Quantum storage in cold atomic ensembles

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Quantum memory : a quantum interface between light and matter

Goal:

To achieve storage and retrieval of quantum variables without measurement

General Strategy:

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

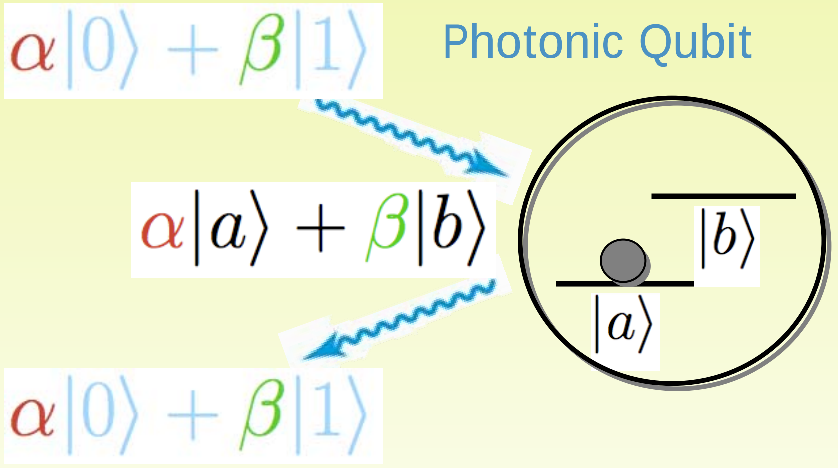
Quantum Memories

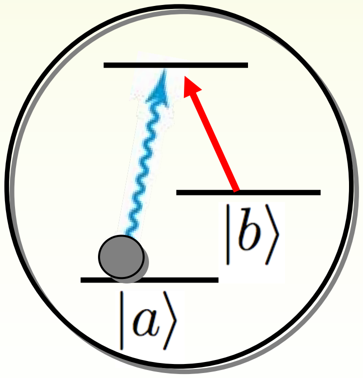
Objective : Storing without measuring and reading on demand, i.e. a coherent and reversible transfer between atoms and light.

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

|a> and |b> usually long lived states to avoid fast decoherence

Two ground states connected via an excited state by a **control field**

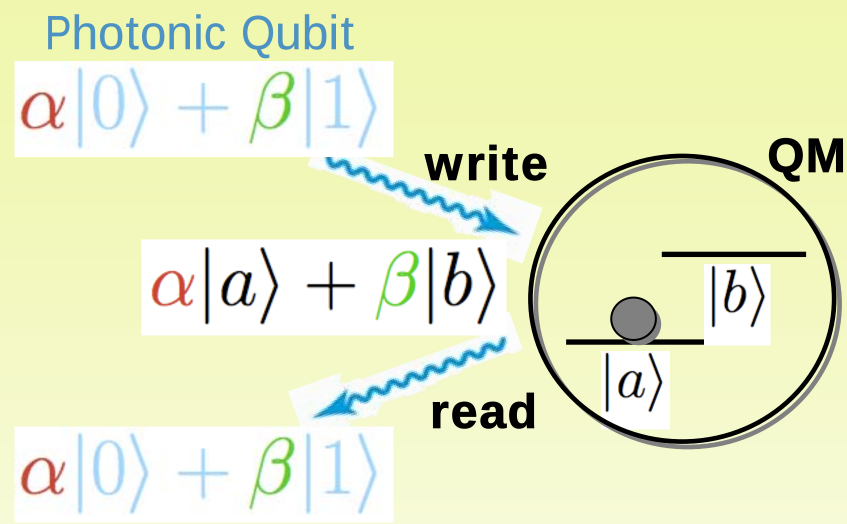




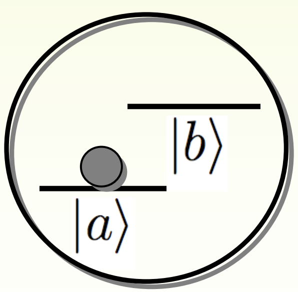
Other aims: λ, bandwidth, memory time, multimode…

Light-Matter Interfaces : How ?

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



Single Atom

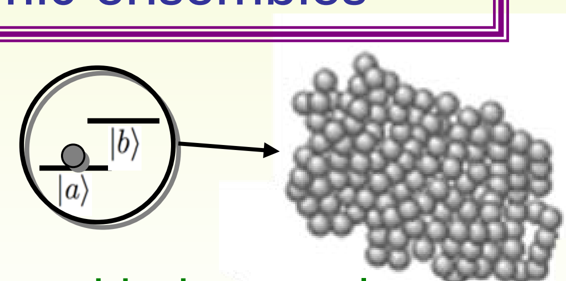


Requires a high-finesse cavity (CQED)

Example for storage of a single photon

$$|a\rangle \rightarrow |b\rangle$$

Atomic ensembles



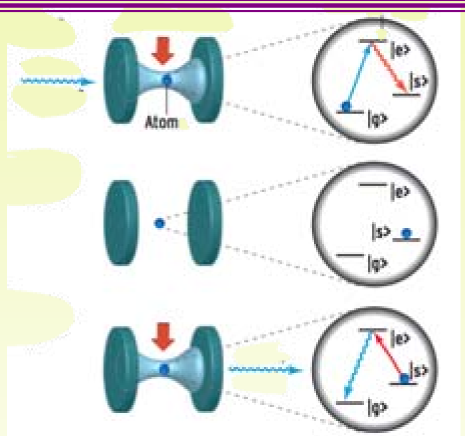
Light easily interact with the sample
Collective state (enhancement)

Example for storage of a single photon

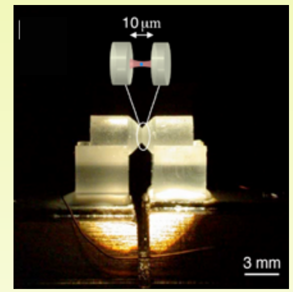
$$|a_1 ... a_i ... a_N\rangle \rightarrow \frac{1}{\sqrt{N}} \sum_i |a_1 ... b_i ... a_N\rangle$$

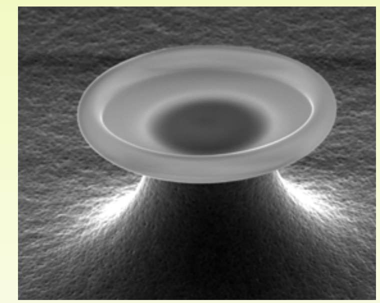
Quantum Memories : an Outlook

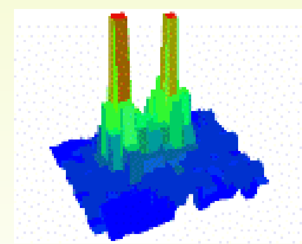
Single Atom



Cavity Quantum
Electro-Dynamics
(strong coupling)





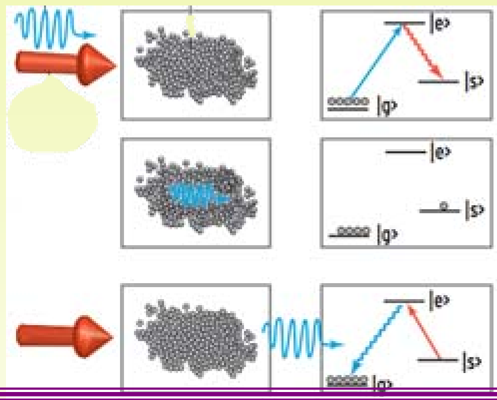


- Single trapped atom in a cavity (Kimble 2007, Rempe 2011)
- Quantum dot « molecules » (Shields 2011)

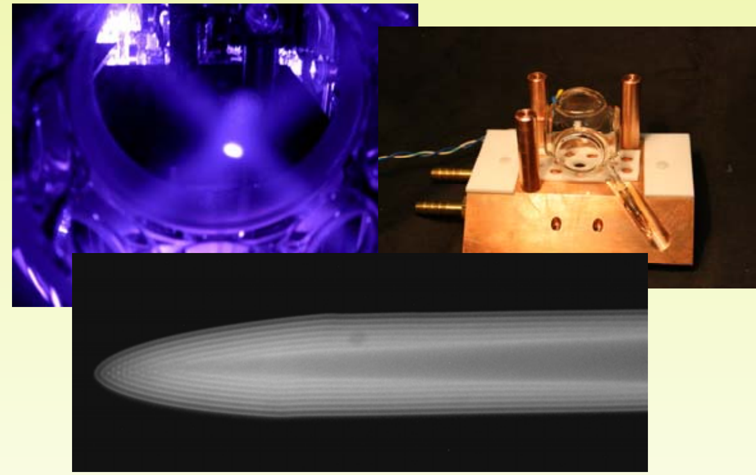
But mode matching is difficult

Quantum Memories : an Outlook

Atomic Ensembles : Collective Excitation



Dynamic EIT
in warm vapors
or cold atoms

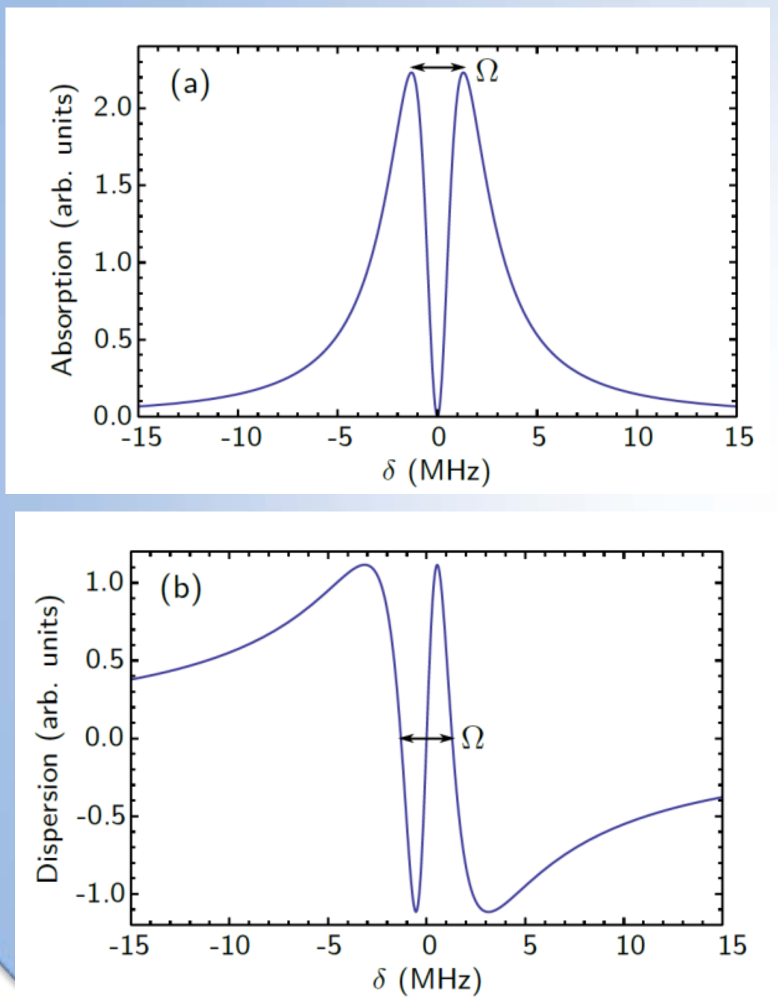


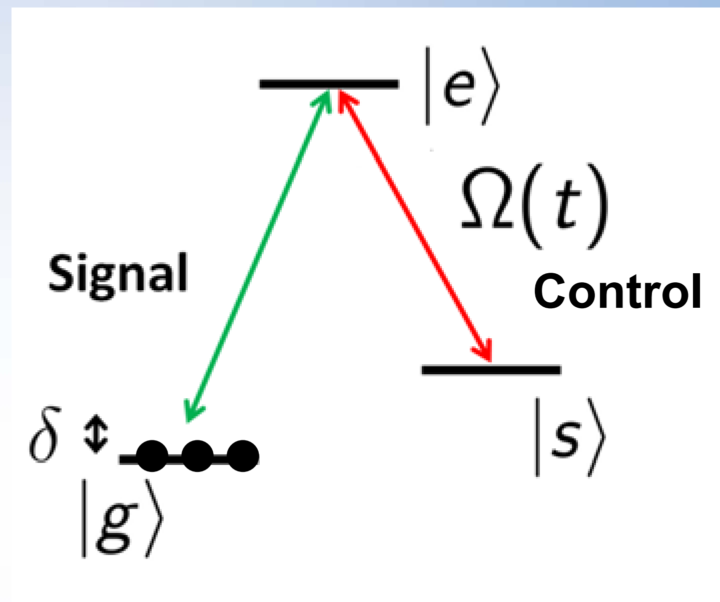
First experiments for optical pulses, based on EIT:
2001 : M. Lukin using Rb vapor, and L. Hau using cold sodium atoms

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)°



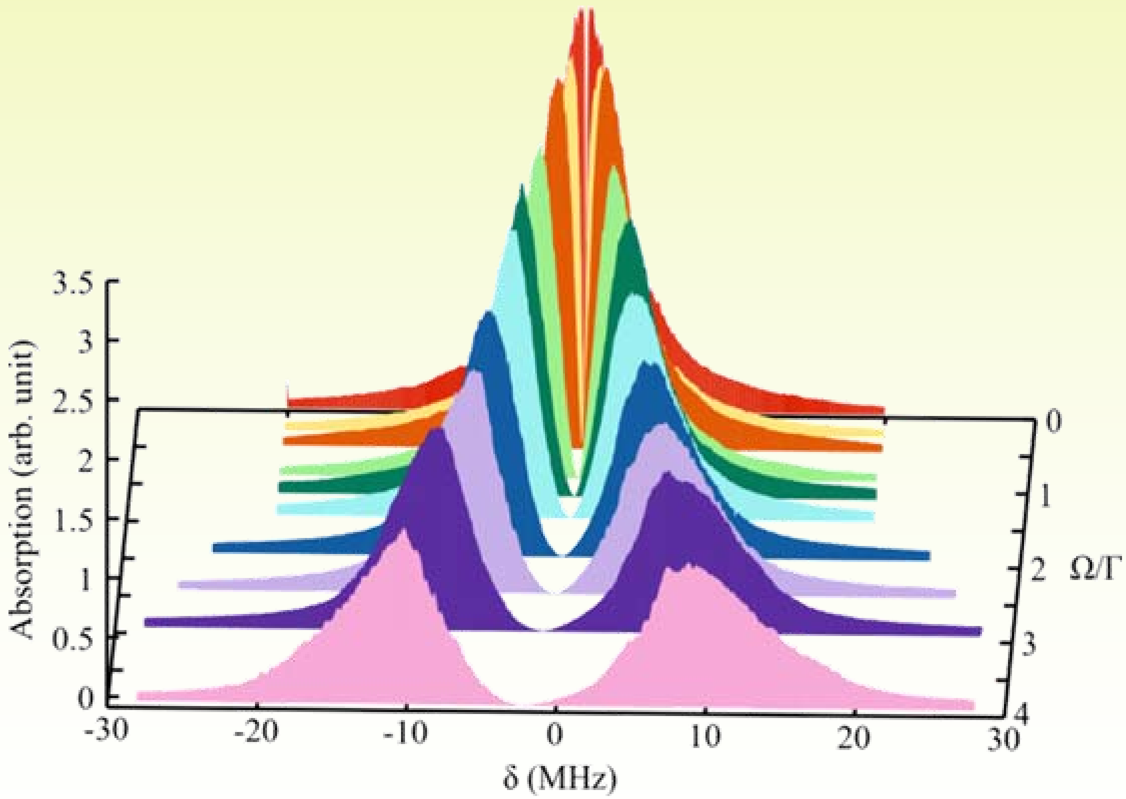


Reduced group velocity

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

Electromagnetically induced transparency (EIT) in cold Cs atoms

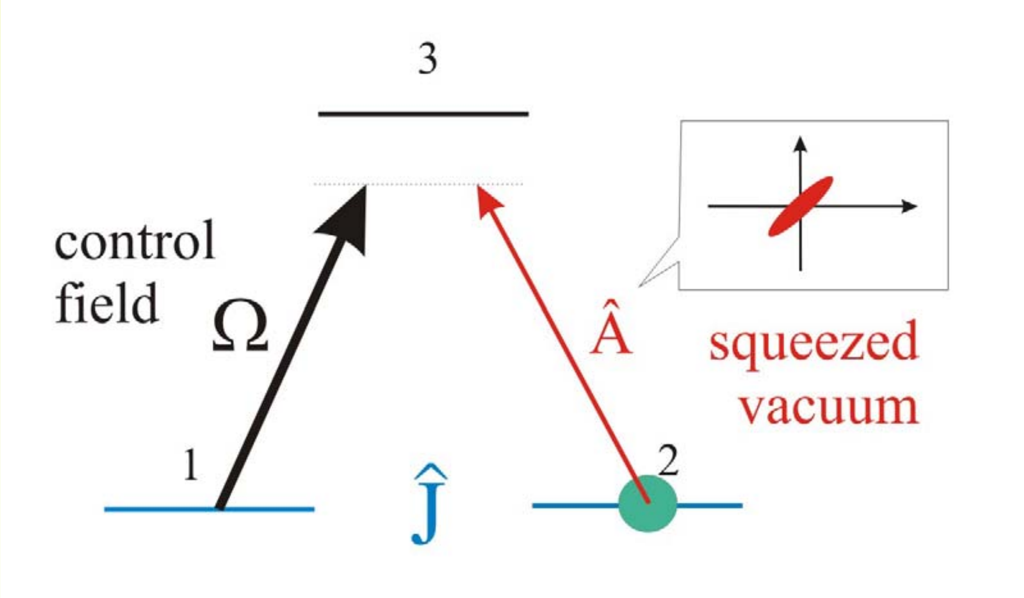
Absorption profiles for various values of Rabi frequency of the control field



L. Giner et al, Phys. Rev. A 87, 013823 (2013)

EIT based quantum memory

Atoms ↔ field transfer



conditions :

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

Expected performances :

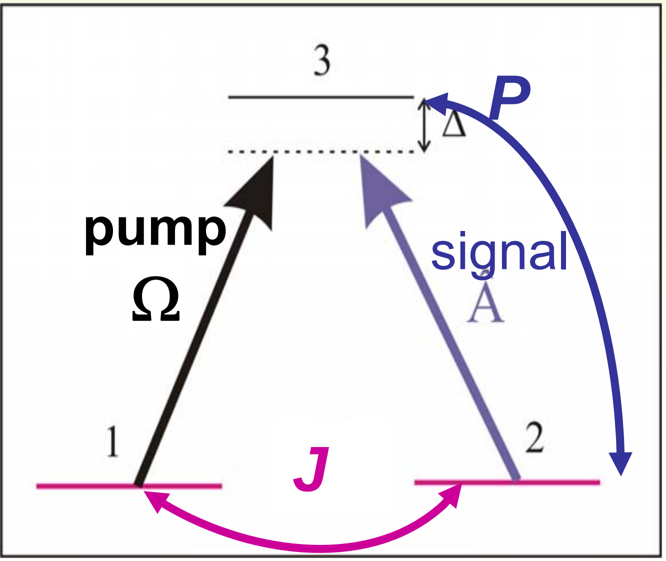
- ► transfert efficiency
- ► storage time > ms
- ► reading/writing time ~ μs

Simplified system : 3-level atomic ensemble in a cavity

- control field is strong : its Rabi frequency Ω plays the role of a parameter
- quantum field A has a very small mean value

Then

- all the atoms are pumped into level 2
- J, P, A are decoupled from the other variables



$$\dot{A} = -(\kappa + i\Delta_c)A + i\frac{g}{\tau}P + \sqrt{\frac{2\kappa}{\tau}}A^{in}$$

$$\dot{P} = -(\gamma + i\Delta)P + igNA + i\Omega J + F$$

$$\dot{J} = -(\gamma_0 - i\delta)J + i\Omega P + f_r$$

Field to atomic spin coupling

Field and optical dipole adiabatically follow the ground state evolution

$$(\tilde{\gamma}_0 - i\omega)J_x = -\beta A_x^{in} + f_x$$

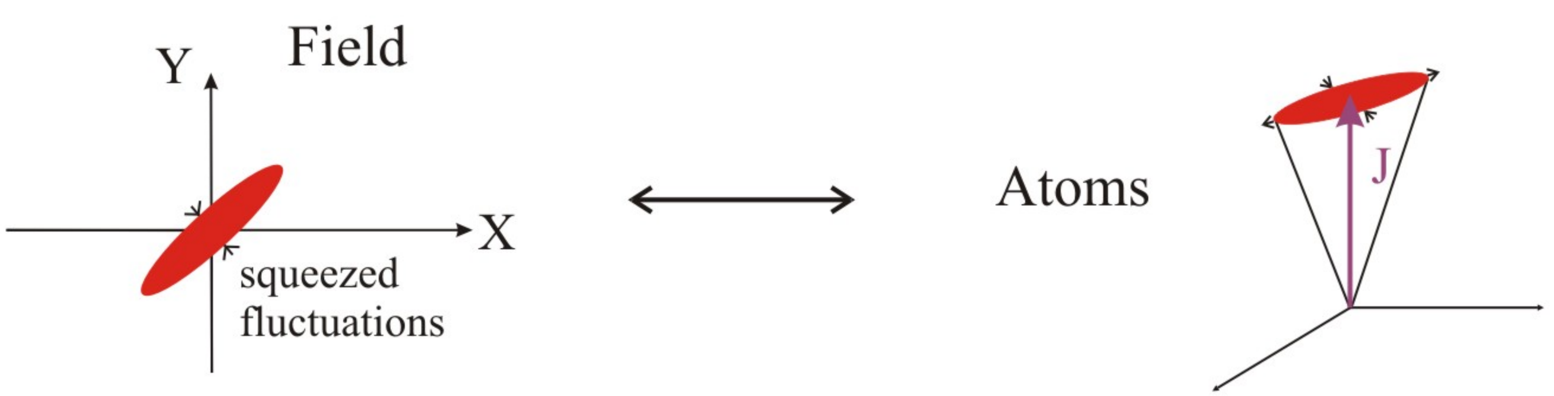
$$(\tilde{\gamma}_0 - i\omega)J_y = -\beta A_y^{in} + f_y$$

$$\tilde{\gamma}_0 = \gamma_0 + \gamma_\varepsilon$$

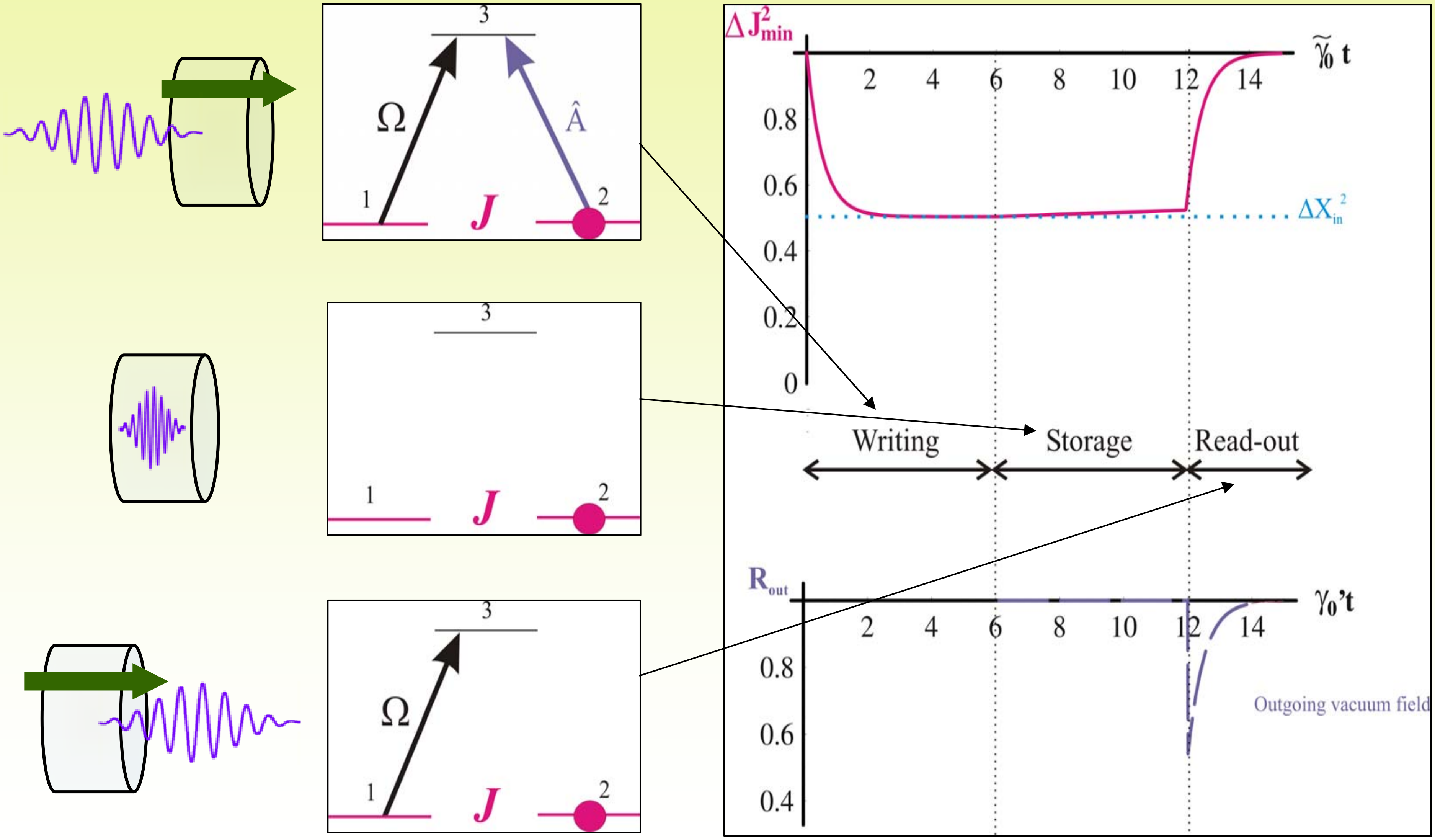
γ_0 : ground state coherence relaxation rate

γ_ε : effective optical pumping rate

The two quadratures of the field are mapped onto the atomic spin



Operation of a quantum memory
Dynamic EIT



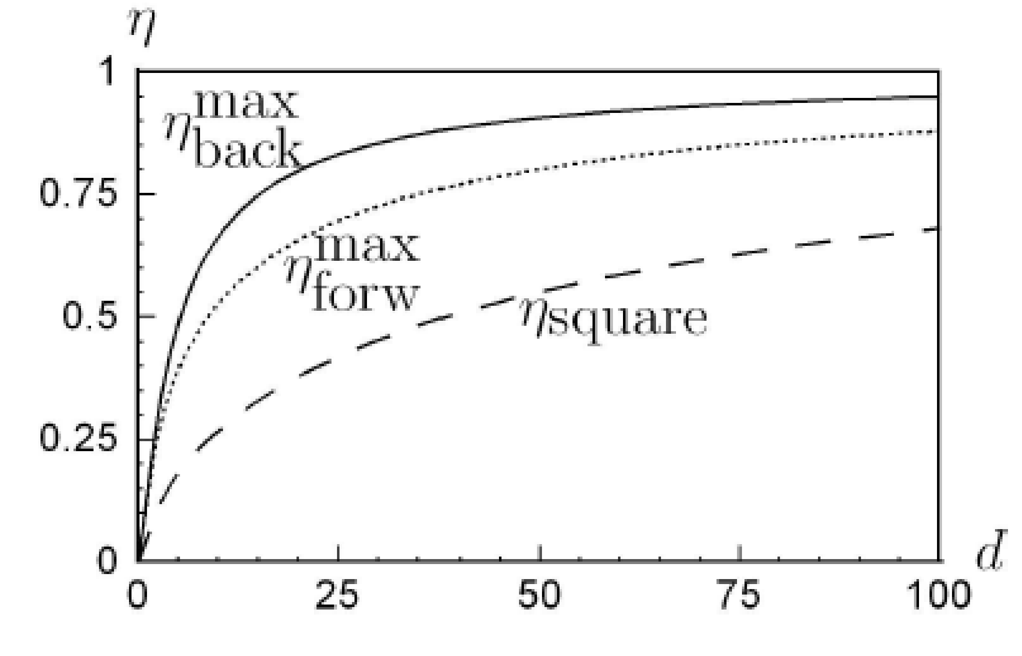
Storage efficiency

Efficiency $\eta = \frac{I_{out}}{I_{in}}$

Optical depth

$$I = I_0 e^{-d}$$

$$d = \frac{g^2 NL}{\gamma c}$$



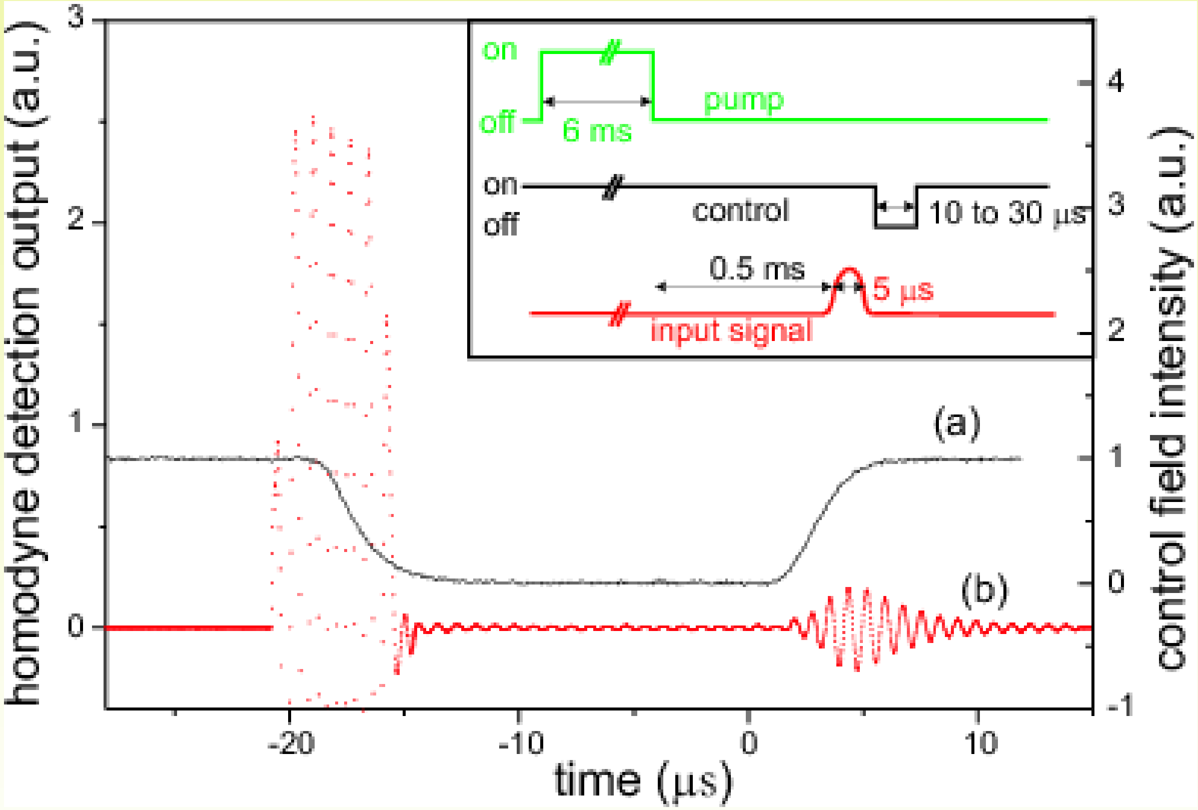
From Gorshkov et al, PRA 76, 033805 (2007)

Fidelity

$\mathfrak{F} = < \psi_{in} | \rho_{out} | \psi_{in} >$ depends on the considered quantum state

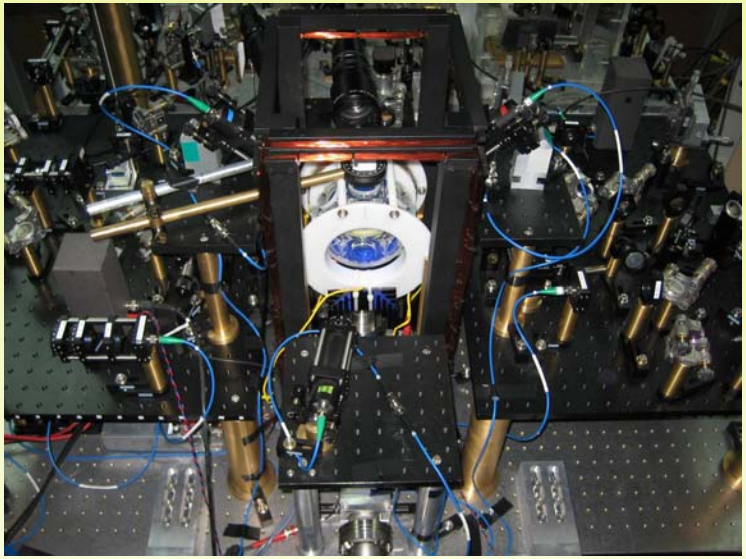
can be larger than the classical limit even for rather small efficiency

Experiment in an atomic vapor



• 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

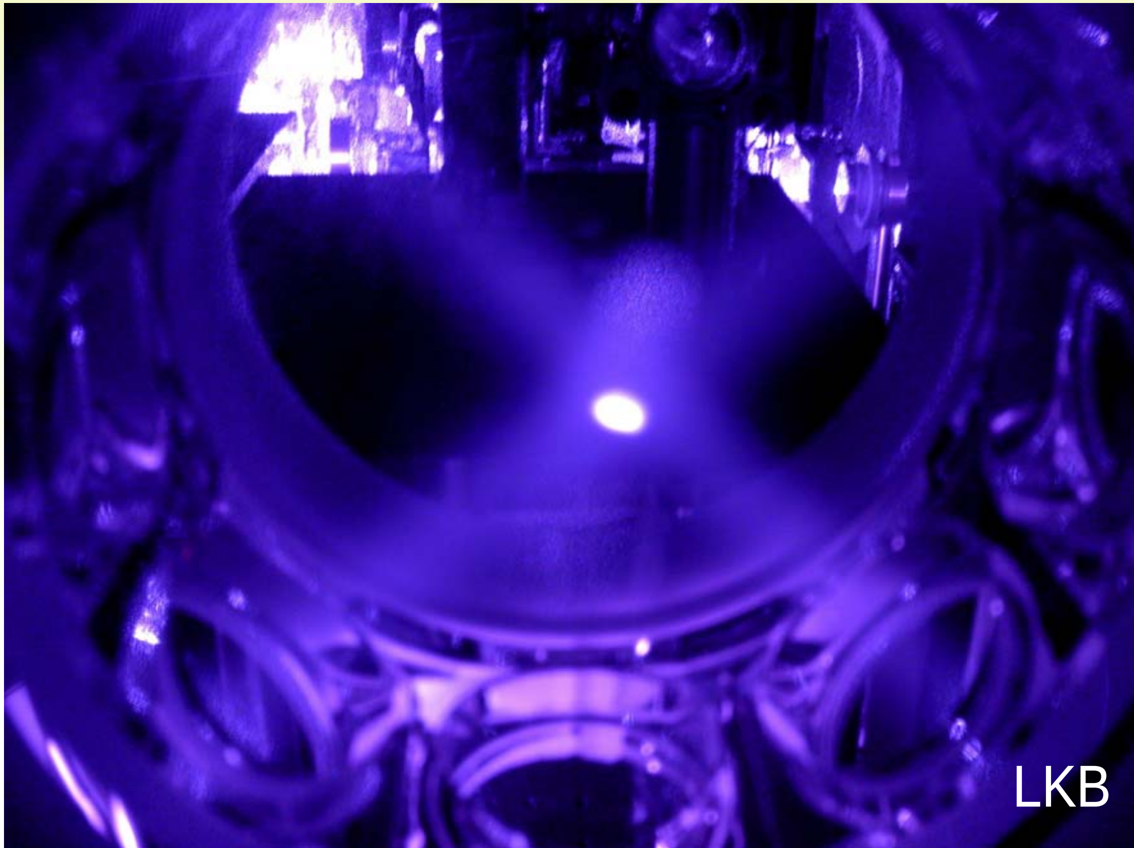
Ensemble of Cold Atoms



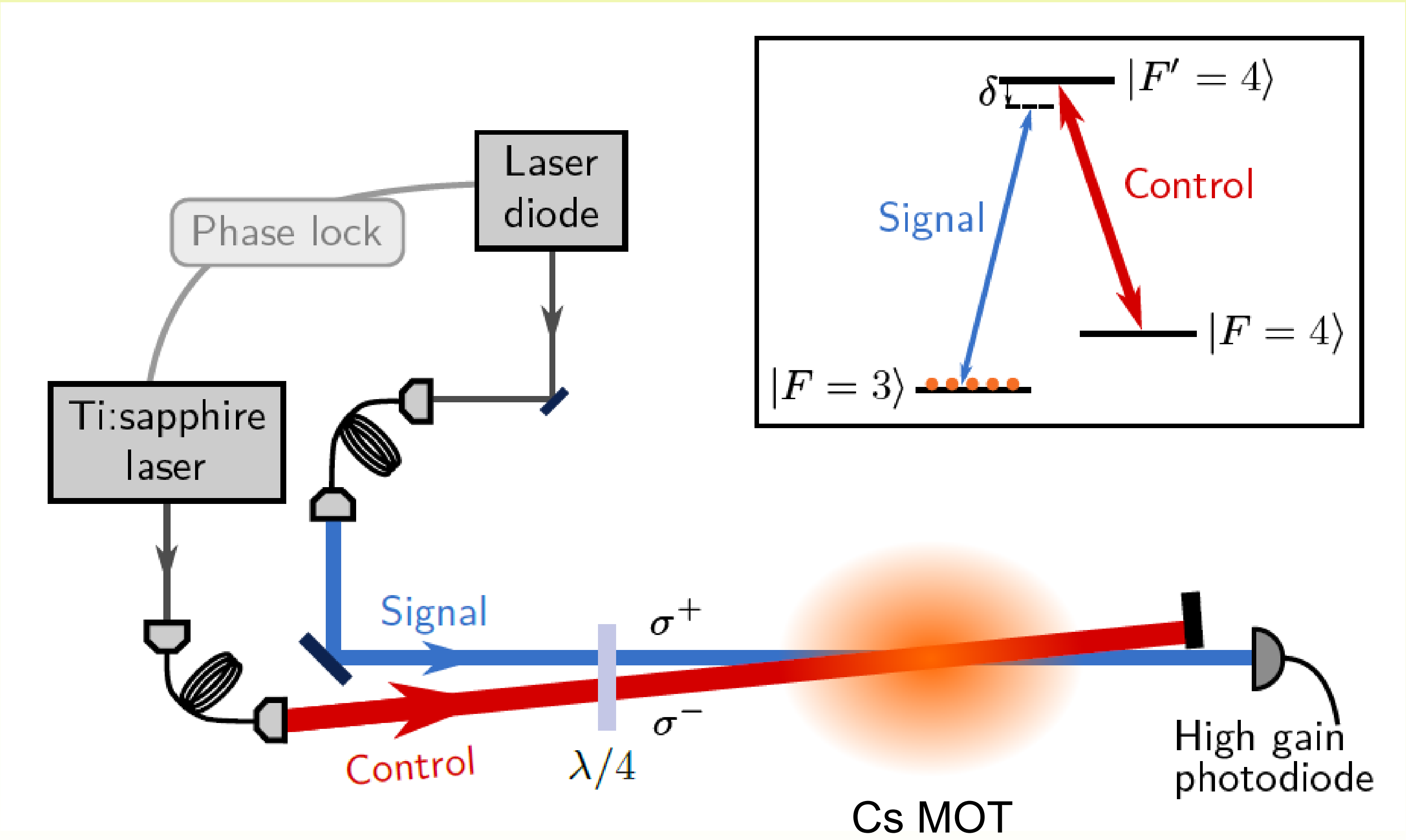
Magneto-optical trap

10^9 atoms in a mm^3 volume

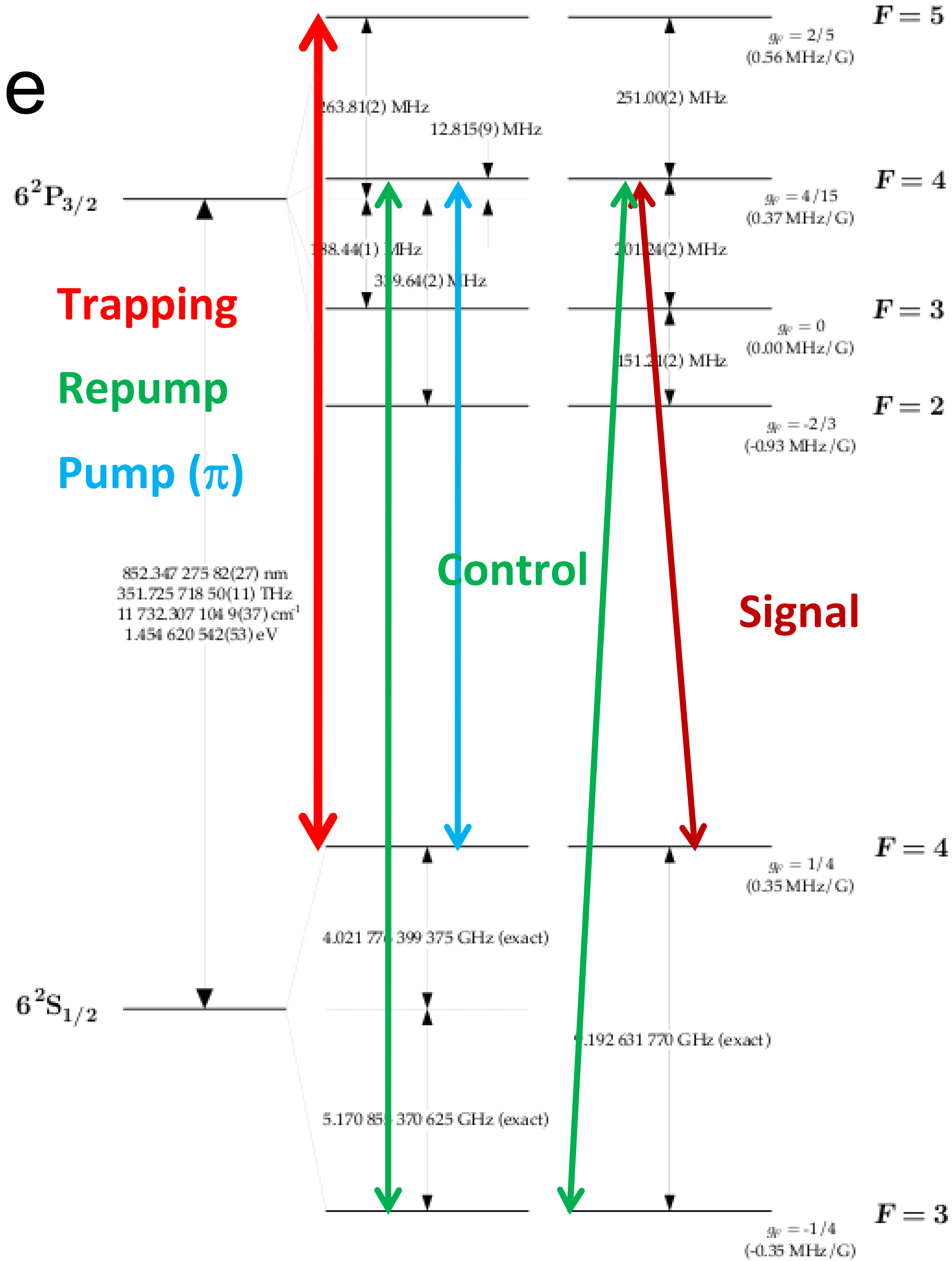
➔ large optical depth



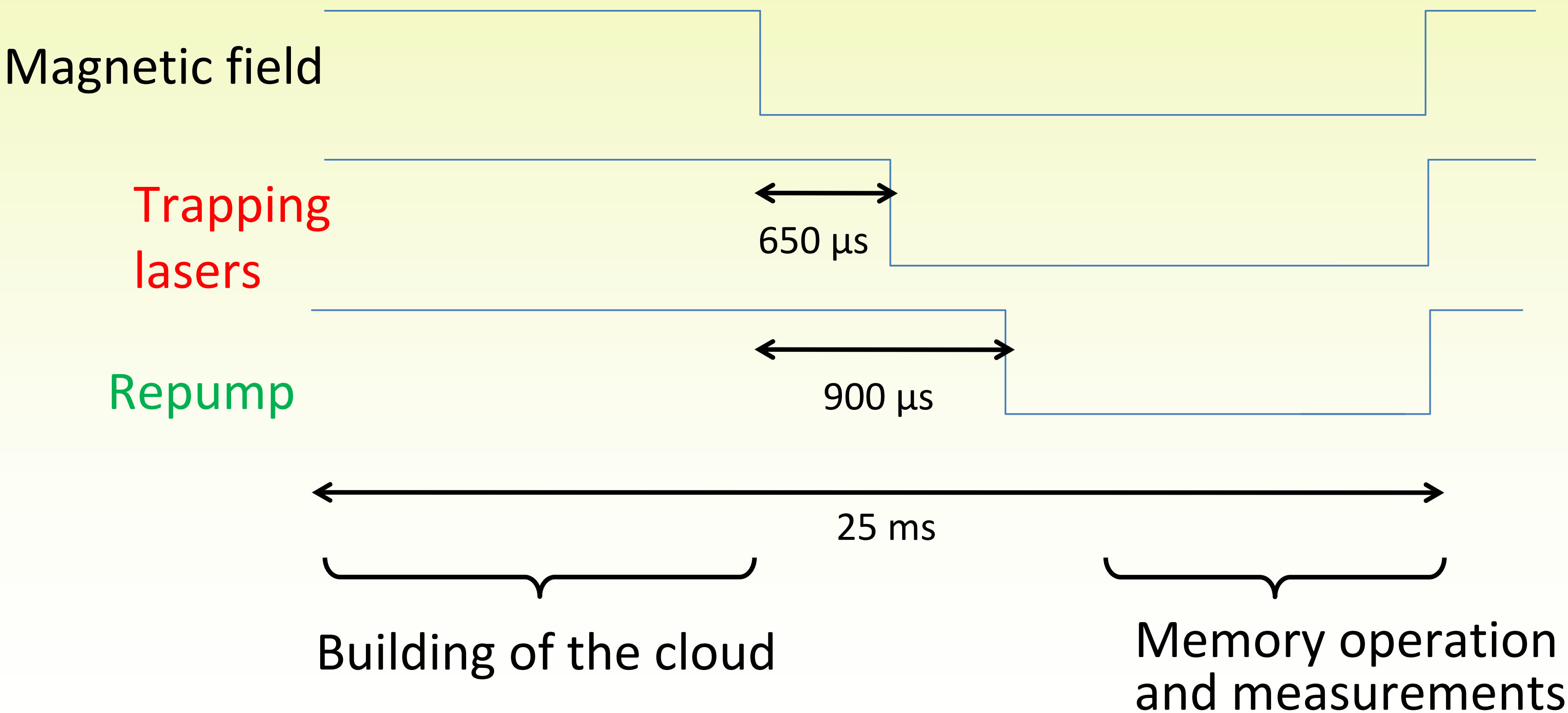
Principle of the experiment



Level scheme
Cs D2 line

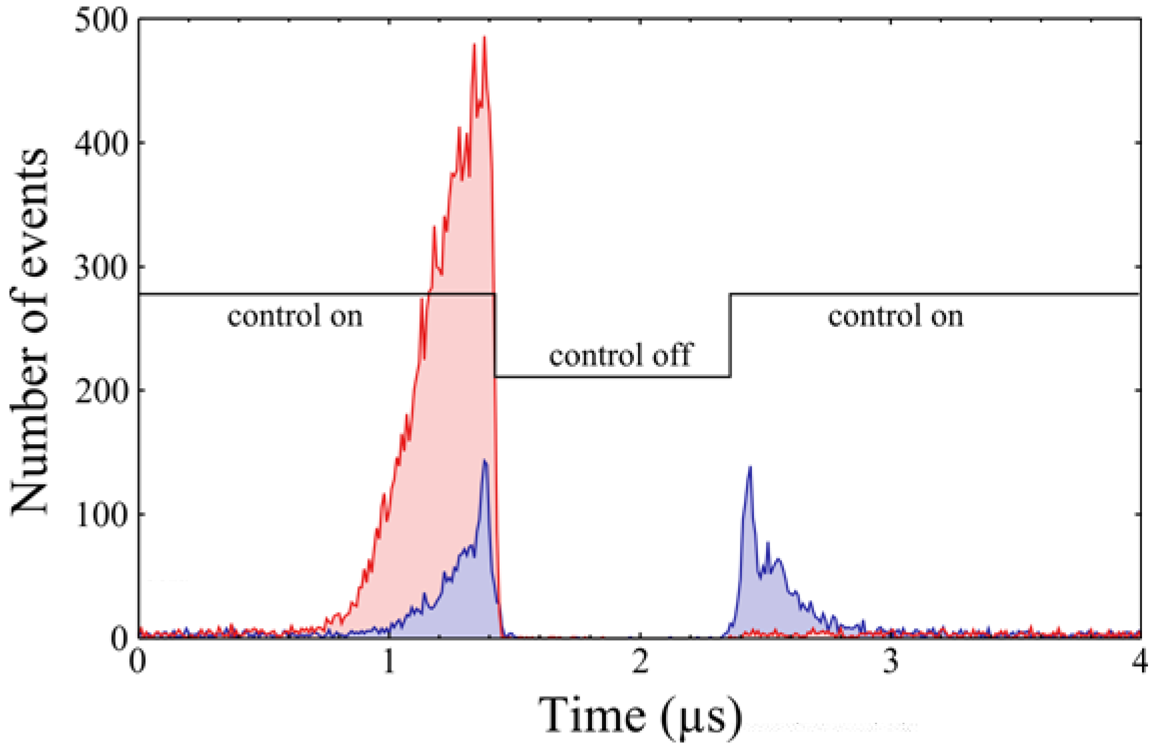


Timing of the experiment



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

- EIT dynamic
- Signal Pulse : 1 μs (0.1 photon/pulse)
- Storage time 1 μs
- **Efficiency : 20** %



Decoherence due to atomic motion

Collective state

$$|\psi(t)\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} e^{i\phi_i(t)} |g_1, g_2, \ldots, s_i, \ldots, g_N\rangle$$

Motional dephasing $\phi_i(t) = \Delta\mathbf{k} \cdot (\mathbf{r}_i + \mathbf{v}_i(t)t)$

Retrieval efficiency

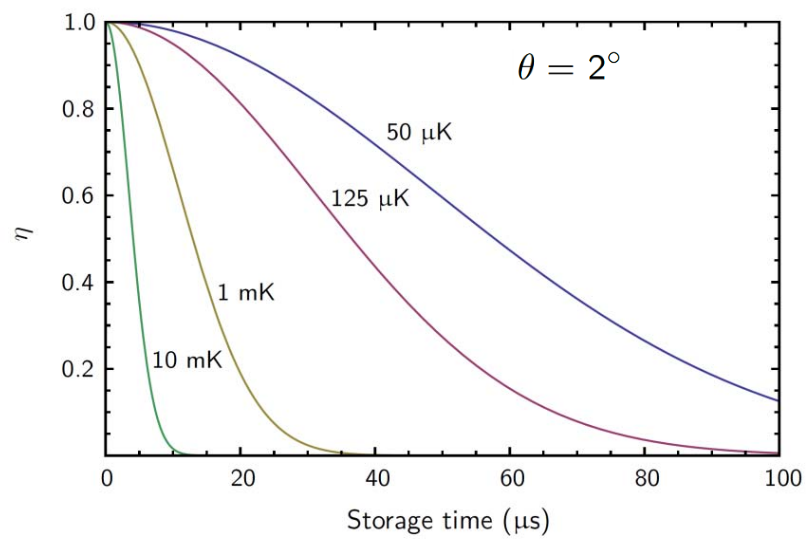
$$\eta(t) \sim |\langle\psi(t=0)|\psi(t)\rangle|^2 = \left| \frac{1}{N} \sum^{N} e^{i\Delta\mathbf{k}\cdot\mathbf{v}_i(t)t} \right|^2$$

$$= e^{-t^2/\tau^2}$$

$$\tau = \frac{\lambda}{2\pi \sin\theta} \sqrt{\frac{m}{k_B T}}$$

Temperature

Angle between the beams



Decoherence due to magnetic field

$$|\psi(t)\rangle = \frac{1}{\sqrt{N}} \sum_{i=1}^{N} e^{i\phi_i(t)} |g_1, g_2, \ldots, s_i, \ldots, g_N\rangle$$

Residual magnetic field

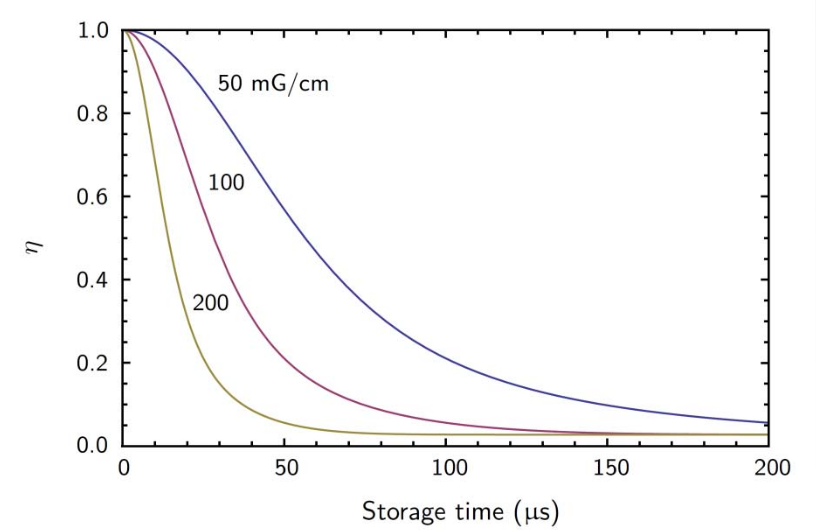
$$|s_i(t)\rangle = \sum_{m_g, m_s} \alpha_{m_g, m_s} e^{iZ(m_g+m_s)B_z(\mathbf{r}_i)\,t} |s, m_s\rangle$$

For Gaussian atomic distribution and magnetic field gradient

$$\eta(t) \sim \left| \sum_{m_g, q_w, q_1} \alpha_{m_g, q_w, q_1} e^{-t^2/\tau^2} \right|^2$$

$$\tau = \frac{2\sqrt{2}}{Z m_g (2 + q_w - q_1) B_1 L}$$

B_1 magnetic field gradient



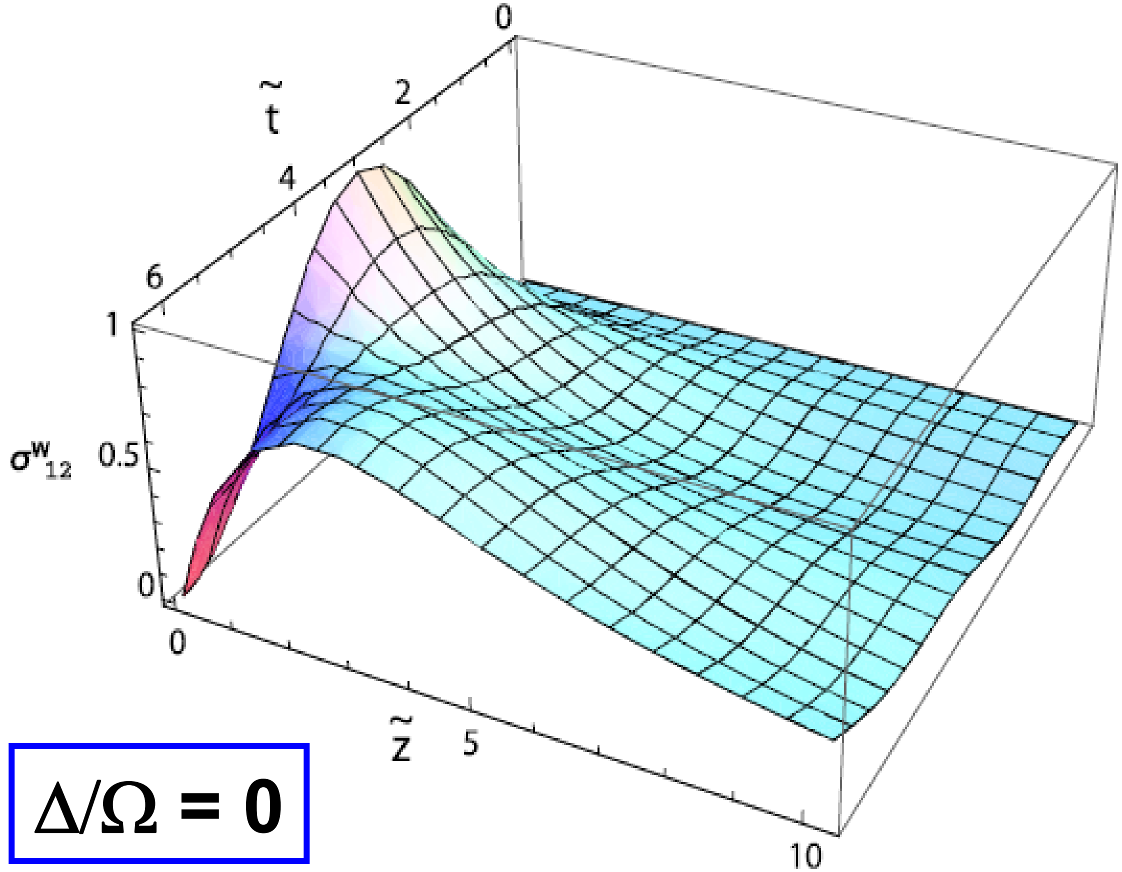
Distribution of the atomic coherence σ^{W}_{12} in space and time

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

Effective length

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

Effective time duration



Δ/Ω = 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.

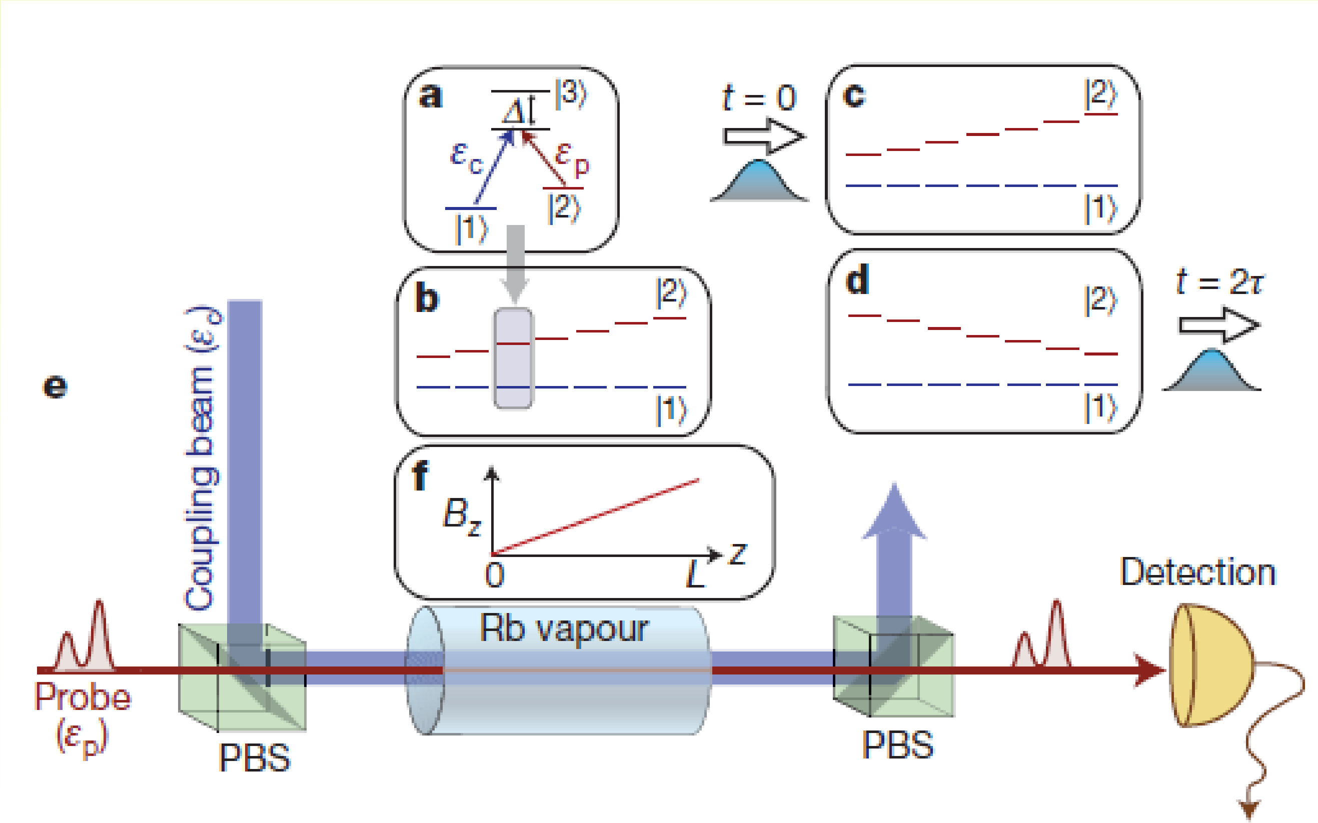
T. Golubeva et al, PRA **83**, 053810 (2011)

Gradient echo memory

Ping Koy Lam, Ben Buchler, Jevon Longdell (ANU, Australia) :
Controlled reversible inhomogeneous broadening

Ensemble of atoms with linearly varying Zeeman shift in the z direction:

Increased efficiency



From : M. Hosseini et al, Nature 461, 241 (2009)

Recent results and performances

Efficiency and lifetime

-78% with EIT : Ite A. Yu (Taiwan) and Shengwang Du (Hong Kong) with cold Rb atoms, lifetime 54μs (2013)

- 43% with Raman scheme and pulses Walmsley (Oxford) in hot Rb vapour (2012)

-Best value 87% Ping-Koy Lam (Canberra) with GEM in Rb vapor, lifetime 50μs (80% in cold Rb, lifetime 195μs) (2011)

- Lifetime 16 sec (n=0.26 at 1μsec) Kuzmich (USA) with cold Rb trapped in a lattice (2013)

Experiments performed with faint pulses, not always in the quantum regime

Going to a multimode basis :

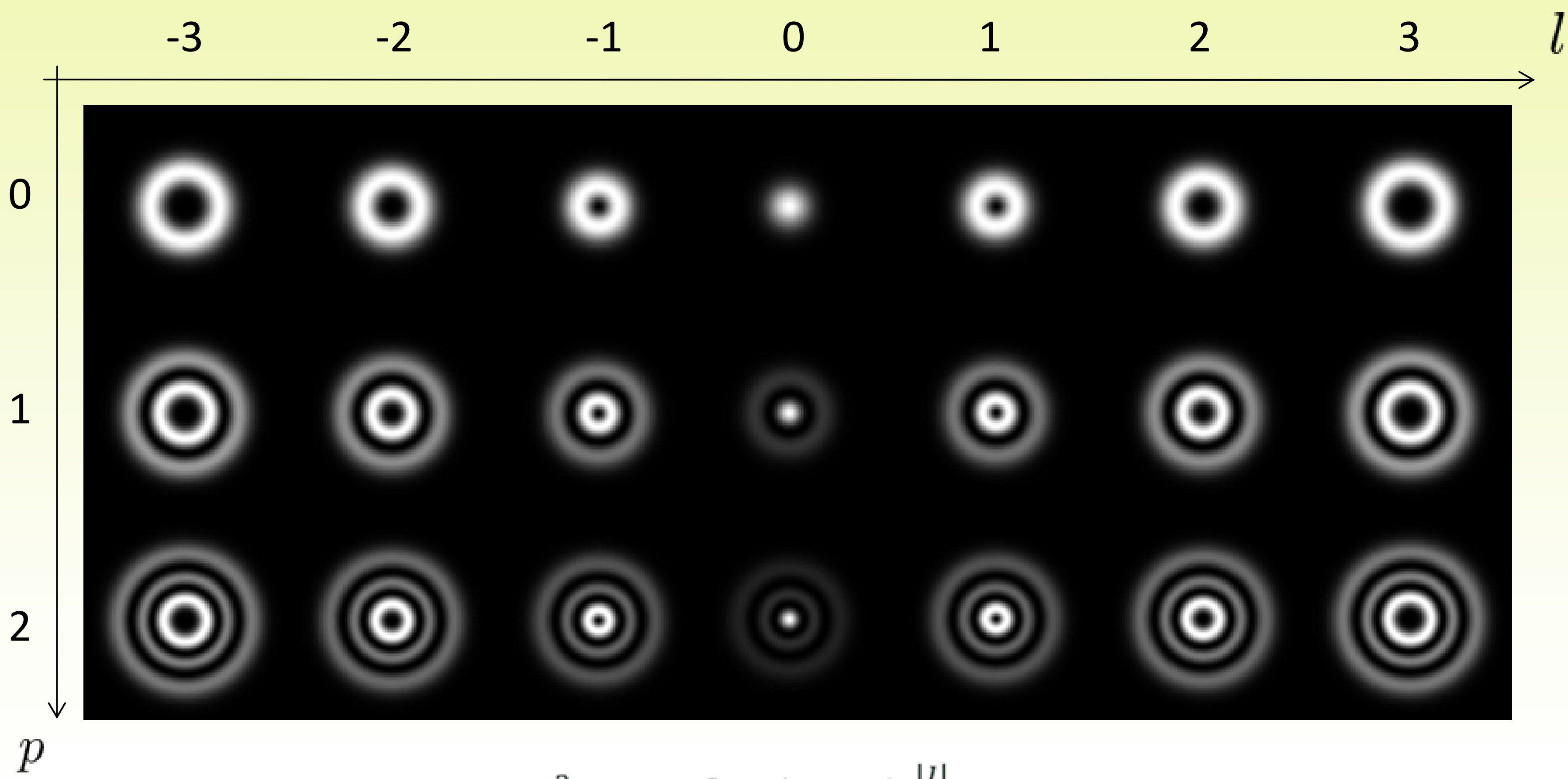
Laguerre-Gauss modes

Laguerre Gaussian modes

A set of optical modes… LG_p^l

l : azimuthal index

p : radial index



$$\mathrm{LG}_p^l = E_0 \frac{w_0}{w(z)} e^{-\left(\frac{r}{w(z)}\right)^2} e^{-ik\frac{r^2}{2R(z)}} \left(\frac{\sqrt{2}r}{w(z)}\right)^{|l|} e^{il\phi} \mathrm{L}_p^{|l|}\left(\frac{2r^2}{w(z)^2}\right) e^{i(2p+|l|+1)\zeta(z)}$$

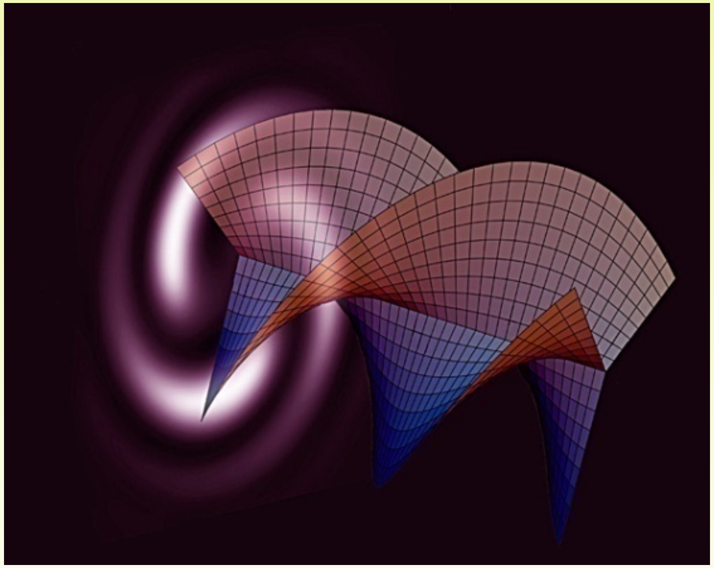
Laguerre Gaussian modes

LG_p^l

l : azimuthal index
p : radial index

Helical wavefront
$\rightarrow$ Twisted photons

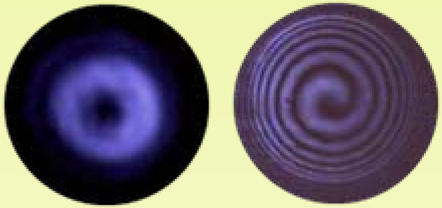
Each photon carries an orbital angular momentum $l \times \hbar$

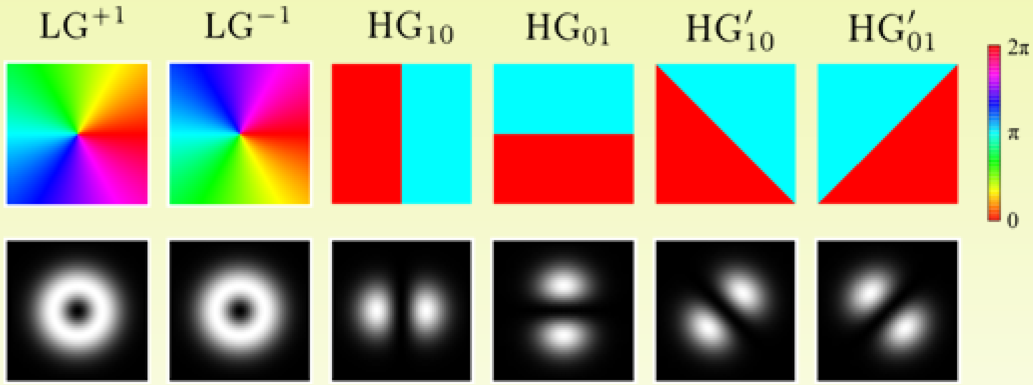


(picture from M. Padgett)

Orbital Angular Momentum of light

- Laguerre-Gaussian and Hermite Gaussian modes





infinite-dimensionnal Hilbert space for high density quantum information encoding !

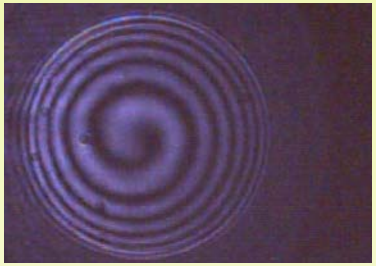
Entanglement of high orbital angular momenta was demonstrated recently
- A.C. Dada et al., Nature Phys. 7, 677 (2011) d= 12
- R. Fickler et al.,, Science 338, 640 (2012) d =100

Photons with orbital angular momentum

Qbit basis :

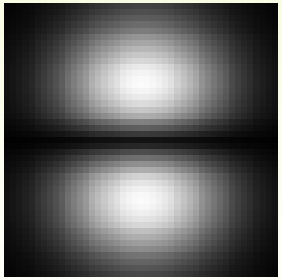
$\{\ |LG_{p=0}^{l=+1}\rangle\ ,\ |LG_{p=0}^{l=-1}\rangle\ \}$

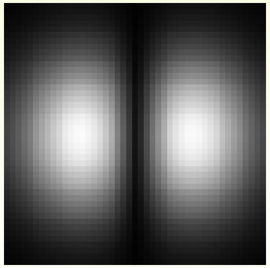
Laguerre-Gauss modes with *l* = ±*1*



Interference between LG and TEM00 modes

Hermite-Gauss modes



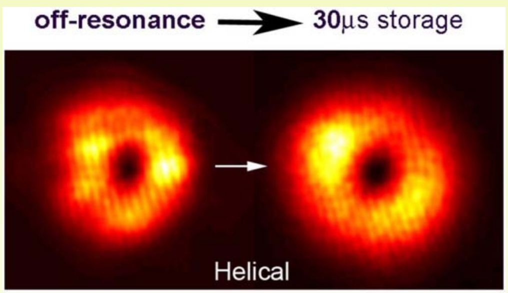


$$\left|HG_{\text{hor}}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|LG^{+}\right\rangle + \left|LG^{-}\right\rangle\right)$$

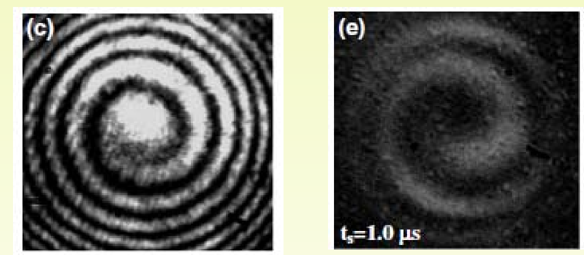
$$\left|HG_{\text{ver}}\right\rangle = \frac{i}{\sqrt{2}}\left(\left|LG^{+}\right\rangle - \left|LG^{-}\right\rangle\right)$$

Light-matter interface for OAM

Storage of bright light beams(classical regime)



Pugatch *et al.*, Phys. Rev. Lett. 9**8**, 203601 (2007)



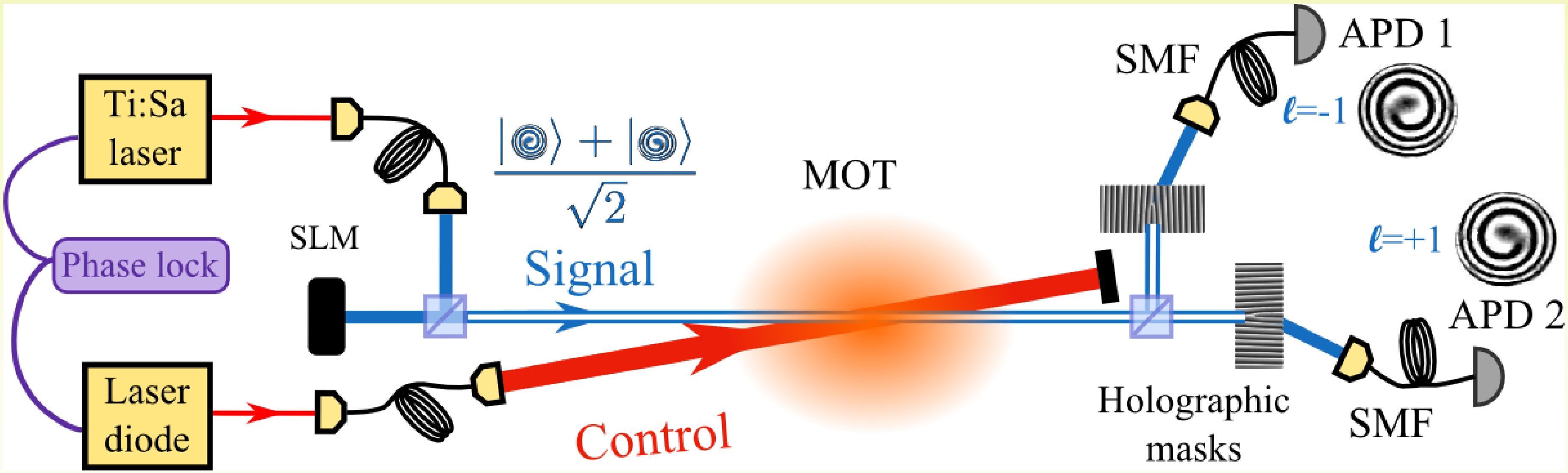
Moretti *et al.*, Phys. Rev. A **79**, 023825 (2009)

Going down to the single-photon level

L. Veissier et al., IJQI 10, 1241011 (2012)
Veissier *et al.*, Opt. Lett. **38**, pp. 712-714 (2013)
Ding et al., arXiv e-print 1305.2675 (2013)

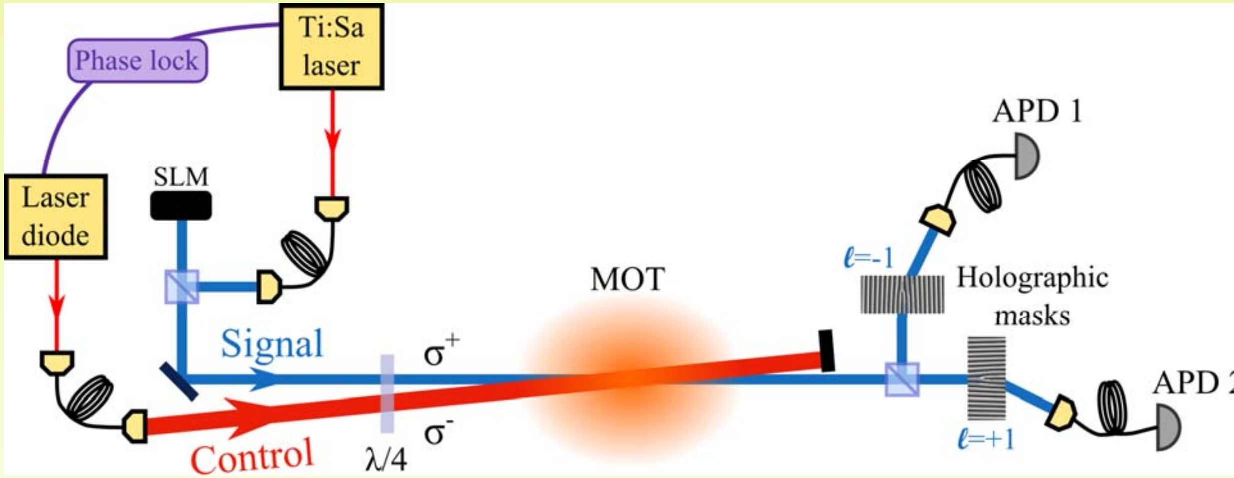
Storage of orbital angular momentum of light in the single photon regime

Signal pulse 0.5 μs
~ 0.7 photon per pulse

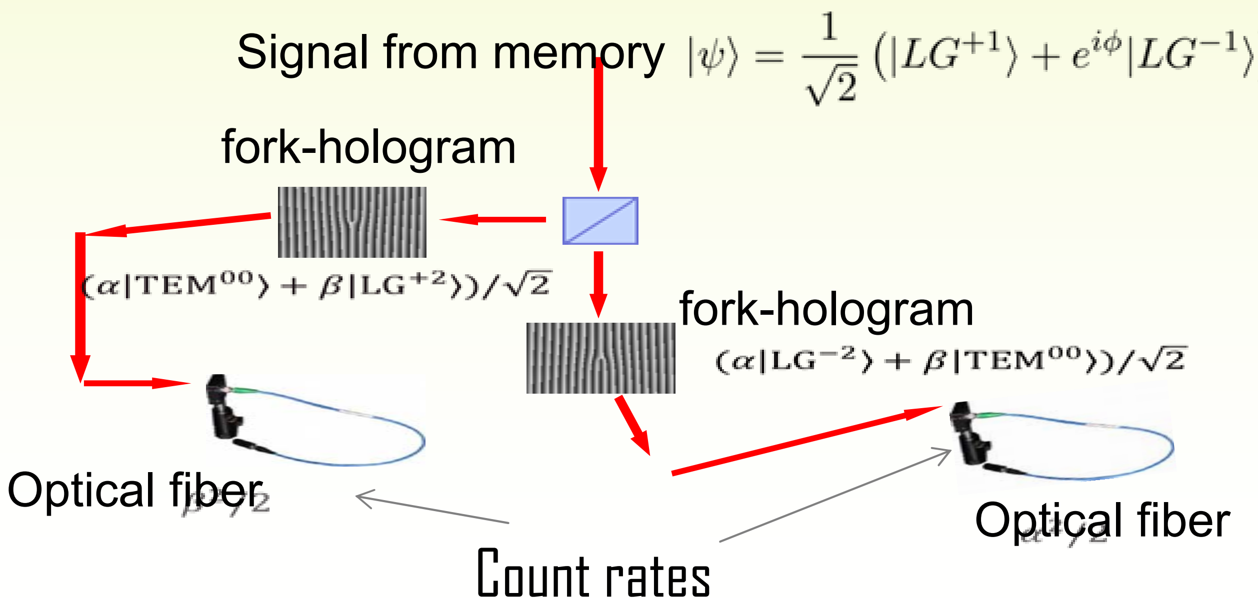


The mode of the signal photons is prepared using a spatial light modulator (SLM).

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

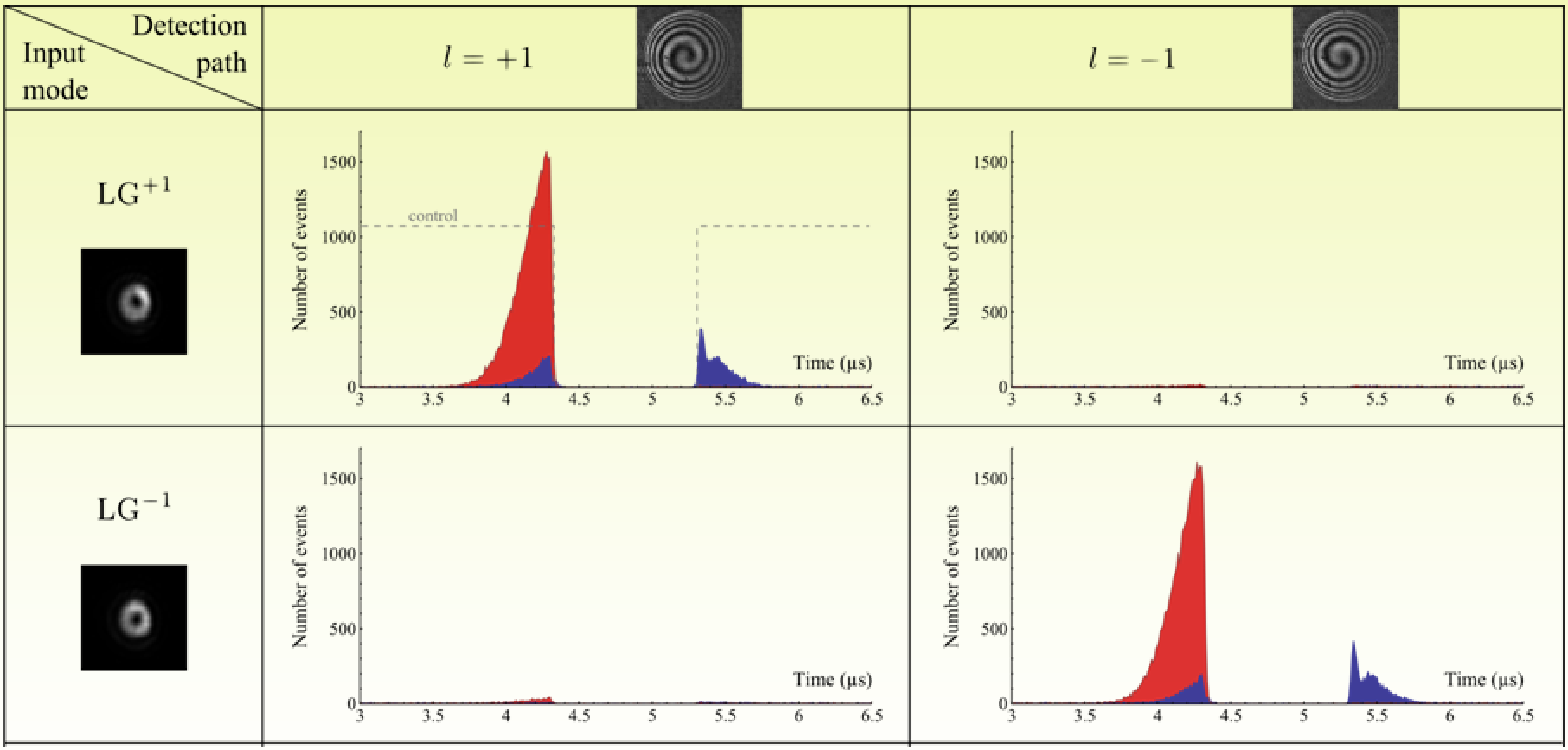


Experimental set-up



- fork phase holograms increase or reduce *l* by 1
- only the mode with *l = 0* can couple efficiently into the subsequent single mode fibers and is detected with an APD.

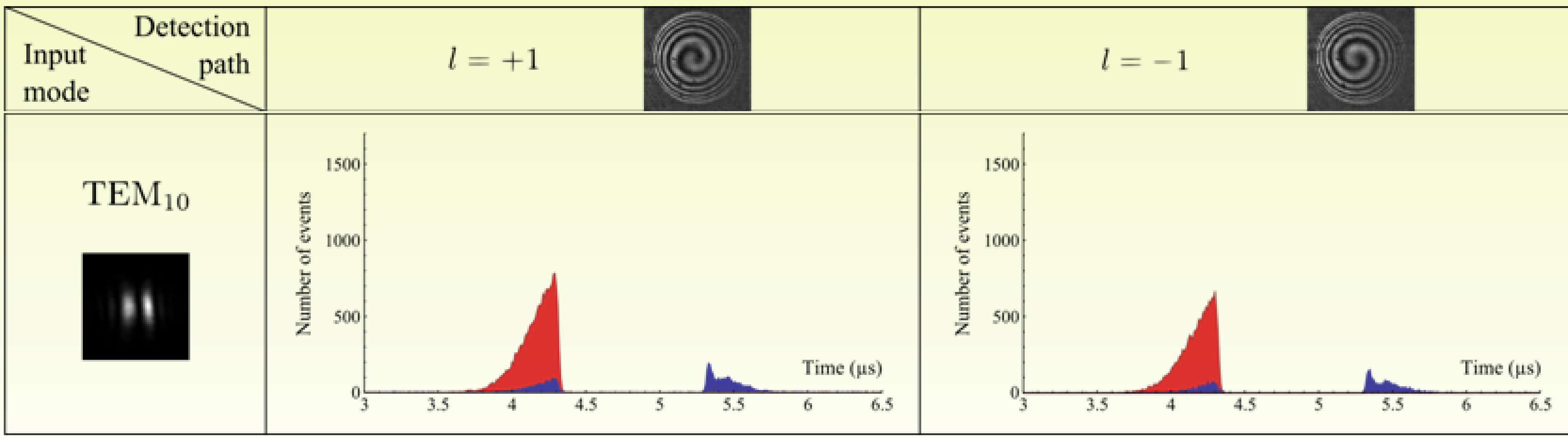
Storage of Laguerre Gauss photons



Storage efficiency ~15% for LG modes

L. Veissier et al., IJQI 10, 1241011 (2012)

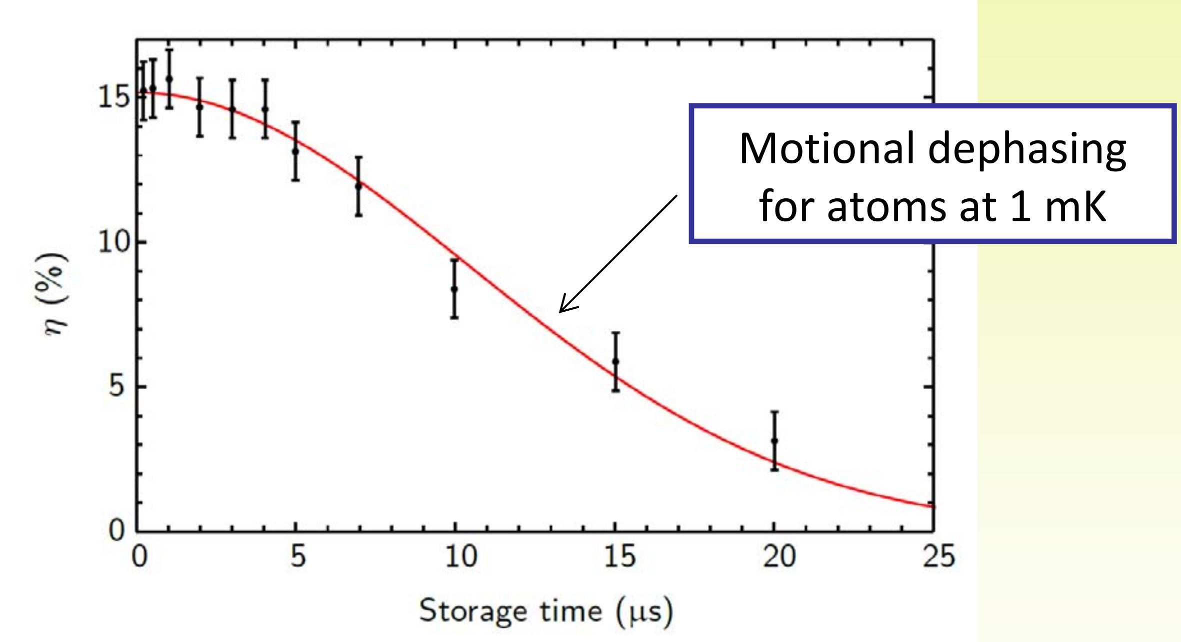
Storage of Hermite-Gauss photons



Storage efficiency ~15% for HG modes

L. Veissier et al, Opt. Lett. 38, 712 (2013)

Storage time



Gaussian distribution with 1/e decay constant of 15 μs $\longrightarrow$ Further cooling to increase the storage time

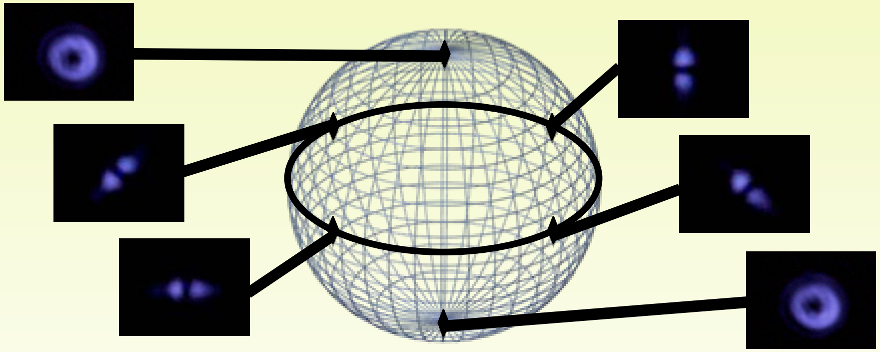
OAM encoded qubit

OAM encoded qubit $|\psi\rangle = \alpha\,|\mathrm{R}\rangle + \beta\,|\mathrm{L}\rangle = \cos\left(\frac{\theta}{2}\right)|\mathrm{R}\rangle + \sin\left(\frac{\theta}{2}\right)e^{i\phi}\,|\mathrm{L}\rangle$

Equally-weighted superpositions

$$|\mathrm{H}\rangle = \frac{|\mathrm{R}\rangle + |\mathrm{L}\rangle}{\sqrt{2}} \quad , \quad |\mathrm{D}\rangle = \frac{|\mathrm{R}\rangle + i\,|\mathrm{L}\rangle}{\sqrt{2}} \, ,$$

$$|\mathrm{V}\rangle = \frac{|\mathrm{R}\rangle - |\mathrm{L}\rangle}{\sqrt{2}} \quad , \quad |\mathrm{A}\rangle = \frac{|\mathrm{R}\rangle - i\,|\mathrm{L}\rangle}{\sqrt{2}} \, .$$



As for polarization qubit

$$\hat{\rho} = \frac{1}{2}\left(\hat{1} + \sum_{i=1}^{3} S_i \hat{\sigma}_i\right)$$

S_i Stokes parameters

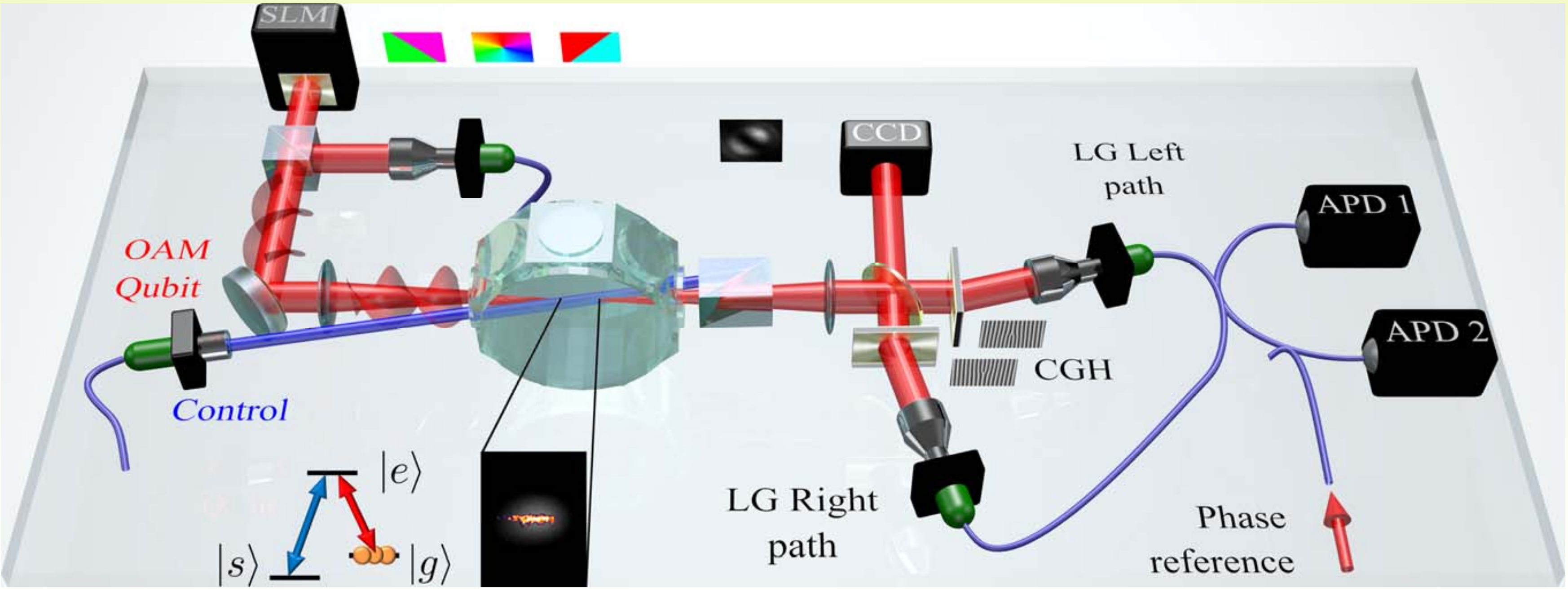
σ_i Pauli matrices

$\longrightarrow$ Three linearly independent measurements

Experimental set-up for full qubit characterization

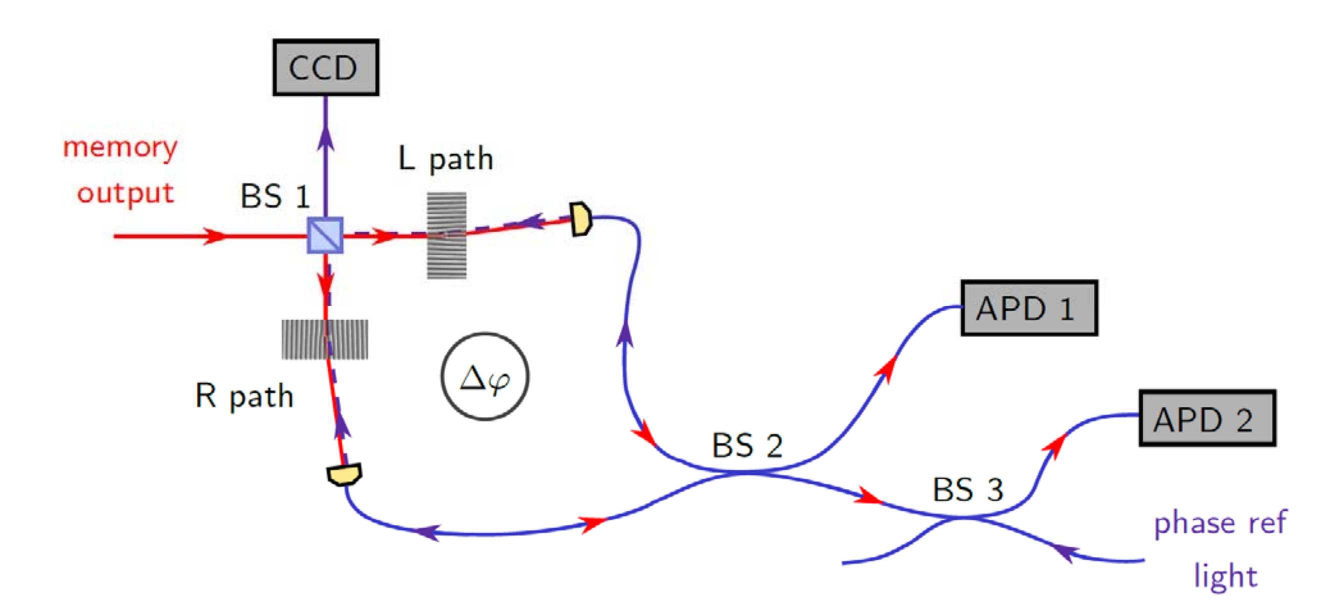
Signal attenuated Ti:Sapph laser
Control : diode laser

$$|\Psi\rangle = a|\mathrm{LG}^{-1}\rangle + b e^{-i\phi}|\mathrm{LG}^{+1}\rangle$$

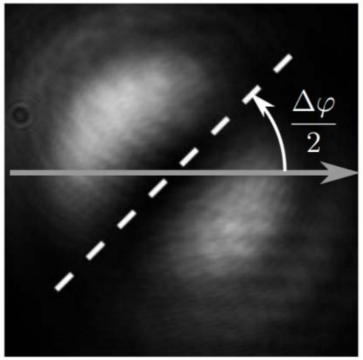


The visibility of a qbit is measured at the output of the interferometer

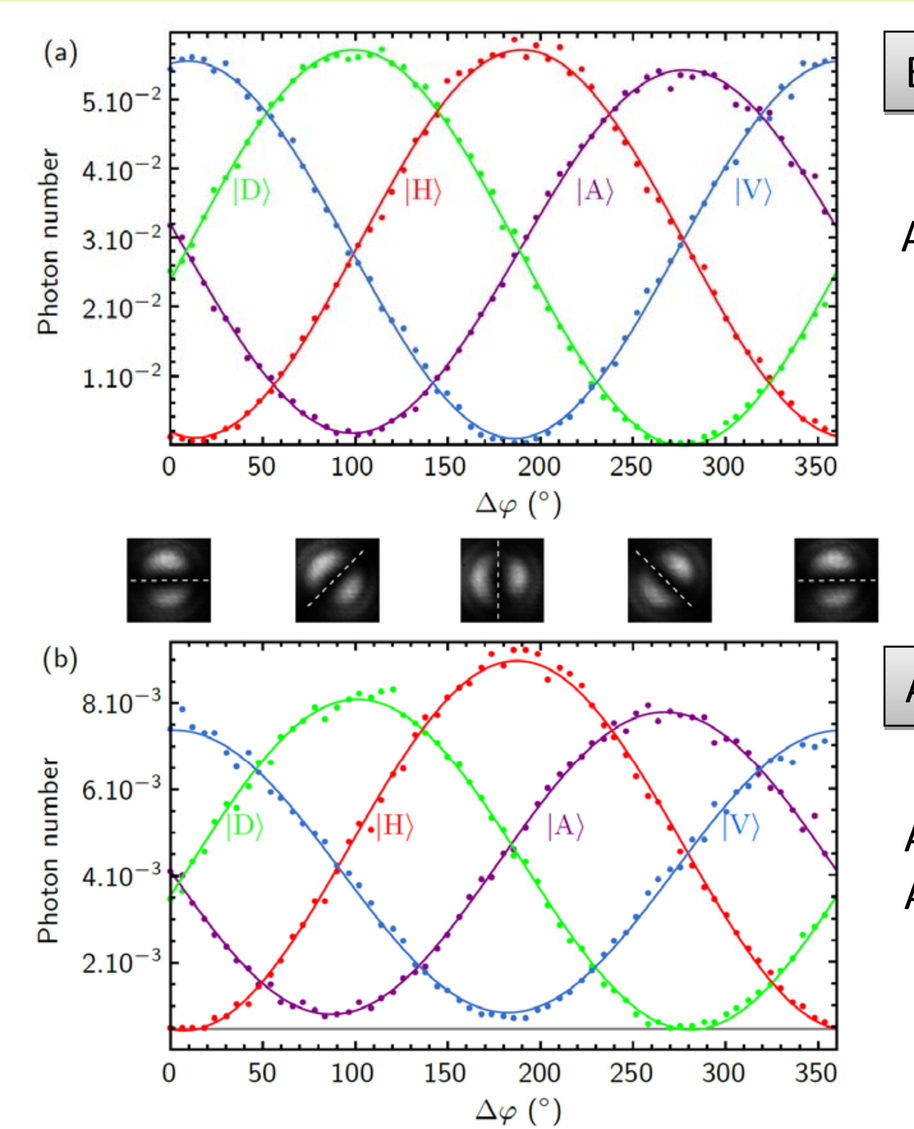
Measuring the interferometer phase



- Reference light sent backwards (12 ms over 15)
- Bright beam but low power (1 nW)
- Forms a HG mode after recombining on BS 1, with symmetry axis related to $\Delta\phi$
- Detected by CCD camera (recording every 125 ms)
- Images analyzed by Python script (phase discretization: 6°)



Interference fringes



Before storage

Average visibility: 95.8%

$\bar{n} = 0.6$

After storage

Average visibility: 85.1%

After background noise correction: 95.7%

Tomography of the quantum memory process (1)

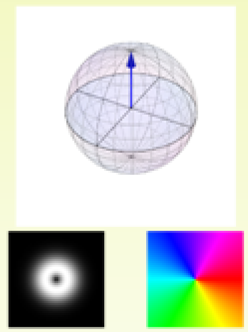
Right (R) and left (L) circularly polarized input states, in the RL basis

Stokes parameters

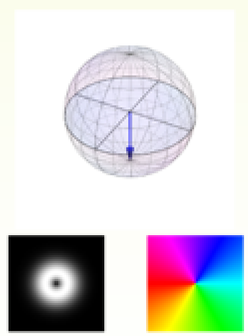
$$\begin{cases} S_1 = & (p_{\mathrm{R}} - p_{\mathrm{L}}) \\ S_2 = & (p_{\mathrm{H}} - p_{\mathrm{V}}) \\ S_3 = & (p_{\mathrm{D}} - p_{\mathrm{A}}) \end{cases}$$

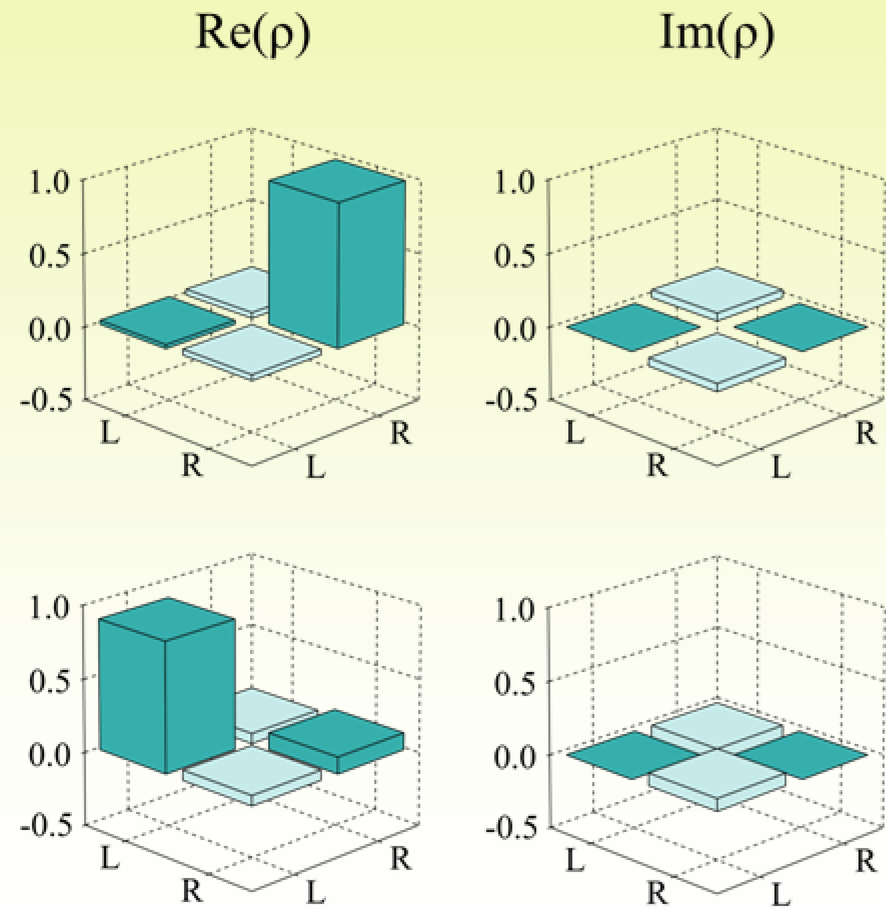
$$\hat{\rho} = \frac{1}{2}\begin{pmatrix} 1+S_1 & S_2 - iS_3 \\ S_2 + iS_3 & 1 - S_1 \end{pmatrix}$$

R



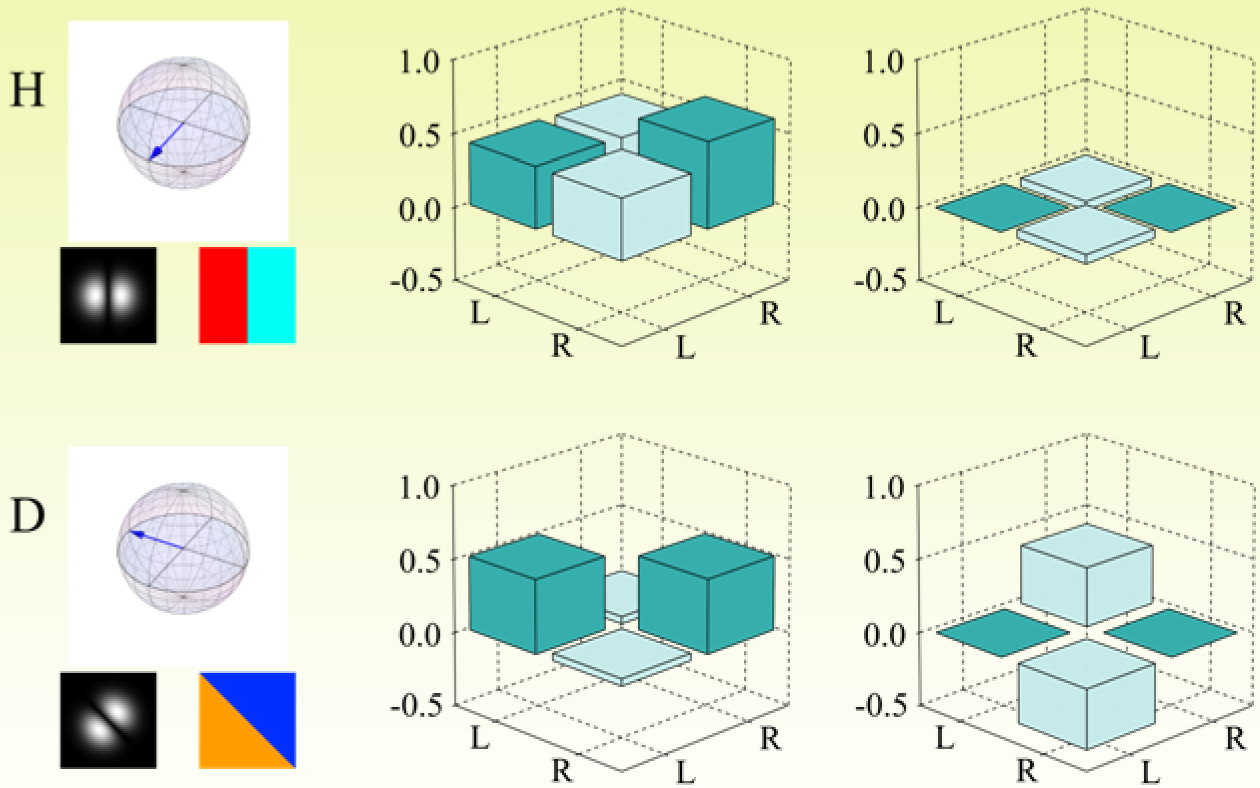
L





Tomography of the quantum memory process (2)

Horizontal (H) and diagonal (D) linearly polarized input states, in the RL basis



Fidelity

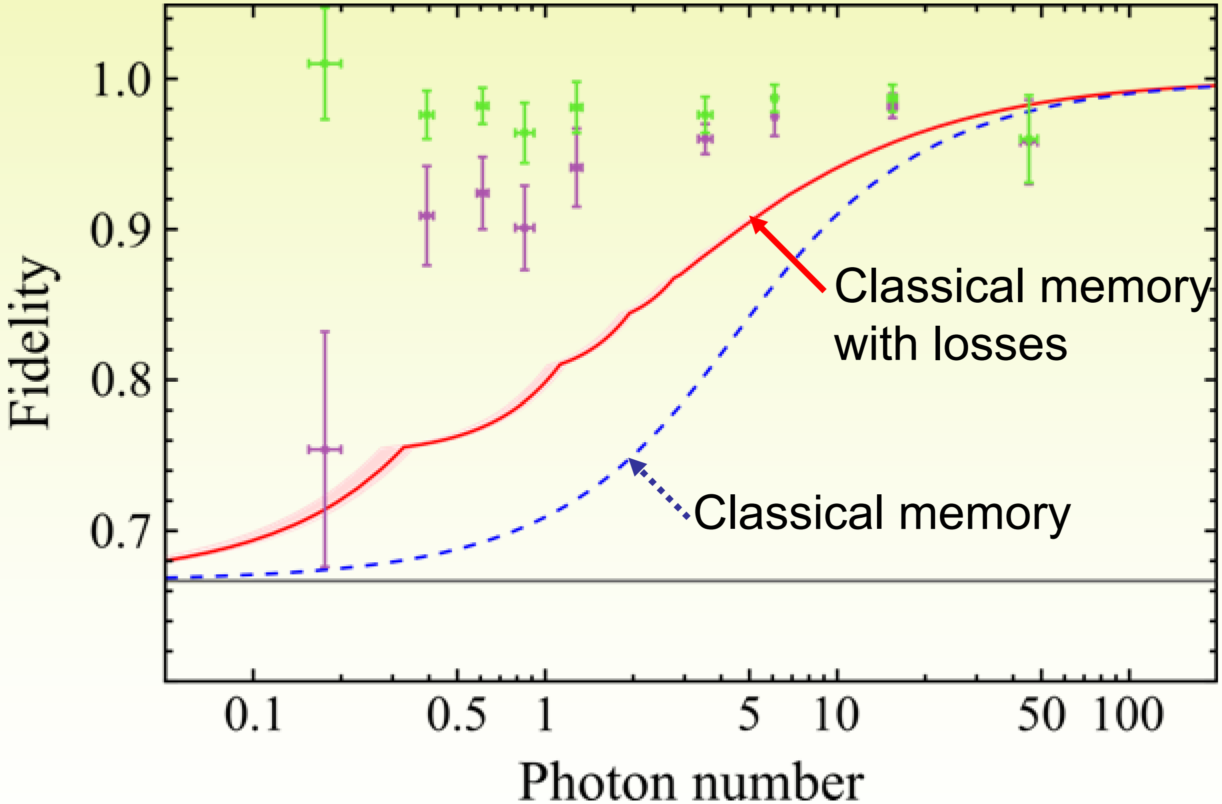
$$\mathcal{F} = \langle\psi|\,\hat{\rho}\,|\psi\rangle$$

Averaged raw fidelity: 92.5±2%

Averaged corrected fidelity: 99±1%

Fidelity of the quantum memory process

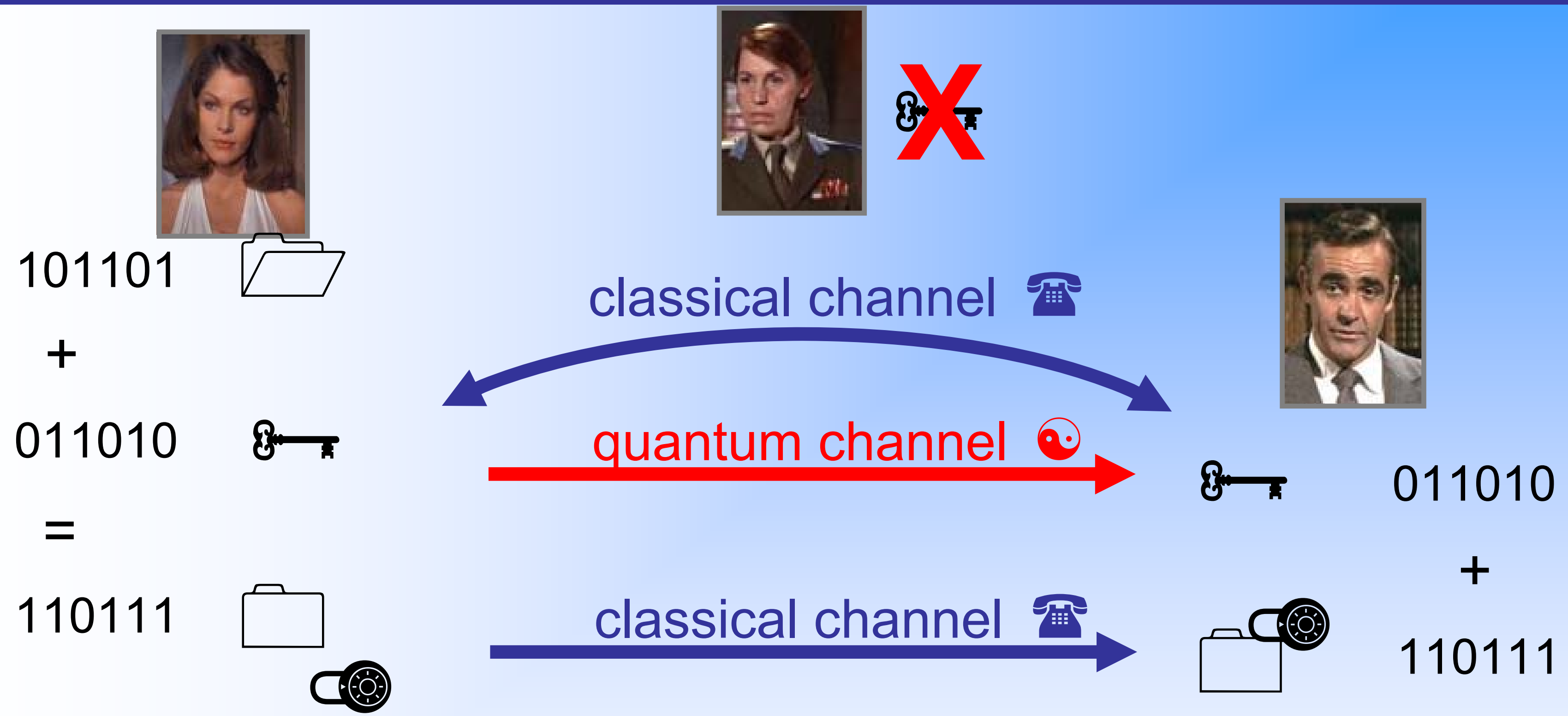
Experimental points show fidelities larger than that of a classical memory

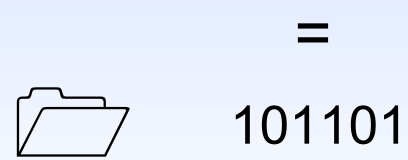


A. Nicolas et al, Nat. Phot. 8, 234 (2014)

Quantum memories are critical tools for secure quantum communications

Quantum cryptography





Any attack by Eve will induce perturbations (errors) that can be detected by Alice and Bob

The security is based on the physical properties of the quantum channel (no-cloning theorem!)

The main problem

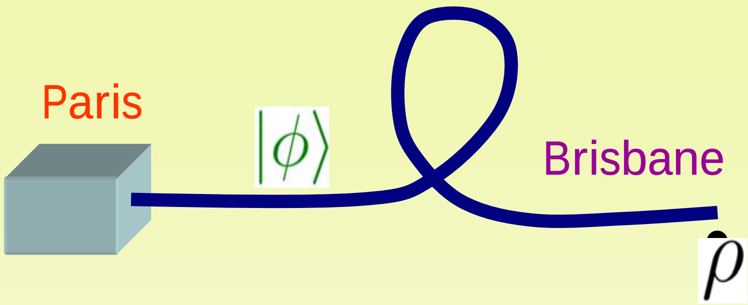
Losses on the telecom lines

~0.2 dB / km

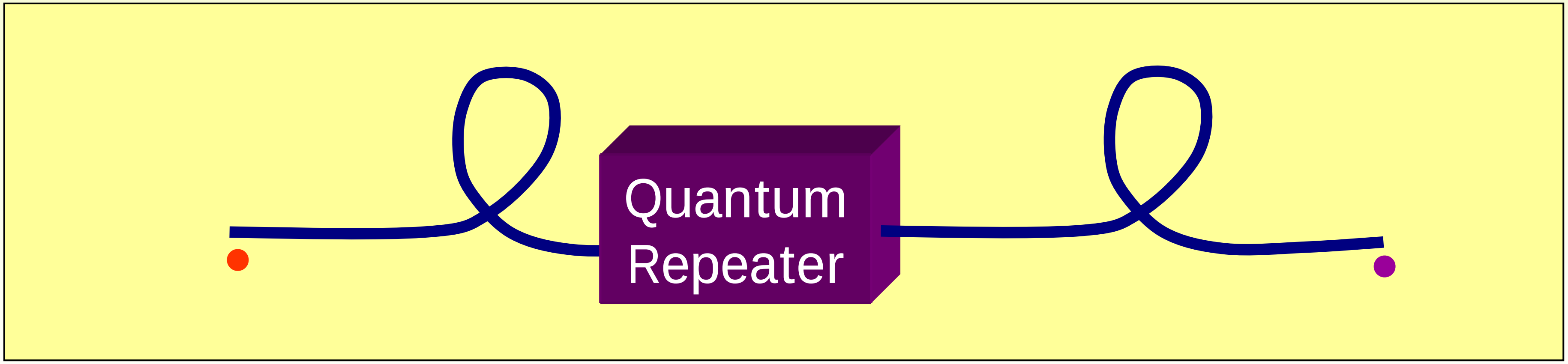
Quantum Repeaters

100 km, Telecom fiber : 99 % loss

For 1000 km, and a qubit source at 10GHz, it would take 300 years to transmit one qubit….



Connection time decays exponentially with the distance

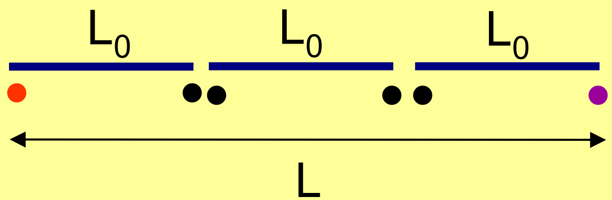


Goal : Connect with a fidelity close to 1 in a "not too long" time

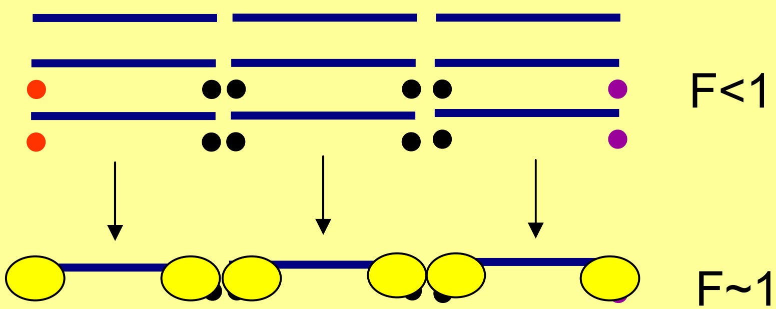
Schemes for quantum repeater proposed by Briegel, Dur, Cirac, Zoller in 1998 and by Duan, Lukin Cirac, Zoller (DLCZ protocol) in 2001

Quantum Repeaters

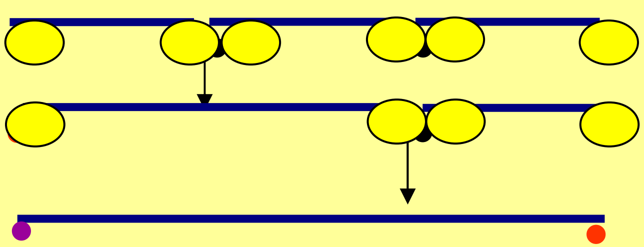
1) Divide into segments and generate entanglement



2) Purify the entanglement



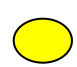
3) Entanglement swapping



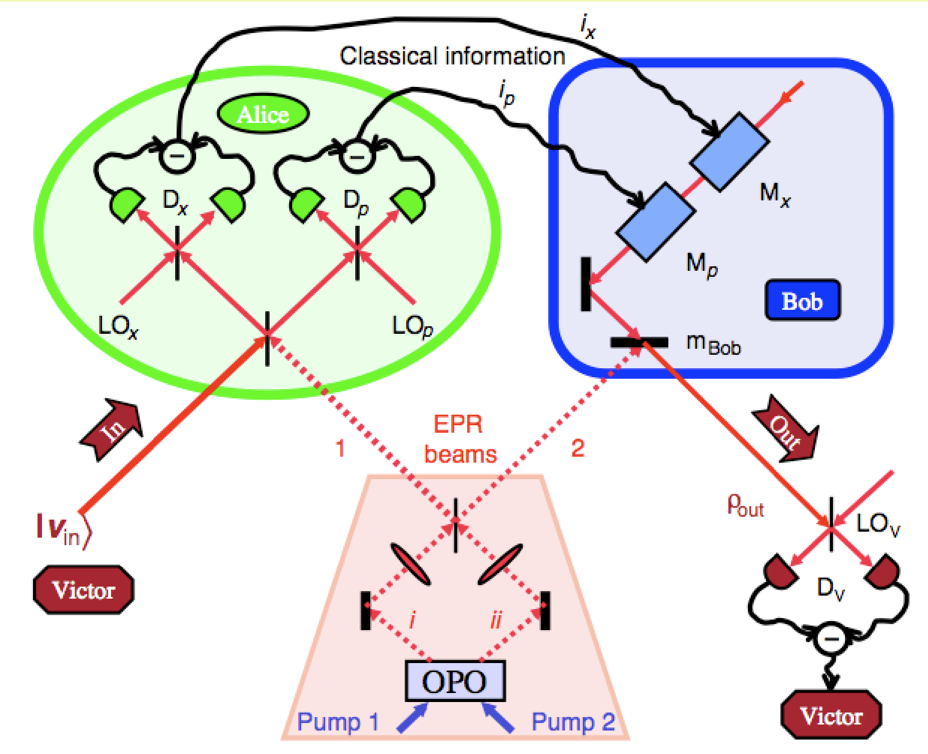
Fidelity close to 1, long distance… But time exponentially large with the distance

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

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

 **: Quantum Memories**

Quantum Teleportation



1- Measurements

$$P = P_{in} - P_1$$

$$Q = Q_{in} + Q_1$$

2- Transmission (classical channel)

3- Modulations

$$P_{out} = P_2 + P = P_{in} + (P_2 - P_1) \quad (P_2 - P_1) \rightarrow 0$$

$$Q_{out} = Q_2 + Q = Q_{in} + (Q_1 + Q_2) \quad (Q_1 + Q_2) \rightarrow 0$$

First teleporation of a coherent states with Fidelity above 0.5 (1/2=classical strategy)

A. Furusawa, JL Sorensen, SL Braunstein, CA Fuchs,HJ Kimble, ES Polzik
Unconditional quantum teleportation, Science 282, 706 (1998)

Conclusions

- Quantum memories and quantum repeaters are crucial elements for quantum communications
- 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 memory in cold atoms : storage of “twisted” photons demonstrated
- Good prospect of OAM for highly multimode storage

Adrien Nicolas

Dominik Maxein

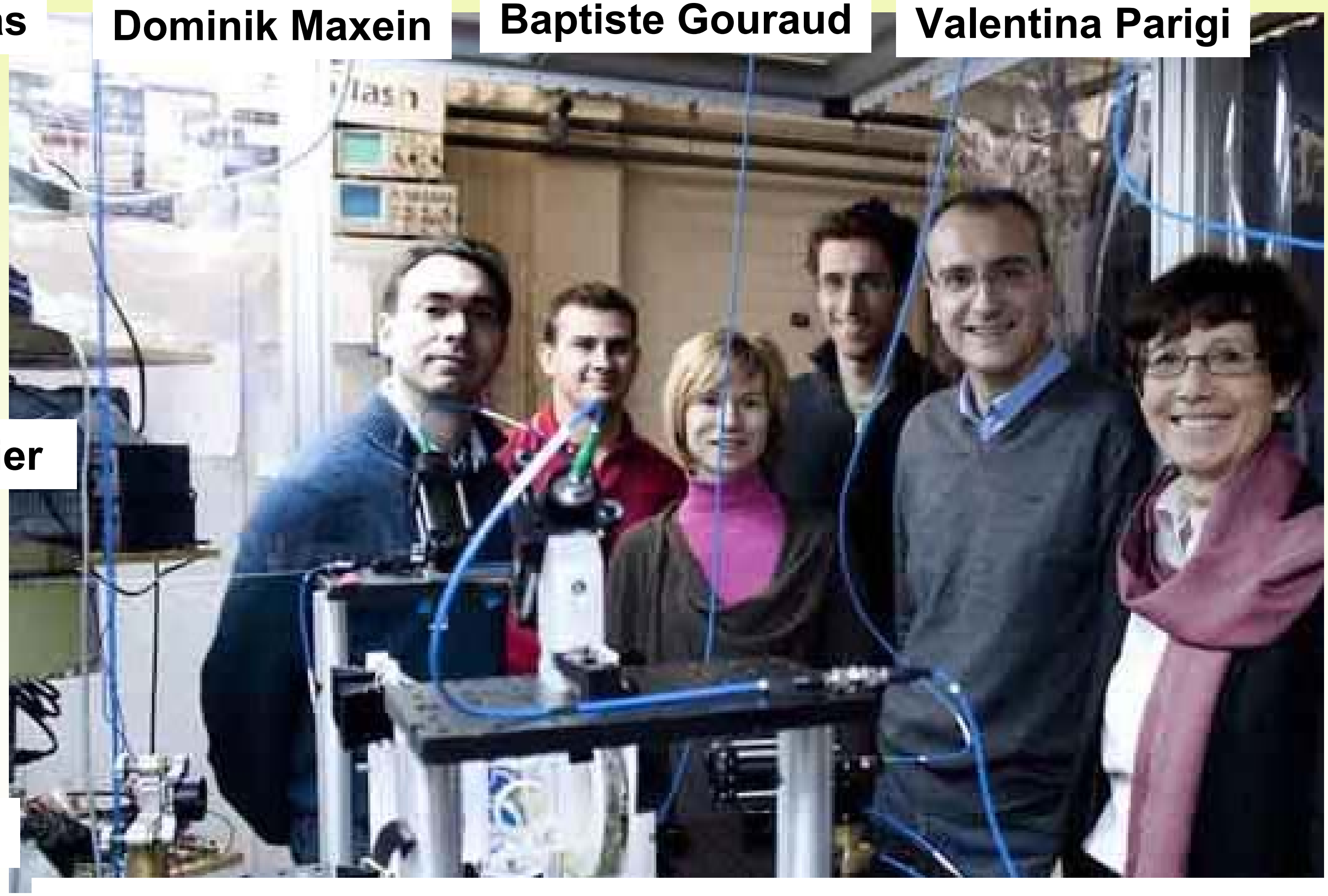
Baptiste Gouraud

Valentina Parigi

Pierre Vernaz-Gris

Lucile Veissier

Sidney Burks



Lambert Giner, Michael Scherman

Julien Laurat, Oxana Mishina, Alberto Bramati, Elisabeth Giacobino

Thank you for your attention