teleportation

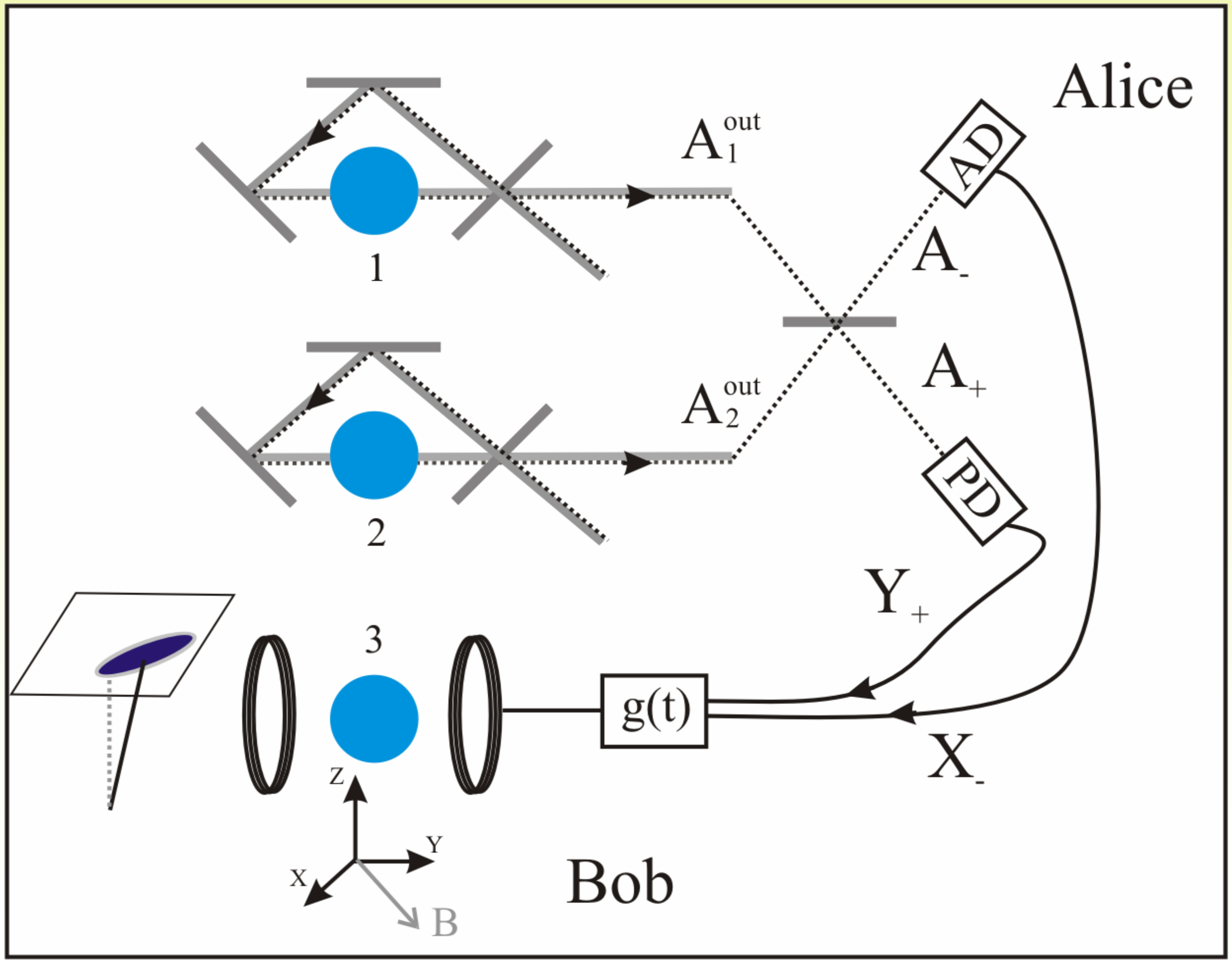
3) Reconstruction : Bob

$$H_B \propto \vec{J}.\vec{B}$$

$$B_x \sim -Y_+,\ B_y \sim X_-$$

$$J_{x3}^{out} = J_{x3} - gJ_{x2} + gJ_{x1} + noise$$

$$J_{y3}^{out} = J_{y3} + gJ_{y2} + gJ_{y1} + noise$$



Atomic teleportation

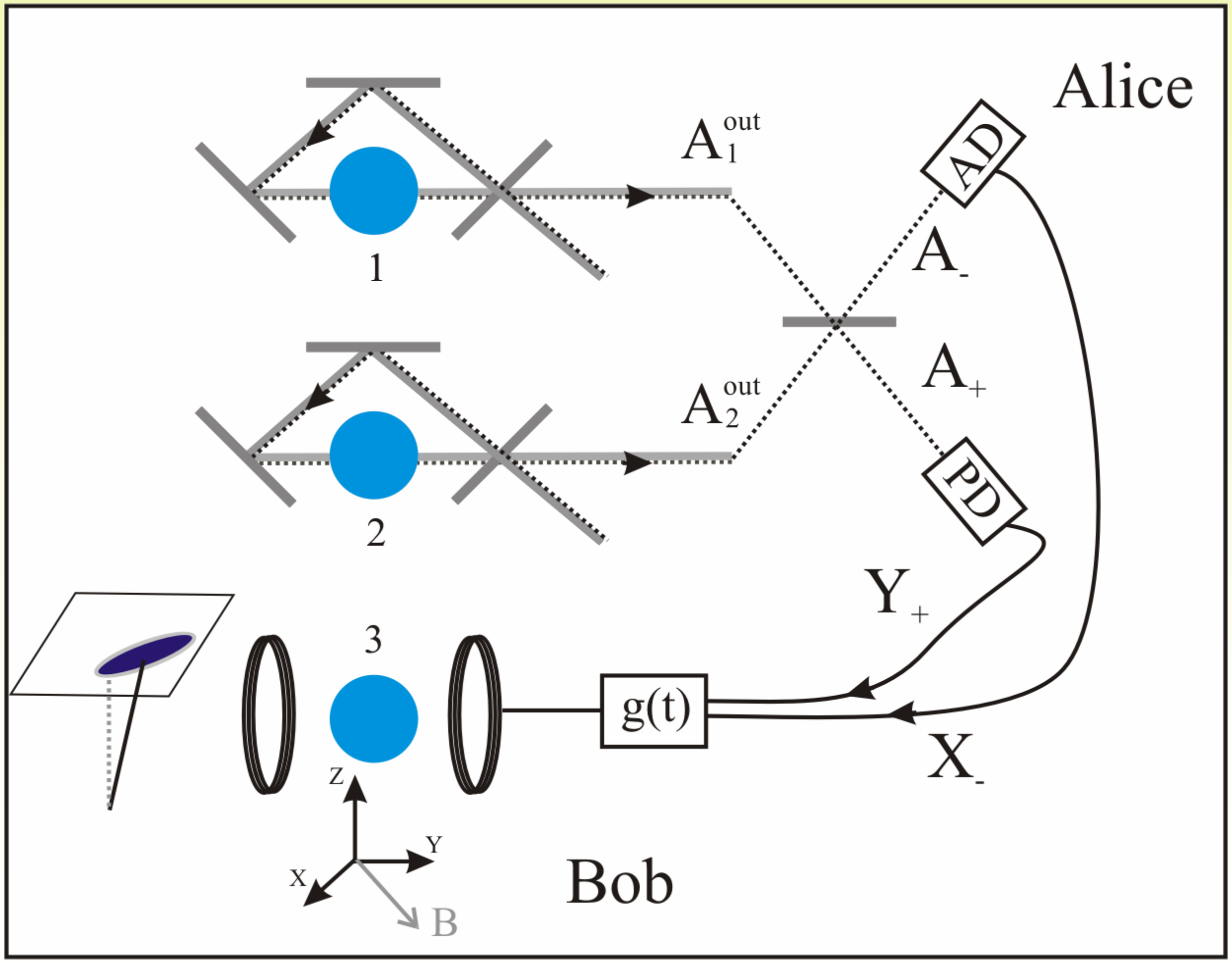
3) Reconstruction : Bob

$$H_B \propto \vec{J}.\vec{B}$$

$$B_x \sim -Y_+,\ B_y \sim X_-$$

$$J_{x3}^{out} = J_{x3} - J_{x2} + J_{x1} + noise$$

$$J_{y3}^{out} = J_{y3} + J_{y2} + J_{y1} + noise$$



A. Dantan *et al.* PRL 94, 50502 (2005)

Summary

- *Generation & storage* of quantum states using cold atoms
- Experiments in progress …
- Other systems: mechanical oscillators, nuclear spins, solid state media …