Atom-Light Entanglement

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Objectives

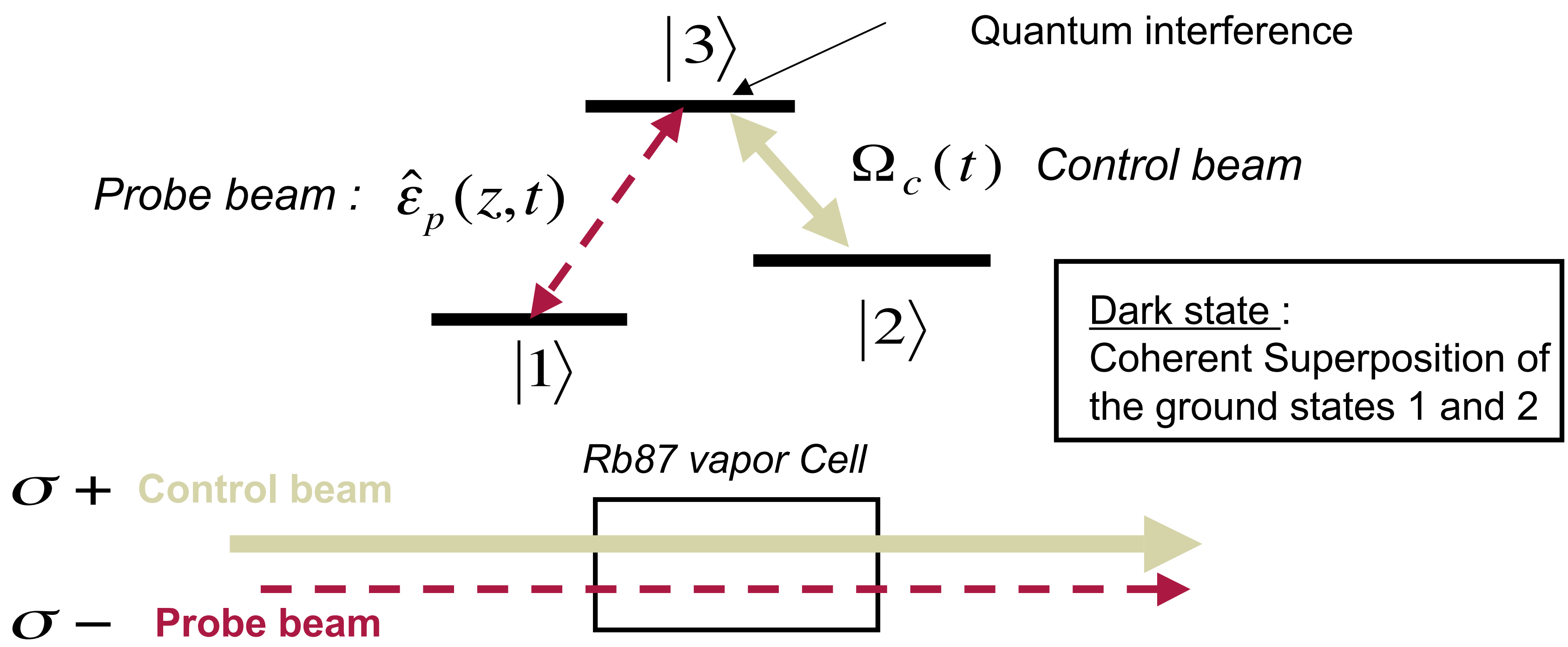
⇨ **Quantum information storage**

AM/PM (Conj. Obs.)
Squeezing
Entanglement

- Quantify EIT-based Quantum memories
  - Theoretically → Stochastic Simulations of light storage
  - Experimentally → Quantum Information Delay/Storage in atomic ensemble.
- Generate non-classical light at atomic wavelengths
  - Self rotation → Too noisy *(M.Hsu et al. To be published in PRA)*
  - SHG/OPO @ 795 nm → In progress

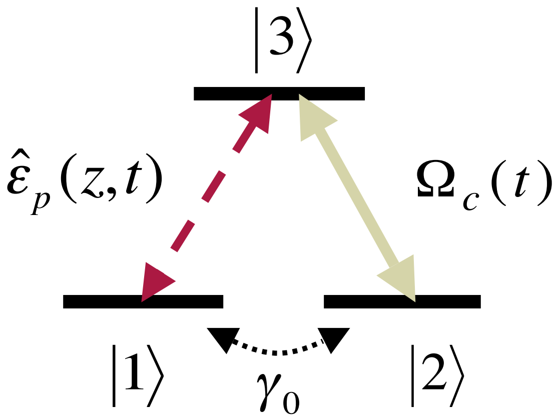
Transfer of quantum states between optical and atomic fields

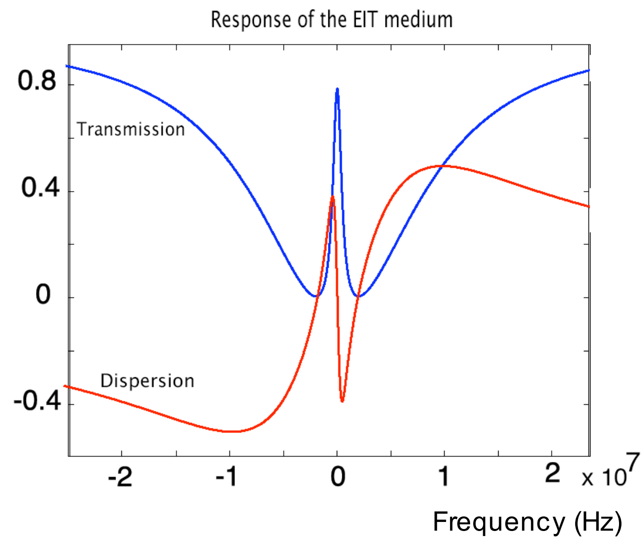
Tool : Electromagnetically induced transparency (EIT)



We want to consider the interaction of the two **quadratures** of the probe field when interacting with such a system in **single pass** and measure their **variances**.

Quantum information delay





Parameters :

$$\begin{cases} \Omega_c(t) = 5\gamma \\ \gamma_0 = 1kHz \\ N = 1.10^{12} at.cm^{-3} \\ \Delta\nu = 2MHz \\ \tau_d = 10\mu s \end{cases}$$

Langevin treatment of the Lambda system in the weak probe approx. :

$$\underline{V^{\theta}_{out}(\omega)} = \eta(\omega)\underline{V^{\theta}_{in}(\omega)} + (1-\eta(\omega))\,\underline{V_{\nu}(\omega)}$$

Input/Output quadrature variances *Vacuum field*

Beam splitter like relation : No extra atomic noise in this regime.

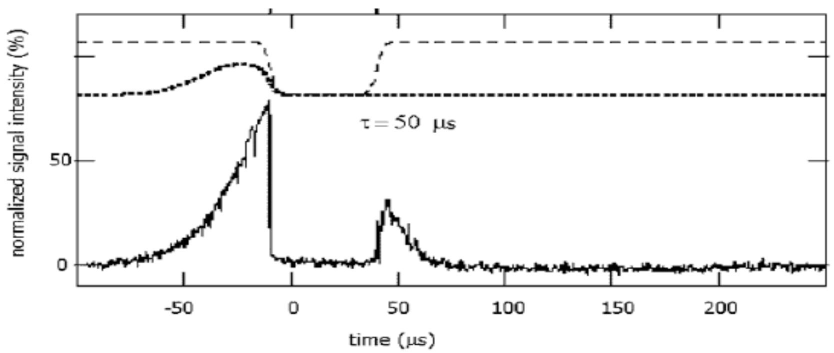
For example : With 4 dB of squeezing input to the system : $V^{sqz}{}_{out}(\omega) = 3.8dB$

A.Peng et al. PRA 71 033809 (2005)

Quantum Information Storage

- Switching off the coupling field : the probe field information is stored into the long lived coherence between the ground states when being delayed
- Switching on the coupling field : the probe field is retrieved

In vapor cells…

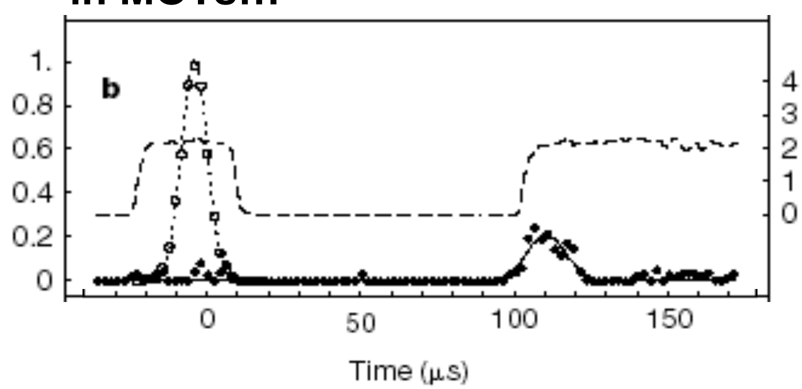


Phillips et al.
Phys. Rev. Lett., 86:783, (2001).

All the experiments in vapor cells present so far the same exponentially decaying output pulse….

Controversy on the interpretation.

in MOTs…



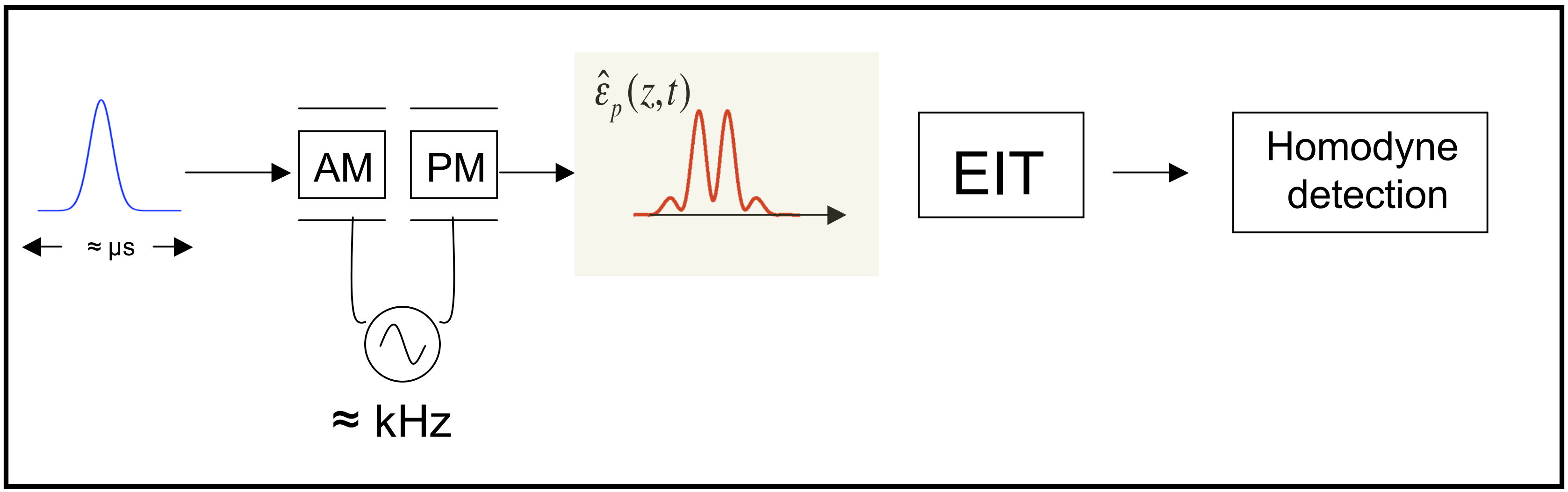
Liu et al.
Nature, 409:490, (2001).

Smaller decoherence rate.
Longer storage time

Quantum Information Storage

- Could the pulse shape be preserved ?
- What is the conjugate observable of a pulse shape ?
- How much quantum information can be stored ?
- Is it a noisy process ?

What we want to do :



Quantum Information Storage

Quantification of this process using quantum information tools:

Similar to Q.teleportation

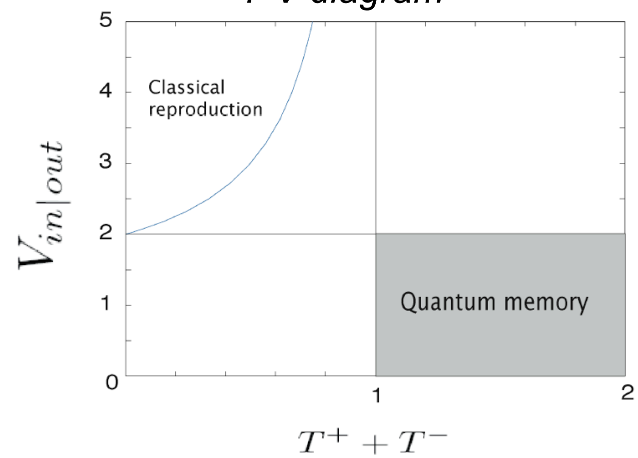
- Average fidelity : $\mathcal{F} = < \Psi_{in} | \rho | \Psi_{in} >$

  Bounded by 1/2 for a classical measure and prepare protocol.
  Hammerer et al. (PRL 2005)

- Signal to noise transfer and conditional variances (T and V).
  Useful when dealing with non-unity gain

  Ralph and Lam criteria (PRL 1998)

T-V diagram



Is it a Quantum Memory when taking into account realistic experimental parameters ?

Modeling using Stochastic methods

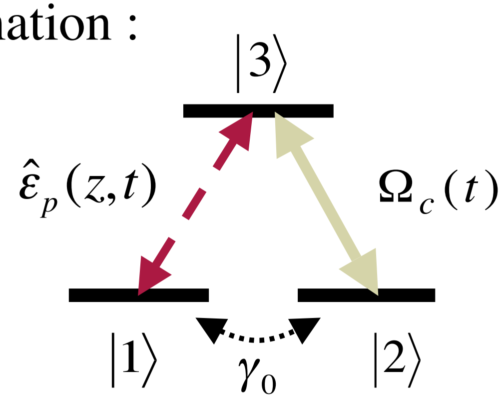
Interaction Hamiltonian for an optically thick medium :

$$\hat{\mathcal{H}}_{\rm int} \;=\; i\hbar n A_{\rm eff}\int_0^l dz\Big[-g\Big(\hat{\mathcal{E}}_p(z,t)\hat{\sigma}_{13}(z,t)+\hat{\mathcal{E}}_p^{\dagger}(z,t)\hat{\sigma}_{31}(z,t)$$

$$+\Omega_c(t)\hat{\sigma}_{32}(z,t)+\Omega_c^*(t)\hat{\sigma}_{32}(z,t)\Big)\Big]$$

Maxwell equations in the rotating wave approximation :

$$\begin{cases} (\dfrac{\partial}{\partial t}+c\,\dfrac{\partial}{\partial z})\;\bar{\alpha}(z,t) \;=\; -gN\;\sigma_{\bar{1}3}(z,t) \\ (\dfrac{\partial}{\partial t}+c\,\dfrac{\partial}{\partial z})\;\bar{\beta}(z,t) \;=\; -gN\;\sigma_{\bar{3}1}(z,t) \end{cases}$$



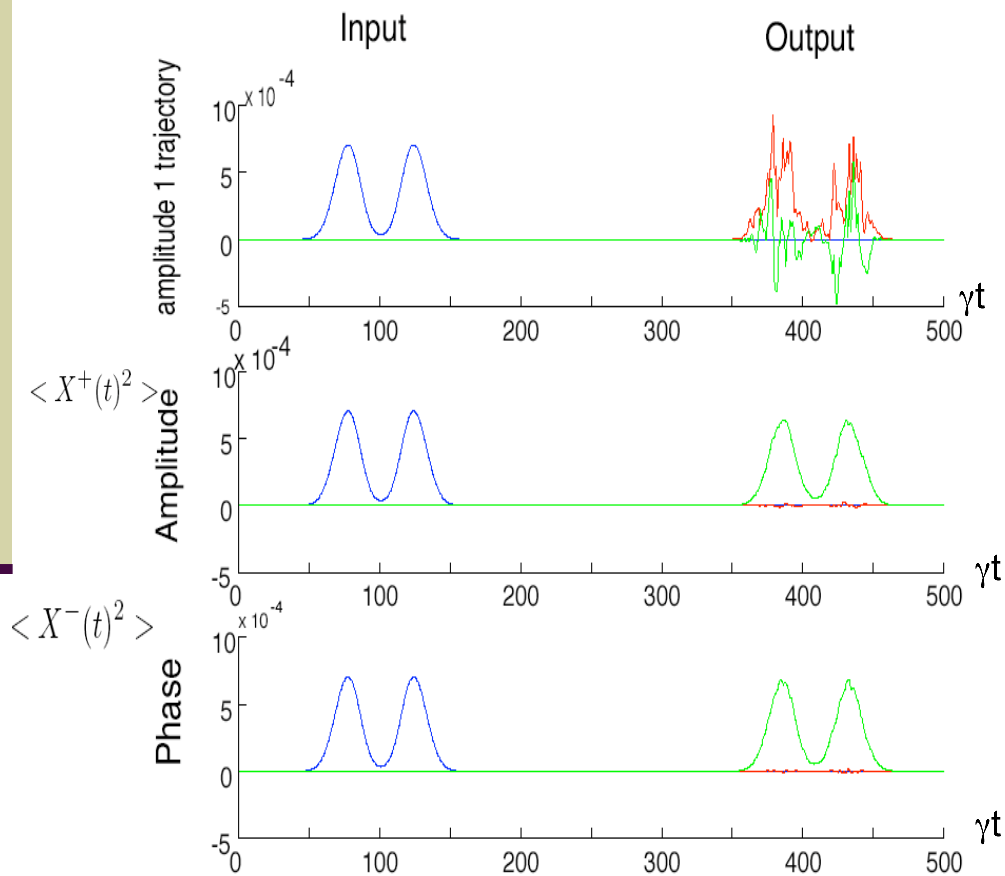
Master equation :

$$\frac{\partial}{\partial t}\hat{\rho} \;=\; i\;\hbar[\hat{\mathcal{H}}_{\rm int},\hat{\rho}]+\mathcal{L}_{13}[\hat{\rho}]+\mathcal{L}_{23}[\hat{\rho}]+\mathcal{L}_{[1,2]}[\hat{\rho}]$$

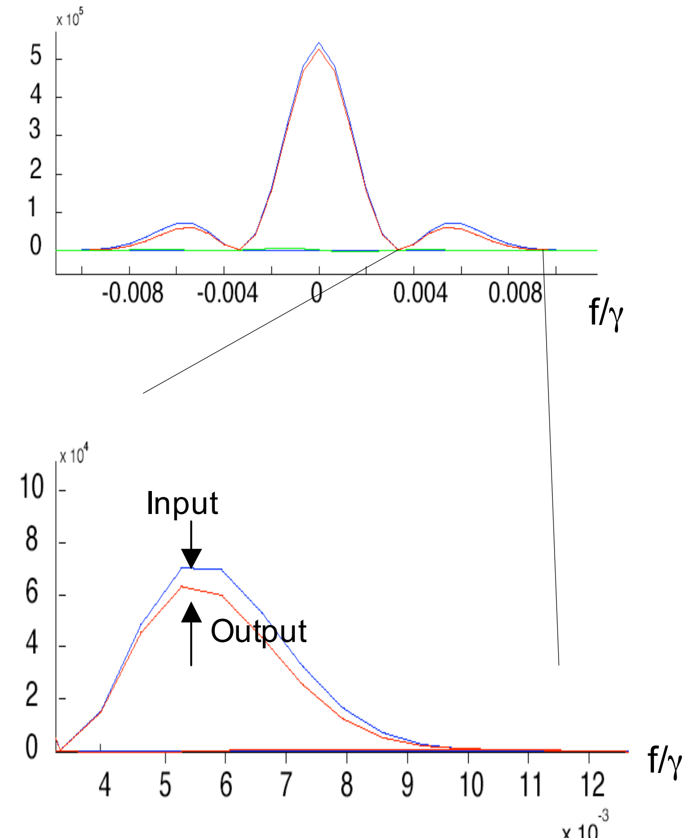
We use the *Positive P representation*,
define normal ordering and obtain a *Fokker Planck equation.*
We finally convert the FPE into a set of *SDE (18 noise terms…)*

Numerical results

Time domain



Fourier domain : $< X^+(\omega) X^+(-\omega) >$



Similar for the phase quadrature…

Realistically…

Next step: Characterize the Quantum state transfer including decoherence factors:

$$\mathcal{L}_{[1,2]}[\hat{\rho}] = \gamma_{coll} \sum_{z_k \in \delta z} (\hat{\sigma}^k_{12}\hat{\rho}\hat{\sigma}^k_{21} - \frac{1}{2}\hat{\sigma}^k_{12}\hat{\sigma}^k_{21}\hat{\rho} - \frac{1}{2}\hat{\rho}\hat{\sigma}^k_{21}\hat{\sigma}^k_{12}) + \gamma_{coll} \sum_{z_k \in \delta z} (\hat{\sigma}^k_{21}\hat{\rho}\hat{\sigma}^k_{12} - \frac{1}{2}\hat{\sigma}^k_{21}\hat{\sigma}^k_{12}\hat{\rho} - \frac{1}{2}\hat{\rho}\hat{\sigma}^k_{12}\hat{\sigma}^k_{21})$$

Collisions

$$\mathcal{L}_{[1,2]}[\hat{\rho}] = \gamma_{deph} \sum_{z_k \in \delta z} \Big((\hat{\sigma}^k_{11} - \hat{\sigma}^k_{22})\hat{\rho}(\hat{\sigma}^k_{11} - \hat{\sigma}^k_{22}) - \frac{1}{2}(\hat{\sigma}^k_{11} + \hat{\sigma}^k_{22})\hat{\rho} - \frac{1}{2}\hat{\rho}(\hat{\sigma}^k_{11} + \hat{\sigma}^k_{22})\Big) + \gamma_{deph} \sum_{z_k \in \delta z} \Big((\hat{\sigma}^k_{22} - \hat{\sigma}^k_{11})\hat{\rho}(\hat{\sigma}^k_{22} - \hat{\sigma}^k_{11}) - \frac{1}{2}(\hat{\sigma}^k_{22} + \hat{\sigma}^k_{11})\hat{\rho} - \frac{1}{2}\hat{\rho}(\hat{\sigma}^k_{22} + \hat{\sigma}^k_{11})\Big)$$

Dephasing

Main theoretical issue: Need for computing time to calculate the noise.

⟹ requires a lot more trajectories (≈10^6)

Main experimental issue:

Need for a good delay (to fit the whole pulse inside the cell)

⟹ narrow transparency window.

⟹ Low frequency information (Squeezing, AM/PM).