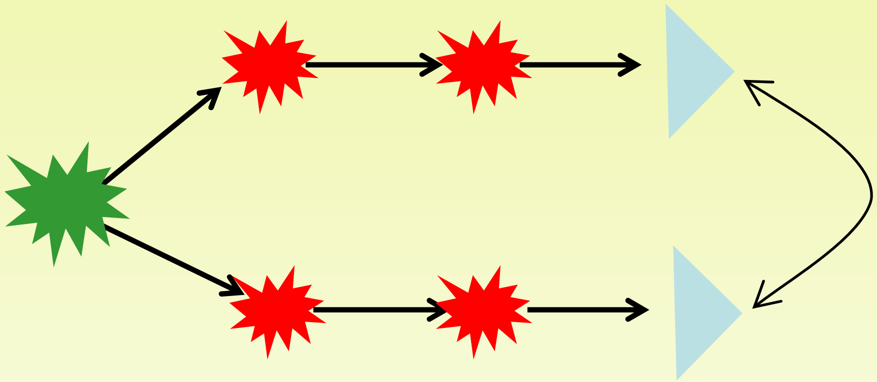
EIT and Raman based quantum memories in atomic ensembles

L. Giner, P. Lombardi, O.S. Mishina, A. Nicolas, A. S. Sheremet, M. Scherman, L. Veissier, J. Laurat, Yuri Golubev, Tania Golubeva
Elisabeth Giacobino

Laboratoire Kastler Brossel,
Ecole Normale Supérieure,
Université Pierre et Marie Curie,
Centre National de la Recherche Scientifique,
Paris, France

Quantum network



Quantum channel
transports / distributes quantum states and quantum entanglement over the network

Quantum node
generates, processes, stores quantum information locally

Objectives:

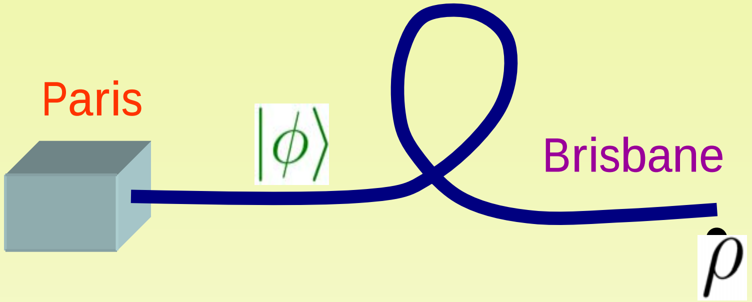
to develop sources for quantum states and quantum entanglement

to develop quantum repeaters to overcome attenuation by optical fibers

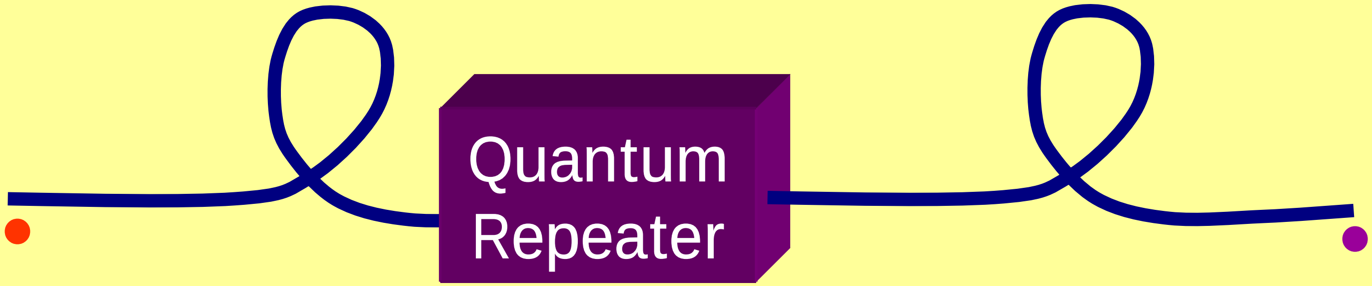
Quantum Repeaters

100 km, Telecom fiber : 99.5 % loss

For 1000 km, and a qubit source at 10GHz, it would take 300000 years to transmit one qubit….



Connection time decays exponentially with the distance

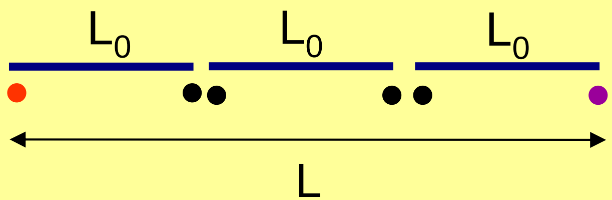


Goal : Connect with a fidelity close to 1 in a “not too long” time

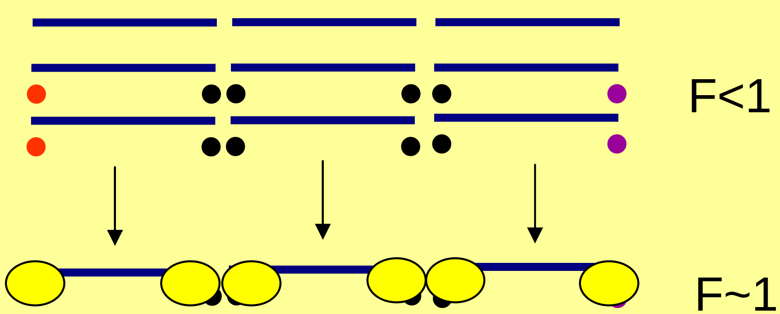
Schemes for quantum repeater proposed by Briegel, Dur, Cirac, Zoller in 1998 and by Duan, Lukin Cirac, Zoller (DLCZ protocol) in 2001

Quantum Repeaters

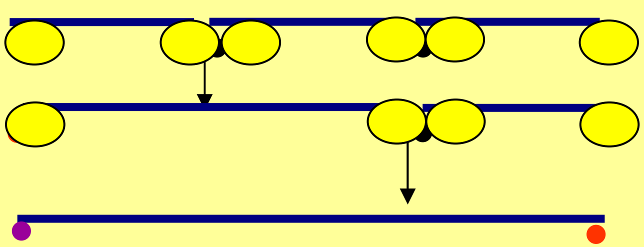
1) Divide into segments and generate entanglement



2) Purify the entanglement



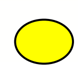
3) Entanglement swapping



Fidelity close to 1, long distance… But time exponentially large with the distance

Entanglement (often) and purification (always) are probabilistic : each step ends at different times.

« Scalability » : requires the storage of entanglement, which enables an asynchronous preparation of the network

 **: Quantum Memories**

Quantum memory : a quantum interface between light and matter

Goal:

achieve storage and retrieval of non commuting quantum variables with a fidelity higher than classical

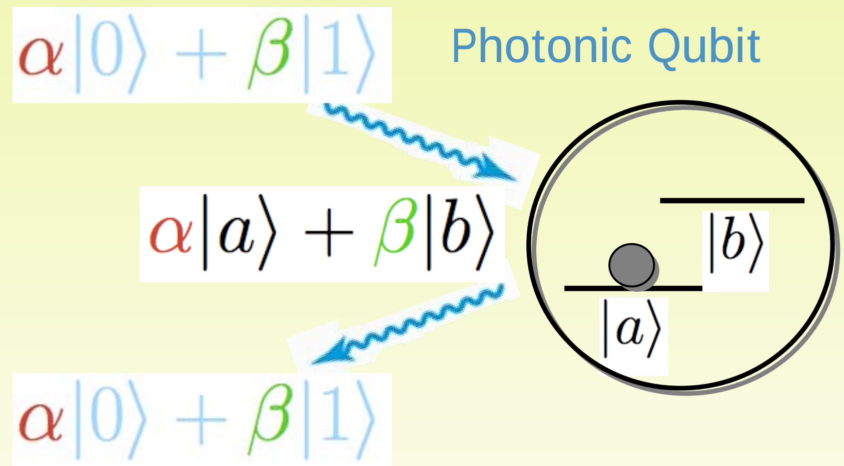
General Strategy:

Mapping a quantum state of light into a quantum superposition of states in an atomic medium

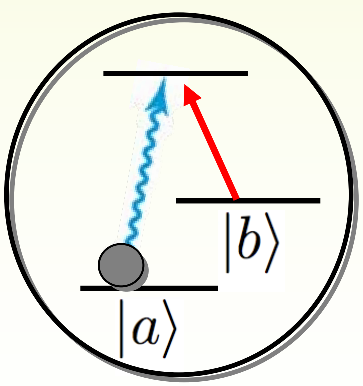
Quantum Memories

Objective : Storing without measuring and reading on demand,
i.e. a coherent and reversible transfer between atoms and light.

Strategy: Mapping light quantum superposition into quantum superposition of elements the storing medium



But |a> and |b> usually have to be ground states to avoid fast decoherence

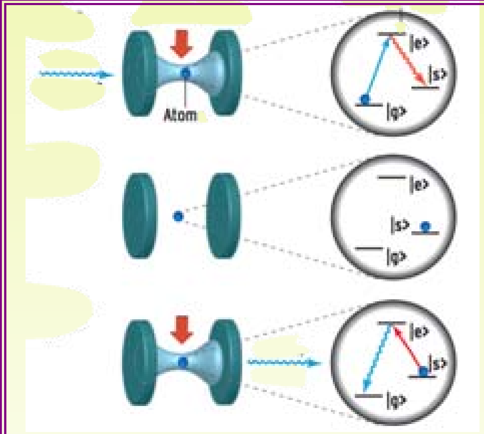


General recipe: Two ground states connected via an excited state by a control field

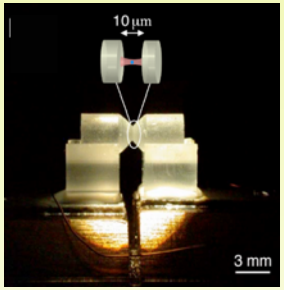
Other desiderata : λ, bandwidth, memory time, multimode…

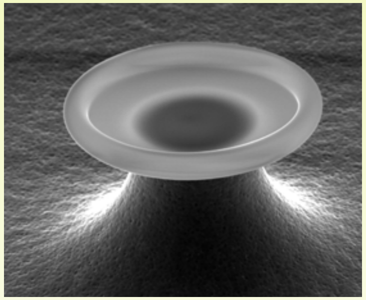
Quantum Memories : an Outlook

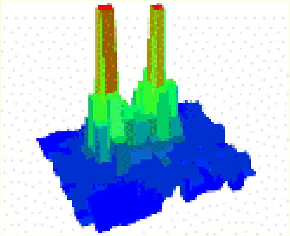
Single Atom



Cavity Quantum
Electro-Dynamics
(strong coupling)





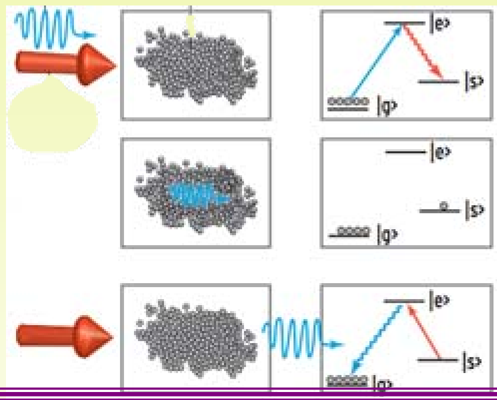


- Single trapped atom in a cavity (Kimble 2007, Rempe 2011)
- Quantum dot « molecules » (Shields 2011)

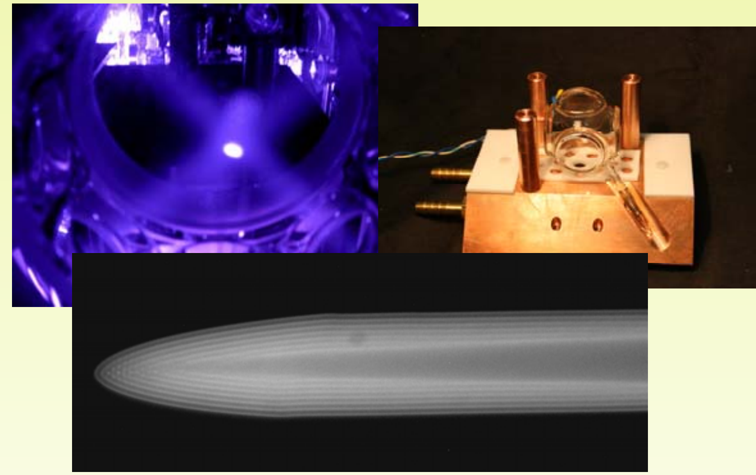
But mode matching is difficult

Quantum Memories : an Outlook

Atomic Ensembles : Collective Excitation



Dynamic EIT
in warm vapors
or cold atoms



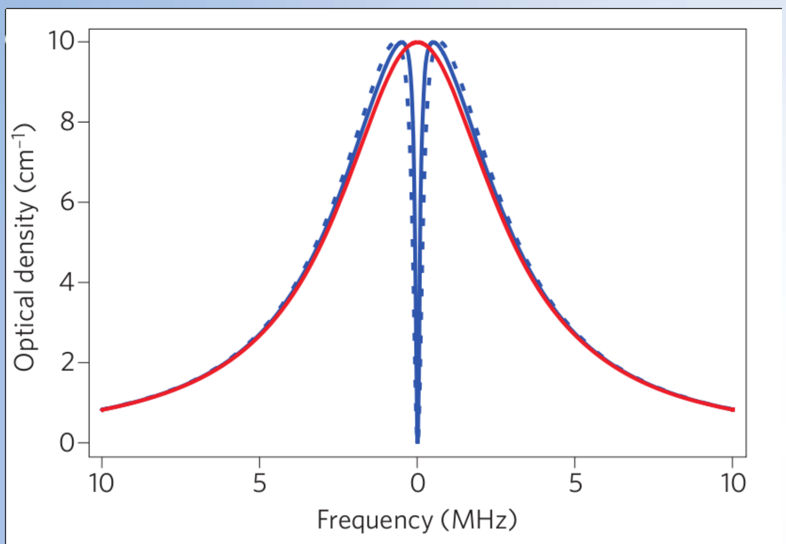
First experiments for optical pulses, based on EIT:
2001 : M. Lukin using Rb vapor, and L. Hau using cold sodium atoms

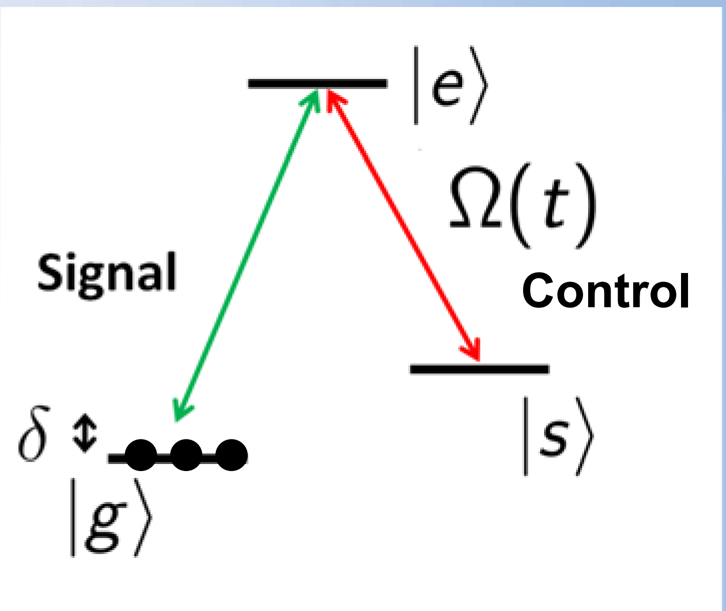
Many experiments since then with efficiencies ranging from a few % to about 50% (M. Lukin, I. Novikova, J.W. Pan, I. Walmsley, P.Lett), but not always in the quantum regime

Also : off-resonant Faraday rotation (Polzik, 2004)

Best results to date ~90% efficiency (PK Lam, 2011) with echo-type technique (Moiseev and Kröll, 2001)

The resource: Electromagnetically induced transparency (EIT)°

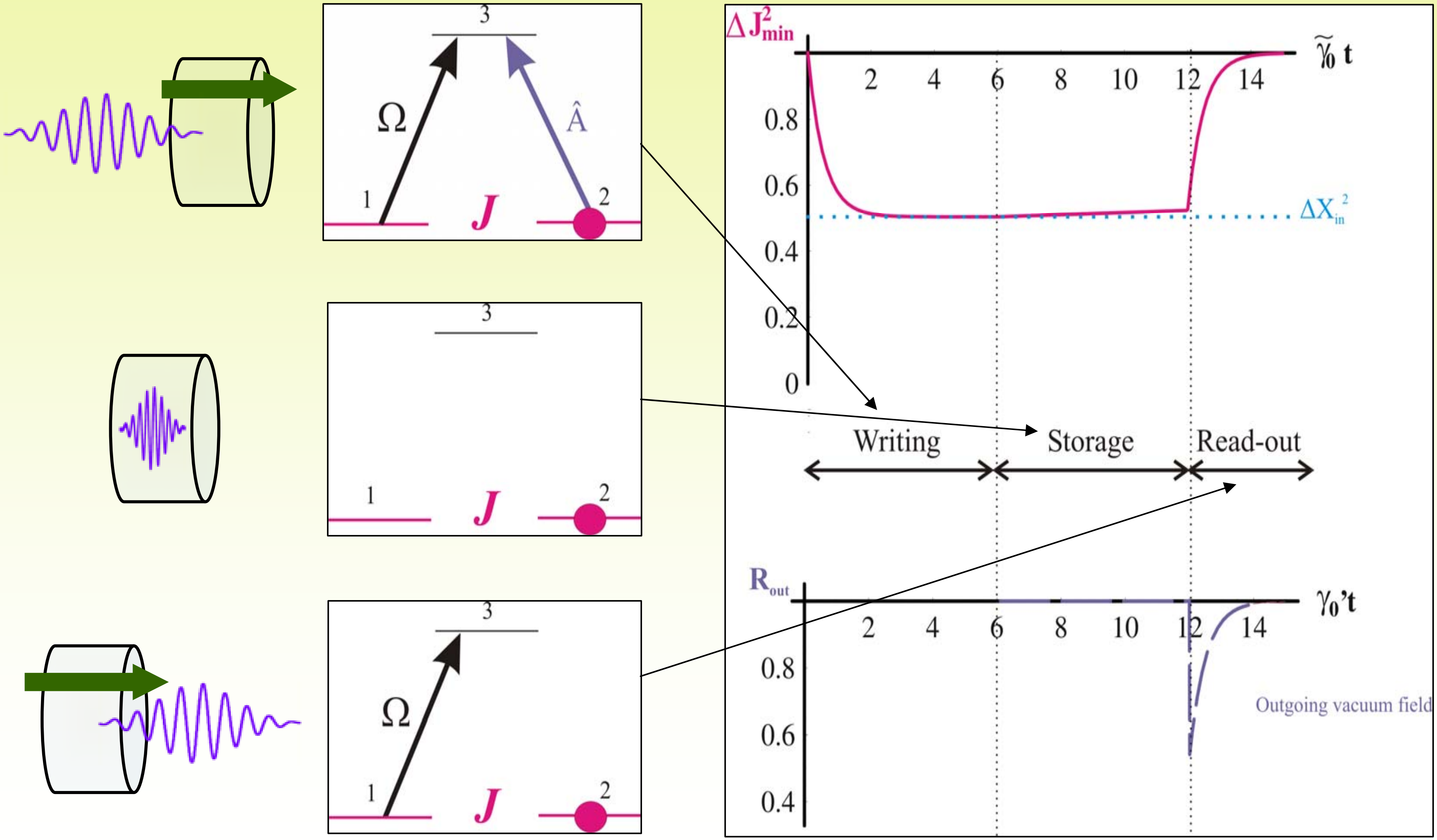




Reduced group velocity

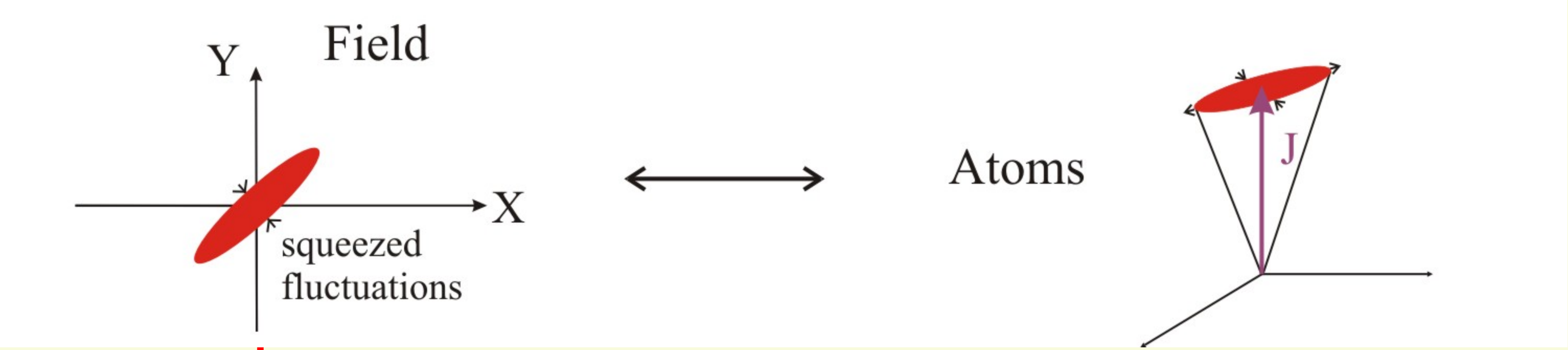
$$v_g = \frac{c}{1 + \frac{g^2 N}{\Omega^2}}$$

Operation of a quantum memory
Dynamic EIT



EIT in the Continuous-Variable Regime

Transfert of the quantum fluctuations from
a light **field** to the collective **angular momentum of atoms**



EIT-based memories

- Storage of squeezed light : <4% noise reduction retrieved

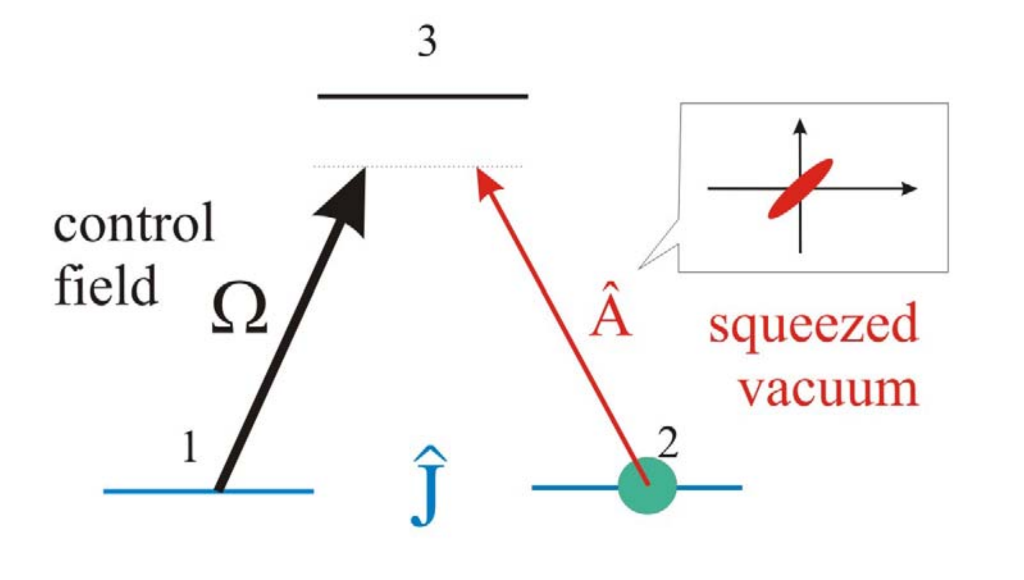
  K. Honda et al., Phys. Rev. Lett. **100**, 093601 (2008) Tokyo
  J. Appel et al., Phys. Rev. Lett. **100**, 093602 (2008) Calgary

- Storage of coherent pulses with quantum fidelity

  J. Cviklinski et al., Phys. Rev. Lett. **101**, 133601 (2008) Paris
  K.F. Reim et al. Phys. Rev. Lett. **107**, 053603 (2011) Oxford
  Fan Yang et al, Phys. Rev. A 83, 063420 (2011) Hefei

An atomic quantum memory

Atoms ↔ field transfer



conditions :

- ► coherence resonantly excited (2-photon resonance)
- ► low losses
  → • Raman or
  • E.I.T.

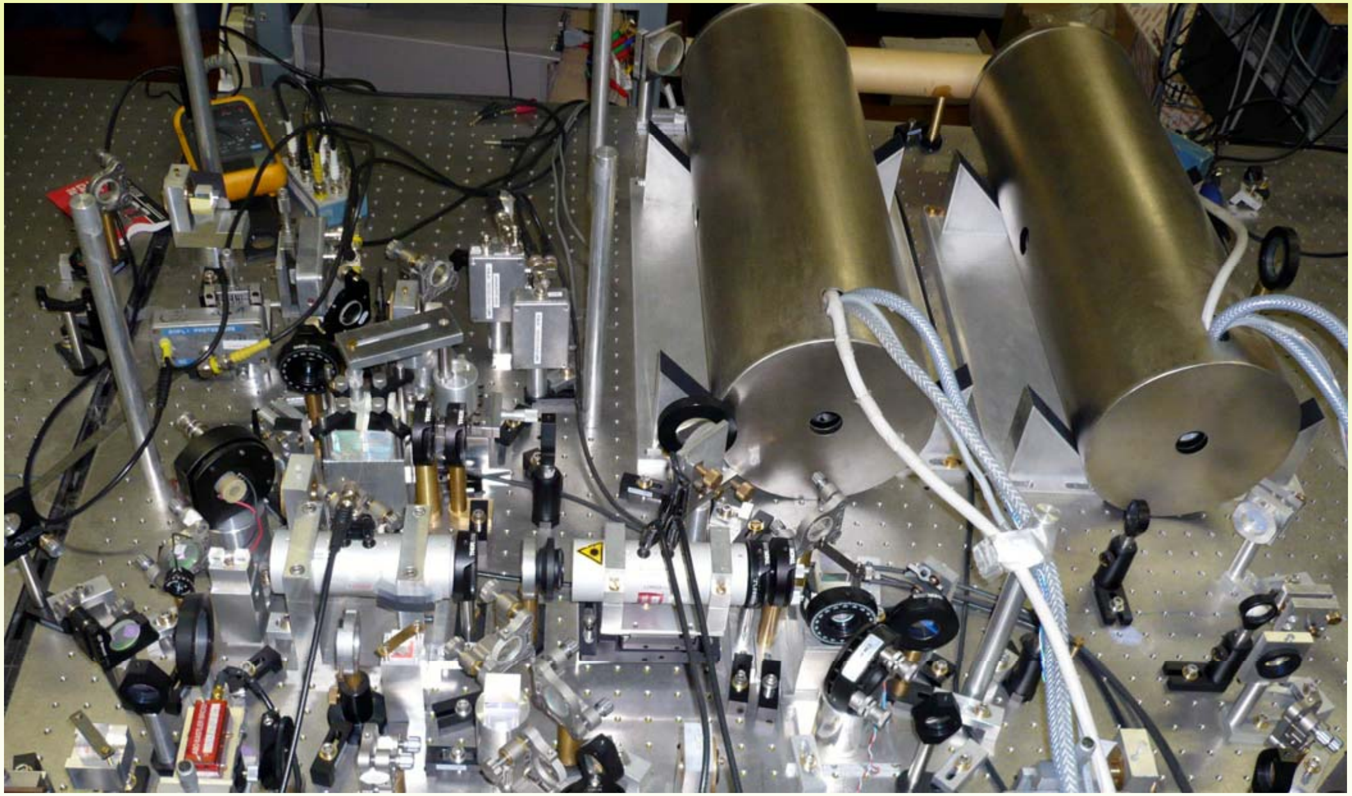
Expected performances :

- ► transfert efficiency
- ► storage time > ms
- ► reading/writing time ~ μs

$$\frac{\textit{atomic squeezing}}{\textit{field squeezing}} > 90\%$$

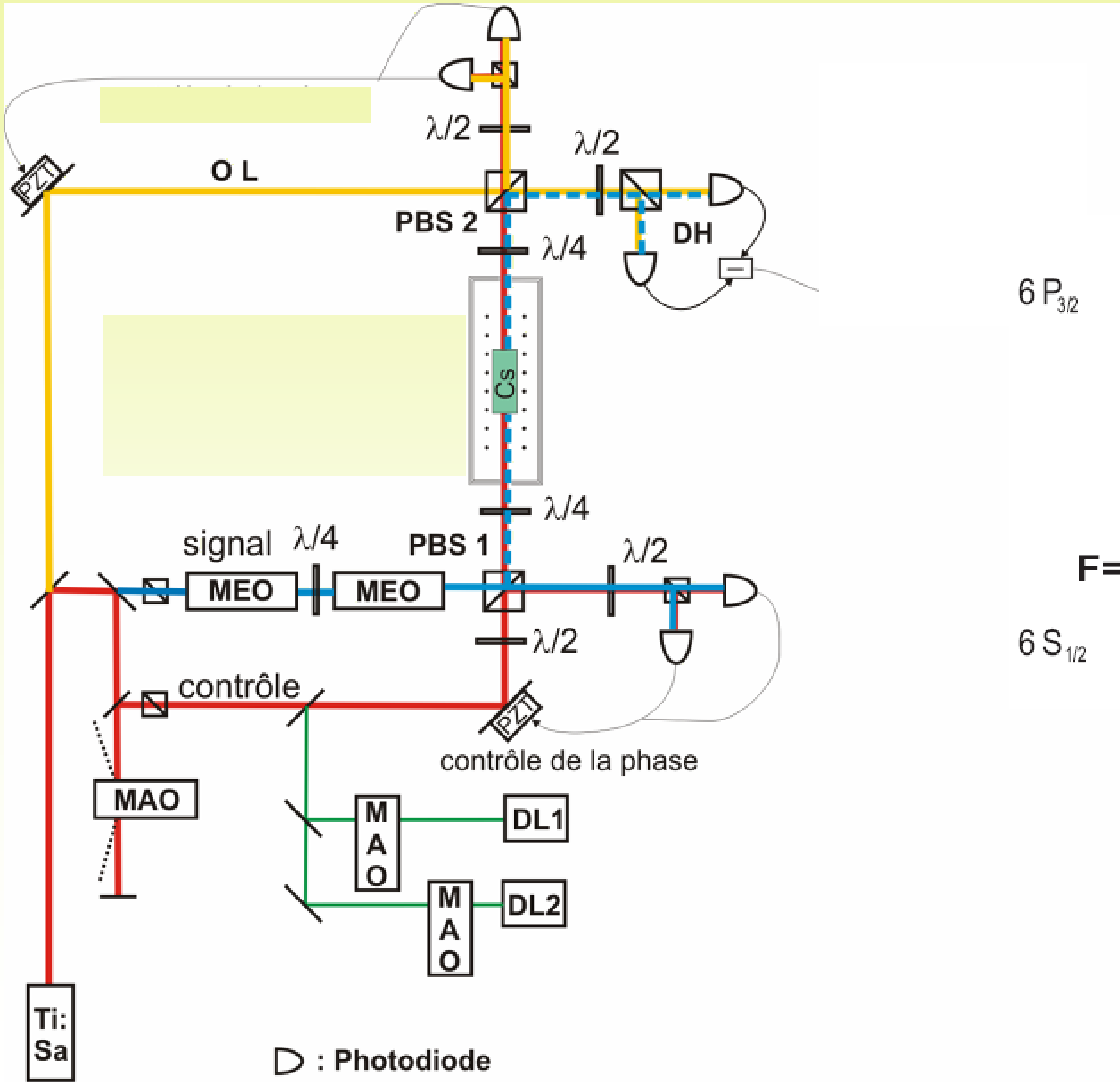
A. Dantan *et al.* PRA 69, 43810 (2004)

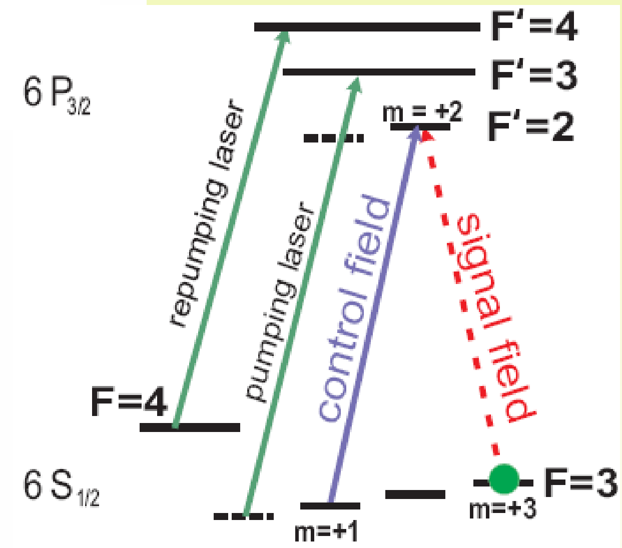
Experiment : warm Cs atomic vapor



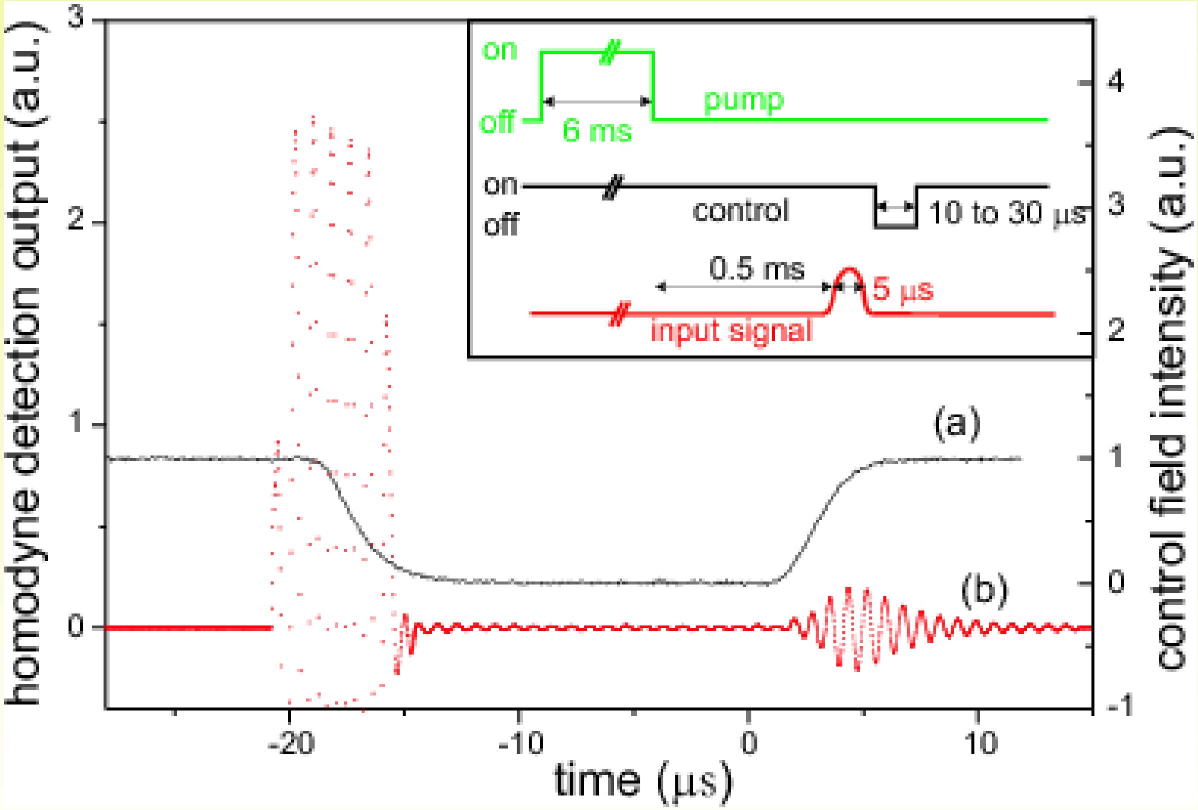
Controlled magnetic environment

Experimental Setup





Experimental sequence



• when the signal pulse is inside the atomic medium, the control field is switched off.

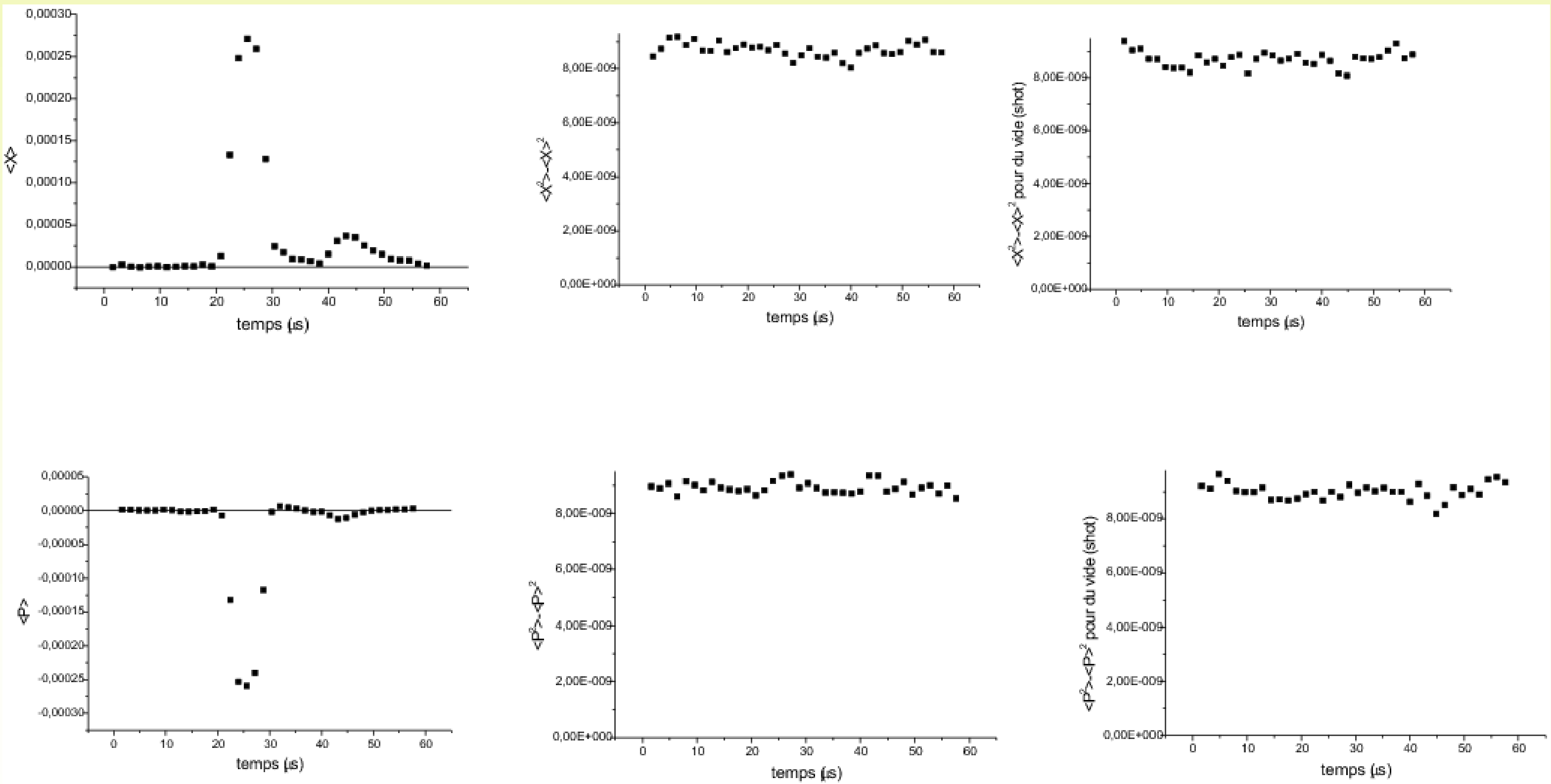
• the two quadratures of the signal field are then stored in two components of the ground state Zeeman coherence.

• for read-out, the control field is turned on again and the medium emits a weak pulse, similar to the original signal pulse

Signal and noise obtained with the homodyne detection

Amplitude quadrature

Phase quadrature



Mean values at Ω

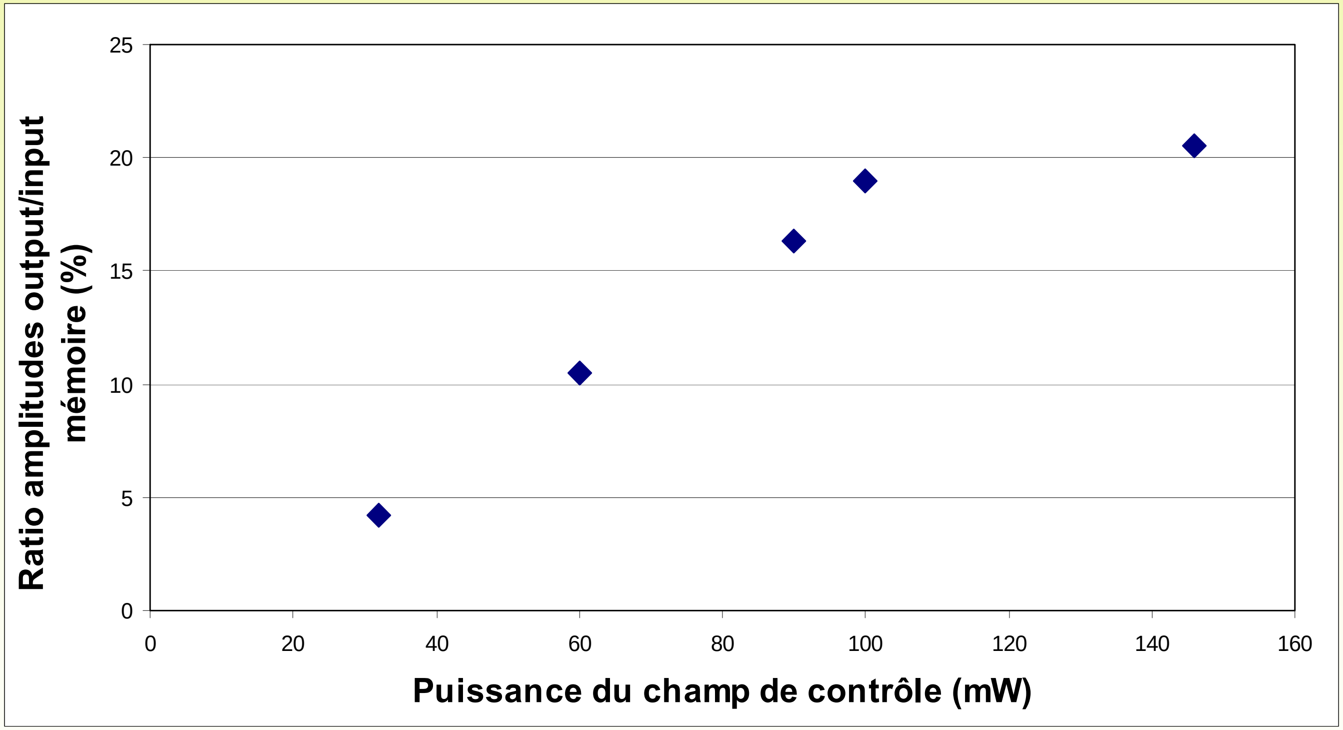
Noise at Ω

Shot noise

J. Cviklinski, et al PRL. 101, 133601 (2008)

Storage efficiency

Measurement of efficiency vs control field power for 4 µs storage time

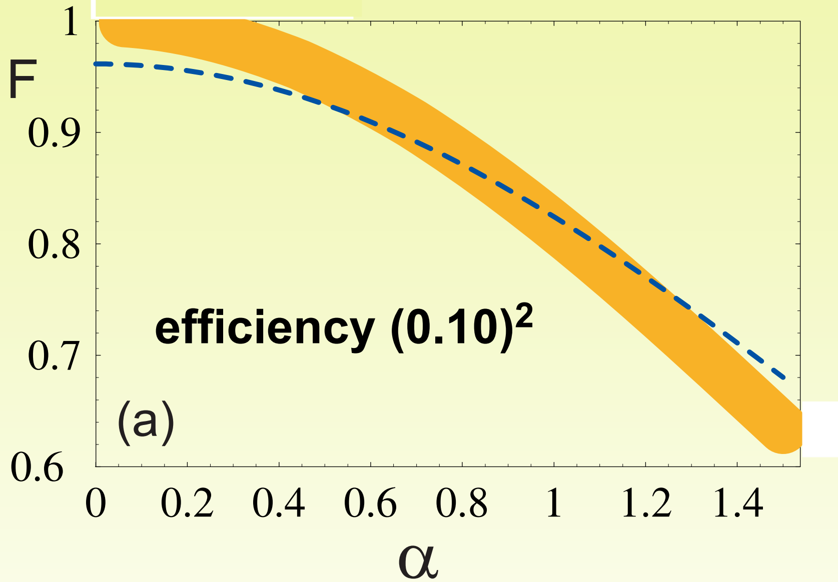


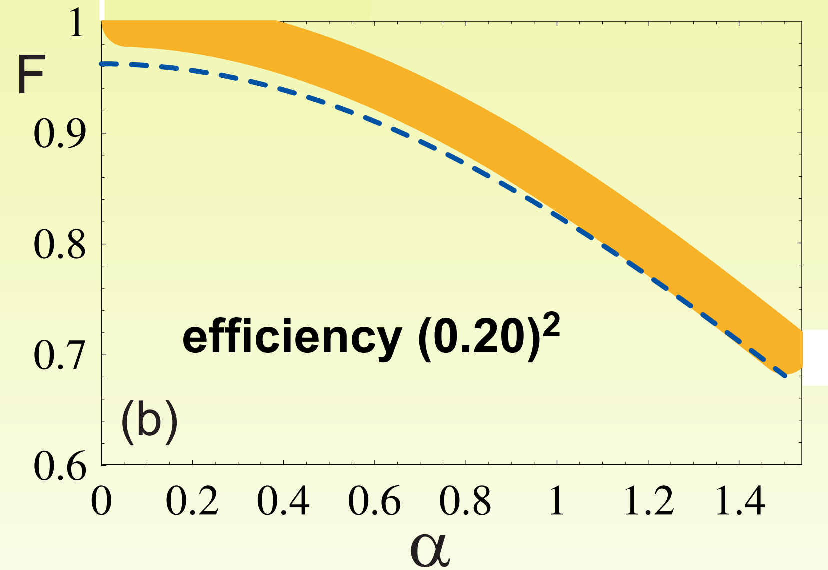
Efficiency increases from $(0.10)^2$ to $(0.20)^2$ when control field power P increases from 60 to 100 mW

But : for P >100 mW, higher noise (~ 20% shot noise)

Fidelity of the quantum memory

$$F = \langle \Psi_{in} | \rho_{out} | \Psi_{in} \rangle$$





For a superposition of faint coherent states Iα>, as a function of <α>

- - - - - - - Fidelity for a classical memory

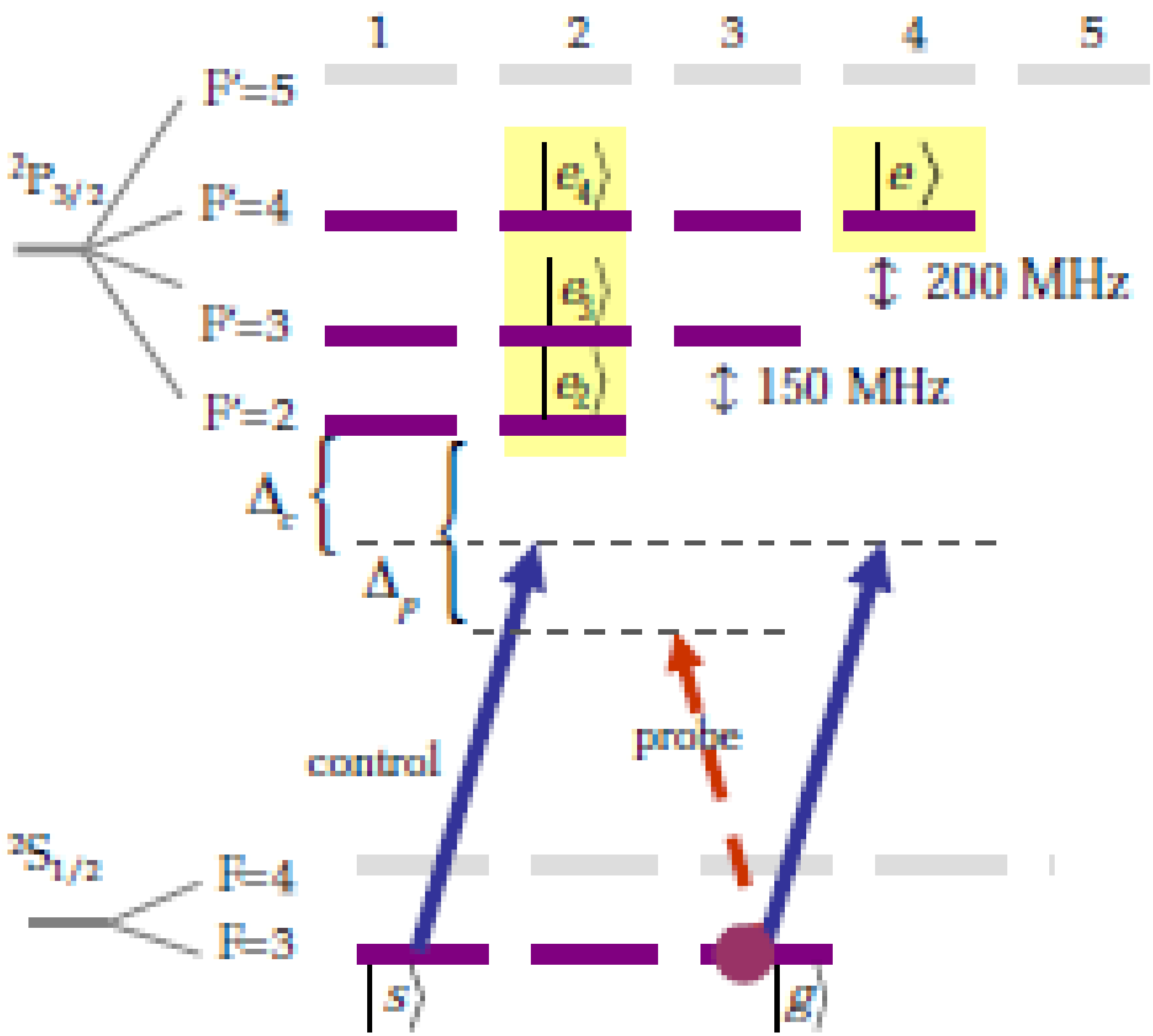
Fidelity for our quantum memory with variance 1 (+or- 5%)

With α~0.5 and no added noise, our device has a fidelity ~0.98, which is in the quantum domain

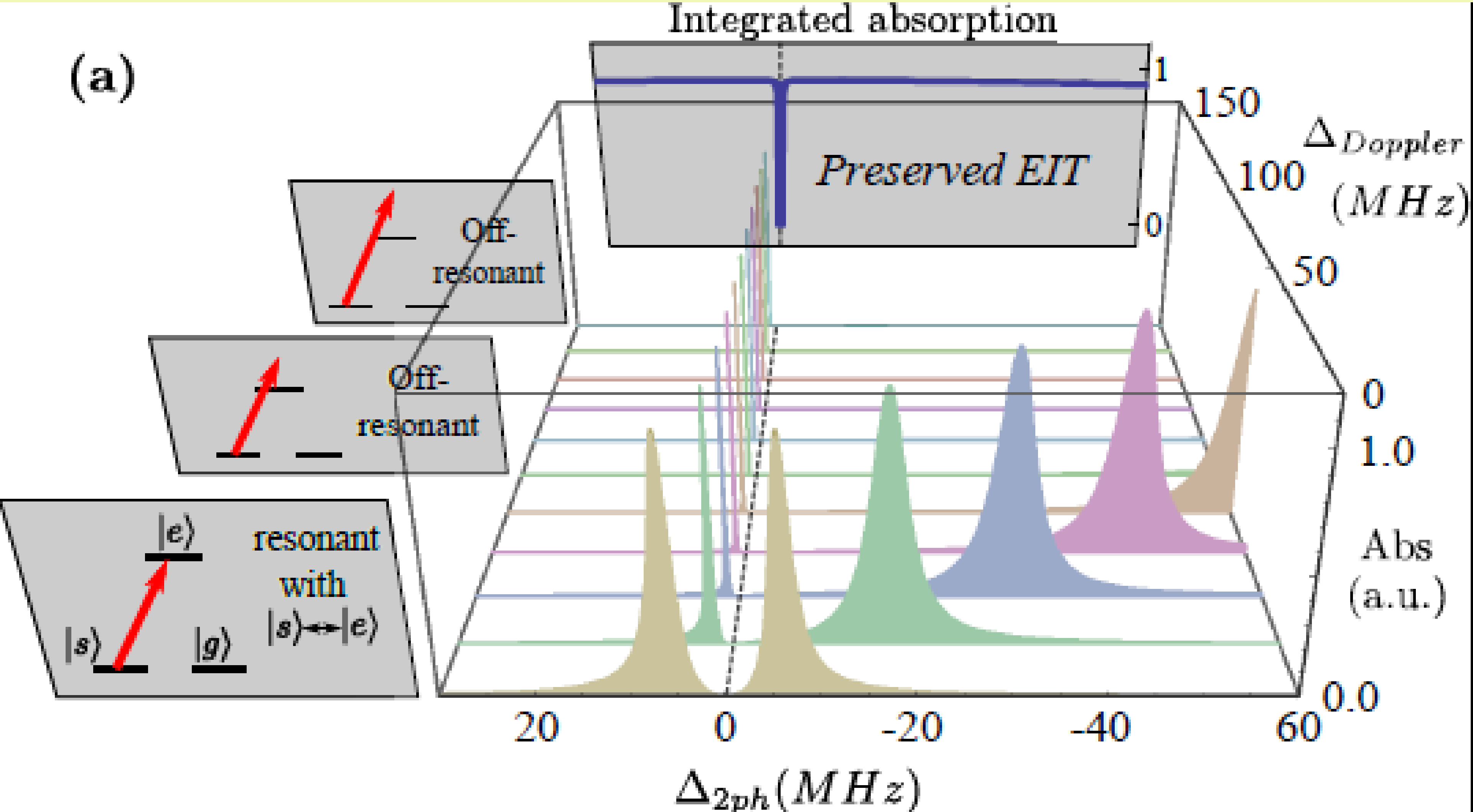
Problem : low efficiency

Ortalo et al, J. Phys B , 2009

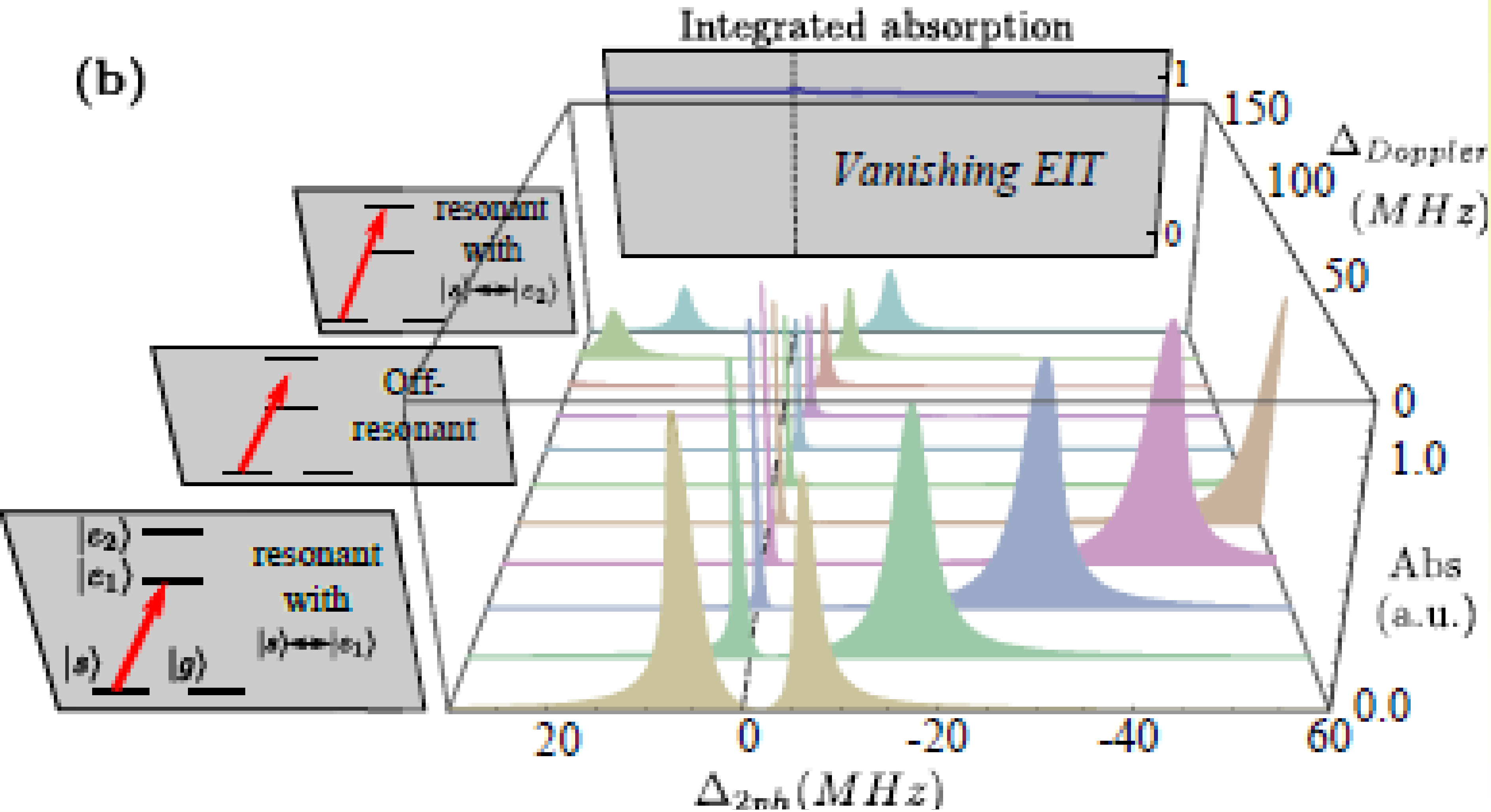
EIT : beyond the Λ approximation



EIT for various velocity classes
3 levels

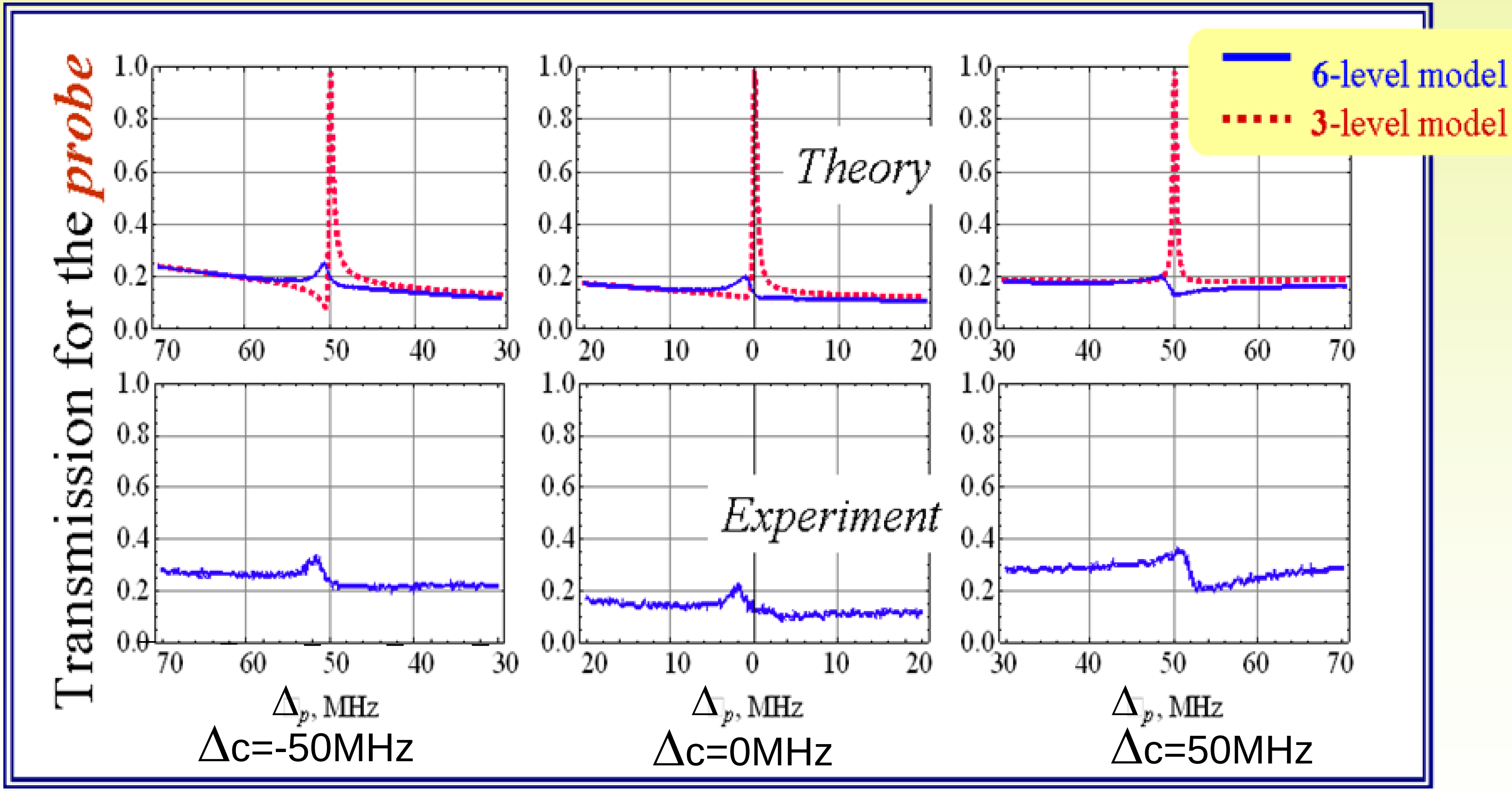


EIT for various velocity classes
6 levels



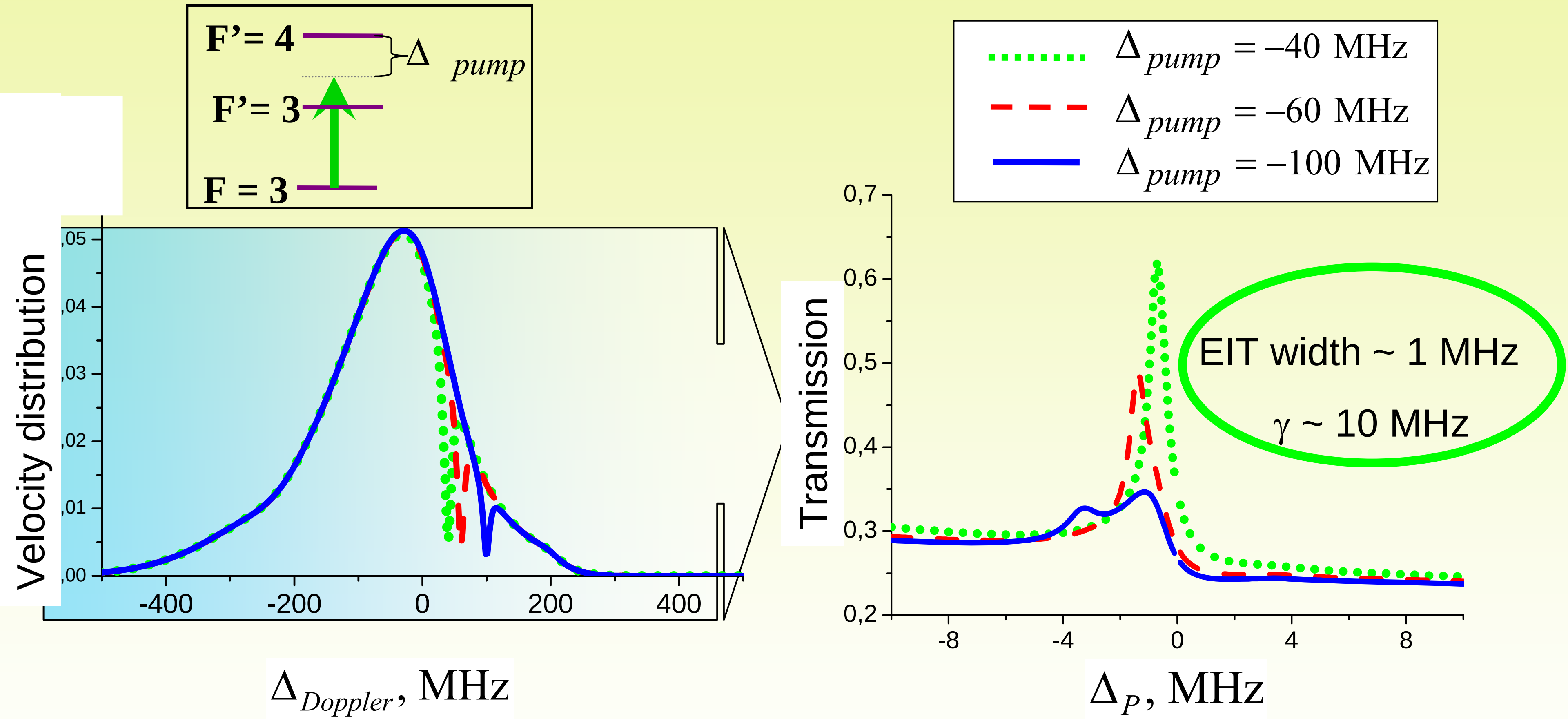
O.S. Mishina, et al PR. A **83**,053809 (2011)

EIT on the Cesium D2 line



How to mitigate this effect ?

EIT Enhancement by hole burning

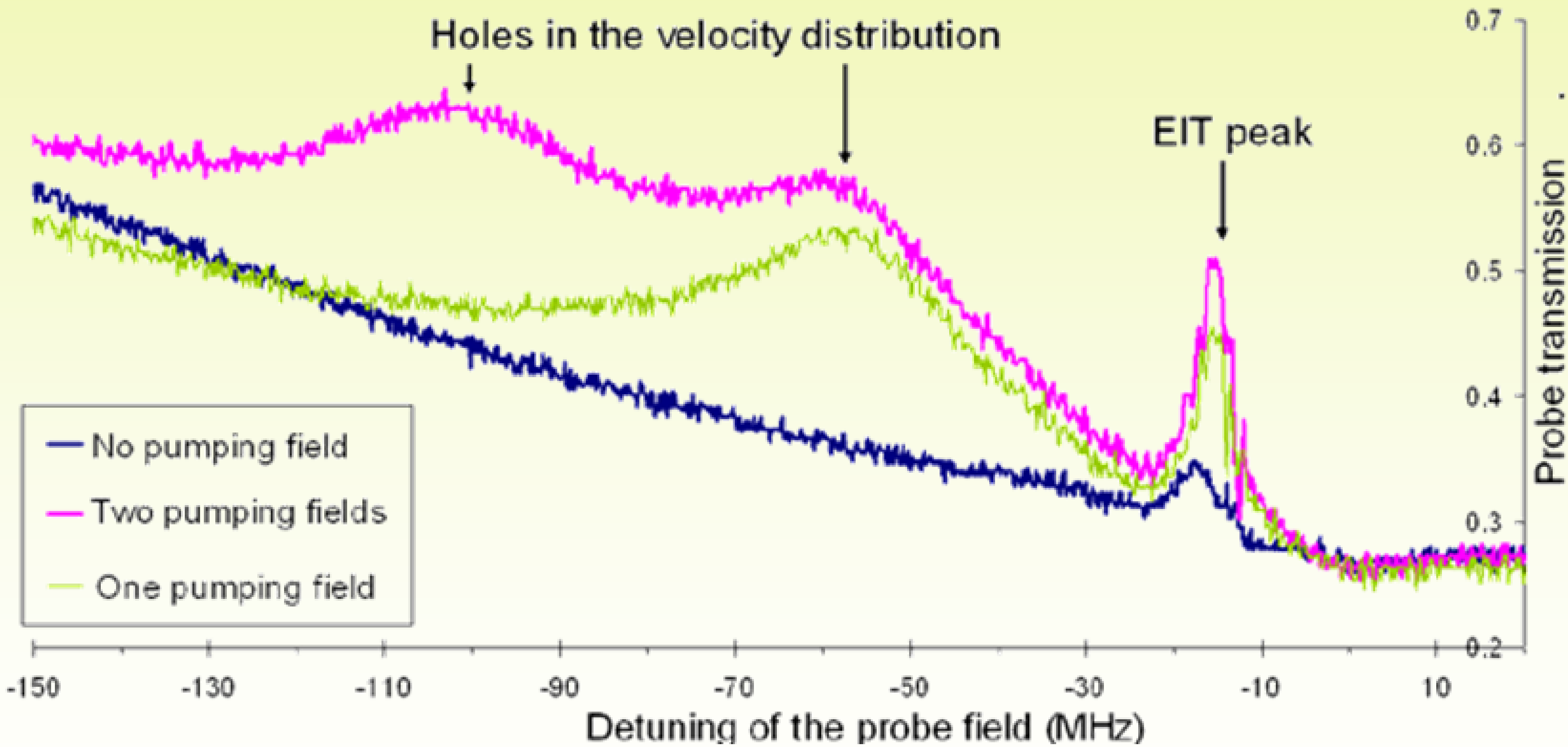


Theoretical prediction

EIT recovered

Experiment

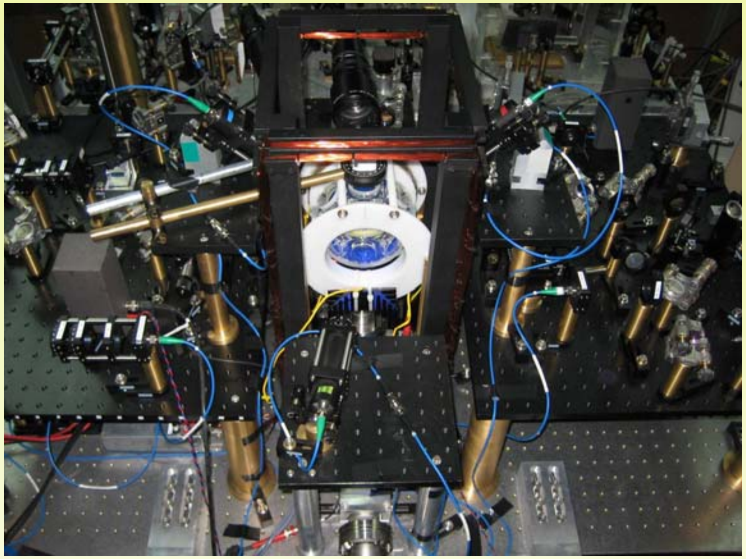
M. Scherman et al, Opt. Expr. 2012



The EIT peak is enhanced by a factor of 5

This result gives good prospect to increase the memory efficiency

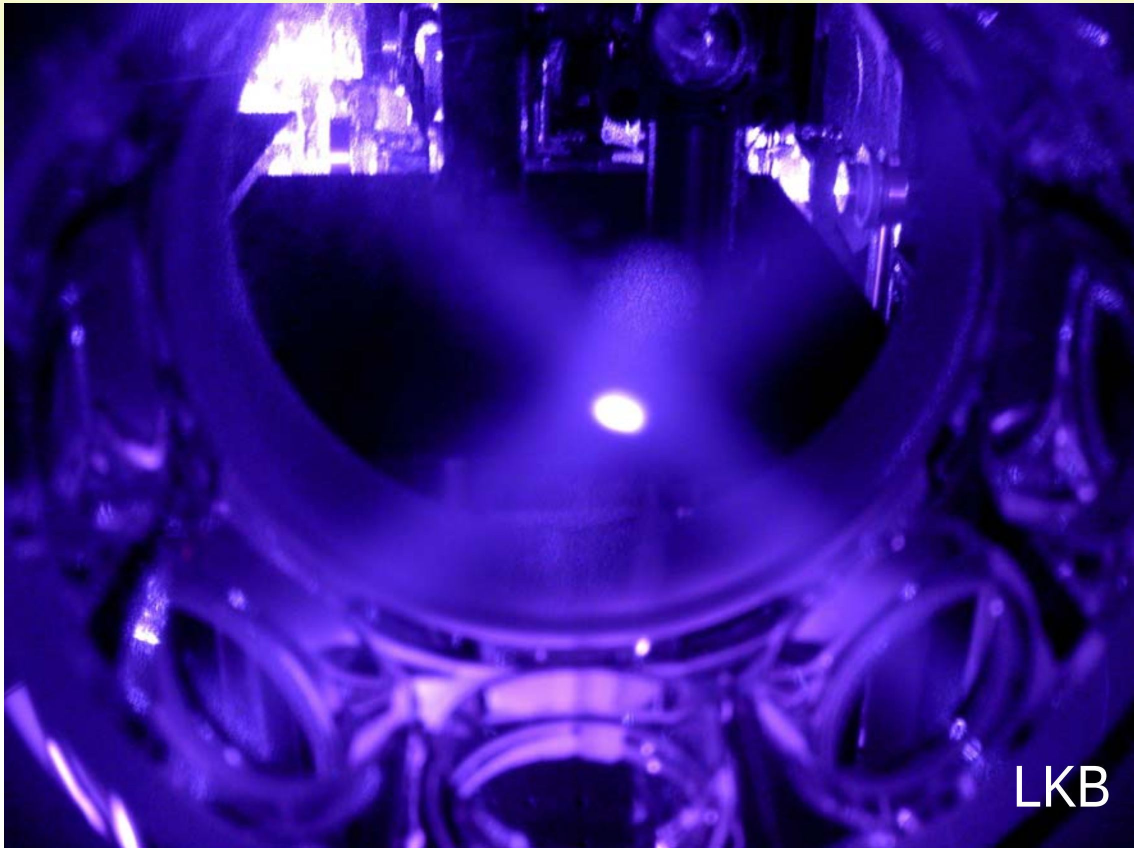
Ensemble of Cold Atoms



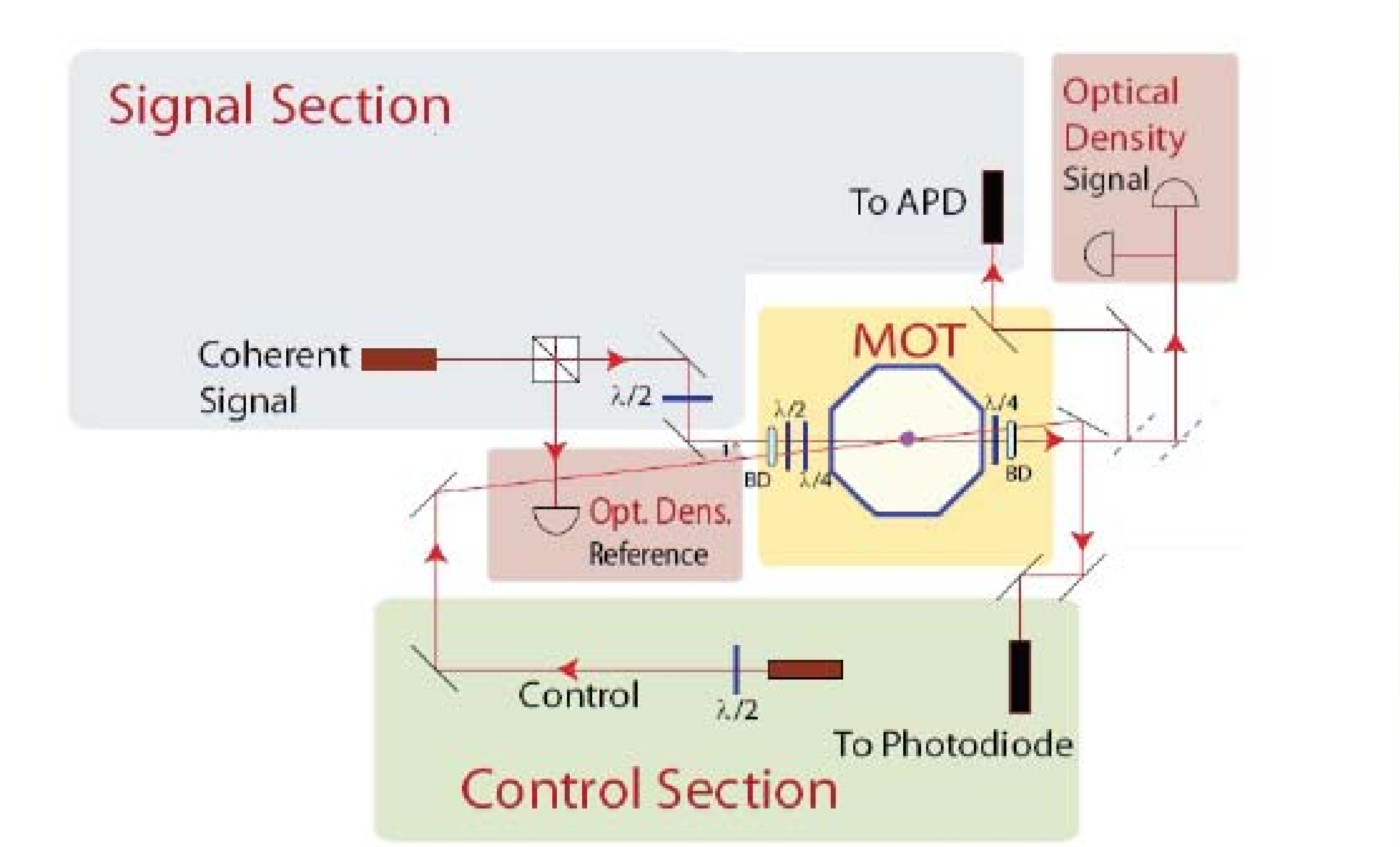
Magneto-optical trap

10^9 atoms in a mm^3 volume

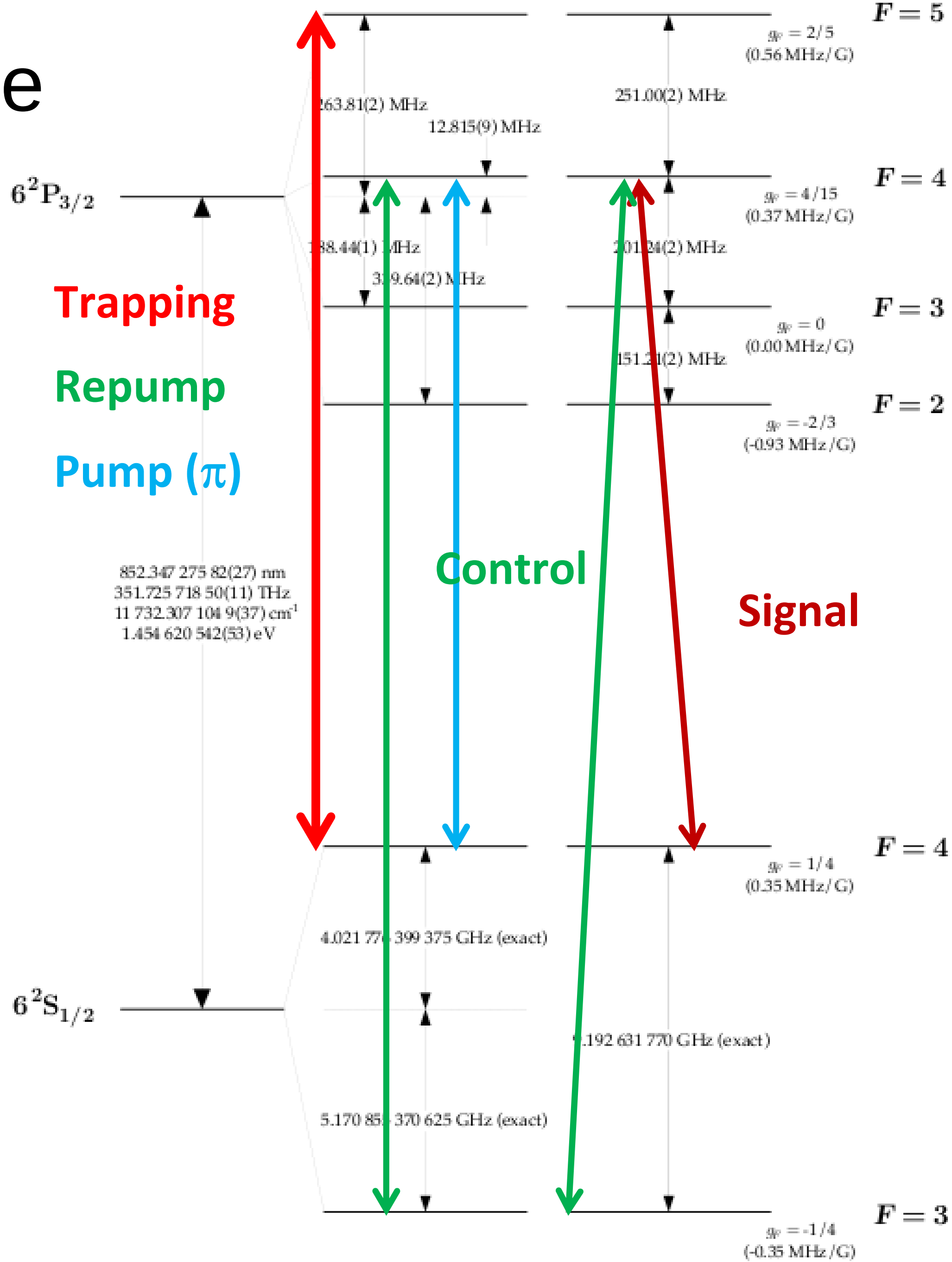
➔Very large optical thickness



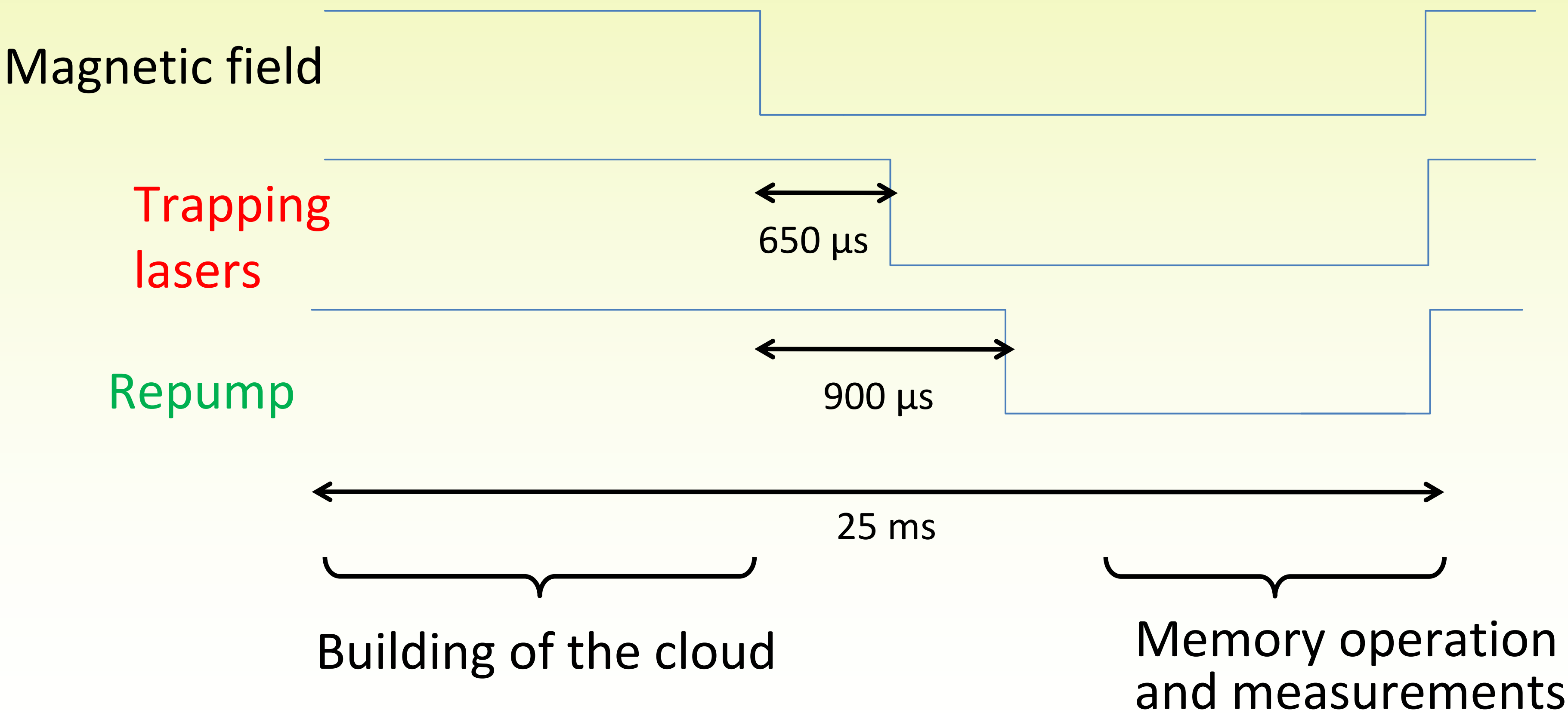
Principle of the experiment



Level scheme

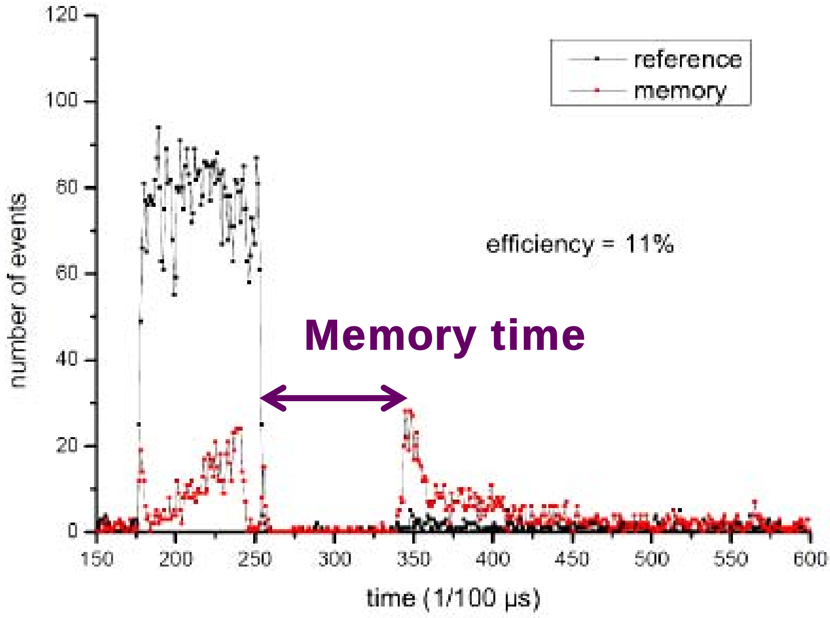


Timing of the experiment

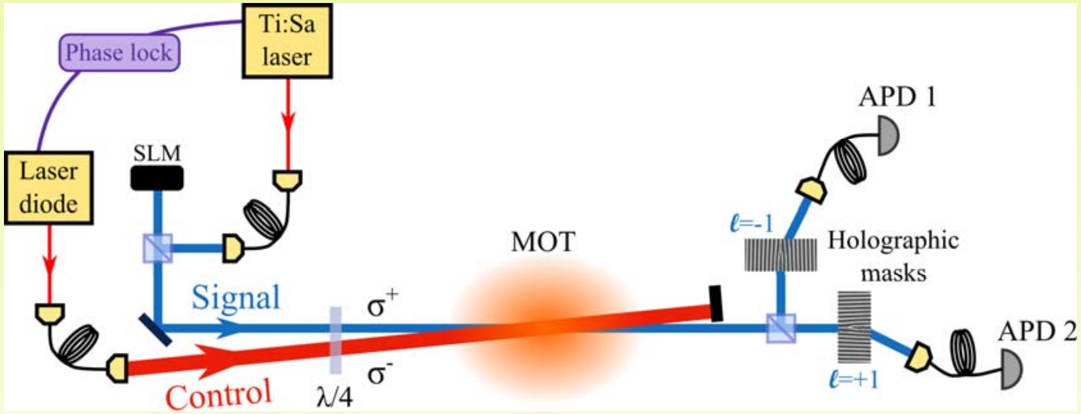


Atomic quantum memory for faint pulses (0.1 photon/pulse)

- EIT dynamic
- Signal Pulse : 1 μs (0.1 photon/pulse)
- Storage time 1 μs
- **Last result : 20 % with a storage time of 20 μs**

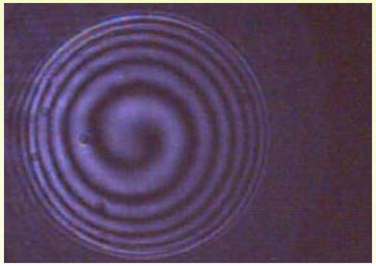


Storage of orbital angular momentum of light in the single photon regime

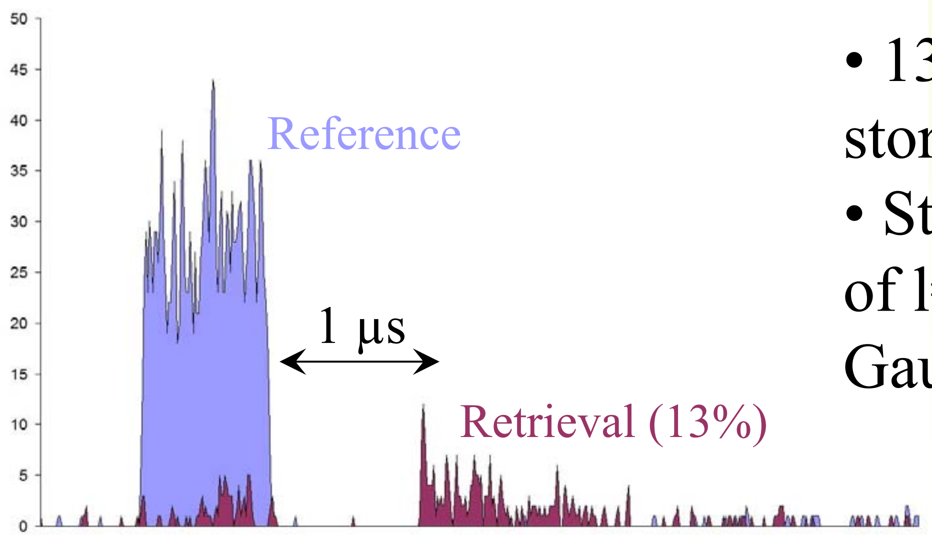


- Qbit basis :

$$\{ |LG_{p=0}^{l=+1}\rangle , |LG_{p=0}^{l=-1}\rangle \}$$



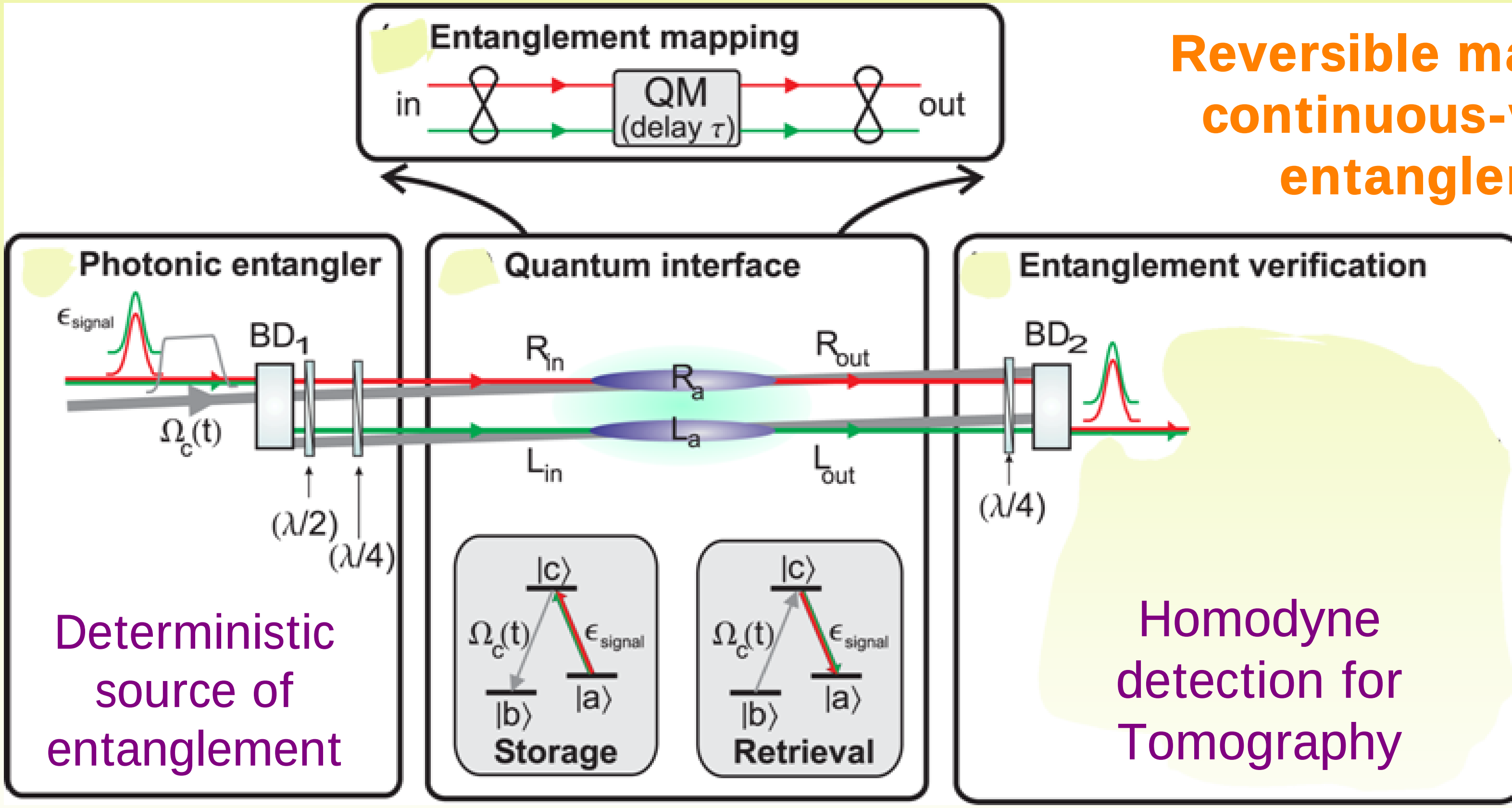
Interference between LG and TEM00 modes

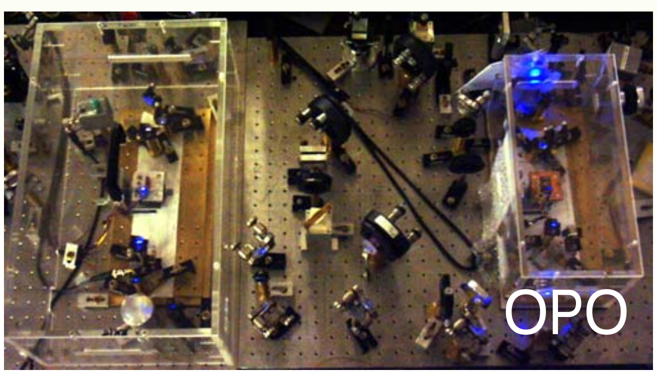


- 13 % quantum efficiency for the storage of l=1 and l=-1 modes
- Storage of a quantum superposition of l=1 and l=-1 modes (Hermite-Gaussian mode)

Towards Deterministic Entanglement

Reversible mapping of continuous-variable entanglement

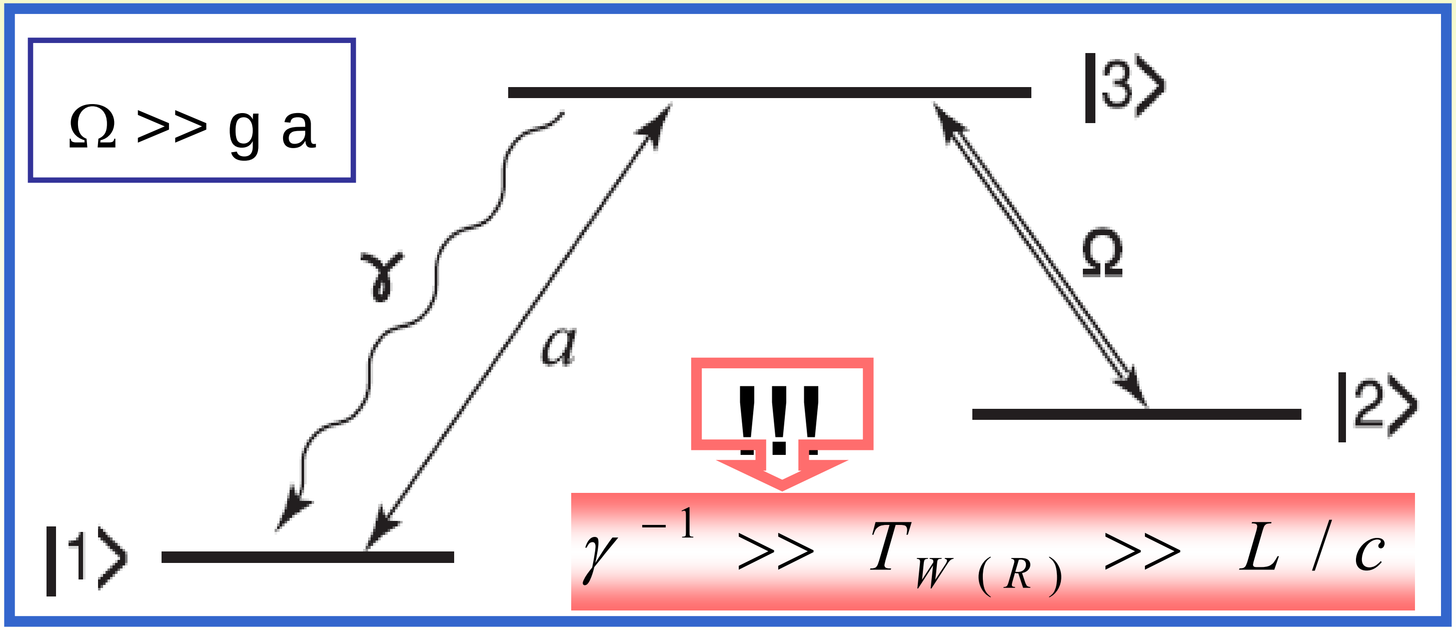




In progress at LKB

High speed atomic memory

Very short light pulse in an atomic ensemble :
the signal and the control pulse are much shorter than the lifetime of the atomic exited state

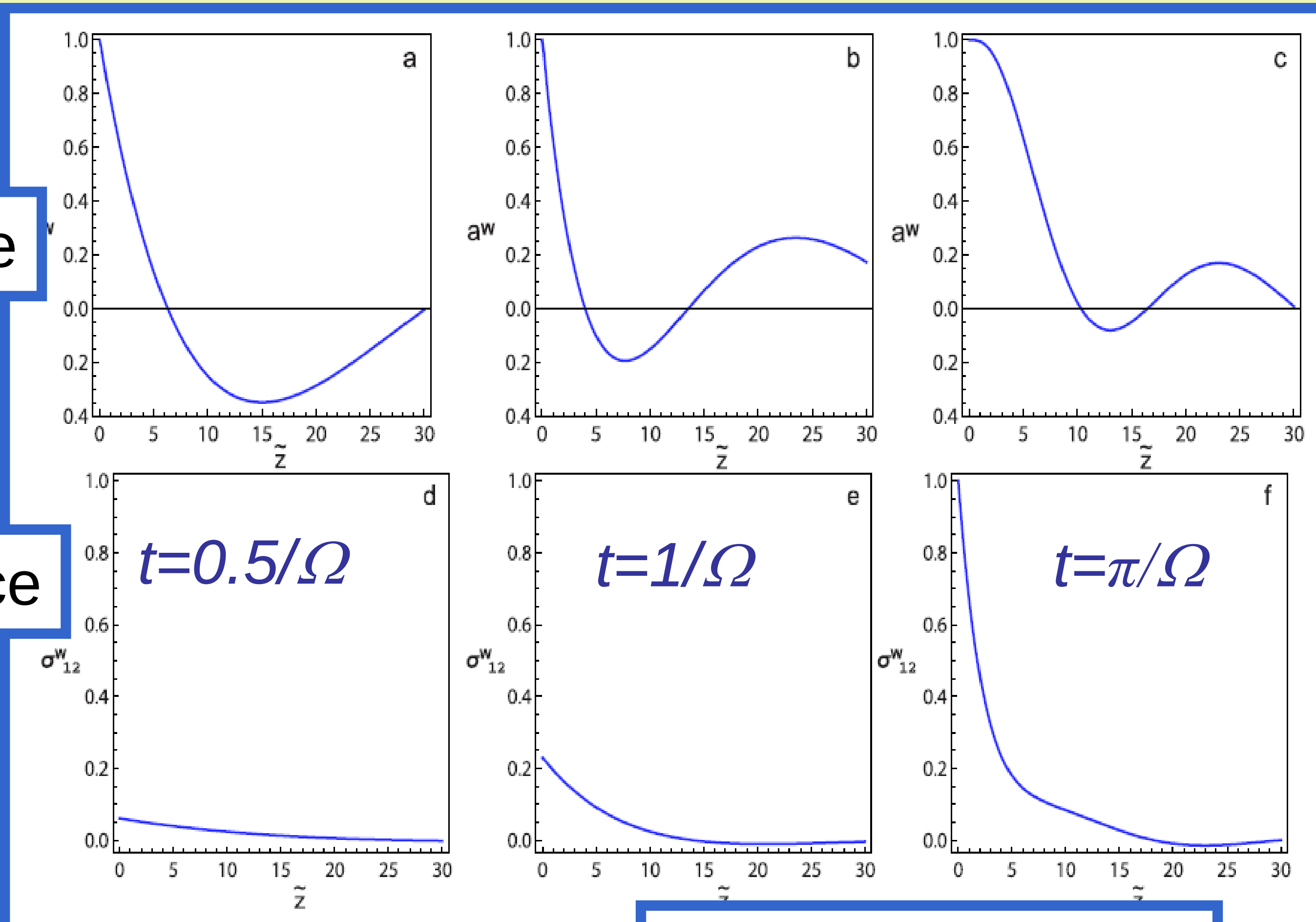


Resonant and Raman case will be considered

System dynamics:
Multiple exchange between atoms and light

Field amplitude

Atomic coherence



Position in medium

$\Delta/\Omega = 0$

Resonant case

T. Golubeva, Yu. Golubev, et al, PRA **83**, 053810 (2011)

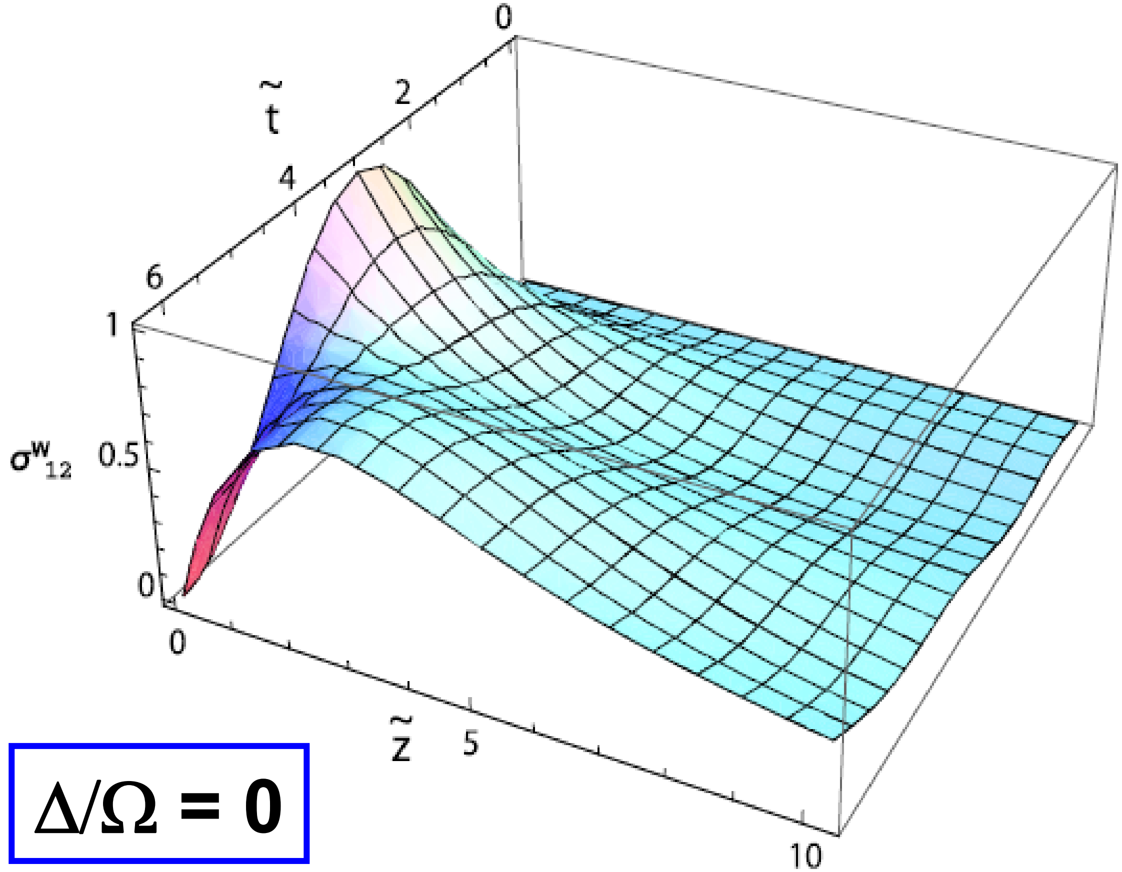
Distribution of the atomic coherence σ^W_{12} in space and time

$$\tilde{L} = \frac{2g^2N}{\Omega}L$$

Effective optical depth

$$\tilde{T} = \Omega T$$

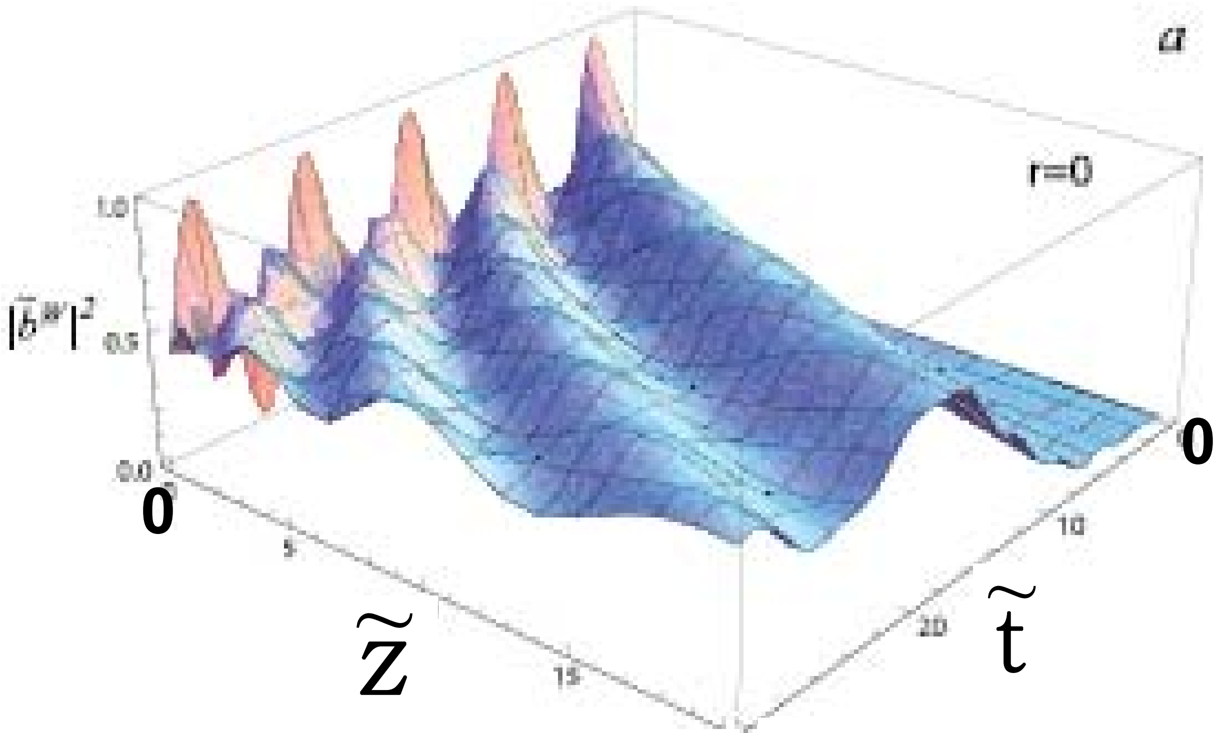
Effective time duration



$\Delta/\Omega = 0$

First, the atomic coherence grows starting from the beginning of the medium. Later, layers deeper inside the medium start to participate in the process and the information moves further inside the ensemble.

System dynamics : resonant case

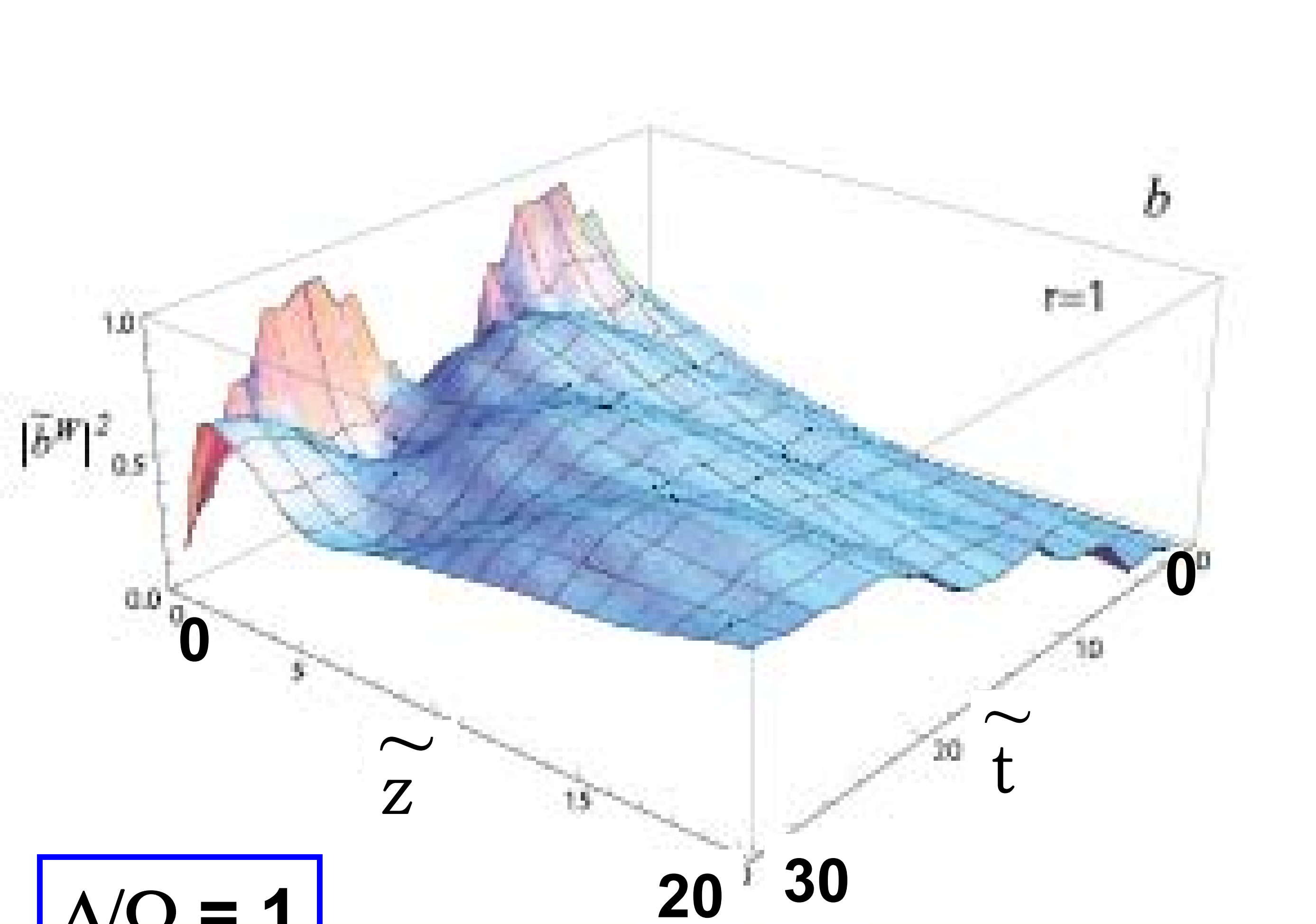


$\Delta/\Omega = 0$

$\tilde{z}$: effective optical depth

$\tilde{t} = t/\Omega$

System dynamics : Raman case

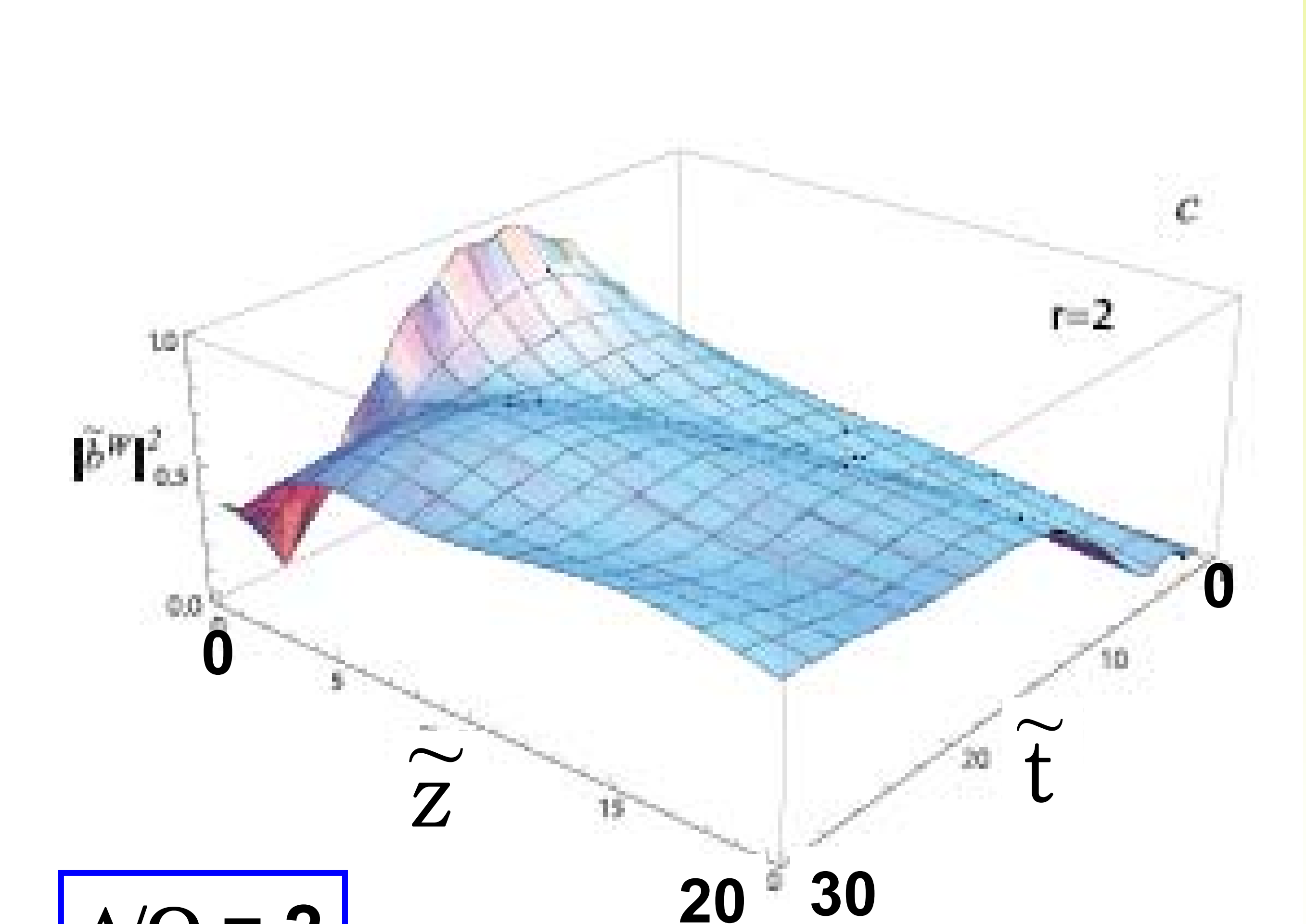


$\Delta/\Omega = 1$

$\tilde{z}$: effective optical depth

$\tilde{t} = t/\Omega$

System dynamics : Raman case



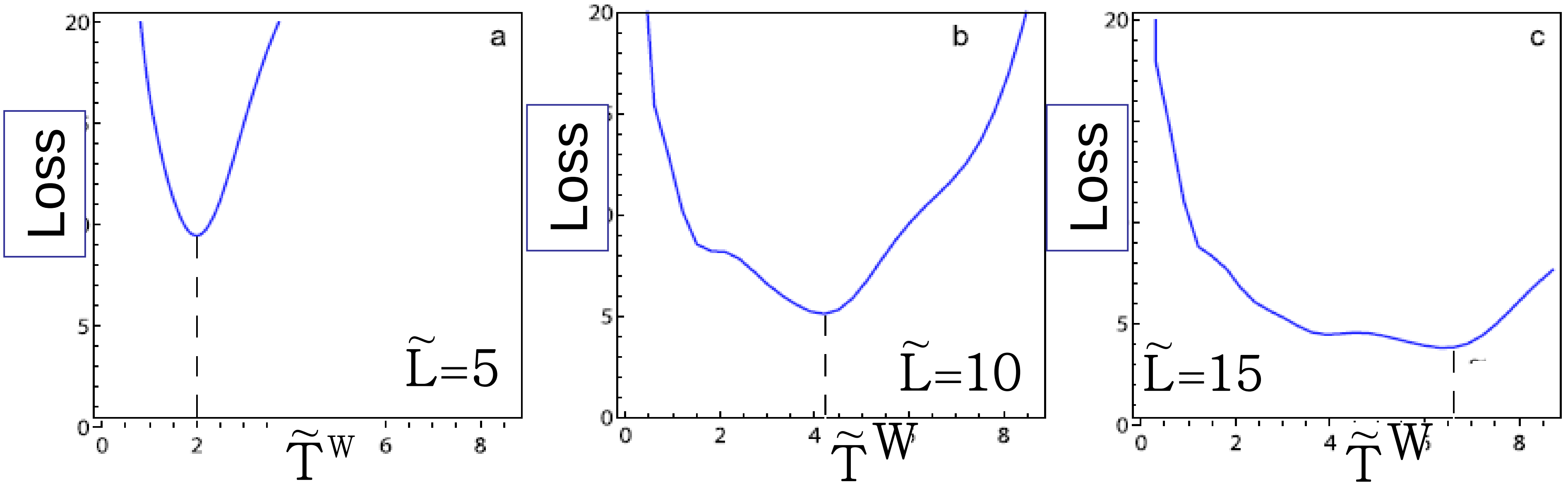
Δ/Ω = 2

$\tilde{z}$: effective optical depth

$\tilde{t}$ = t/Ω

Optimization of the memory protocol

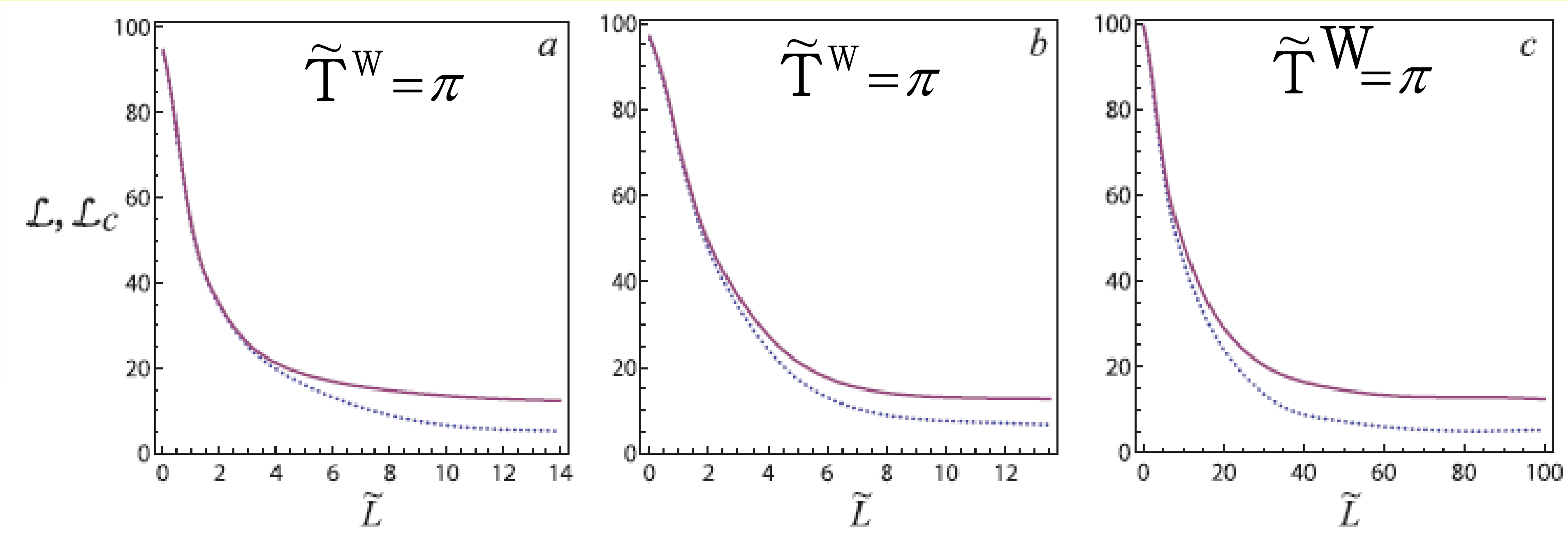
Transmitted signal field energy during the writing stage (normalized to input field energy) ***for $\Delta/\Omega = 0$***



The efficiency increases when the length of the medium is increased. F***or each optical depth, there is an optimal value of the pulse duration***.

Optimization of the memory protocol

Relative losses due to leakage (blue, dotted lines) and relative total losses (red, full lines)

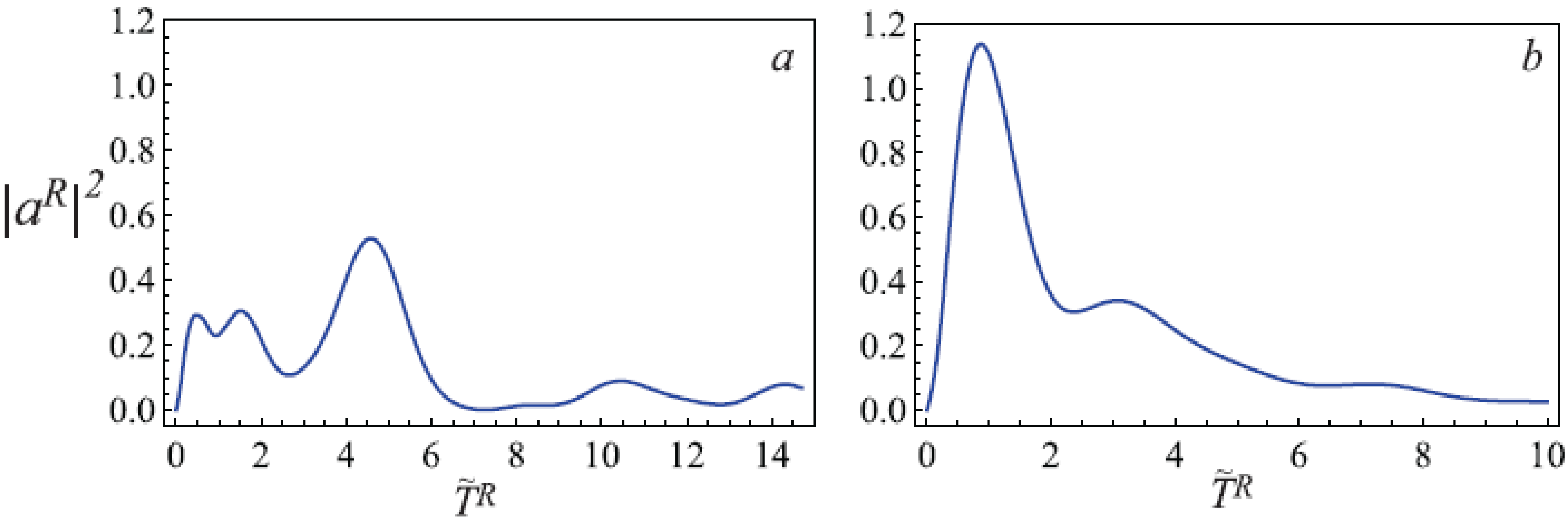


$\Delta/\Omega = 0$ $\Delta/\Omega = 0.5$ $\Delta/\Omega = 2$

The efficiency for a fixed pulse duration increases when the optical depth of the medium is increased.

Retrieval efficiency

Field intensity at the output of the medium for Δ/Ω = 0.5,
for $\tilde{T}^W = \pi$ and $\tilde{L} = 10$



Forward retrieval Backward retrieval

T. Golubeva, Yu. Golubev, et al, arXiv 1112.4852

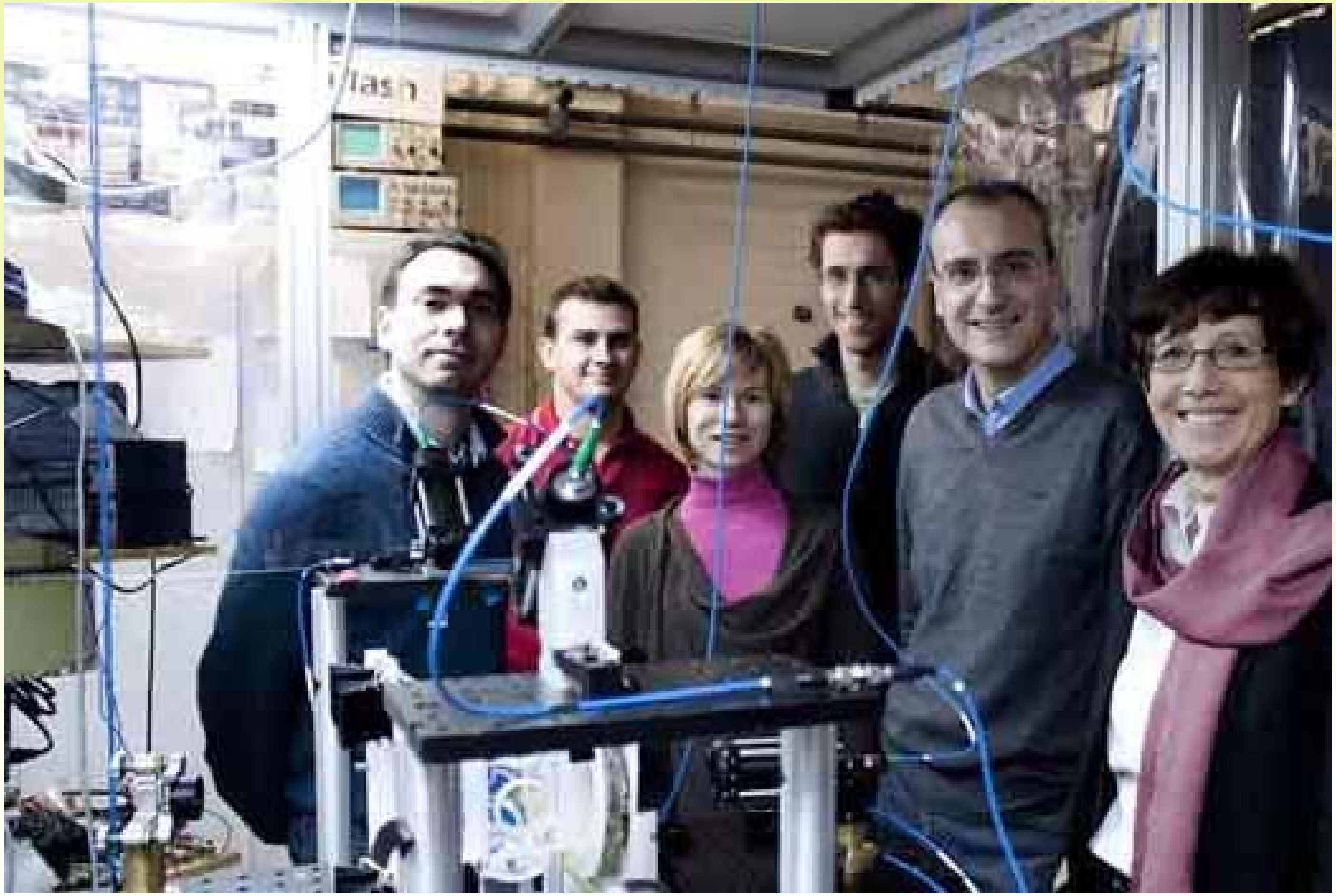
Conclusions

- Atoms are a valuable model resource for quantum information processing and storage

- EIT-based quantum storage of continuous variables was been studied in Cs vapor and methods to improve efficiency were proposed

- Quantum storage in cold atoms : better efficiency

- Memories with ultrashort pulses are quite promising



Lambert Giner, Michael Scherman
Julien Laurat, Oxana Mishina, Alberto Bramati,
Elisabeth Giacobino

Thank you for your attention