Collaborations et financements: ANR, scala, DGA, IUF, JST

Laboratoire Kastler Brossel
Physique quantique et applications

Perspectives: from Quantum feedback to Non-local quantum physics

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Tutelles: ENS, UPMC, CNRS, Collège de France

Aim of the experiment

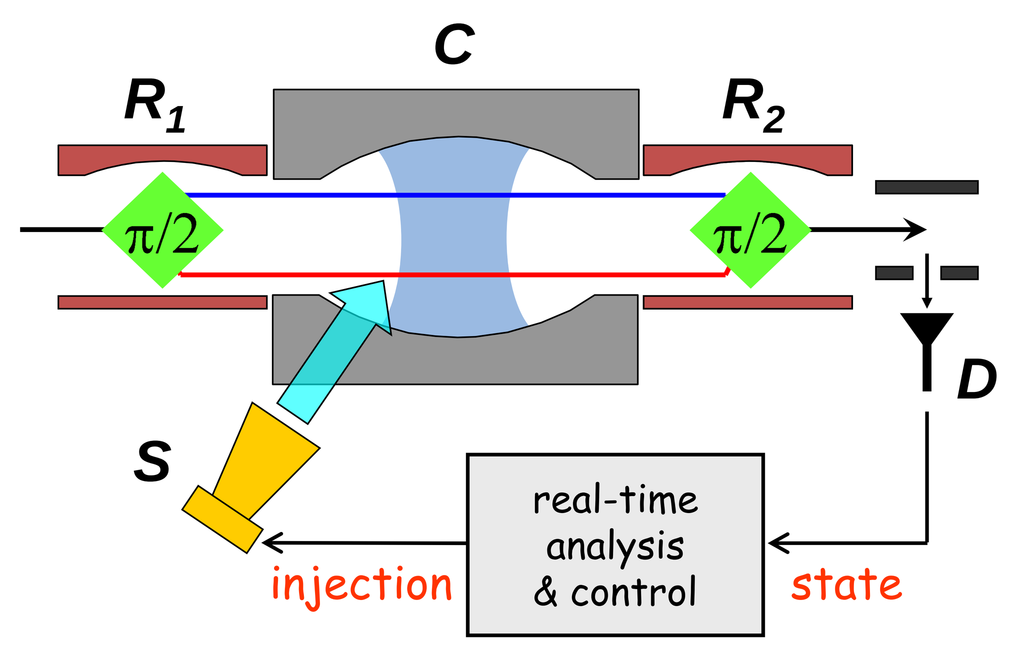
- Use information from repeated QND measurements of the cavity field for preparation of quantum states (e.g. Fock states) and protect them against decoherence.
- Non-local quantum physics: generation and detection of various non-local superposition states, teleportation of quantum states, etc.

Methods

- Quantum feedback realized by atoms as QND probes and small injections into the cavity mode as a control.
- Experimental setup with two high-finesse cavities, which allows atoms to selectively interact with them and thus to realize effective coupling of the two remote cavity modes.

Quantum feedback: Preparation and preservation of photon-number states

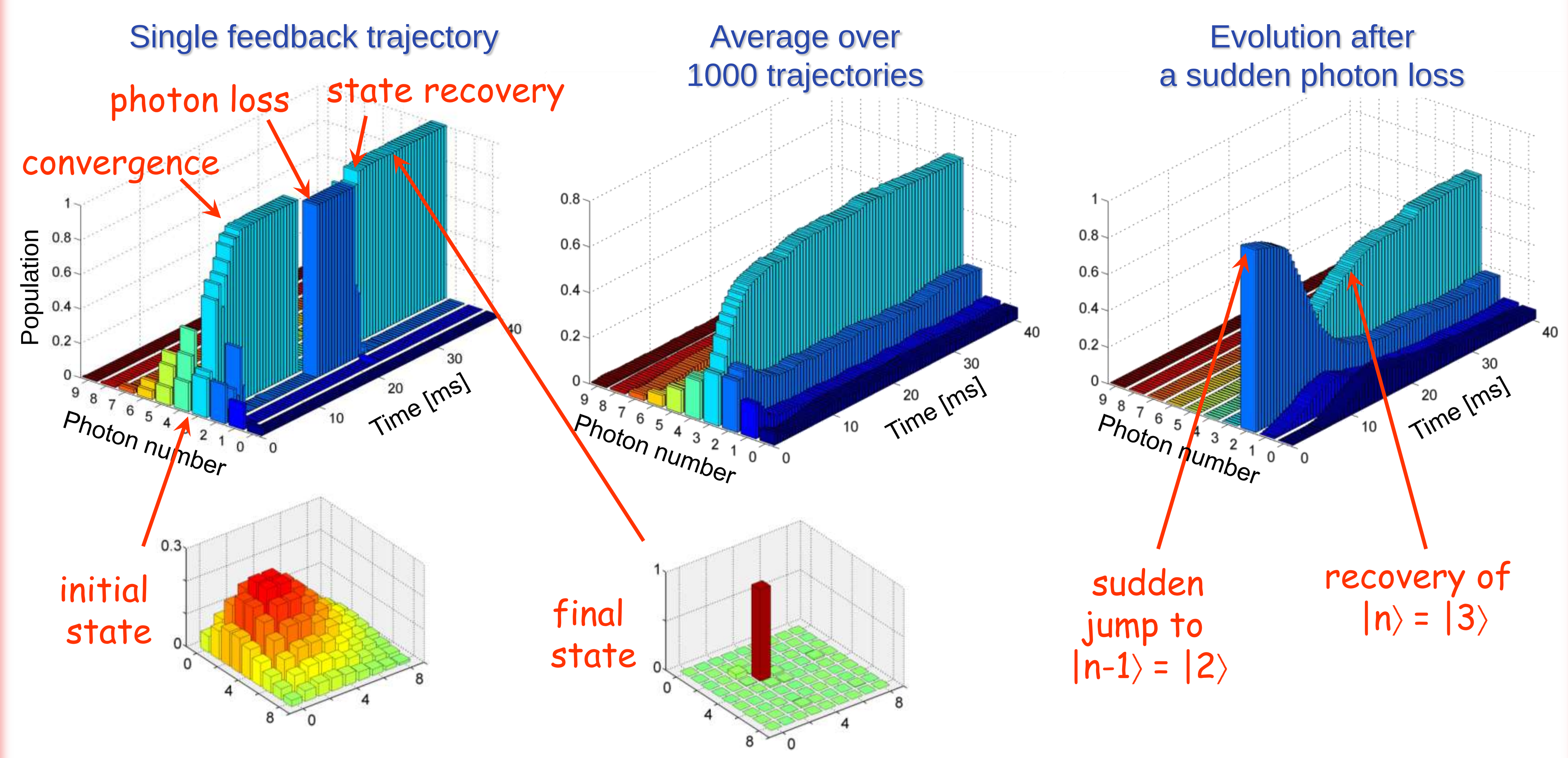
in collaboration with P. Rouchon and M. Mirrahimi, Ecole des Mines



Feedback protocol:

- Inject initial coherent field into the cavity.
- Send one-by-one atoms in a Ramsey configuration.
- Detection of each atom projects cavity field into a new state ρ_i.
- Calculate displacement α_i, which maximizes overlap $F = \mathrm{Tr}(\rho_{target} \cdot D(\alpha_i)\rho_i D(-\alpha_i))$ between target and displaced state.
- Close feedback loop by injecting a control coherent field $|\alpha_i\rangle$.
- Repeat feedback cycles until success when $F \approx 1$.

Simulation results for a target Fock state $\rho_{target} = |3\rangle$

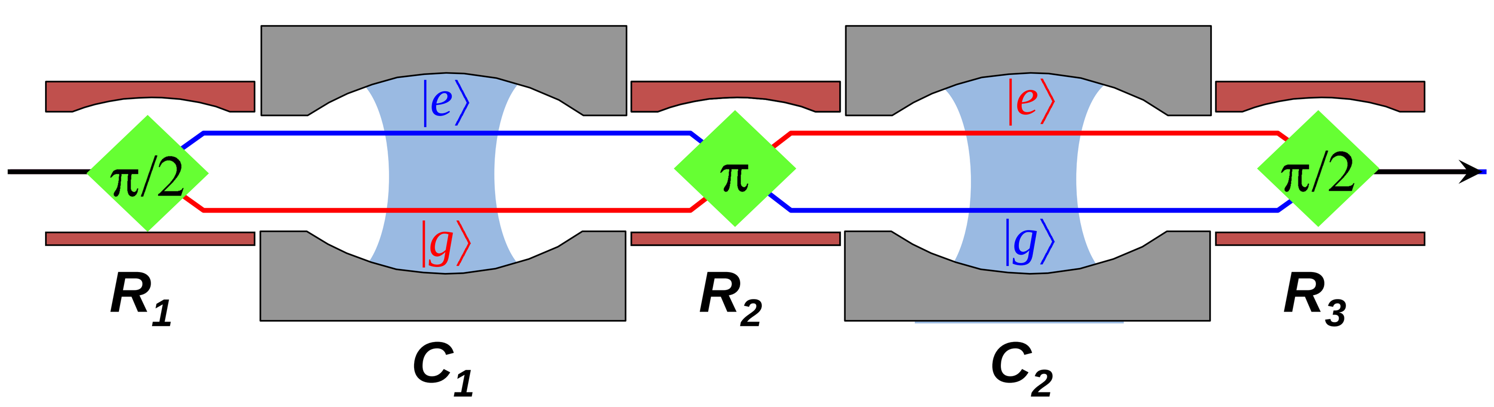


Simulation parameters:
- target Fock state: |3⟩
- Hilbert space size: 10
- cavity decay time: 130 ms
- black-body thermal field: 0.05 ph
- separation of atomic pulses: 100 ms
- average number of atoms per pulse: 0.4
- detection efficiency: 80%
- false state detection: 10%
- real experimental geometry

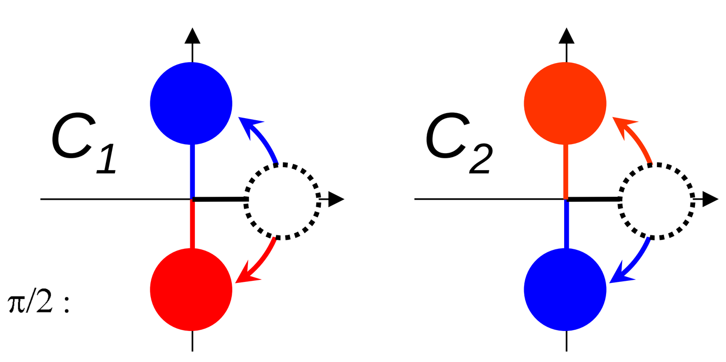
Non-local Schrödinger's cat state

Step 1: Inject coherent field $|\alpha\rangle$ into both cavities

Step 2: Send a dephasing atom



Dispersive atom-cavity coupling: two fields get state dependently dephased



phase shift per photon $\phi = \pi/2$:

Entangled field state $\frac{1}{\sqrt{2}}\left(|i\alpha\rangle|-i\alpha\rangle + |-i\alpha\rangle|i\alpha\rangle\right)$

Step 3: Add up another coherent field $|i\alpha\rangle$

Non-local mesoscopic quantum superposition $\frac{1}{\sqrt{2}}\left(|\alpha'\rangle|0\rangle + |0\rangle|\alpha'\rangle\right)$

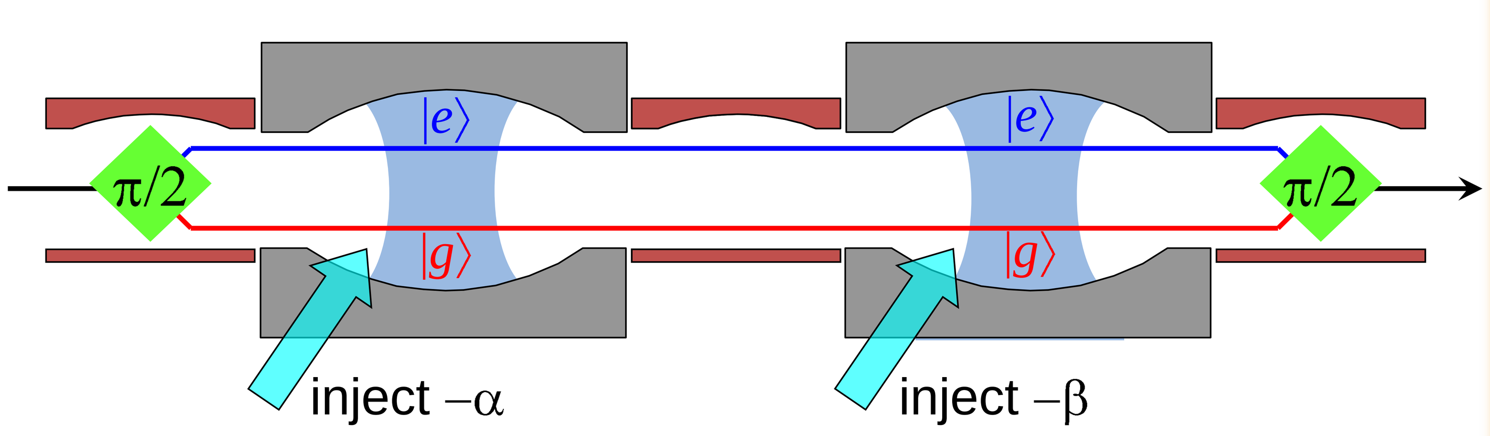
Step 4: QND photon-number measurement

Non-local photon-number superposition - "NOON" state $\frac{1}{\sqrt{2}}\left(|N\rangle|0\rangle + |0\rangle|N\rangle\right)$

Superpositions of "all photons in C_1" and "all photons in C_2"

Measurement of generalized Wigner function

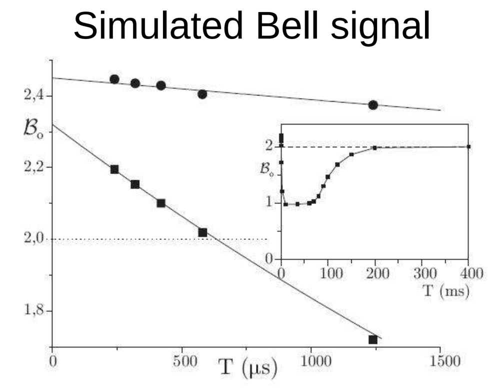
$$W(\alpha,\beta) = \frac{4}{\pi^2}\,\mathrm{Tr}\left[\hat{\rho}_{\mathrm{joint}}\,\hat{D}_1(\alpha)D_2(\beta)\,e^{i\pi\hat{a}^\dagger\hat{a}}e^{i\pi\hat{b}^\dagger\hat{b}}\,\hat{D}_1(-\alpha)\hat{D}_2(-\beta)\right]$$



- Inject coherent field (−α) into C_1 and (−β) into C_2
- Send atoms through both cavities & measure the joint parity P_{joint}
- Obtain $W(\alpha,\beta)$ by multiplying P_{joint} by $4/\pi^2$

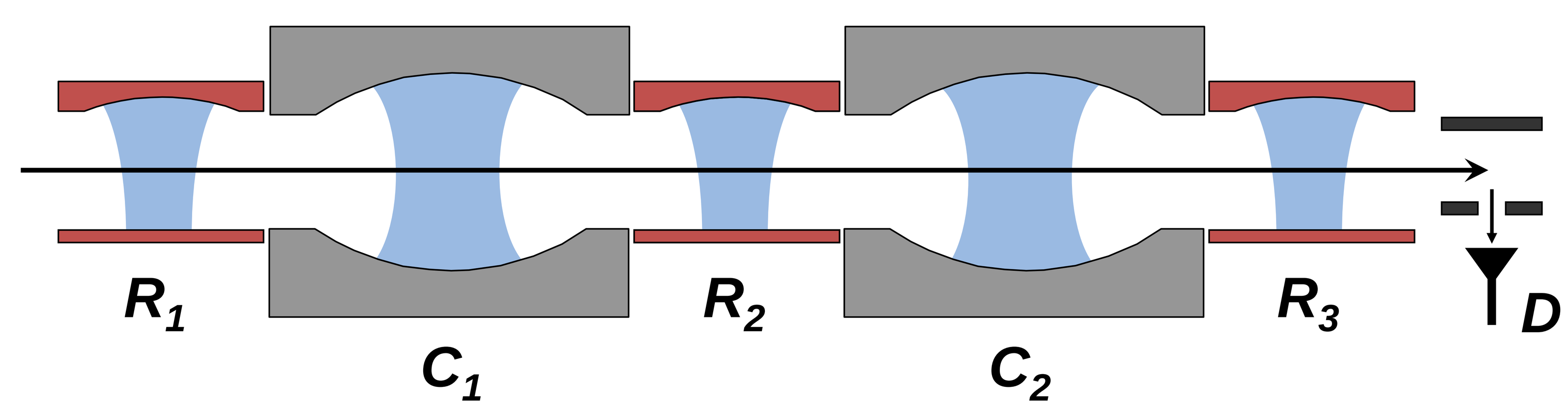
Observation of decoherence, Violation of Bell's inequality

Simulated Bell signal



P. Milman *et al*, EPJD **32**, 233 (2005)

Teleportation of an atomic quantum state



Step 1: Preparation of a cavity EPR pair

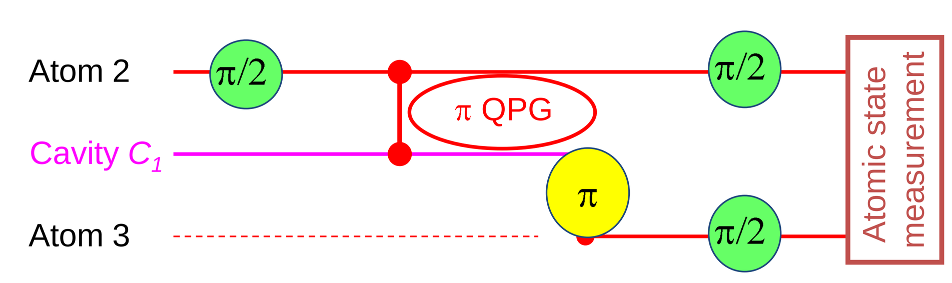
Atom 1: resonant interaction with C_1 (π/2-pulse) and C_2 (π-pulse)

$$\Psi_{\mathrm{ent}} = |g_1\rangle \otimes \frac{1}{\sqrt{2}}\left(|0,1\rangle + |1,0\rangle\right)$$

Step 2: Bell state measurement

State to teleport is carried by **Atom 2** $\quad \Psi_{\mathrm{i}} = \alpha|e_2\rangle + \beta|g_2\rangle$

Bell measurement on **Atom 2** and C_1 (need **Atom 3**)



The four A_2-C_1 Bell states are mapped into 4 detection events:

$e_2e_3 \rightarrow |\Psi^-\rangle \rightarrow -\alpha|0\rangle + \beta|1\rangle$
$e_2g_3 \rightarrow |\Psi^+\rangle \rightarrow \alpha|0\rangle + \beta|1\rangle$
$g_2e_3 \rightarrow |\Phi^-\rangle \rightarrow \beta|0\rangle - \alpha|1\rangle$
$g_2g_3 \rightarrow |\Phi^+\rangle \rightarrow \beta|0\rangle + \alpha|1\rangle$

Cavity 2

Step 3: "Correction" of the teleported state

Teleported state transferred to **Atom 4**: π-pulse in C_2 and correction pulse in R_3

initial state $\Psi_{\mathrm{i}} = \alpha|e_2\rangle + \beta|g_2\rangle$ → teleported state $\Psi_{\mathrm{f}} = \alpha|e_4\rangle + \beta|g_4\rangle$

L. Davidovich *et al*, PRA **50**, R895 (1994)

Other perspectives

- Deterministic source of single atoms
- One-cavity experiments with improved detection efficiency
- Error correction codes for quantum information experiments (several qubits)