Content of the lectures

Lecture 1 Introduction to quantum noise, squeezed light and entanglement generation

Quantization of light, Continuous-variable, Homodyne detection, Gaussian states, Optical parametric oscillators, Entanglement, Teleportation

Lecture 2 Quantum state engineering

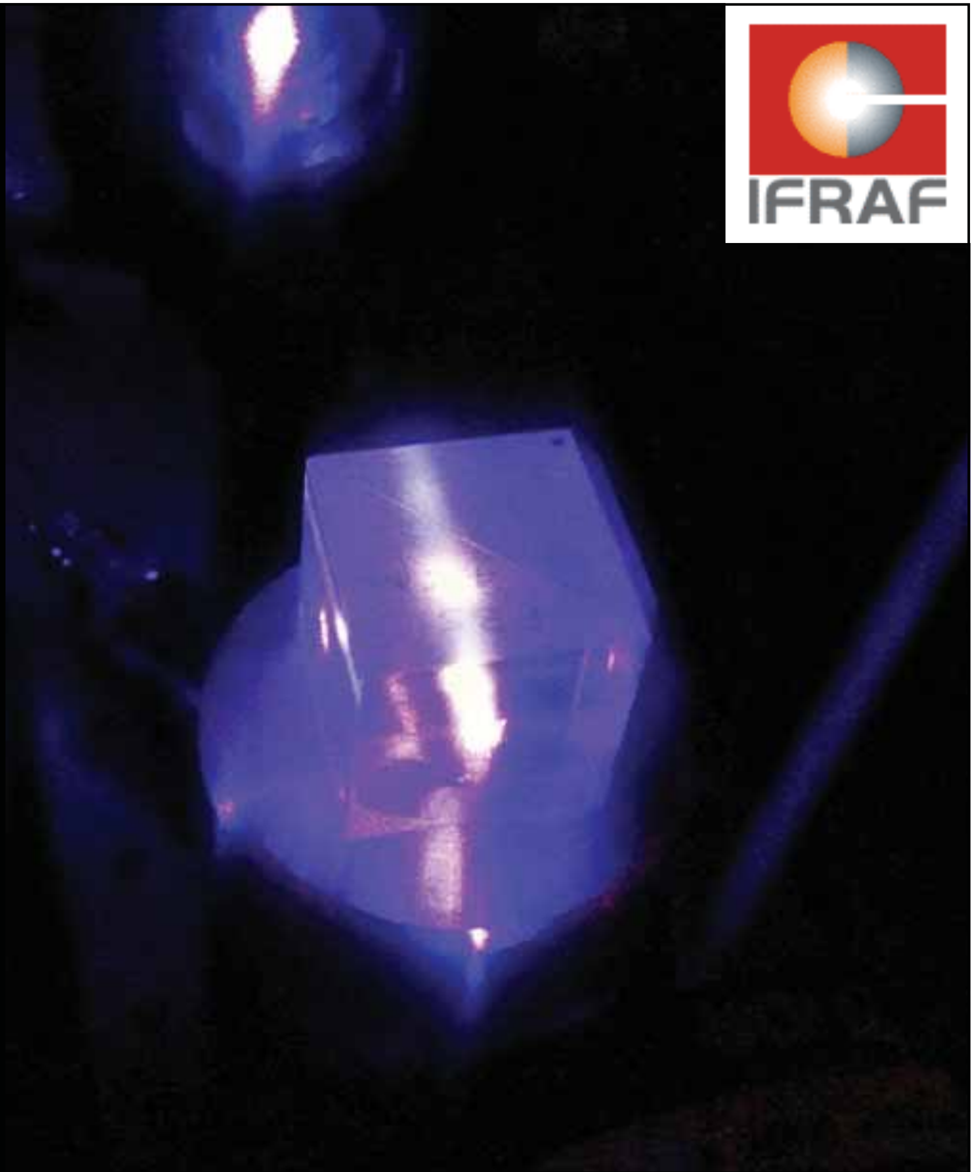
Conditional preparation, Non-Gaussian states, Schrödinger cat states, Hybrid approaches, Quantum detectors, POVM and detector tomography

Lecture 3 Optical quantum memories.

Quantum repeaters, atomic ensembles, DLCZ, EIT, Photon-echo, Matter-Matter entanglement

Laboratoire Kastler Brossel
Physique quantique et applications

Lecture 3
Optical Quantum Memories



Julien Laurat

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Ecole Normale Supérieure and CNRS

julien.laurat@upmc.fr

Taiwan-France joint school, Nantou, May 2011

Lecture 3

• Introduction to quantum memories for light and scalable QIT

• How ? Single-atom and ensemble-based quantum memories

<u>Ensemble-based techniques</u>

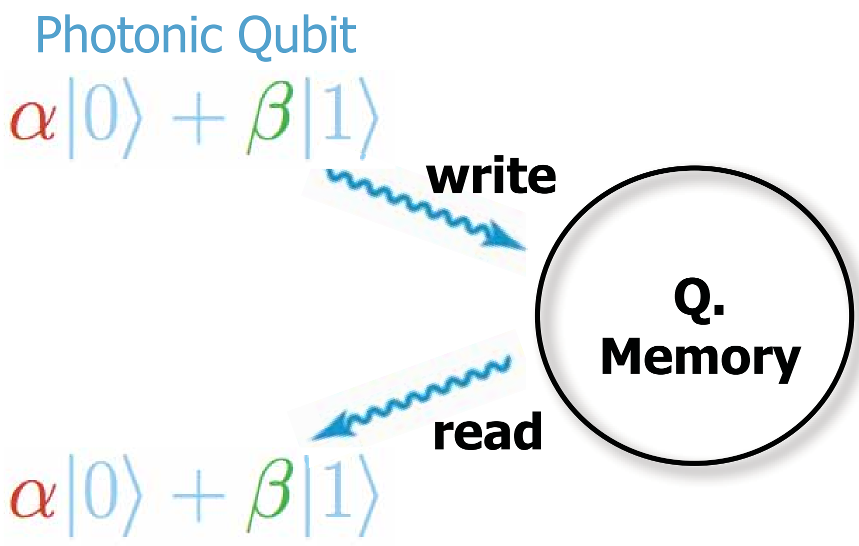
• Duan-Lukin-Cirac-Zoller approach

• Dynamic EIT memories

• Photon-echo techniques

Quantum Memories for Light

Desideratum : Storing a quantum state without measuring it and reading on demand, i.e. a coherent and reversible transfer between atoms and light.



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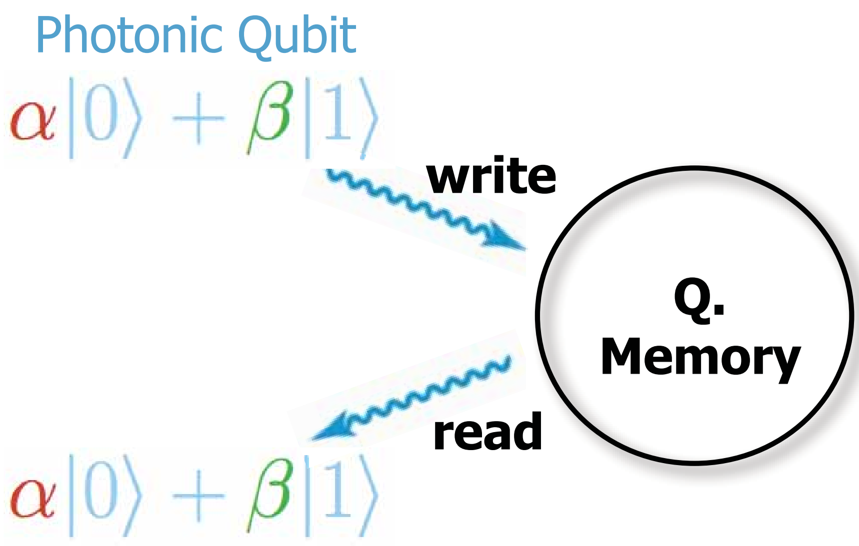
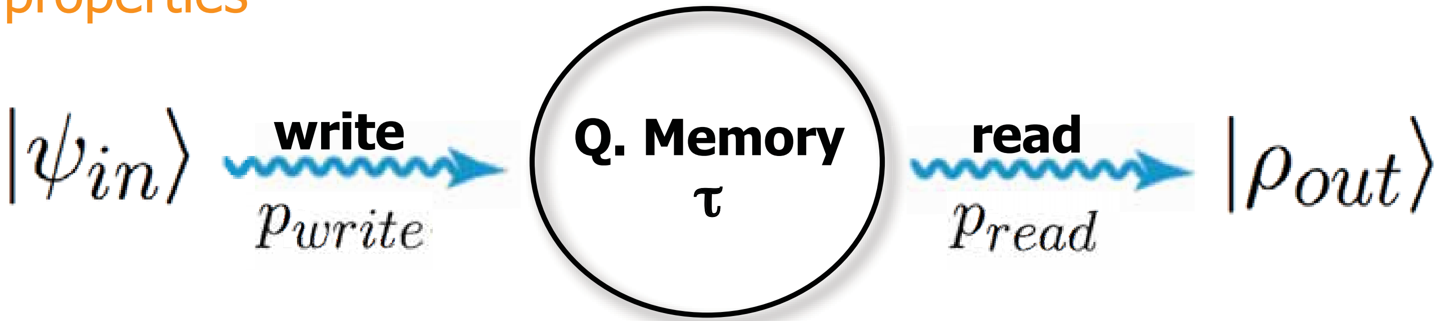


Some important properties



- Storage time τ
- Efficiency $\eta = p_{write} \cdot p_{read}$
- Fidelity (conditional or not) $F_{cond} = \langle \psi_{in} | \rho_{out} | \psi_{in} \rangle_{cond}$
- Bandwidth, wavelength, mutimode storage…

Quatum Memories for Scalable QIT

Memory for light

- Synchronizing tool for protocols involving several probabilistic processes
- Deterministic photon gun
- Flying/stationnary qubit convertor
- Building block of Q.Computer

Quatum Memories for Scalable QIT

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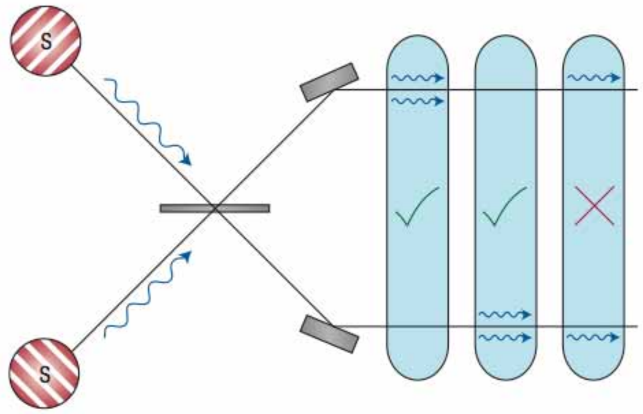
HOM experiment and conditional logic
28-fold enhancement in count rate!



D. Felinto et al., Nature Phys. 2, 844 (2006)

Quatum Memories for Scalable QIT

Memory for light

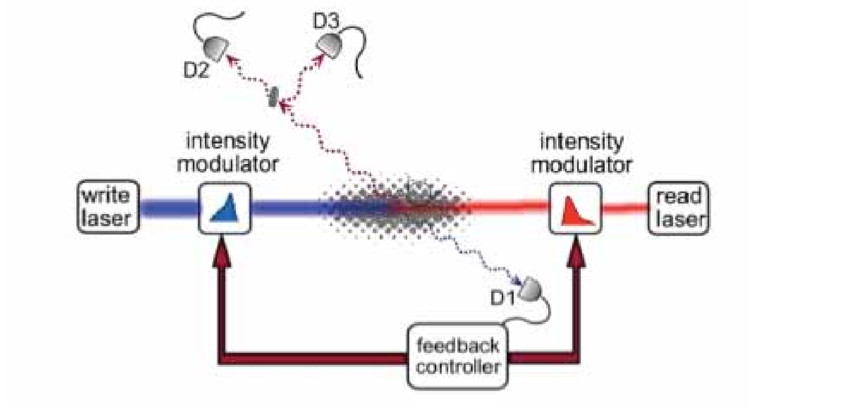
• Synchronizing tool for protocols involving several probabilistic processes

• Deterministic photon gun

• Flying/stationnary qubit convertor

• Building block of Q.Computer

(Almost) deterministic single-photon

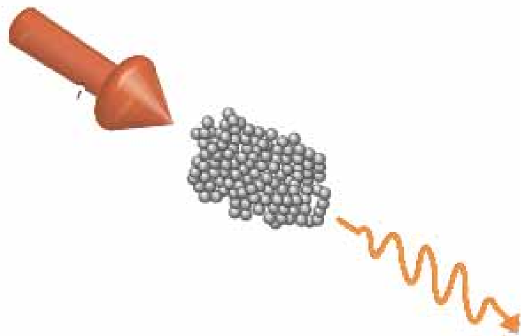


D.N. Matsukevich et al., Phys. Rev. Lett. ***97****, 013601 (2006)*

« Quantum Networking »

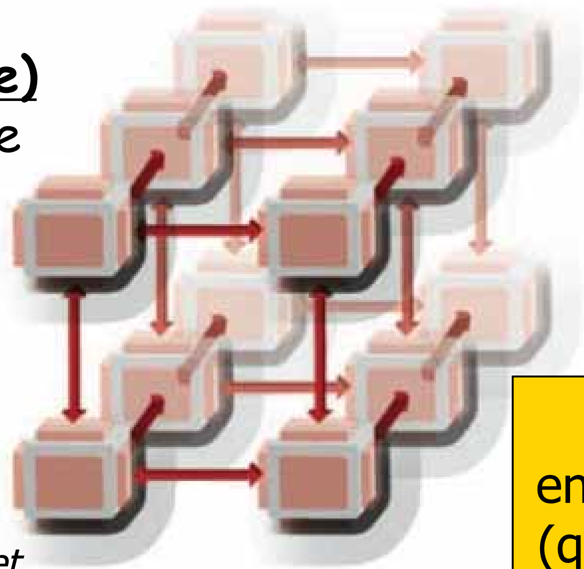
Memory for light

- Synchronizing tool for protocols involving several probabilistic processes
- Deterministic photon gun
- Flying/stationnary qubit convertor
- Building block of Q.Computer



Quantum node (Light-Matter interface)

generate, process, store quantum information locally



Quantum channel – transport / distribute quantum entanglement over the entire network

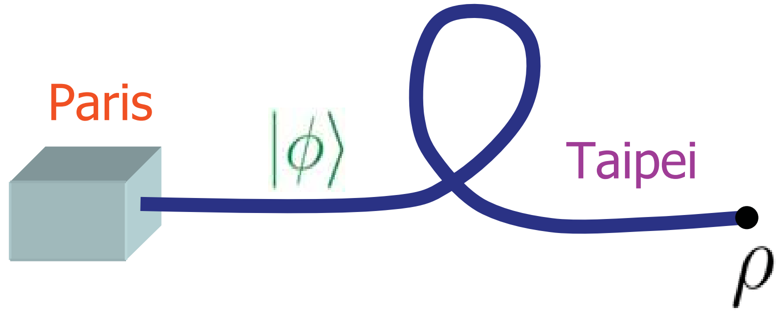
*H.J. Kimble, The Quantum Internet, Nature **453**, 1023 (2008)*

Develop the resources that enable scalable quantum networks (quantum repeaters on long-scale, quantum simulation,...)

One example : Quantum Repeaters

Problem : Decoherence

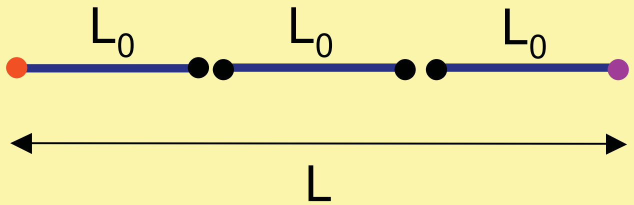
Result : Entanglement decays exponentially with the distance



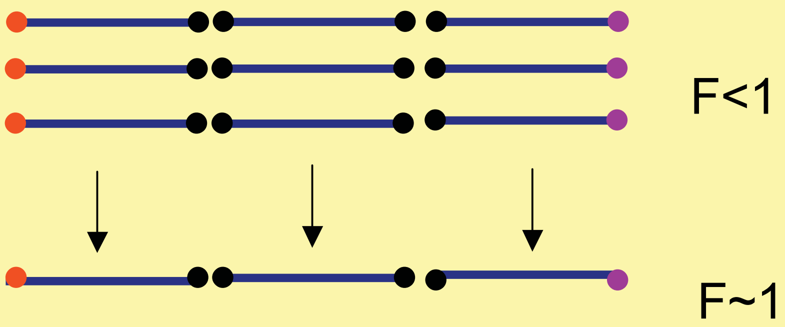
Goal : Connect with a fidelity close to 1 in a "not too long" time

One example : Quantum Repeaters

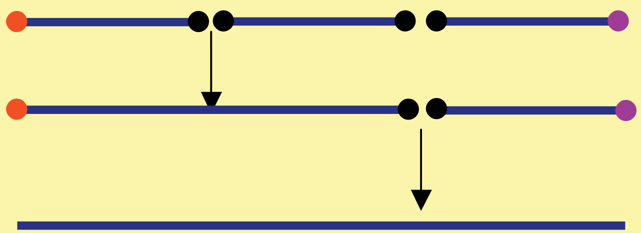
1) **Divide into segments and generate entanglement**



2) **Purify the entanglement**



3) **Connect the pairs**



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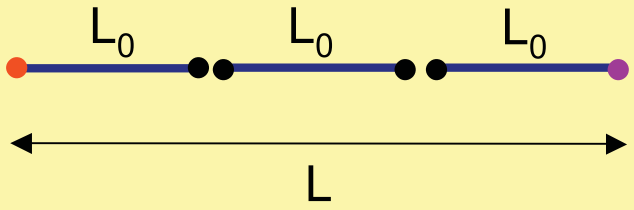

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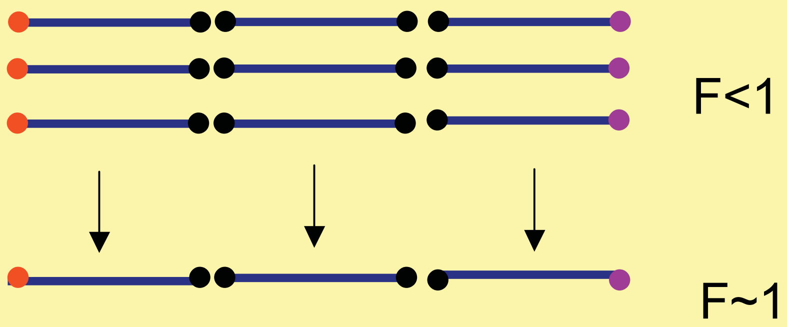

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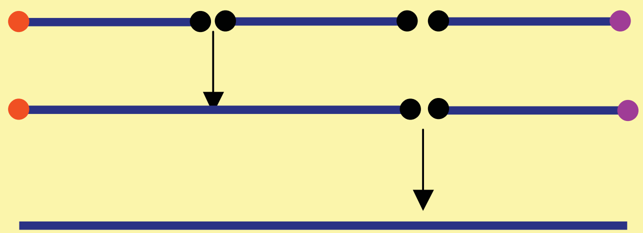
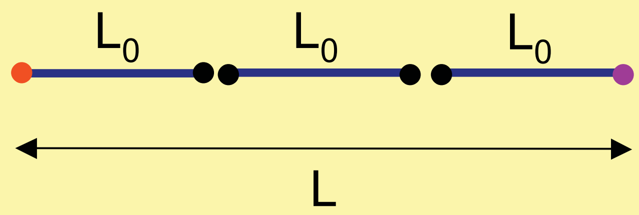


Fidelity close to 1, long distance… But time exponentially large with the distance

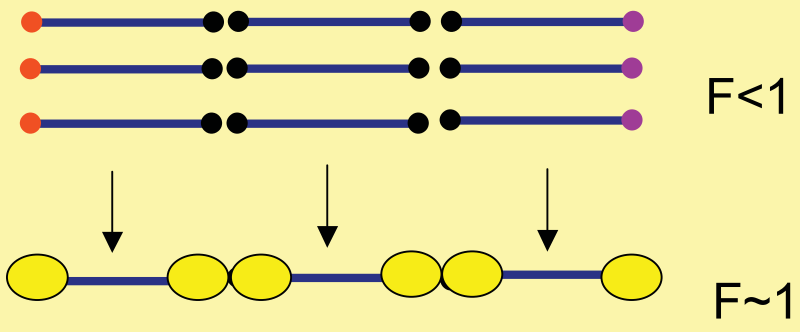
Entanglement (often) and purification (always) are probabilistic : each step ends at different times.

One example : Quantum Repeaters

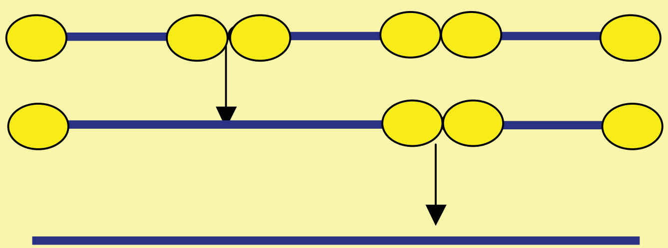
1) Divide into segments and generate entanglement



2) Purify the entanglement



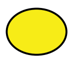
3) Connect the pairs



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

Lecture 3

- Introduction to quantum memories for light and scalable QIT

- How ? Single-atom and ensemble-based quantum memories

Ensemble-based techniques

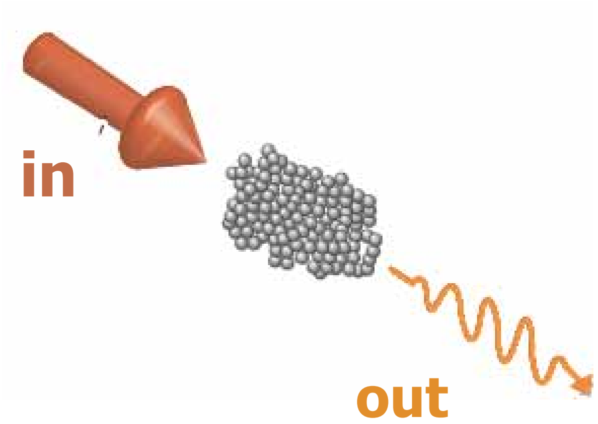
- Duan-Lukin-Cirac-Zoller approach

- Dynamic EIT memories

- Photon-echo techniques

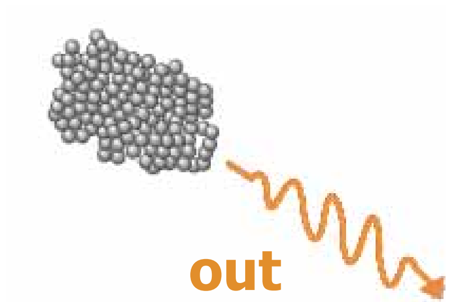
Two Types of Quantum Memories

Absorptive quantum memory



- Flexible in wavelength (e.g.storing one photon entangled with another photon at telecom wavelength)
- Flexible in states to be stored (single photons, CV states,…)

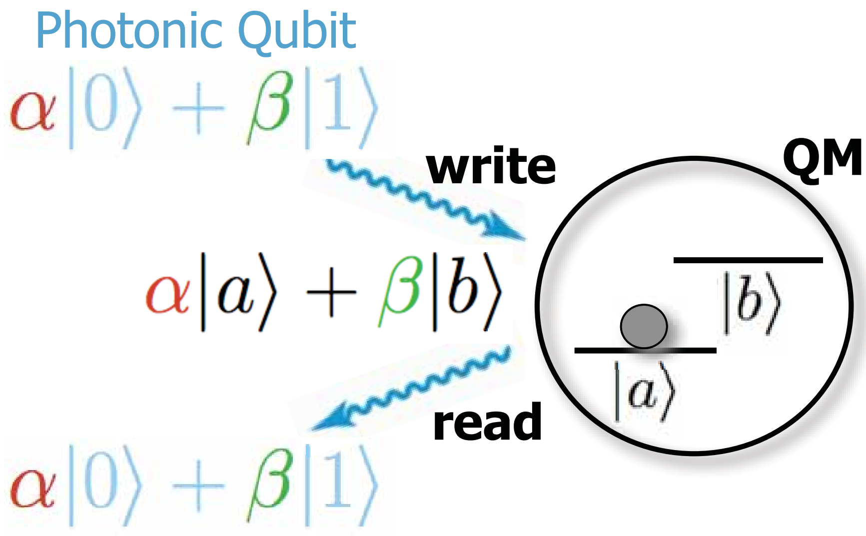
Emissive-only quantum memory



- Source and memory in the same time (non-classicality is "built-in", writing is done with a classical state…)
- Much less flexible… Emission not at telecom wavelengths… Useful anyway, as we will see!

Light-Matter Interfaces : How ?

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



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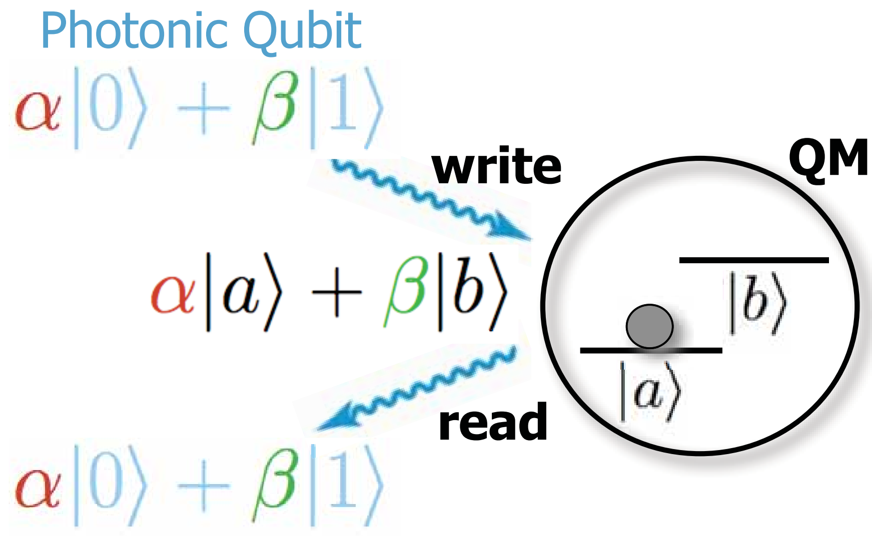
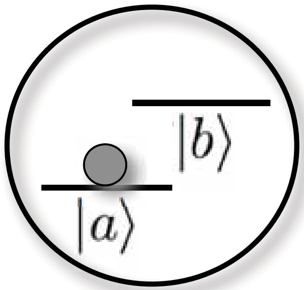


Single Atom

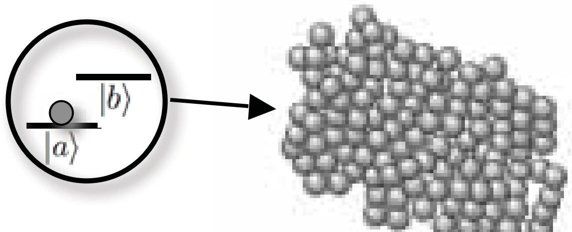


Requires a high-finesse cavity (CQED)

Example for storage of a single photon

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

Atomic ensembles



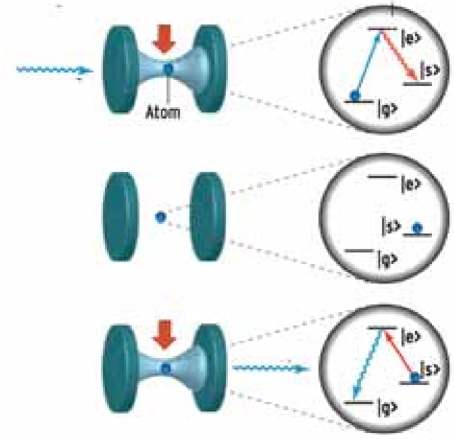
Light easily interact with the sample
Collective state (enhancement)

Example for storage of a single photon

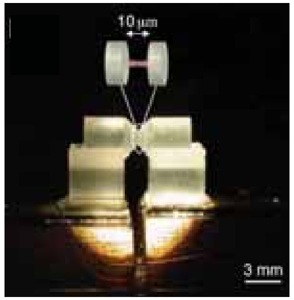
$$|a_1 \ldots a_i \ldots a_N\rangle \rightarrow \frac{1}{\sqrt{N}} \sum_i |a_1 \ldots b_i \ldots a_N\rangle$$

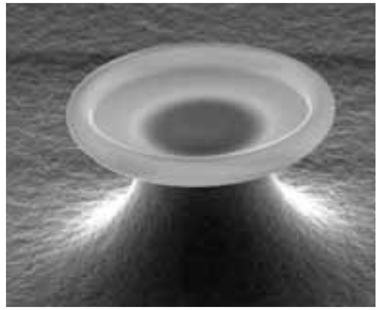
Light-Matter Interfaces : How ?

Single Atom

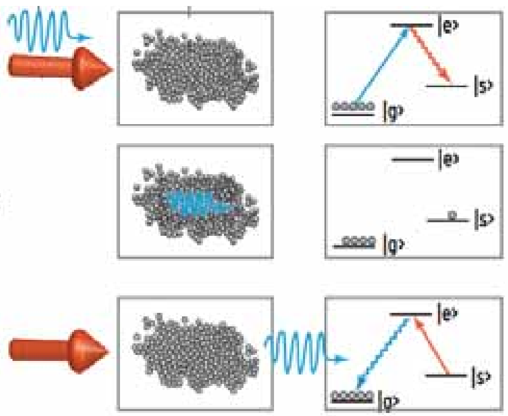


Cavity Quantum Electro-Dynamics (strong coupling, high finesse cavities)

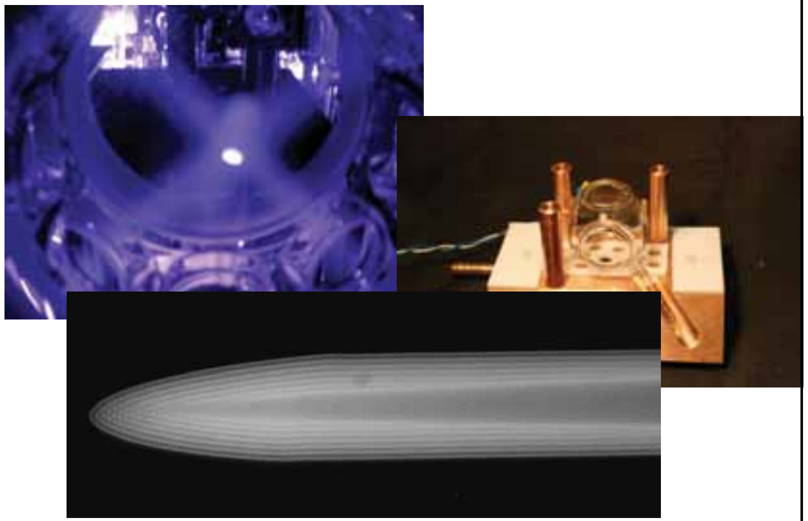


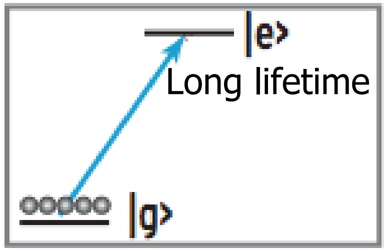


Atomic Ensembles : Collective Exc.



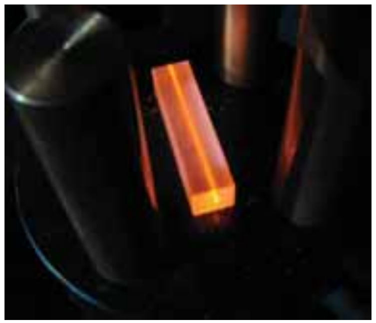
- Dynamic EIT
- DLCZ protocol (emissive-only)





Rephasing protocol
- CRIB and AFC -

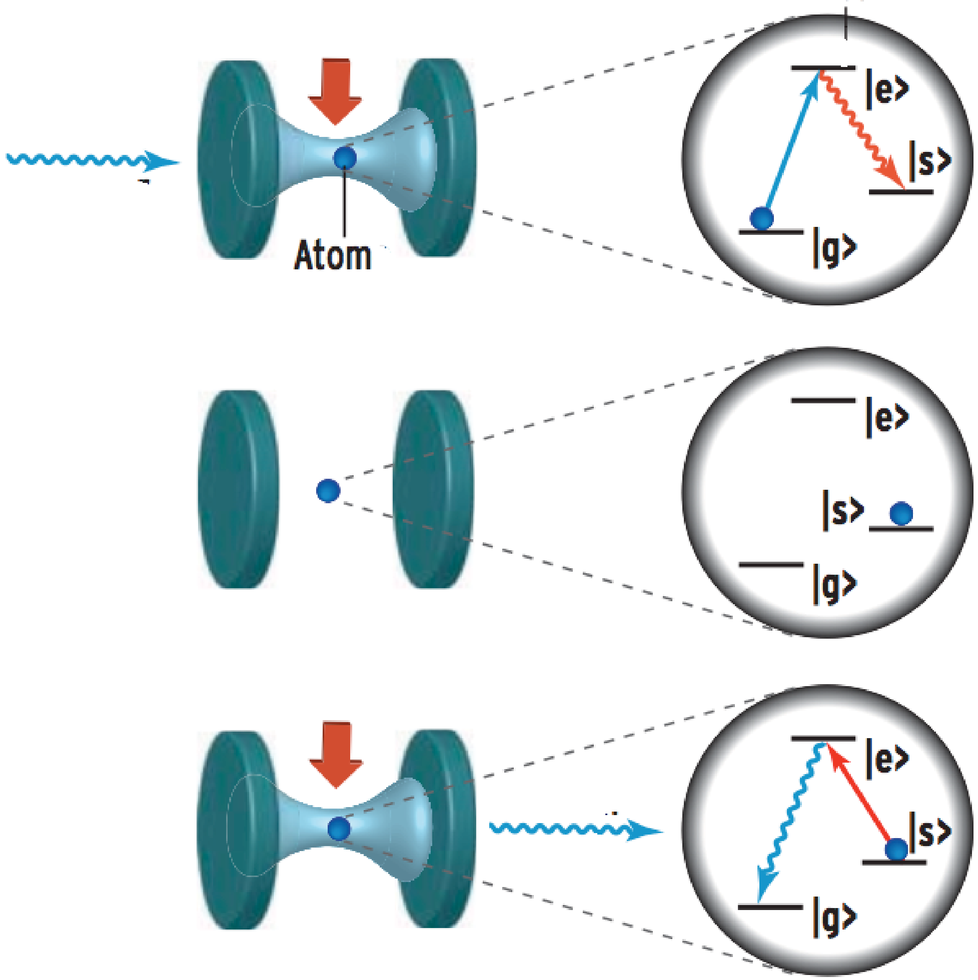
Rare-earth ions in solids at cryogenic temperature



Towards a Single Atom Memory

One atom in a high finesse cavity (strong coupling)

General strategy : two ground states connected via an additional control field (we will find that also later for EIT and some photon-echo techniques)



Towards a Single Atom Memory

One atom in a high finesse cavity (strong coupling)

First demonstration of a reversible mapping

PRL **98**, 193601 (2007) PHYSICAL REVIEW LETTERS week ending 11 MAY 2007

Reversible State Transfer between Light and a Single Trapped Atom

A. D. Boozer, A. Boca, R. Miller, T. E. Northup, and H. J. Kimble

Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125, USA

(Received 25 February 2007; published 8 May 2007)

We demonstrate the reversible mapping of a coherent state of light with a mean photon number $\bar{n} \simeq 1.1$ to and from the hyperfine states of an atom trapped within the mode of a high-finesse optical cavity. The coherence of the basic processes is verified by mapping the atomic state back onto a field state in a way that depends on the phase of the original coherent state. Our experiment represents an important step toward the realization of cavity QED-based quantum networks, wherein coherent transfer of quantum states enables the distribution of quantum information across the network.

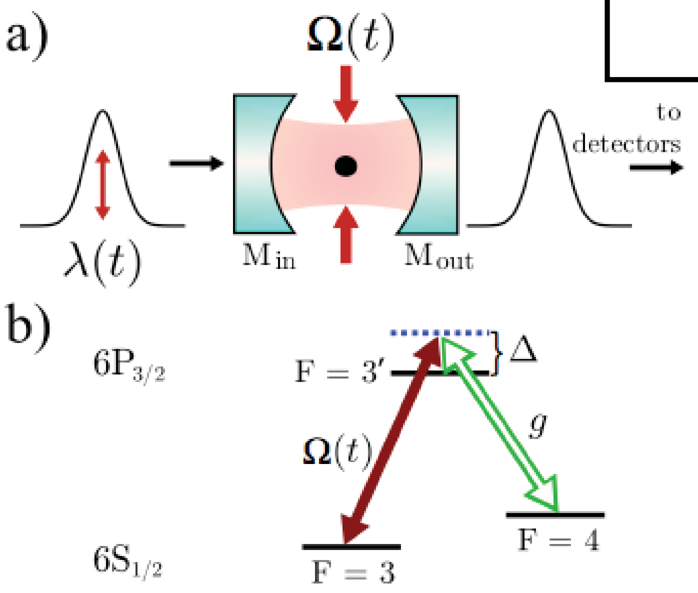


FIG. 2 (color online). (a) Schematic of the experiment. The probe $\lambda(t)$ resonantly drives the cavity through input mirror M_{in}; the classical field $\Omega(t)$ excites the atom transverse to the cavity axis. Photons emitted from the output mirror M_{out} are directed to a pair of avalanche photodiodes. (b) Atomic level diagram. Double arrow g indicates the coherent atom-cavity coupling, and $\Omega(t)$ is the classical field. The cavity and Ω field are blue-detuned from atomic resonance by Δ.

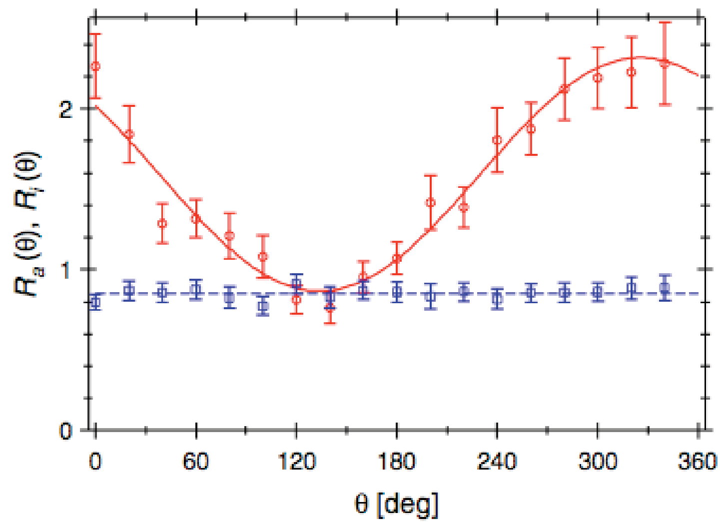


FIG. 5 (color online). Ratios $R_a(\theta), R_i(\theta)$ for photon generation as a function of the relative phase θ between the $\lambda_{1,2}$ fields. Red data points (○): $R_a(\theta)$ for adiabatic state transfer with Ω_1 on. Blue points (□): $R_i(\theta)$ for the incoherent process with Ω_1 off. The full curve is a fit to obtain the fringe visibility $v_a \simeq 0.46 \pm 0.03$. On average, each point represents about 130 atoms.

A Single Atom Quantum Memory

One atom in a high finesse cavity (strong coupling)

Storage and read-out of a weak coherent pulse with arbitrary polarization state

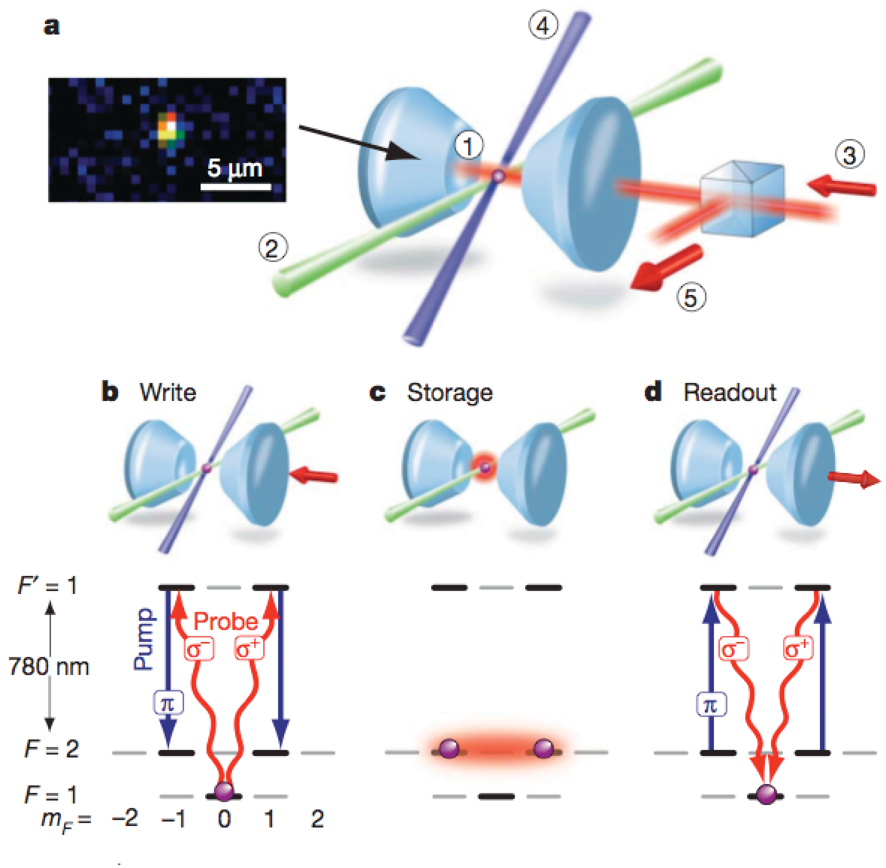
LETTER

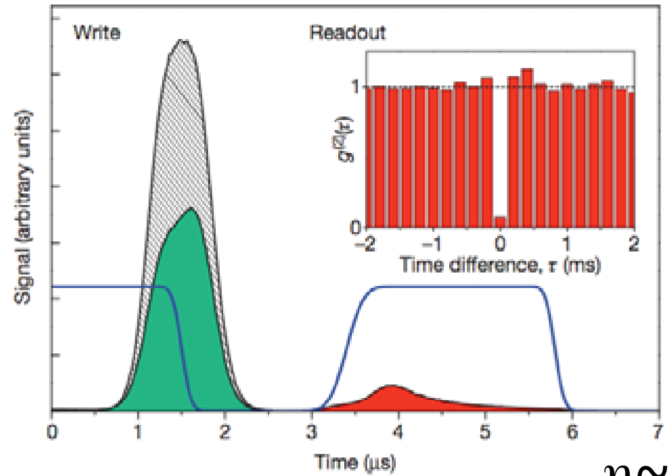
Nature, may 2011

doi:10.1038/nature09997

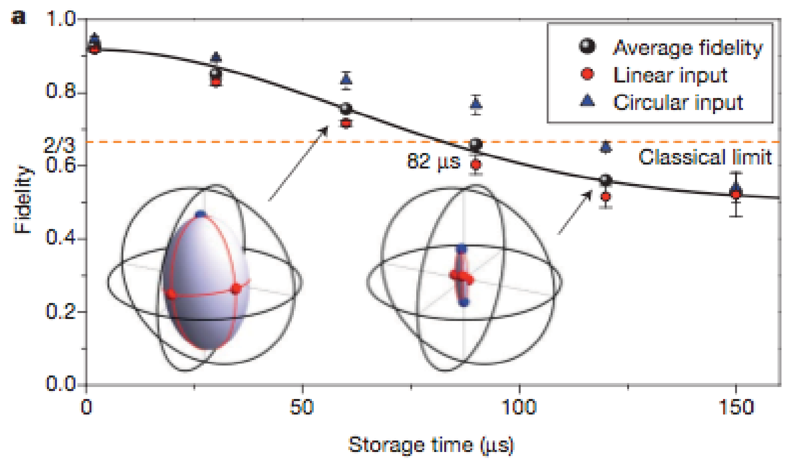
A single-atom quantum memory

Holger P. Specht[1]†, Christian Nölleke[1], Andreas Reiserer[1], Manuel Uphoff[1], Eden Figueroa[1], Stephan Ritter[1] & Gerhard Rempe[1]





η~9%



Lecture 3

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Ensemble-based techniques

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- Dynamic EIT memories

- Photon-echo techniques

The DLCZ Paradigm (2001)

NATURE | VOL 414 | 22 NOVEMBER 2001 | www.nature.com

articles

Long-distance quantum communication with atomic ensembles and linear optics

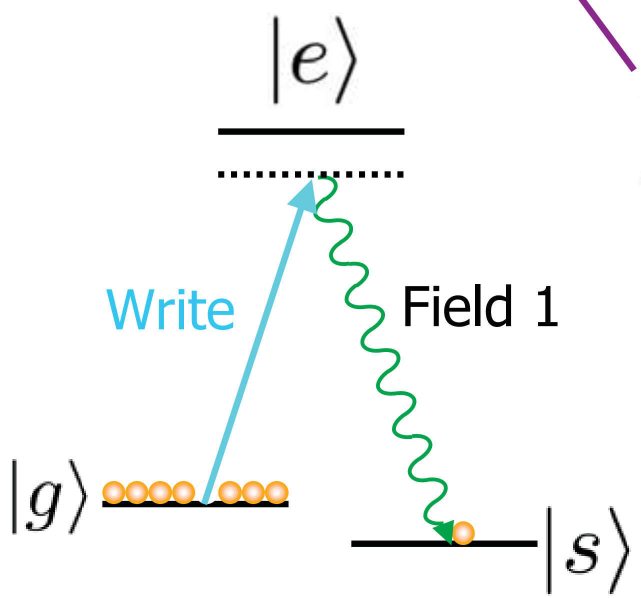
L.-M. Duan*†, M. D. Lukin‡, J. I. Cirac* & P. Zoller*

* *Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria*
† *Laboratory of Quantum Communication and Computation, USTC, Hefei 230026, China*
‡ *Physics Department and ITAMP, Harvard University, Cambridge, Massachusetts 02138, USA*

Quantum communication holds promise for absolutely secure transmission of secret messages and the faithful transfer of unknown quantum states. Photonic channels appear to be very attractive for the physical implementation of quantum communication. However, owing to losses and decoherence in the channel, the communication fidelity decreases exponentially with the channel length. Here we describe a scheme that allows the implementation of robust quantum communication over long lossy channels. The scheme involves laser manipulation of atomic ensembles, beam splitters, and single-photon detectors with moderate efficiencies, and is therefore compatible with current experimental technology. We show that the communication efficiency scales polynomially with the channel length, and hence the scheme should be operable over very long distances.

Creating a Single Collective Excitation

Nonclassical correlations between field 1 and the ensemble

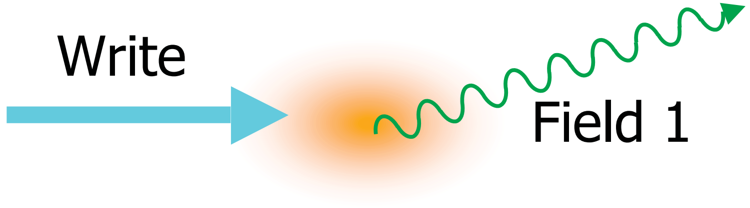


$$|\psi_{1at}\rangle = |0_1, 0_{at}\rangle + \sqrt{p}|1_1, 1_{at}\rangle + O(p)$$

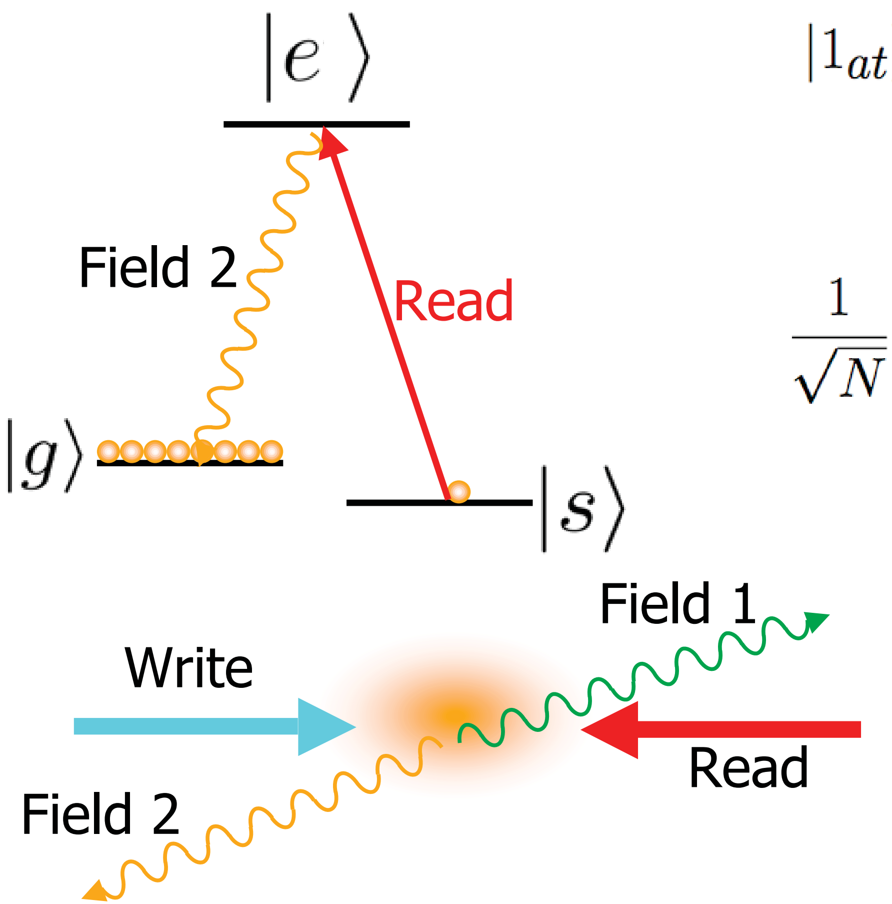
p : the excitation probability

$$|1_{at}\rangle = \frac{1}{\sqrt{N}} \sum_i e^{i(\vec{k}_w - \vec{k}_{f1}).\vec{x}_i} |g_1 ... s_i ... g_N\rangle$$

Collective atomic state



Retrieving the Single Excitation



$$|1_{at}\rangle = \frac{1}{\sqrt{N}} \sum_i e^{i(\vec{k}_w - \vec{k}_{f1}).\vec{x}_i} |g_1 ... s_i ... g_N\rangle$$

$$\downarrow$$

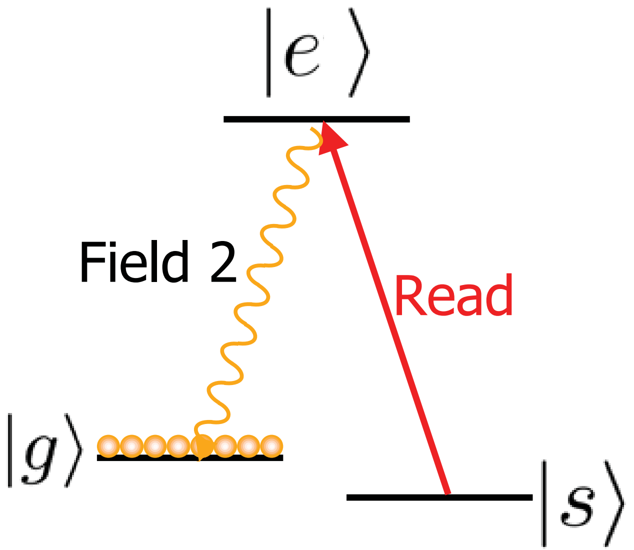
$$\frac{1}{\sqrt{N}} \sum_i e^{i(\vec{k}_w - \vec{k}_{f1}).\vec{x}_i} e^{i(\vec{k}_r - \vec{k}_{f2}).\vec{x'}_i} |g_1 ... g_i ... g_N\rangle$$

Collective enhancement if :

Atoms at rest : $\vec{k}_w + \vec{k}_r = \vec{k}_{f1} + \vec{k}_{f2}$

Moving atoms: $\vec{k}_w = \vec{k}_r$ and $\vec{k}_{f1} = \vec{k}_{f2}$

Retrieving the Single Excitation



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$$\downarrow$$

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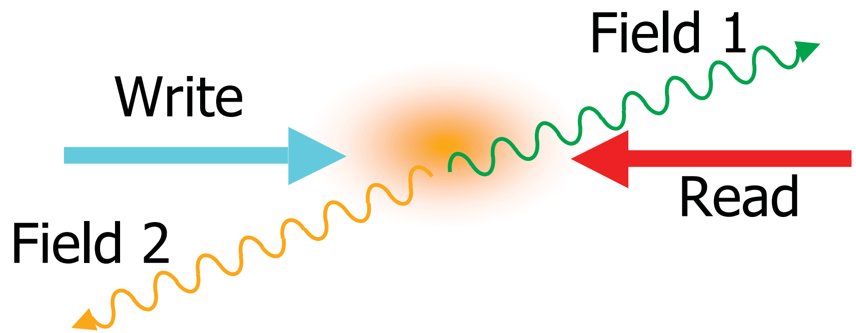


Collective enhancement if :

Atoms at rest : $\vec{k}_w + \vec{k}_r = \vec{k}_{f1} + \vec{k}_{f2}$

Moving atoms: $\vec{k}_w = \vec{k}_r$ and $\vec{k}_{f1} = \vec{k}_{f2}$

A good source of heralded single-photons!

- Retrieval in a single mode fiber ~ 50 %
- Suppression of two-photon component : 1%

J. Laurat et al., Opt. Express **14**, 6912 (2006)

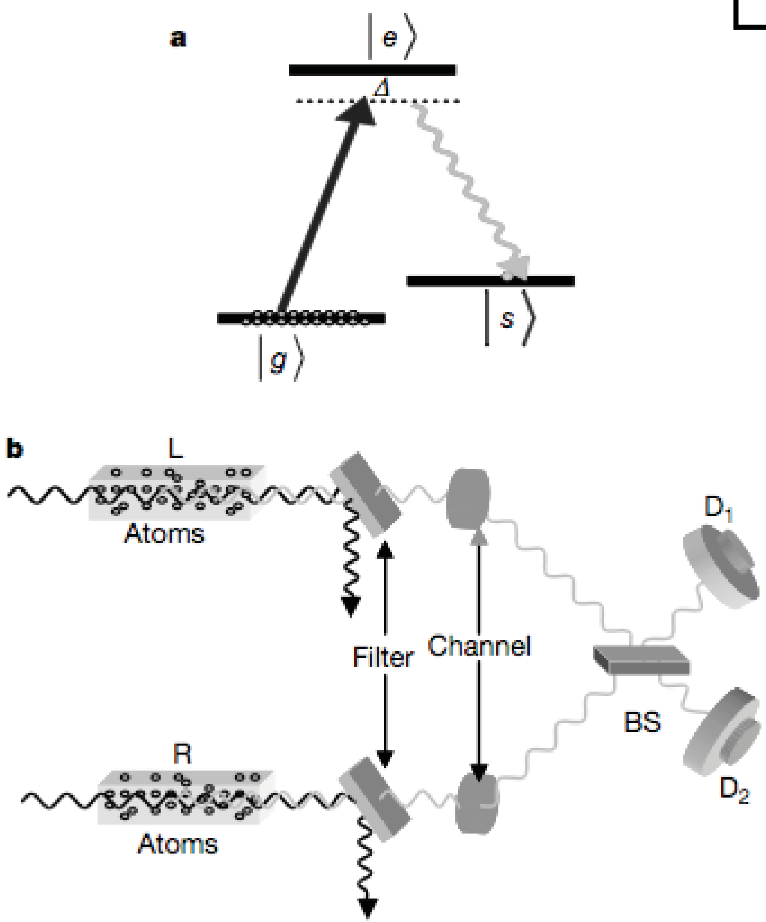
Entanglement between Two Ensembles

Heralded entanglement between remote memories, induced by a measurement.
First experimental demonstration in 2005

LETTERS
Nature 438, 828 (2005)

Measurement-induced entanglement for excitation stored in remote atomic ensembles

C. W. Chou[1], H. de Riedmatten[1], D. Felinto[1], S. V. Polyakov[1], S. J. van Enk[2] & H. J. Kimble[1]



Scheme from the DLCZ paper

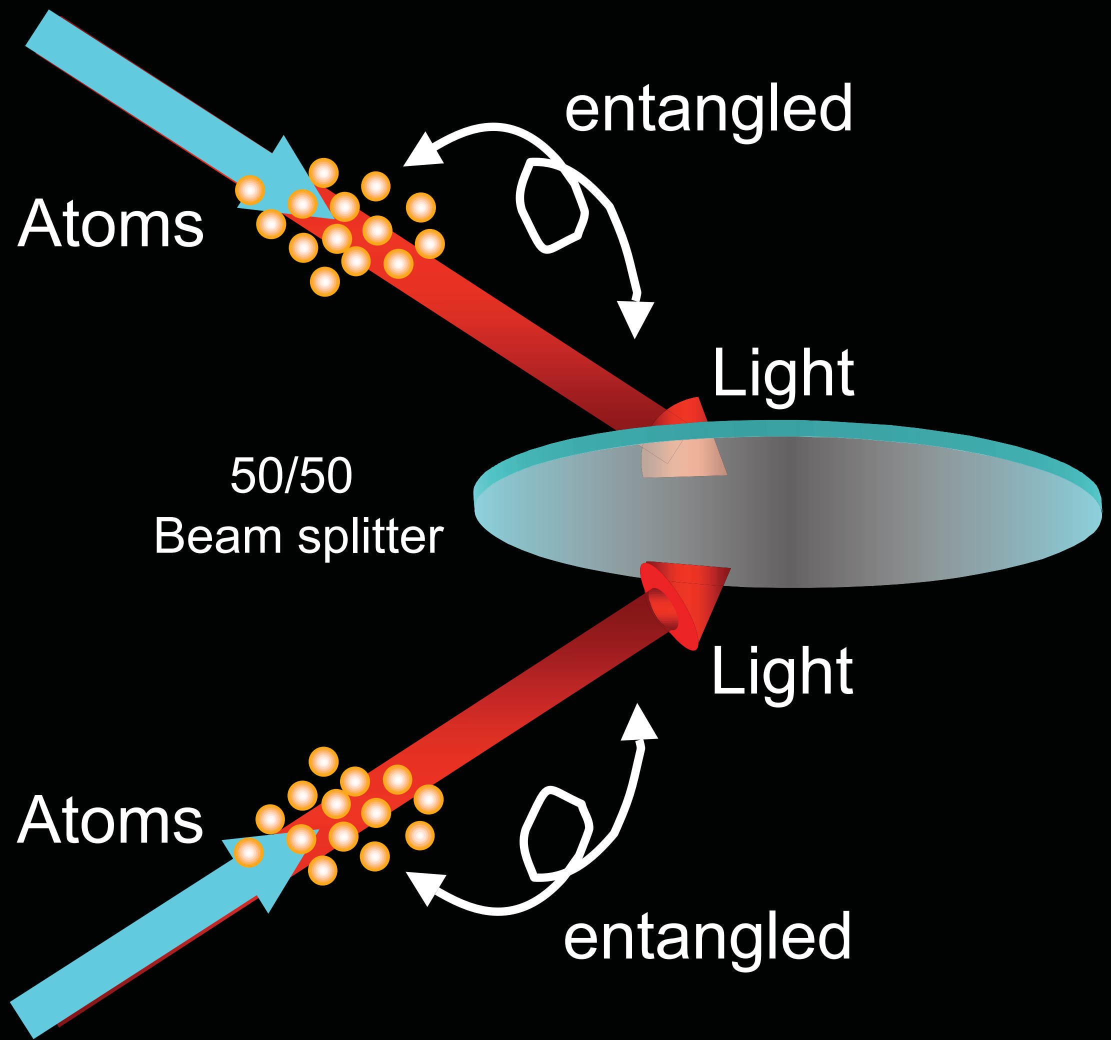
Goal - generate the entangled state:

$$|\psi_{LR}\rangle = \frac{1}{\sqrt{2}}(|0\rangle_L|1\rangle_R\rangle + |1\rangle_L|0\rangle_R\rangle)$$

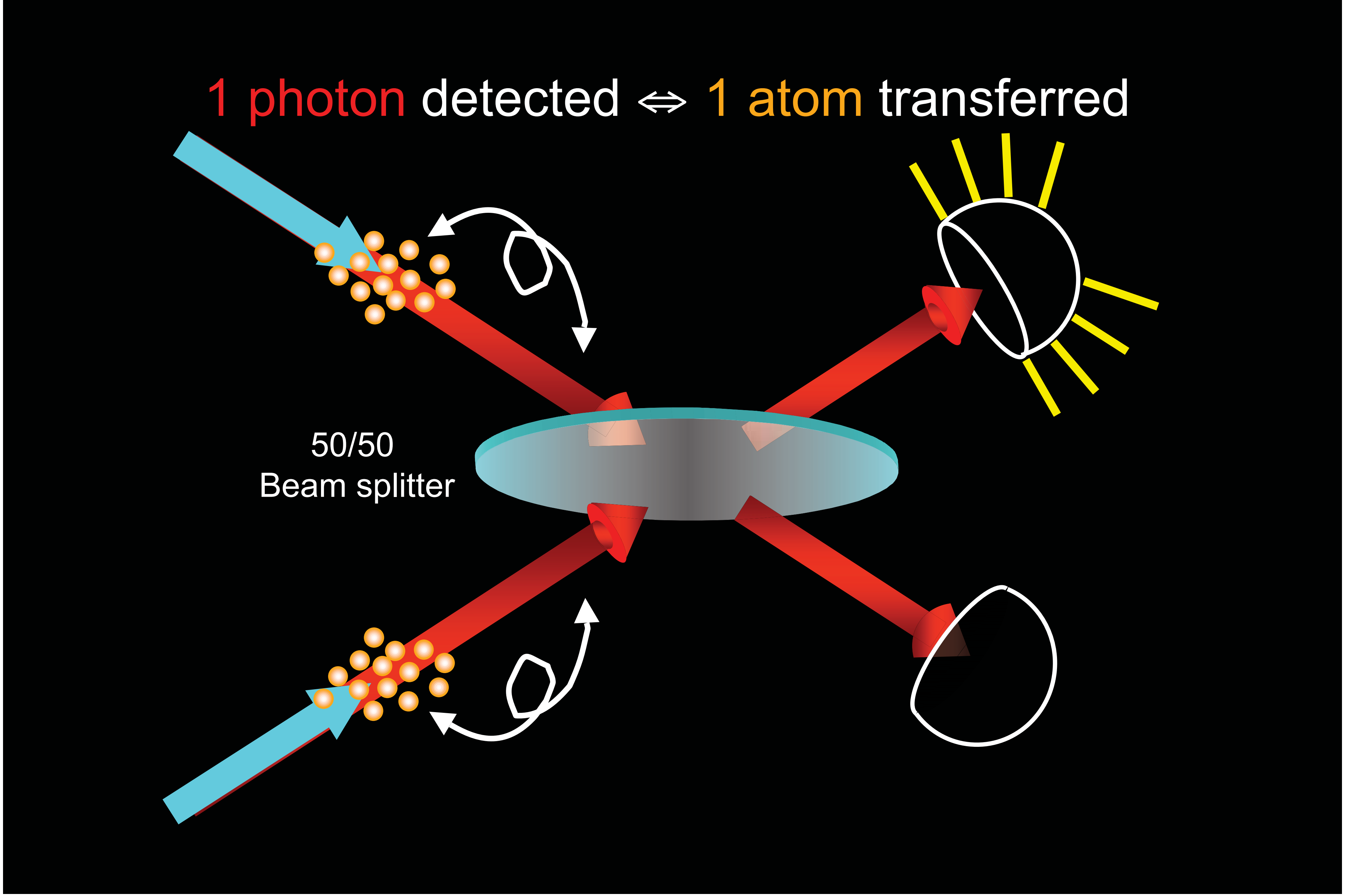
One collective excitation “delocalized” between the two ensembles

Successful demonstration for memories separated by 3 meters

Entanglement between Two Ensembles

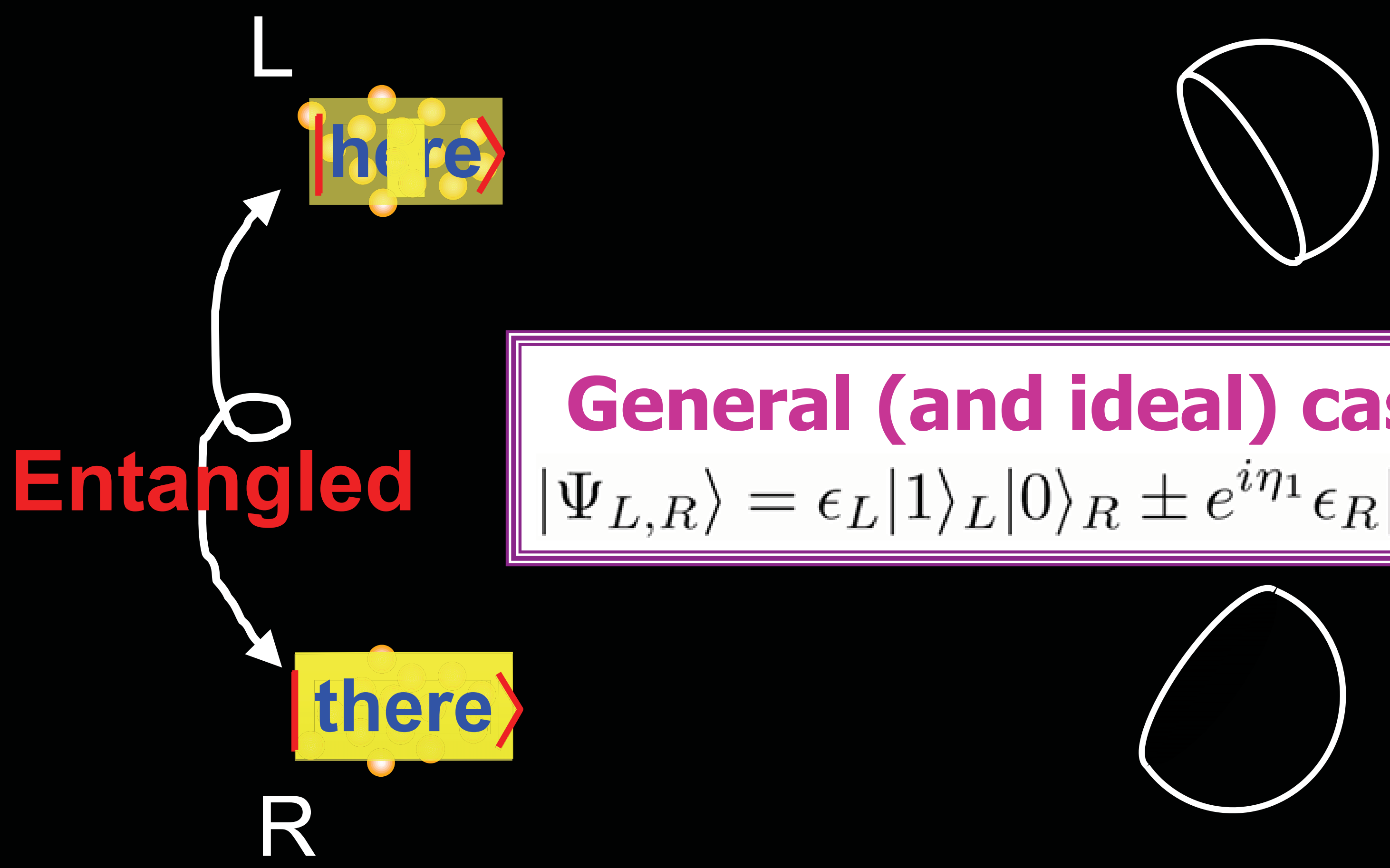


Entanglement between Two Ensembles



Entanglement between Two Ensembles

1 photon detected ⇔ 1 atom transferred



General (and ideal) case

$$|\Psi_{L,R}\rangle = \epsilon_L |1\rangle_L |0\rangle_R \pm e^{i\eta_1} \epsilon_R |0\rangle_L |1\rangle_R$$

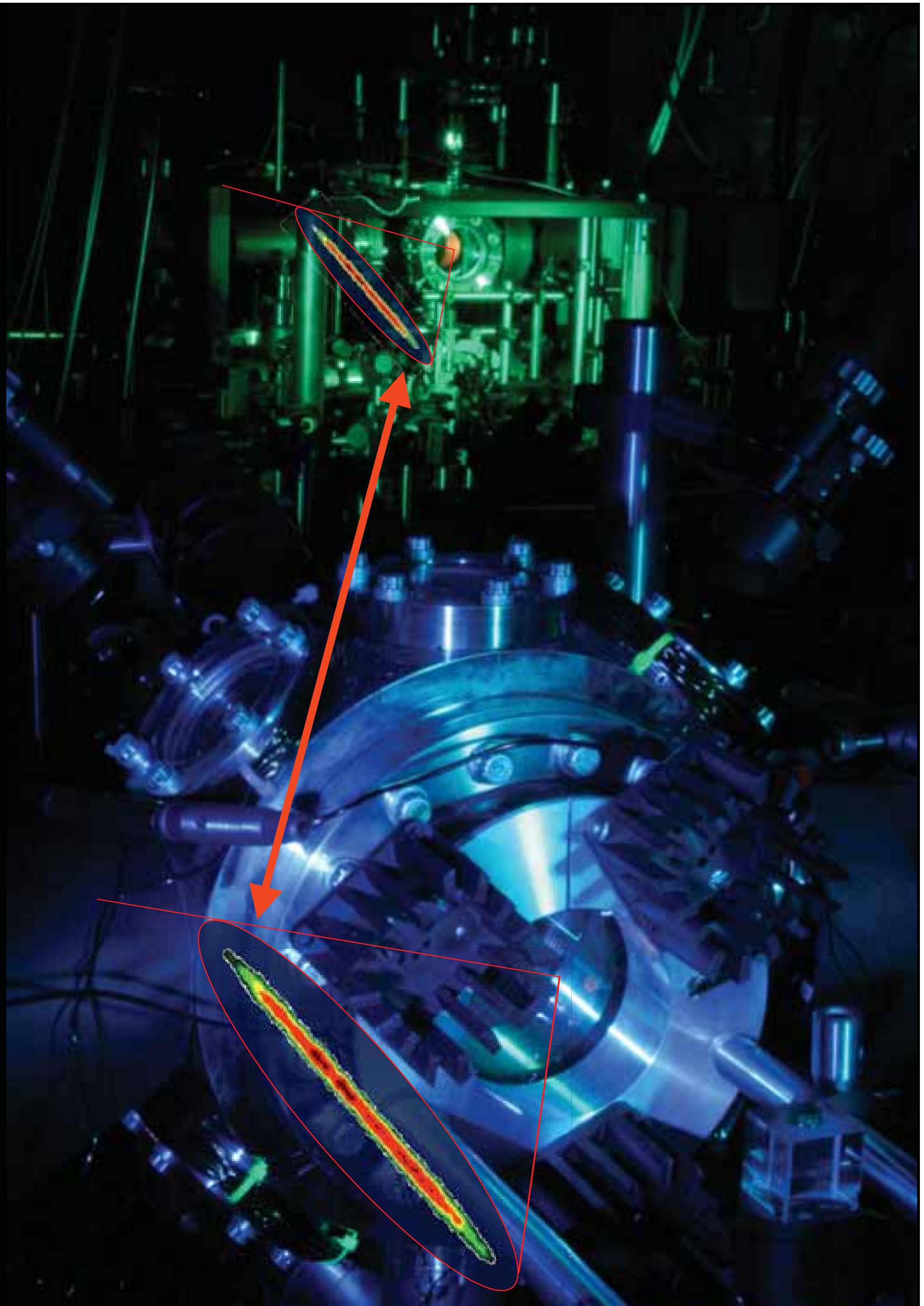
|where⟩ = |here⟩ + |there⟩

• 2 memories
separated by 3m

• 1 collective excitation
shared in an entangled state
between the two ensembles

$$C^{1a}_{L,R} \geq C^{z_2}_{1a}\left(\tilde{\rho}^{z_2}_{2_L,2_R}\right) \simeq 0.021 \pm 0.006 > 0,$$

$$C^{1b}_{L,R} \geq C^{z_2}_{1b}\left(\tilde{\rho}^{z_2}_{2_L,2_R}\right) \simeq 0.016 \pm 0.006 > 0$$



C.W. Chou et al., Measurement-induced entanglement for excitation stored in remote atomic ensembles, Nature 438, 828 (2005)

Entanglement between Two Ensembles

Heralded entanglement with 'large' concurrence and study of the temporal dynamics

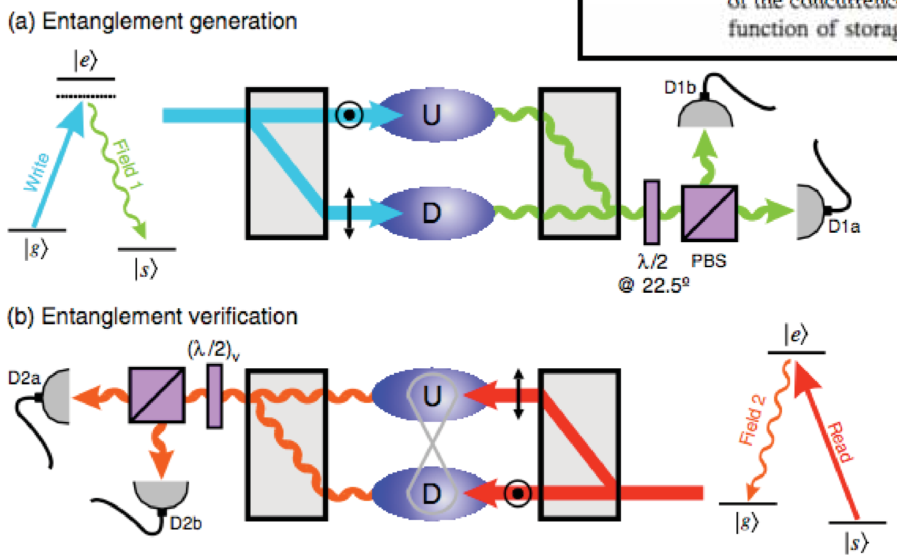
PRL 99, 180504 (2007) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2007

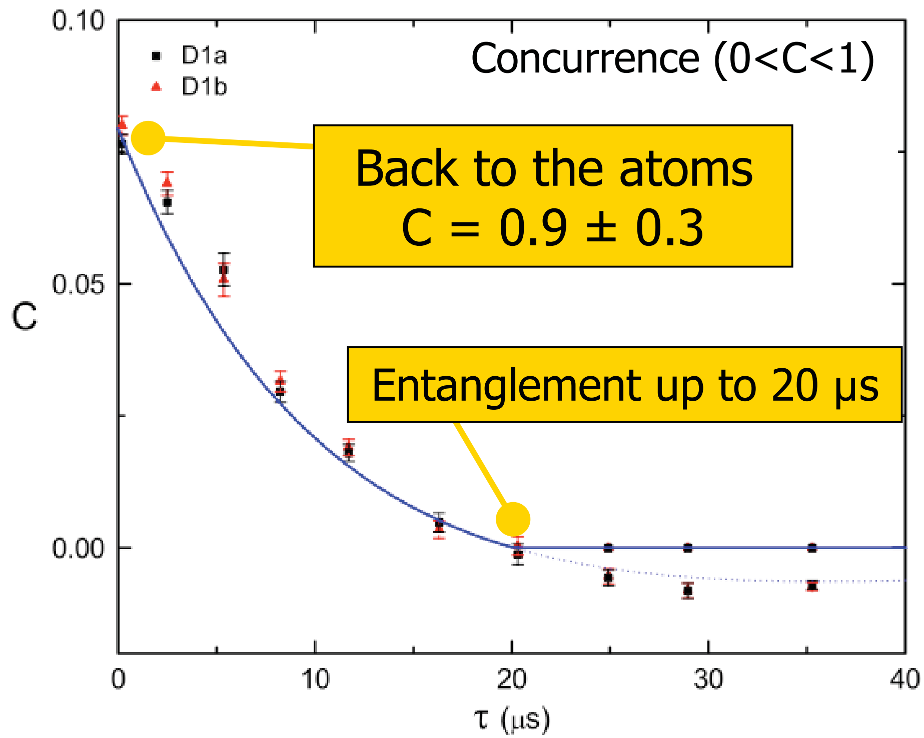
Heralded Entanglement between Atomic Ensembles: Preparation, Decoherence, and Scaling

J. Laurat, K. S. Choi, H. Deng, C. W. Chou, and H. J. Kimble
Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125, USA

(Received 26 May 2007; published 2 November 2007)

Heralded entanglement between collective excitations in two atomic ensembles is probabilistically generated, stored, and converted to single-photon fields. By way of the concurrence, quantitative characterizations are reported for the scaling behavior of entanglement with excitation probability and for the temporal dynamics of various correlations resulting in the decay of entanglement. A lower bound of the concurrence for the collective atomic state of 0.9 ± 0.3 is inferred. The decay of entanglement as a function of storage time is also observed, and related to the local dynamics.



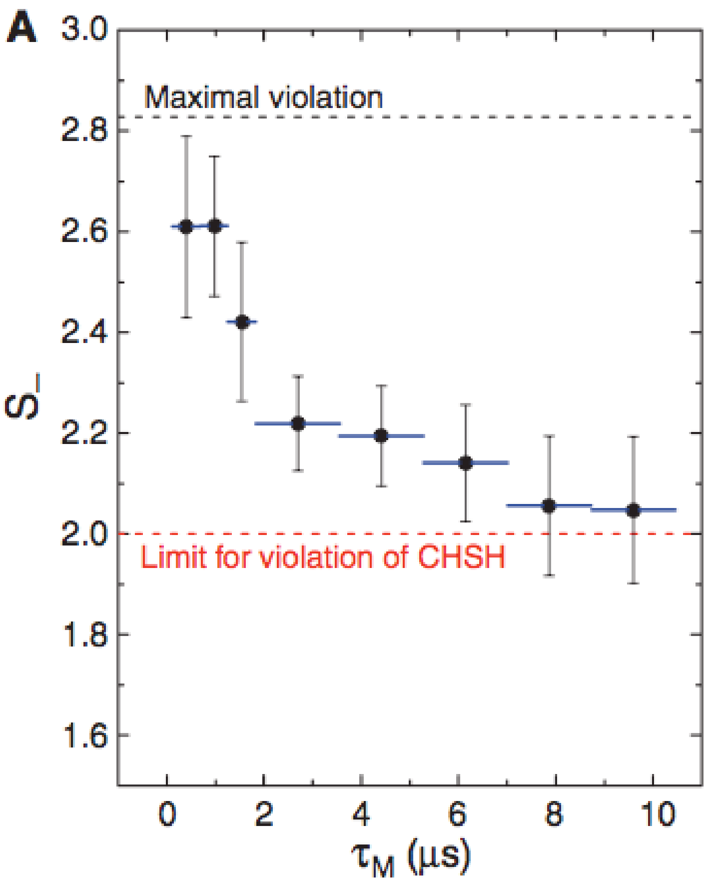


Inherent compromise:
low preparation probability (=single excitation regime) for large entanglement

A Quantum Repeater Segment

A rudimentary repeater segment

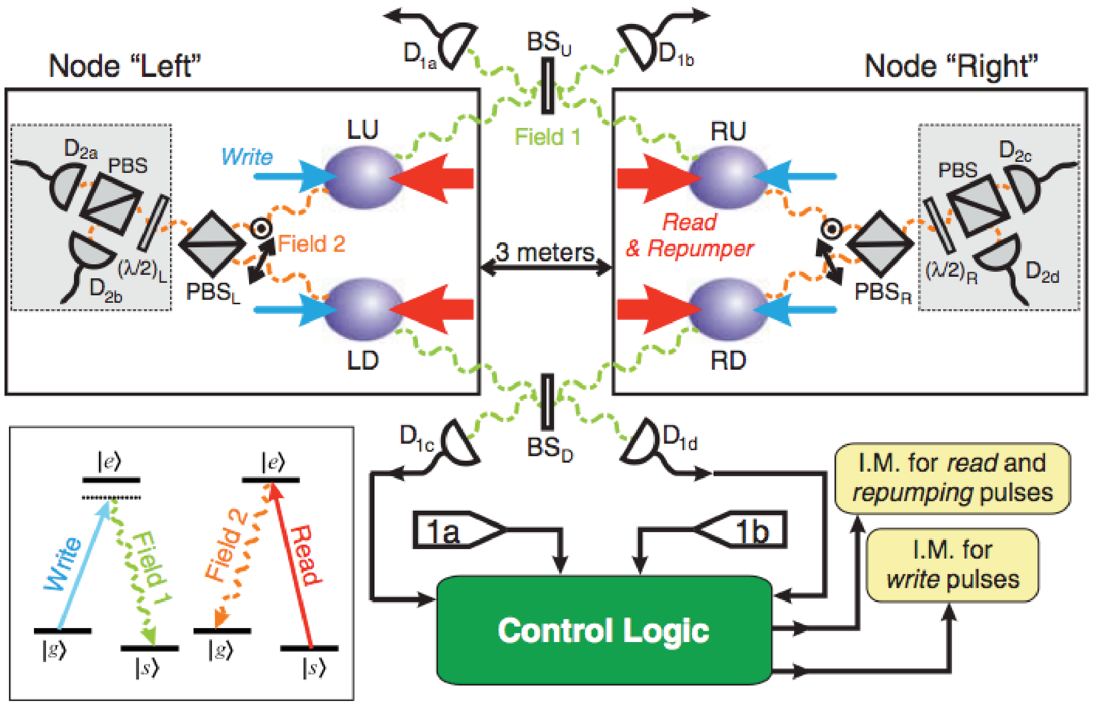
All the ingredients : parallel pairs, asynchronous preparation, Bell violation…



Functional Quantum Nodes for Entanglement Distribution over Scalable Quantum Networks

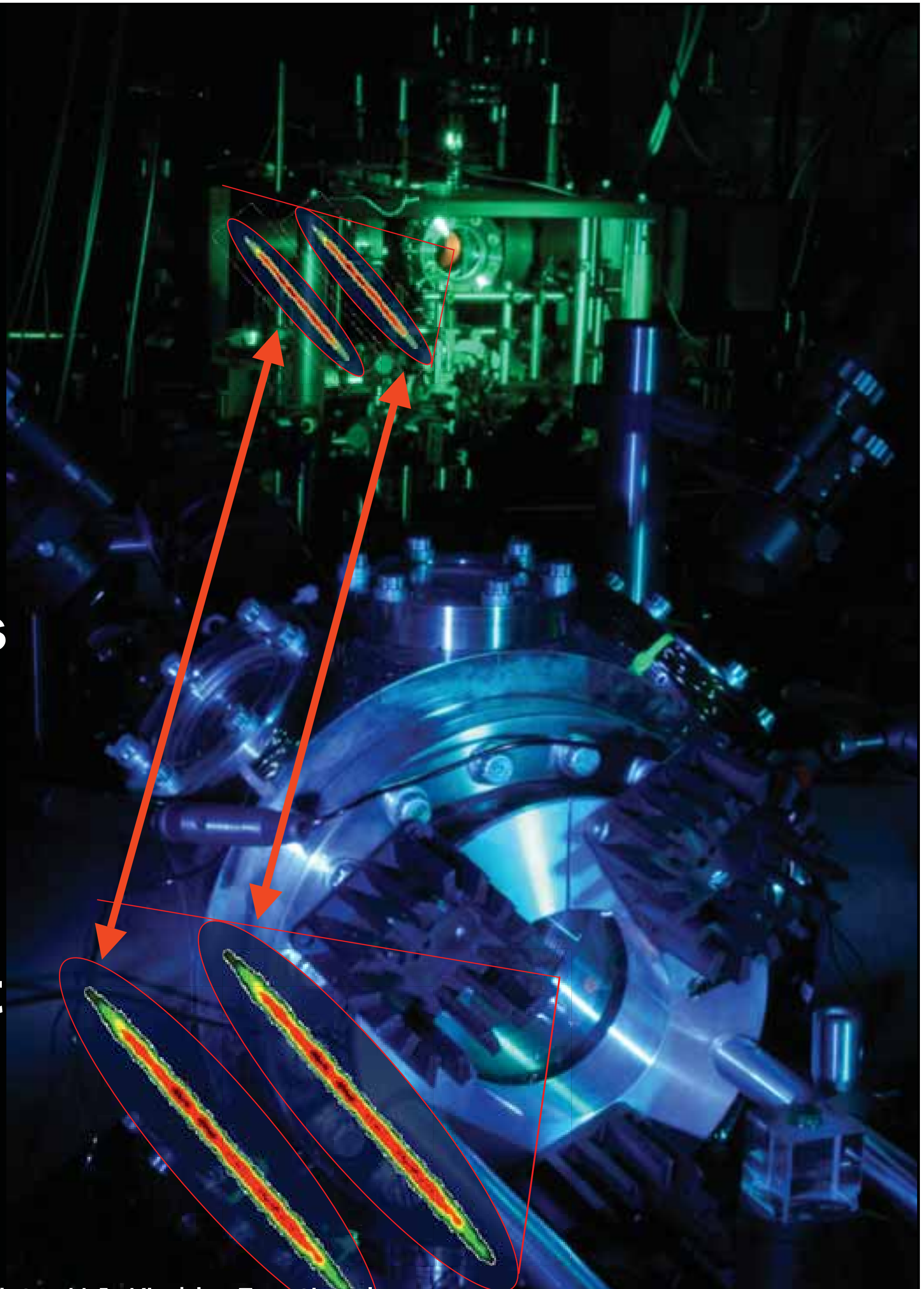
Chin-Wen Chou, Julien Laurat, Hui Deng, Kyung Soo Choi, Hugues de Riedmatten,* Daniel Felinto,† H. Jeff Kimble‡

We demonstrated entanglement distribution between two remote quantum nodes located 3 meters apart. This distribution involves the asynchronous preparation of two pairs of atomic memories and the coherent mapping of stored atomic states into light fields in an effective state of near-maximum polarization entanglement. Entanglement is verified by way of the measured violation of a Bell inequality, and it can be used for communication protocols such as quantum cryptography. The demonstrated quantum nodes and channels can be used as segments of a quantum repeater, providing an essential tool for robust long-distance quantum communication.



- 2 nodes separated by 3m
- 2 ensembles per node
- Asynchronous preparation (memory) of 2 parallel number-state entangled pairs
- Polarization coding and passive phase stability

➔ Polarization entanglement distribution, violating Bell



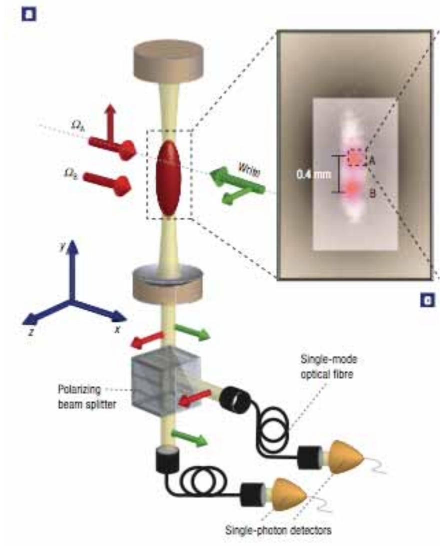
C.W. Chou, J. Laurat, H. Deng, K.S. Choi, H. de Riematten, D. Felinto, H.J. Kimble, Functional Quantum Nodes for Entanglement Distribution over Scalable Quantum Networks, Science **316**, 1316 (2007)

DLCZ-based Exeriments : Progress

Single-photon bus connecting spin-wave quantum memories

Nature Phys. 3, 765 (2007)

JONATHAN SIMON[1,2]*, HARUKA TANJI[1,2], SAIKAT GHOSH[2] AND VLADAN VULETIĆ[2]
[1]Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
[2]Department of Physics, MIT-Harvard Center for Ultracold Atoms, and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA



Ensemble inside a cavity : readout>80%

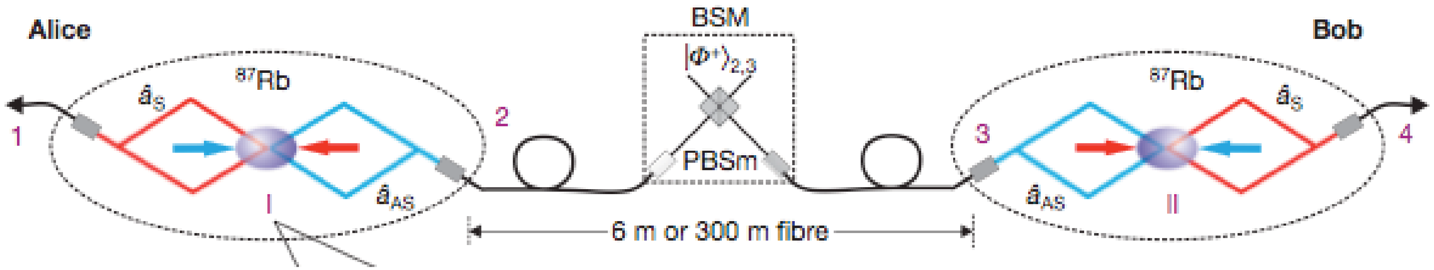
Experimental demonstration of a BDCZ quantum repeater node

Nature 454, 1098 (2008)

Zhen-Sheng Yuan[1,2]*, Yu-Ao Chen[1,2]*, Bo Zhao[1], Shuai Chen[1], Jörg Schmiedmayer[3] & Jian-Wei Pan[1,2]

Another example of elementary repeater segment

a



DLCZ-based Exeriments : Progress

Memory time in the ms range…

nature physics | LETTERS
PUBLISHED ONLINE: 7 DECEMBER 2008 | DOI: 10.1038/NPHYS1153

A millisecond quantum memory for scalable quantum networks

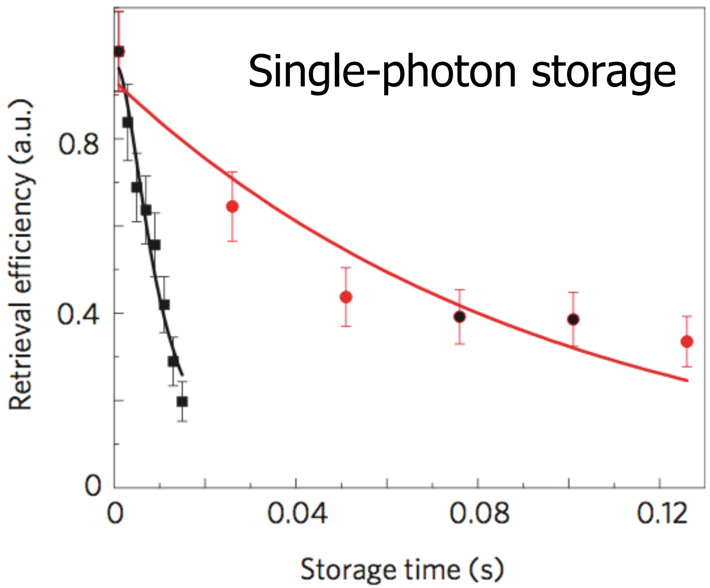
Bo Zhao[1*], Yu-Ao Chen[1,2*], Xiao-Hui Bao[1,2], Thorsten Strassel[1], Chih-Sung Chuu[1], Xian-Min Jin[2], Jörg Schmiedmayer[3], Zhen-Sheng Yuan[1,2], Shuai Chen[1] and Jian-Wei Pan[1,2]

LETTERS | nature physics
PUBLISHED ONLINE: 7 DECEMBER 2008 | DOI: 10.1038/NPHYS1152

Long-lived quantum memory

R. Zhao[1], Y. O. Dudin[1], S. D. Jenkins[1,2*], C. J. Campbell[1], D. N. Matsukevich[3], T. A. B. Kennedy[1] and A. Kuzmich[1]

In the 0.1s range…

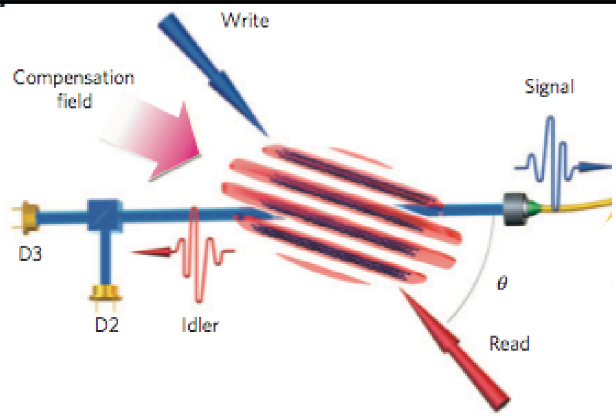


ARTICLES | nature physics
PUBLISHED ONLINE: 26 SEPTEMBER 2010 | DOI:10.1038/NPHYS1773

A quantum memory with telecom-wavelength conversion

A. G. Radnaev†, Y. O. Dudin†, R. Zhao, H. H. Jen, S. D. Jenkins, A. Kuzmich and T. A. B. Kennedy*

In a fibre-based quantum information network, telecom-wavelength transmission between quantum memory elements is required to minimize absorption. Owing to the paucity of suitable ground-state atomic transitions, a quantum memory interfaced with telecom light has not been previously realized. We report its demonstration by converting to telecom wavelength near-infrared light emitted on a ground-state transition. The conversion is achieved with a diamond configuration of atomic transitions, in an optically thick gas of cold rubidium. The quantum memory is also realized with cold rubidium, but confined in an optical lattice to suppress motional dephasing on a submillisecond timescale. We observe quantum memory lifetimes in excess of 0.1s by laser compensation of the lattice light shifts that limited the previous generation of atomic memory to 7 ms. By measuring quantum correlations of light fields before and after telecom down-conversion, transmission and up-conversion, we demonstrate a basic memory element for a scalable, long-distance quantum network.



Lecture 3

- Introduction to quantum memories for light and scalable QIT

- How ? Single-atom and ensemble-based quantum memories

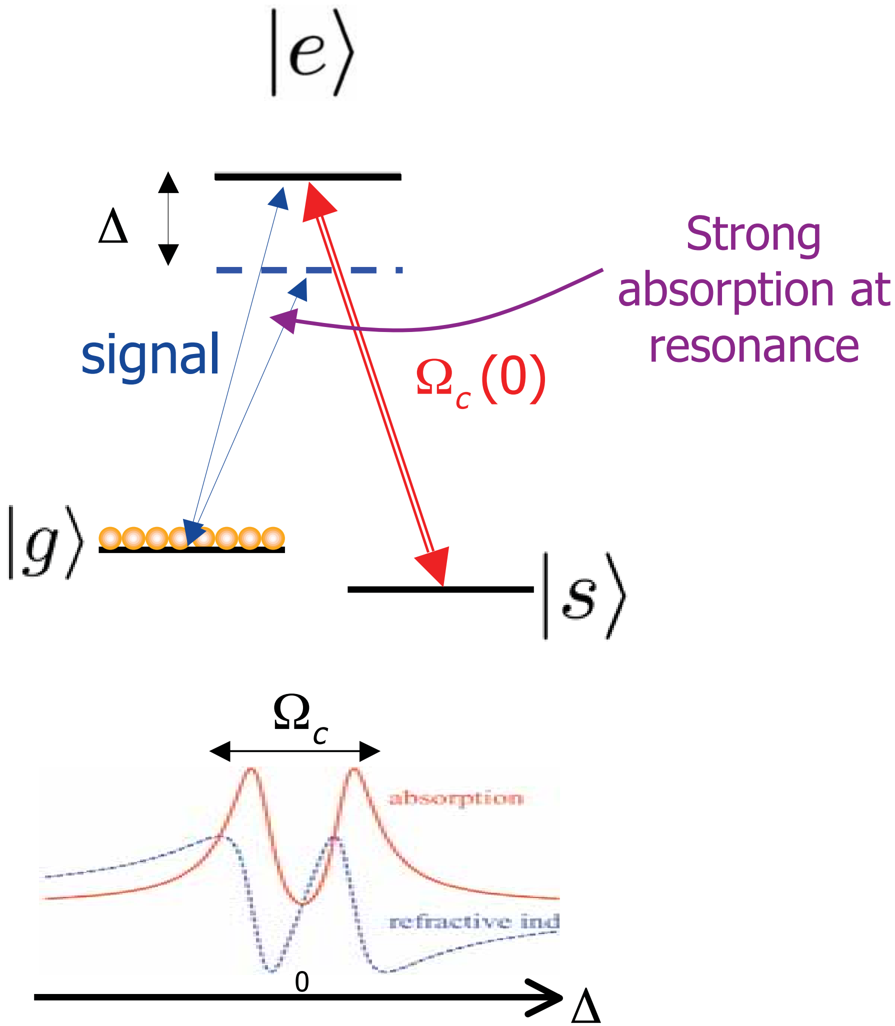
Ensemble-based techniques

- Duan-Lukin-Cirac-Zoller approach

- Dynamic EIT memories

- Photon-echo techniques

Electromagnetically-Induced Transparency



Quantum interference effects in the amplitudes of optical transitions in atomic medium can lead to strong modifications of its optical properties.

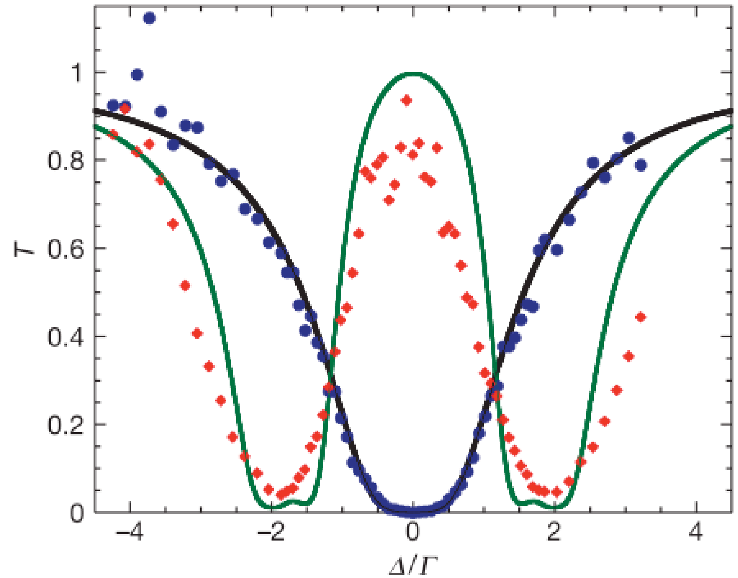
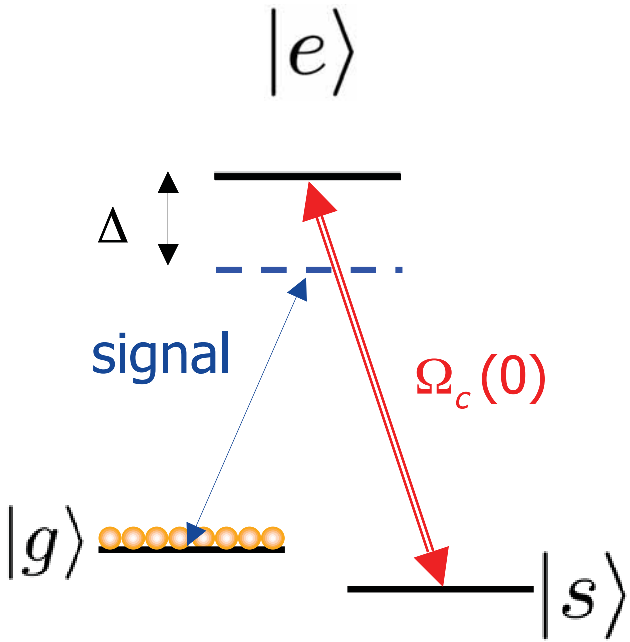


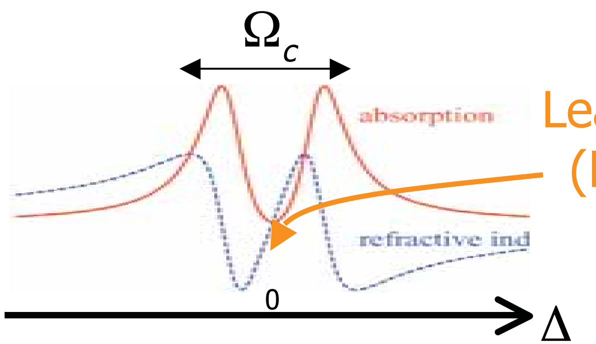
Figure 2 | Measured transmission spectra of a coherent probe field as a function of probe detuning in the presence of, and absence of, EIT.

From Nature 438, 833 (2005)

Electromagnetically-Induced Transparency



Quantum interference effects in the amplitudes of optical transitions in atomic medium can lead to strong modifications of its optical properties.



Leads to 'Slow light' (Reduction of the group velocity)

Kramers-Kronig relations : anomaly in absorption spectrum is accompanied by anomaly in the dispersion

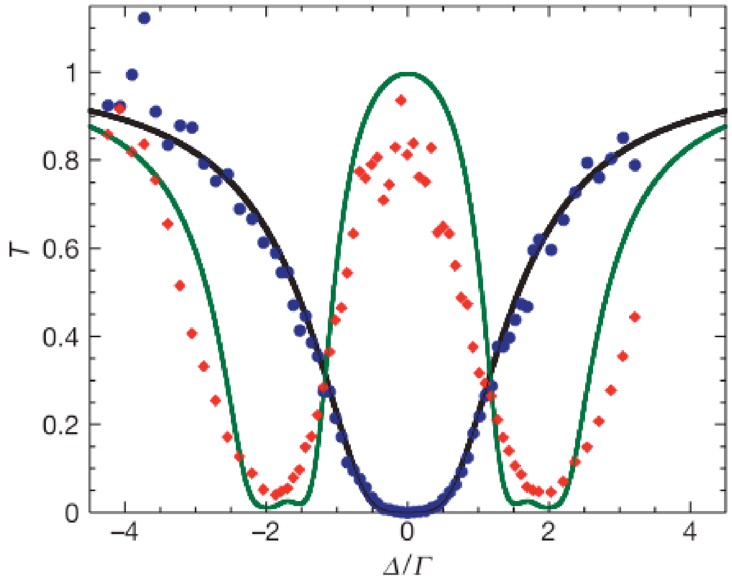
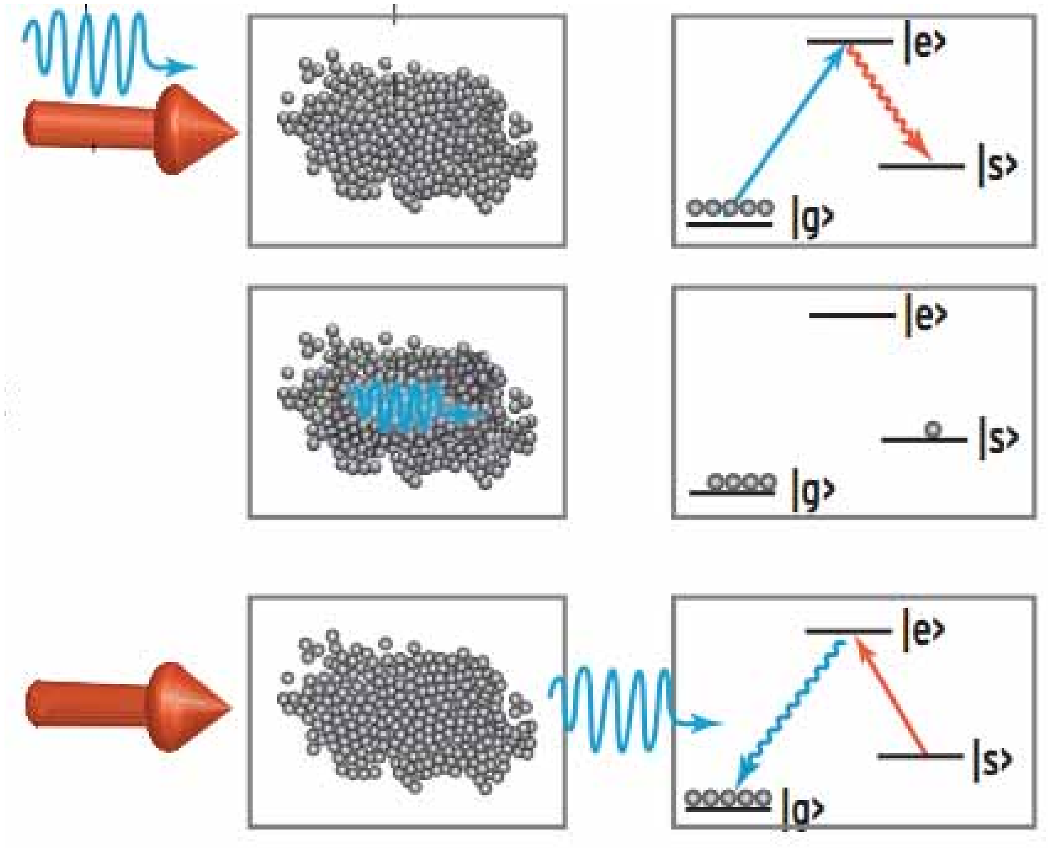


Figure 2 | Measured transmission spectra of a coherent probe field as a function of probe detuning in the presence of, and absence of, EIT.

From Nature 438, 833 (2005)

Dynamic EIT based Memory



When the pulse has been spatially compressed into the medium, the control field is adiabatically switched off.

The quantum state of light is in this way transferred to the atomic coherence between the two ground states.

Later, on demand, by switching on again the control field, the coherence is mapped back to propagating light field.

EIT Storage and Retrieval of Single-Photons

Electromagnetically induced transparency with tunable single-photon pulses

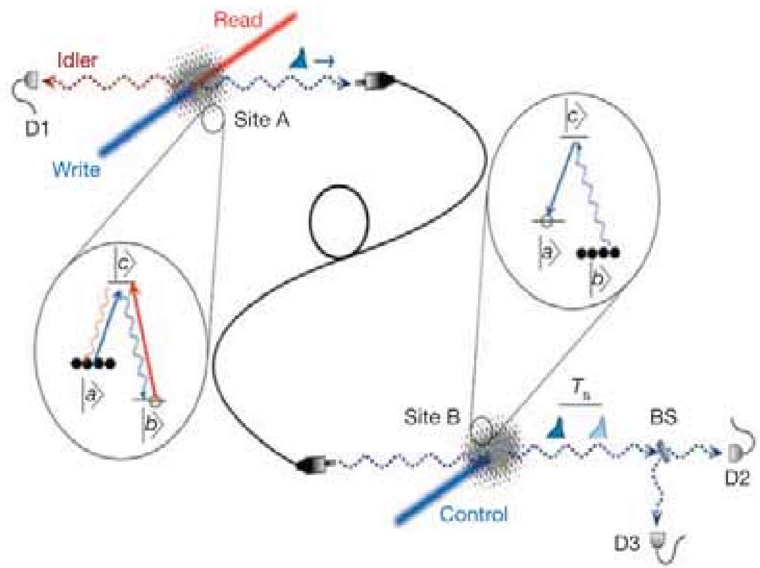
Nature 438, 837 (2005)

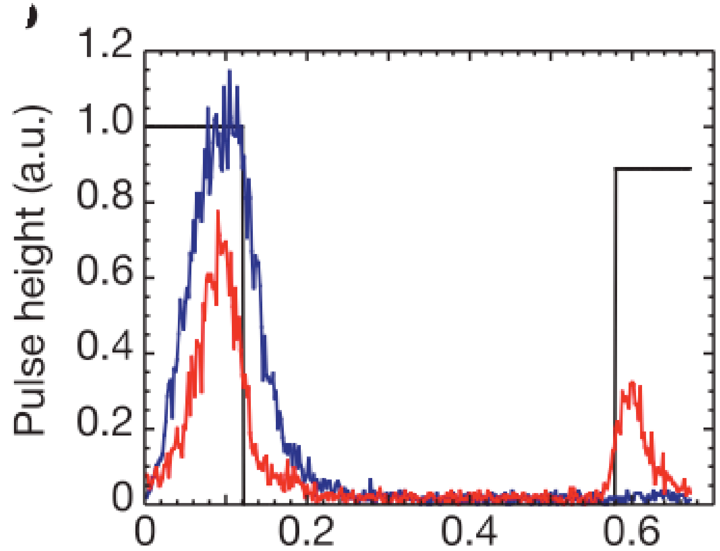
M. D. Eisaman[1], A. André[1], F. Massou[1], M. Fleischhauer[1,2,3], A. S. Zibrov[1,2,4] & M. D. Lukin[1]

Storage and retrieval of single photons transmitted between remote quantum memories

Nature 438, 833 (2005)

T. Chanelière[1], D. N. Matsukevich[1], S. D. Jenkins[1], S.-Y. Lan[1], T. A. B. Kennedy[1] & A. Kuzmich[1]





Mapping Entanglement Into and Out

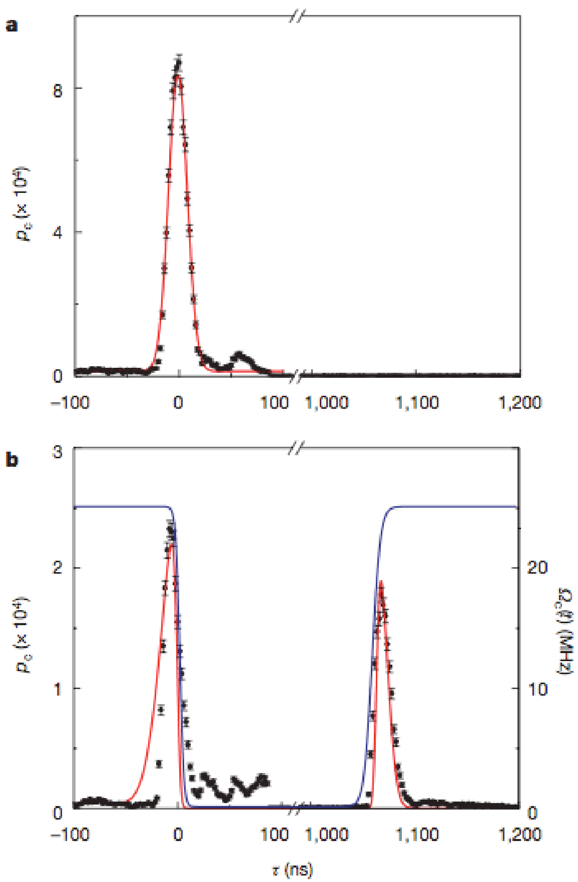
Idea

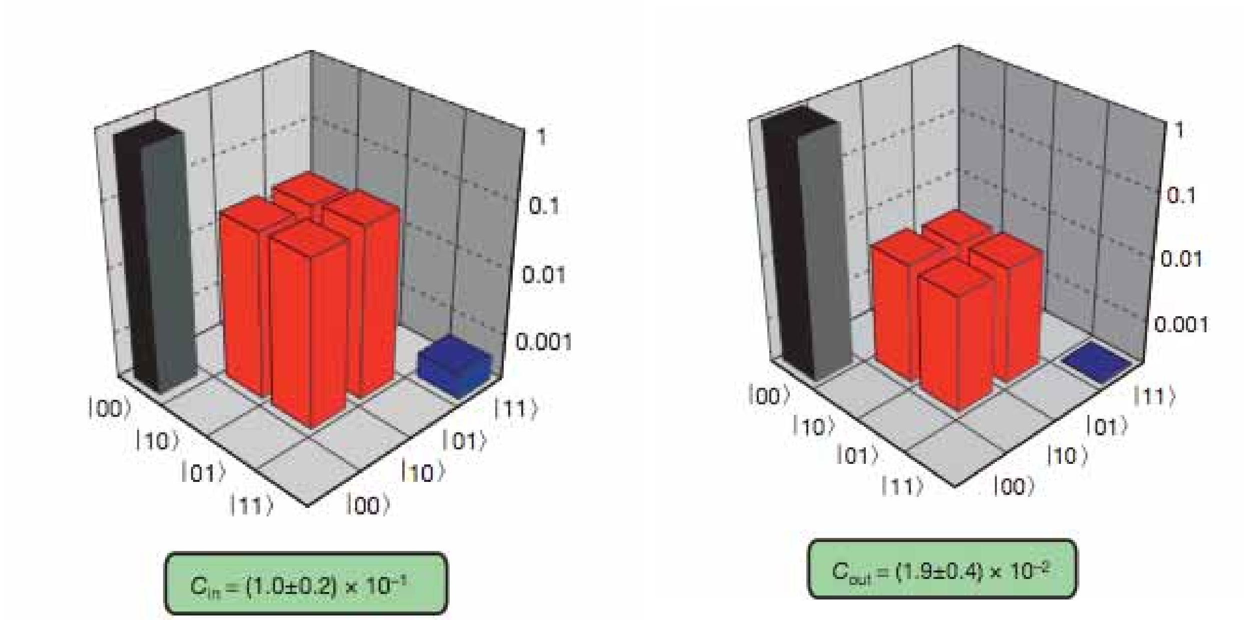
Mapping of Single Photon Entanglement

Mapping photonic entanglement into and out of a quantum memory

K. S. Choi[1], H. Deng[1], J. Laurat[1]† & H. J. Kimble[1]

Nature 452, 67 (2008)



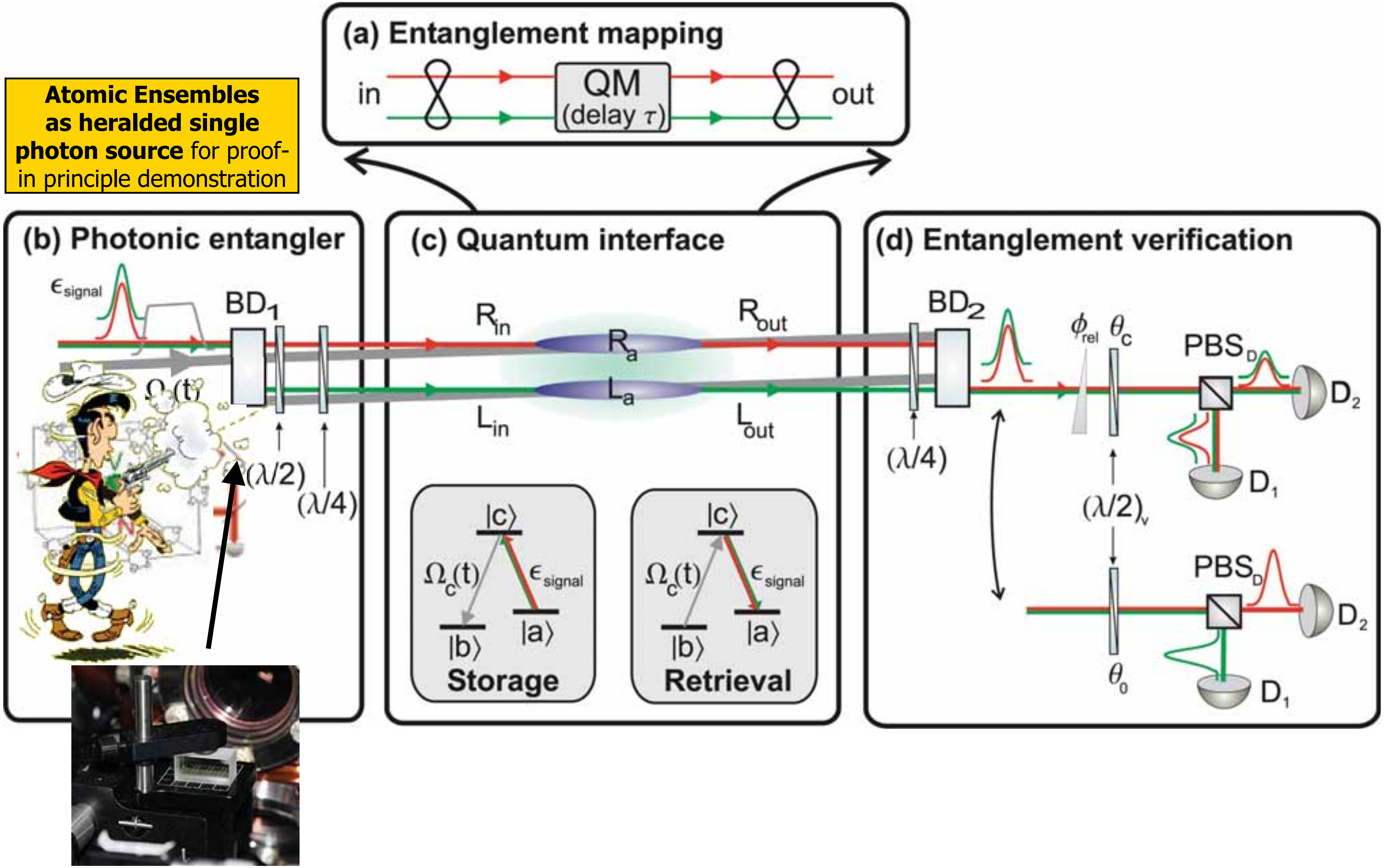


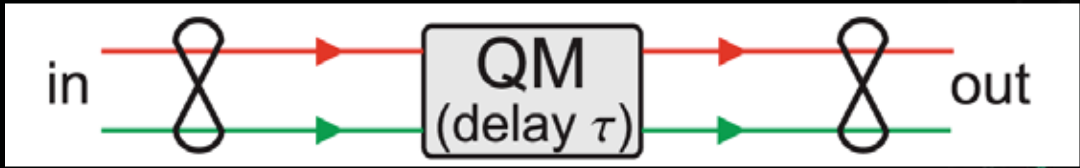
C_{out}/C_{in} : 20% entanglement transfert

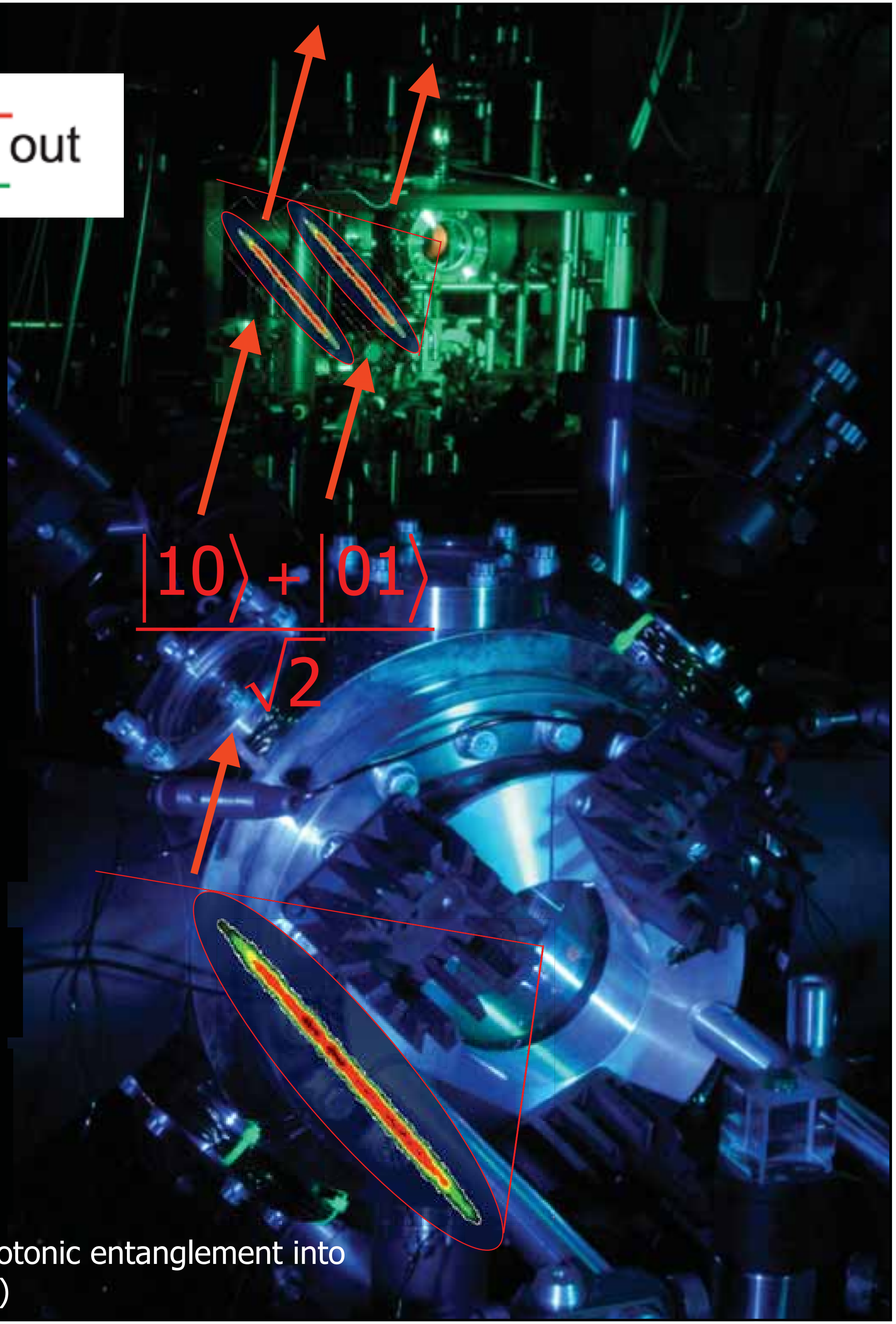
Let's see more in details this experiment in the next slides…

Mapping Entanglement Into and Out

Atomic Ensembles as heralded single photon source for proof-in principle demonstration

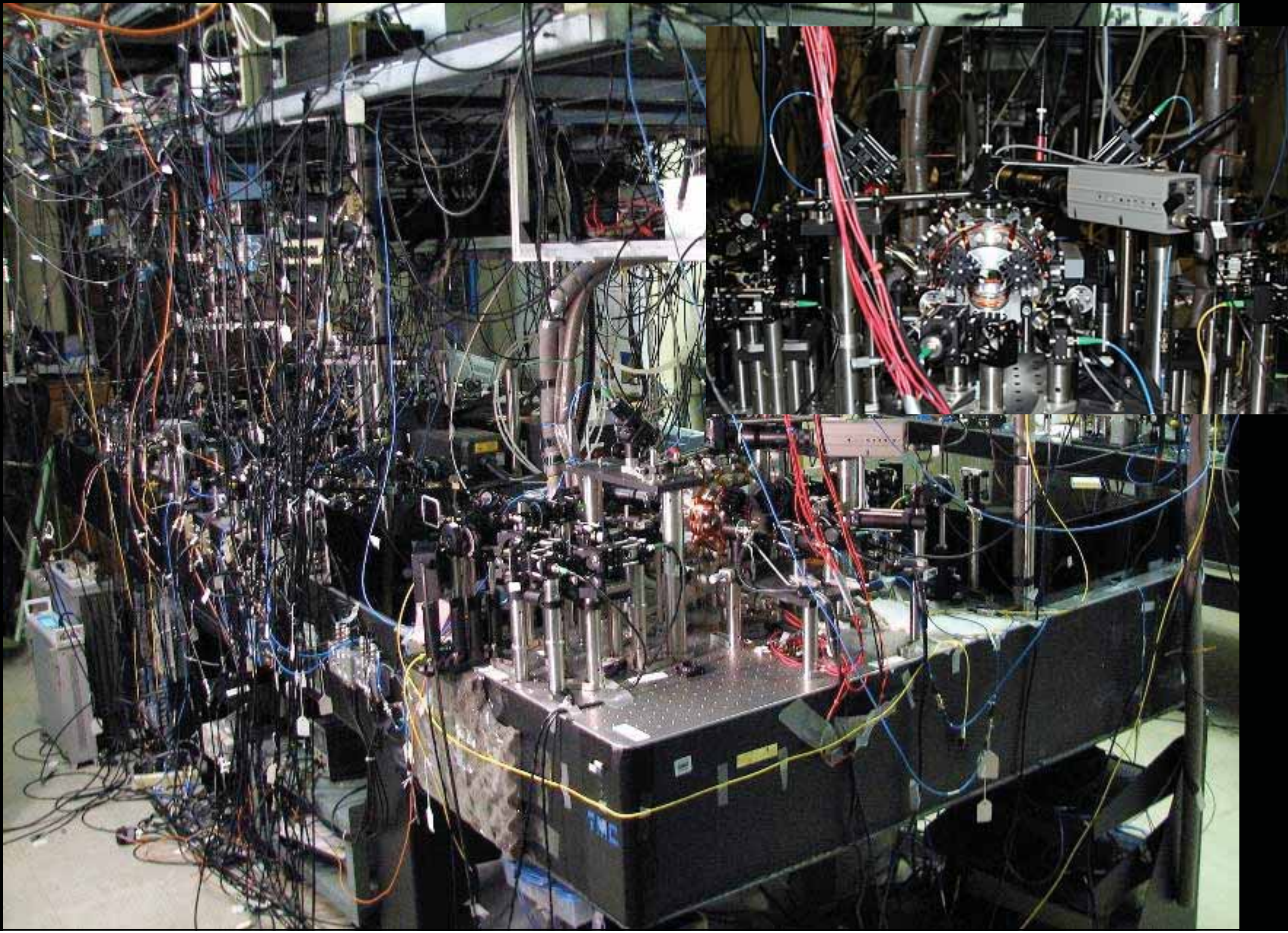






K. S. Choi, H. Deng, J. Laurat and H. J. Kimble., Mapping photonic entanglement into and out of a quantum memory, Nature 452, 67 (March 2008)

The Real Story



EIT Storage in the CV Regime

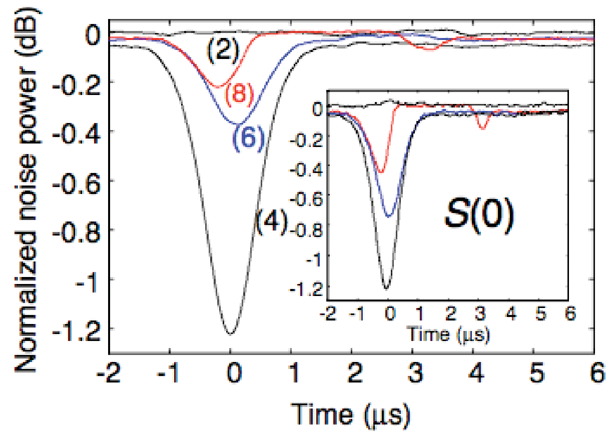
PRL **100,** 093601 (2008) PHYSICAL REVIEW LETTERS week ending 7 MARCH 2008

Storage and Retrieval of a Squeezed Vacuum

Kazuhito Honda,[1] Daisuke Akamatsu,[2] Manabu Arikawa,[2] Yoshihiko Yokoi,[2] Keiichirou Akiba,[2] Satoshi Nagatsuka,[2] Takahito Tanimura,[2] Akira Furusawa,[3] and Mikio Kozuma[1,2,4]

[1]*Interactive Research Center of Science, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8550, Japan*
[2]*Department of Physics, Tokyo Institute of Technology, 2-12-1 O-okayama, Meguro-ku, Tokyo 152-8550, Japan*
[3]*Department of Applied Physics, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan*
[4]*PRESTO, CREST, Japan Science and Technology Agency, 1-9-9 Yaesu, Chuo-ku, Tokyo 103-0028, Japan*

(Received 23 September 2007; published 3 March 2008)



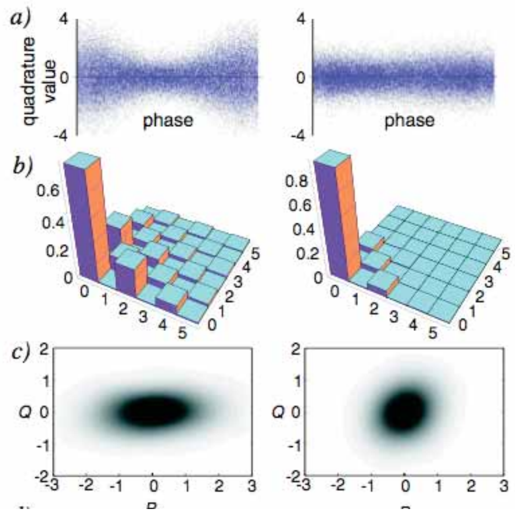
PRL **100,** 093602 (2008) PHYSICAL REVIEW LETTERS week ending 7 MARCH 2008

Quantum Memory for Squeezed Light

Jürgen Appel,* Eden Figueroa, Dmitry Korystov, M. Lobino, and A. I. Lvovsky

Institute for Quantum Information Science, University of Calgary, Calgary, Alberta T2N 1N4, Canada†

(Received 11 October 2007; published 5 March 2008)



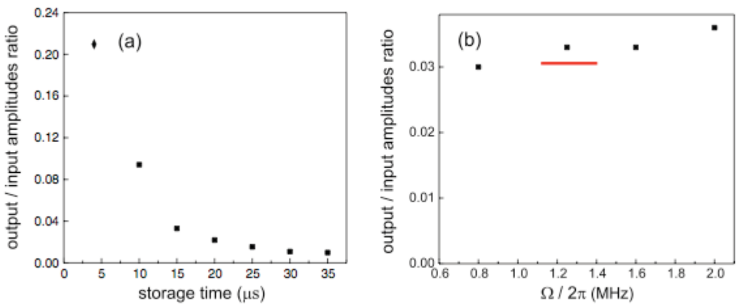
PRL **101,** 133601 (2008) PHYSICAL REVIEW LETTERS week ending 26 SEPTEMBER 2008

Reversible Quantum Interface for Tunable Single-Sideband Modulation

J. Cviklinski, J. Ortalo, J. Laurat, A. Bramati, M. Pinard, and E. Giacobino

Laboratoire Kastler Brossel, Université Pierre et Marie Curie, Ecole Normale Supérieure, CNRS, 4 place Jussieu, F75252 Paris Cedex 05, France

(Received 2 November 2007; revised manuscript received 22 July 2008; published 26 September 2008)



Lecture 3

• Introduction to quantum memories for light and scalable QIT

• How ? Single-atom and ensemble-based quantum memories

Ensemble-based techniques

• Duan-Lukin-Cirac-Zoller approach

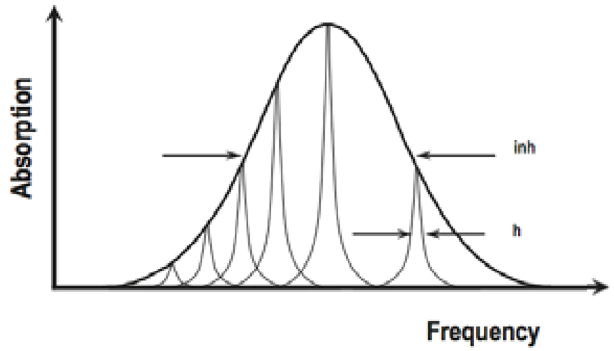
• Dynamic EIT memories

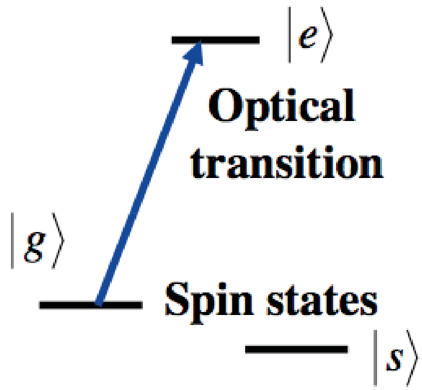
• Photon-echo techniques

Solid State Atomic Ensembles

Rare-earth ions doped into inorganic crystals.

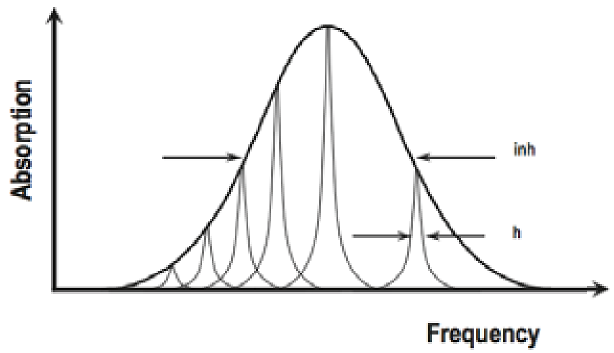
Ex.: Thulium, Praseodymium

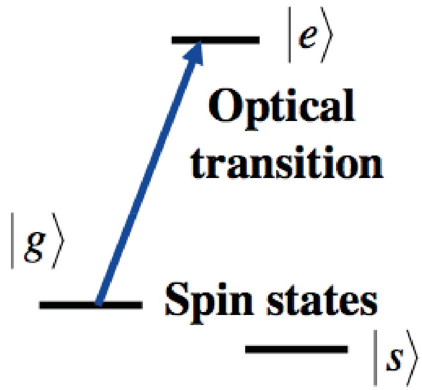




Solid State Atomic Ensembles

Rare-earth ions doped into inorganic crystals.
Ex.: Thulium, Praseodymium



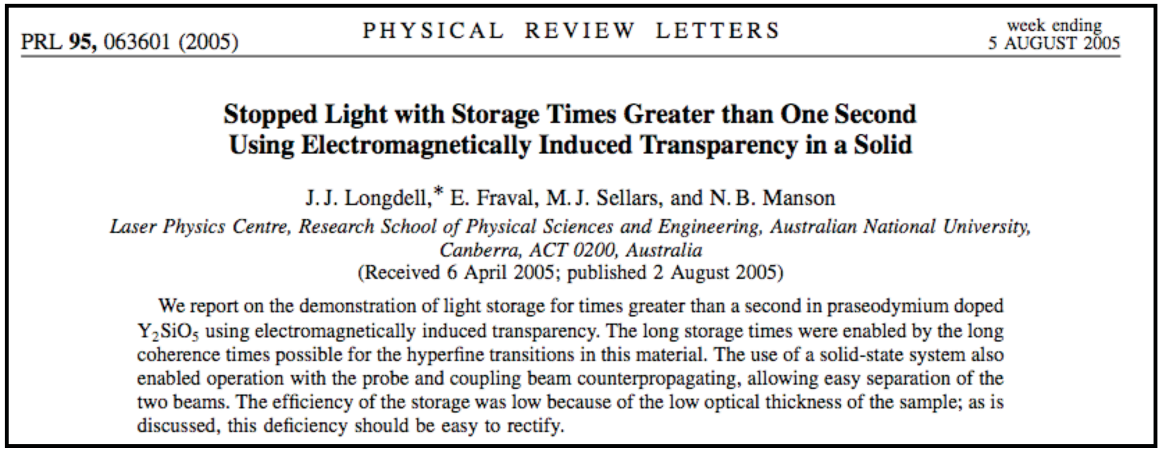


Why they look interesting?

- Large number of atoms. No trapping needed

- Non-moving atoms : echo can be efficiently implemented

- Excellent coherence properties at cryogenic temperature (T<4K)
Coherence time from ms to s



PRL **95,** 063601 (2005) PHYSICAL REVIEW LETTERS week ending 5 AUGUST 2005

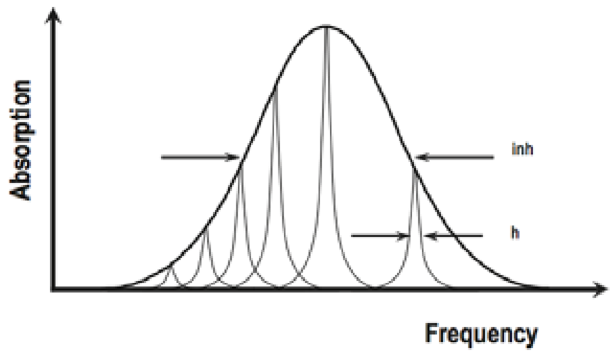
Stopped Light with Storage Times Greater than One Second Using Electromagnetically Induced Transparency in a Solid

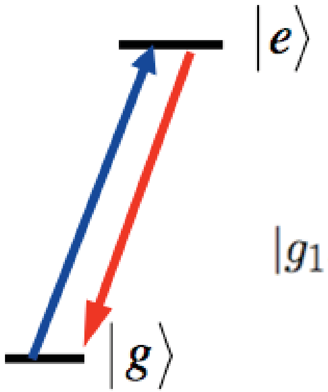
J. J. Longdell,* E. Fraval, M. J. Sellars, and N. B. Manson
Laser Physics Centre, Research School of Physical Sciences and Engineering, Australian National University, Canberra, ACT 0200, Australia
(Received 6 April 2005; published 2 August 2005)

We report on the demonstration of light storage for times greater than a second in praseodymium doped Y_2SiO_5 using electromagnetically induced transparency. The long storage times were enabled by the long coherence times possible for the hyperfine transitions in this material. The use of a solid-state system also enabled operation with the probe and coupling beam counterpropagating, allowing easy separation of the two beams. The efficiency of the storage was low because of the low optical thickness of the sample; as is discussed, this deficiency should be easy to rectify.

General Idea : Photon-Echo Techniques

Inhomogeneous dephasing





Collective state :

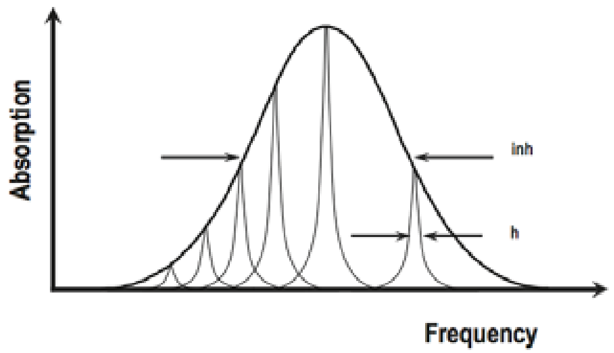
$$|g_1 ... g_i ... g_N\rangle \rightarrow \frac{1}{\sqrt{N}} \sum_i e^{i\vec{k}.\vec{x}_i} e^{i\Delta_i t} |g_1 ... e_i ... g_N\rangle$$

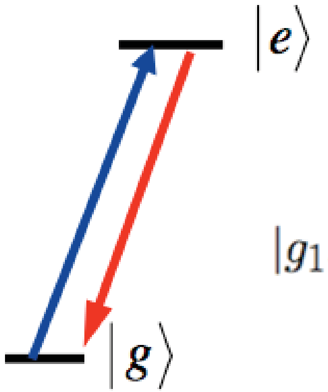
Very fast decay of the alignement of the atomic dipoles

Needs a controlled rephasing process

General Idea : Photon-Echo Techniques

Inhomogeneous dephasing





Collective state :

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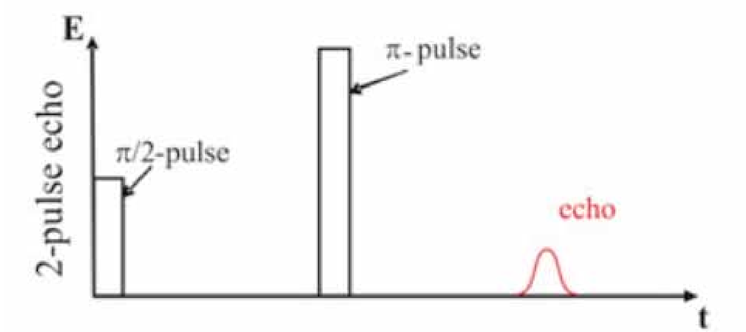
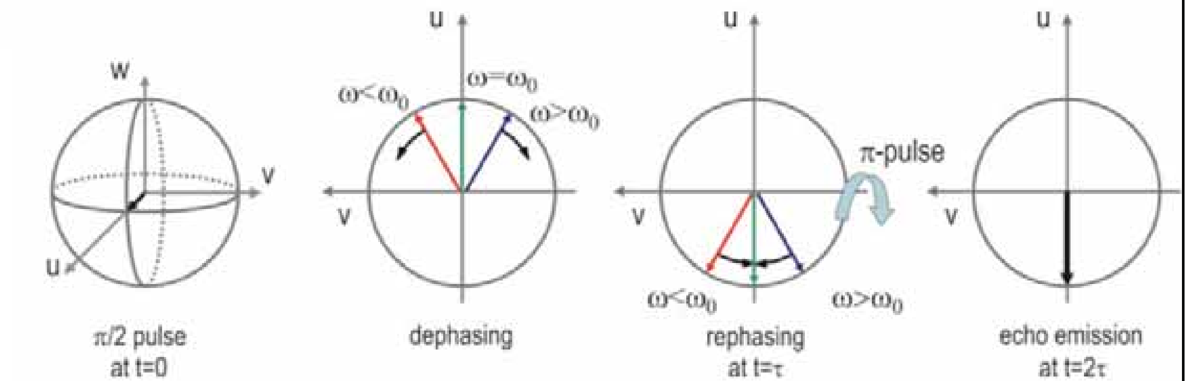
Very fast decay of the alignement of the atomic dipoles

Needs a controlled rephasing process

2-pulse photon echo



In the Bloch sphere :

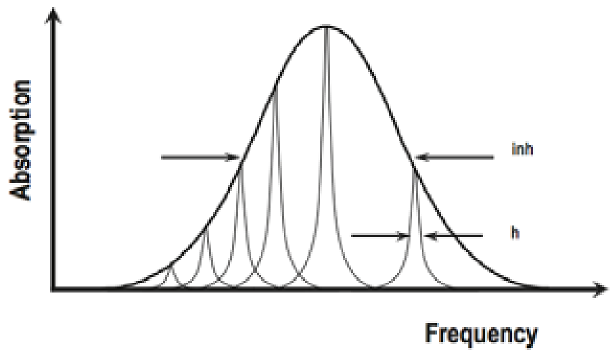


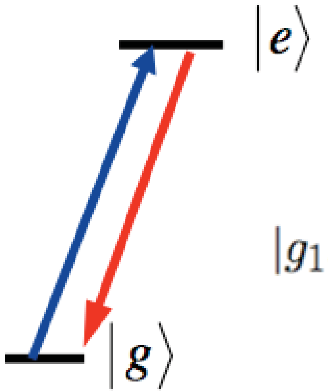
Rephasing at a certain time of all the dipoles triggers the re-emission of the absorbed signal

Illustrations from W. Tittel et al., Laser Photonics Review 4, 244 (2009)

General Idea : Photon-Echo Techniques

Inhomogeneous dephasing



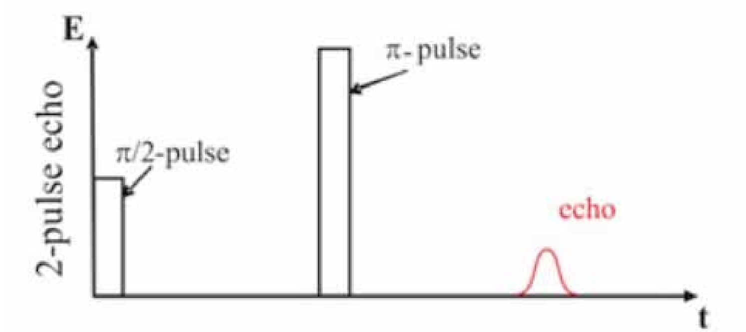


Collective state :

$$|g_1 \ldots g_i \ldots g_N\rangle \rightarrow \frac{1}{\sqrt{N}} \sum_i e^{i\vec{k}.\vec{x}_i} e^{i\Delta_i t} |g_1 \ldots e_i \ldots g_N\rangle$$

Very fast decay of the alignement of the atomic dipoles
Needs a controlled rephasing process

2-pulse photon echo



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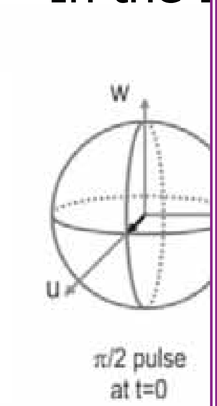

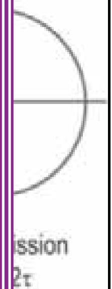

Rephasir ... ers

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Illustrations from W. Tittel et al., Laser Photonics Revie

Not a good QM strategy…

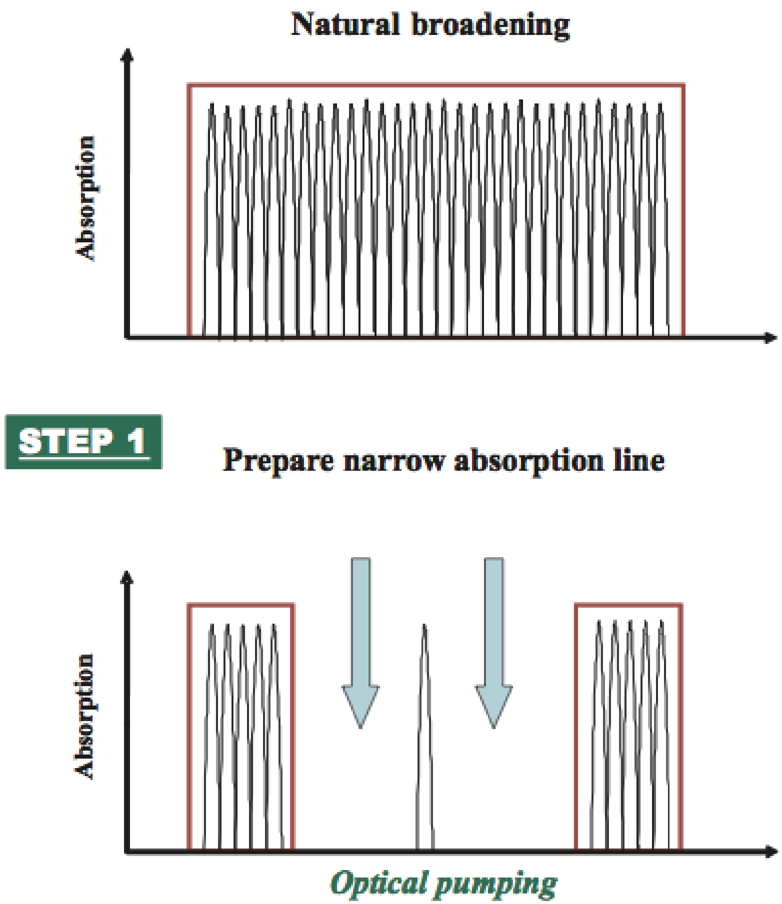
- Strong optical pulse in the quantum channel

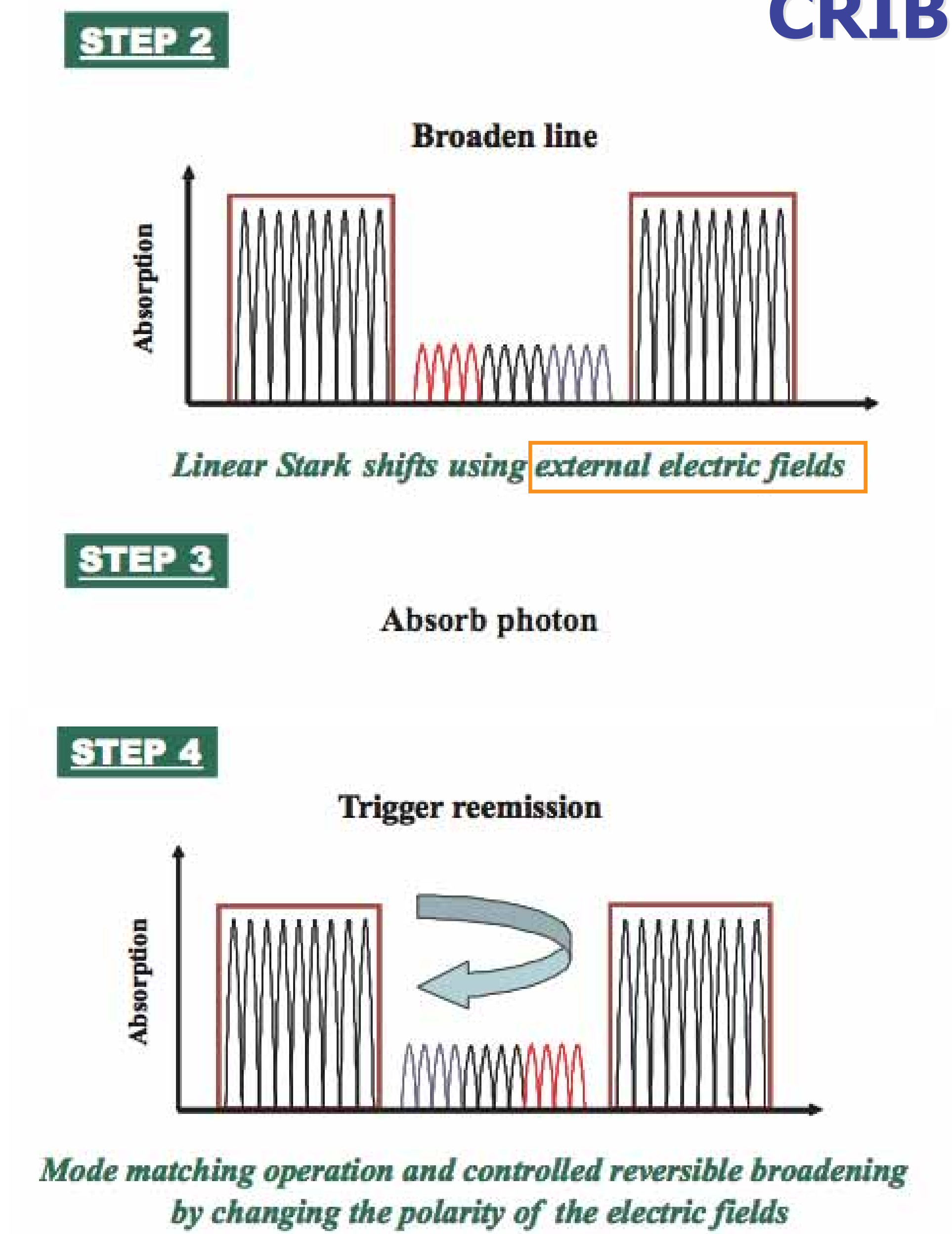
- Contamination of the single-photon echo by unavoidable fluorescence

How to avoid these contaminations ?
2 ways : CRIB and AFC

Controlled Reversible Inhomogenous Broadening

CRIB





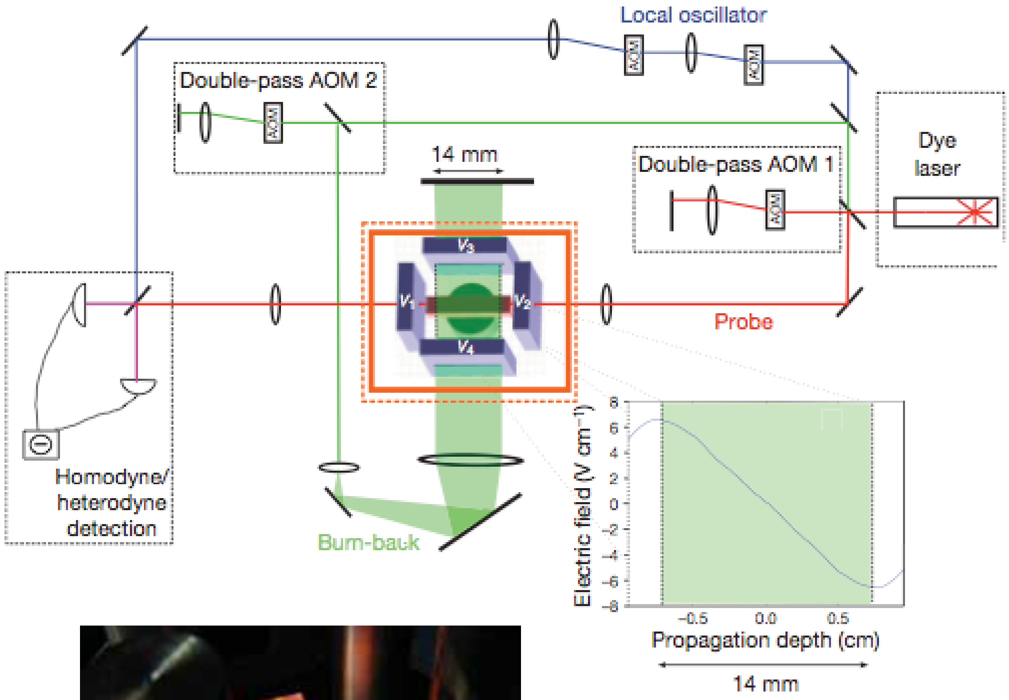
Illustrations from W. Tittel et al.,
Laser Photonics Review 4, 244 (2009)

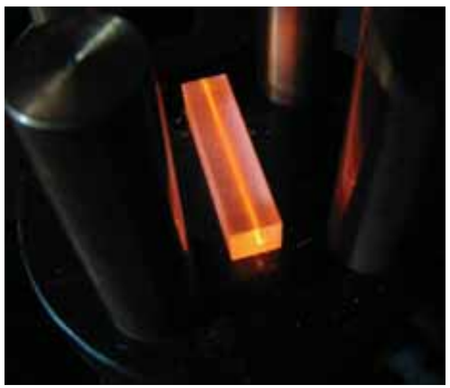
Controlled Reversible Inhomogenous Broadening

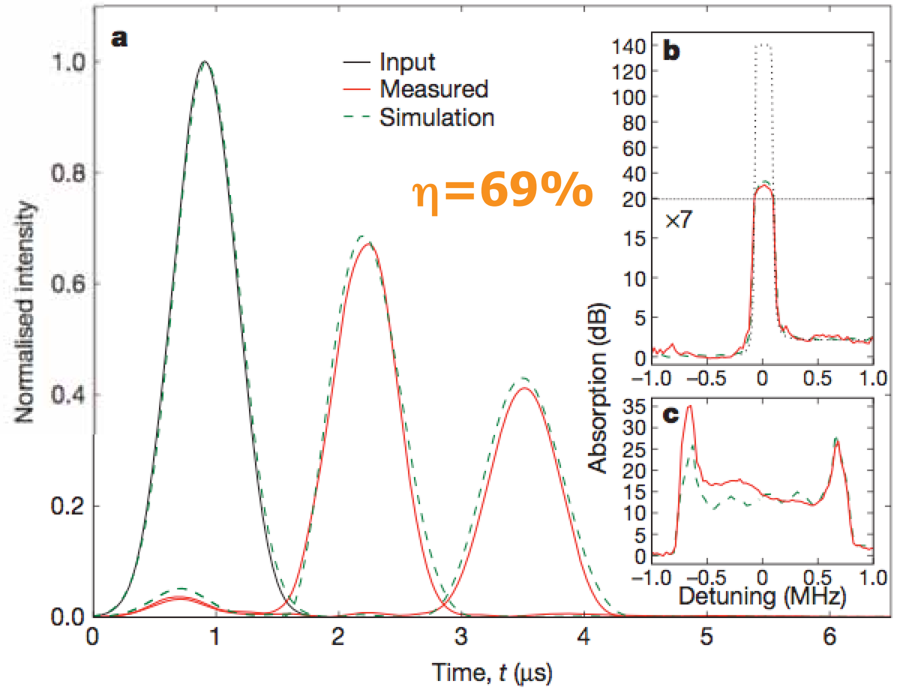
Efficient quantum memory for light

Morgan P. Hedges[1], Jevon J. Longdell[2], Yongmin Li[3] & Matthew J. Sellars[1]

Nature 465, 1052 (2010)





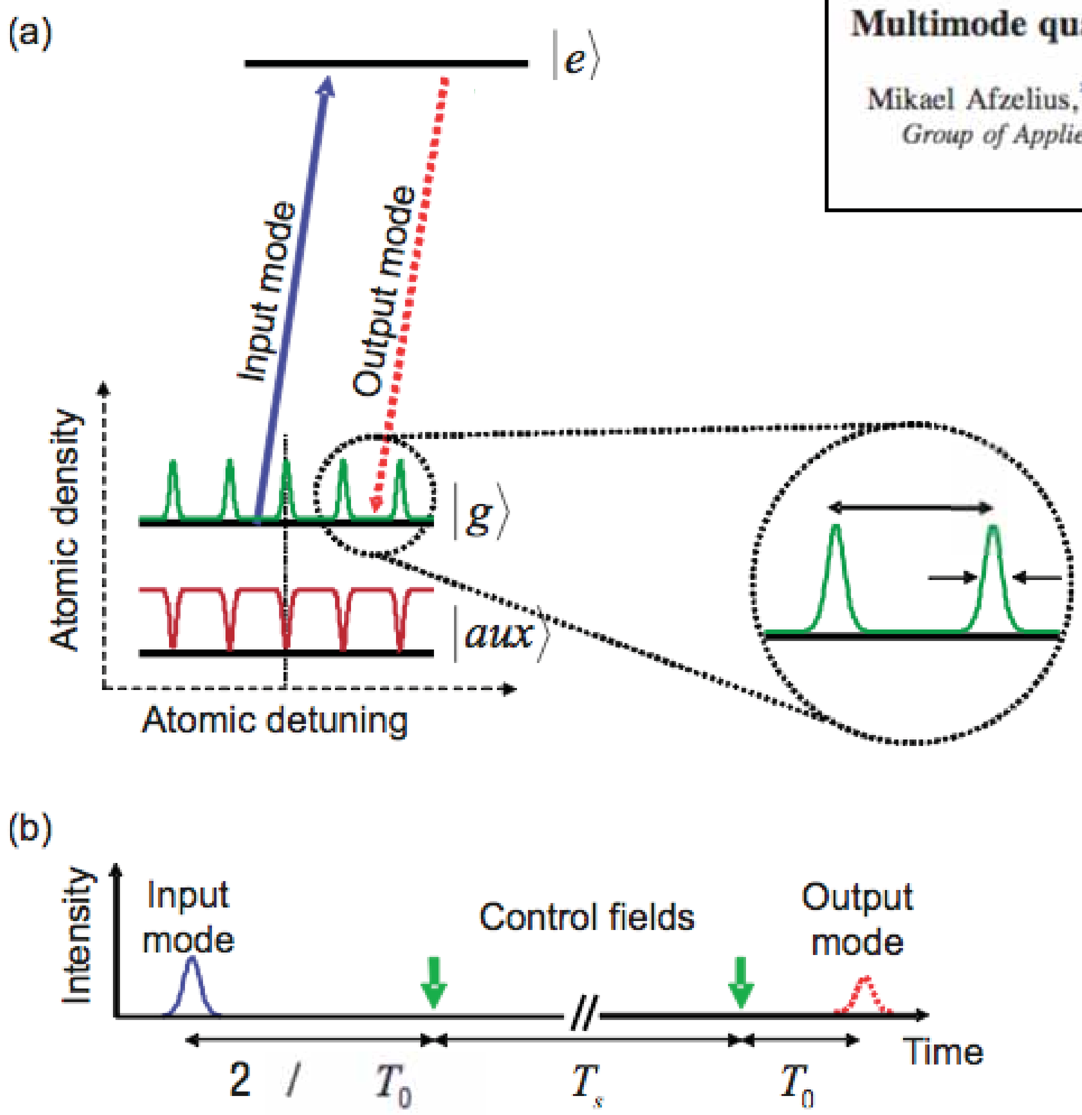


Atomic Frequency Comb (AFC)

PHYSICAL REVIEW A **79**, 052329 (2009)

Multimode quantum memory based on atomic frequency combs

Mikael Afzelius,* Christoph Simon, Hugues de Riedmatten, and Nicolas Gisin
Group of Applied Physics, University of Geneva, CH-1211 Geneva 4, Switzerland
(Received 9 June 2008; published 21 May 2009)



- Collective state at t=0

$$\frac{1}{\sqrt{N}}\sum_k c_k|g_1 \ldots e_k \ldots g_N\rangle$$

- After a time t (dephasing)

$$\frac{1}{\sqrt{N}}\sum_k c_k e^{-i\delta_k t}|g_1 \ldots e_k \ldots g_N\rangle$$

$$\delta_k = m.\Delta$$

- Rephasing after a time

$$t_e = 2\pi/\Delta$$

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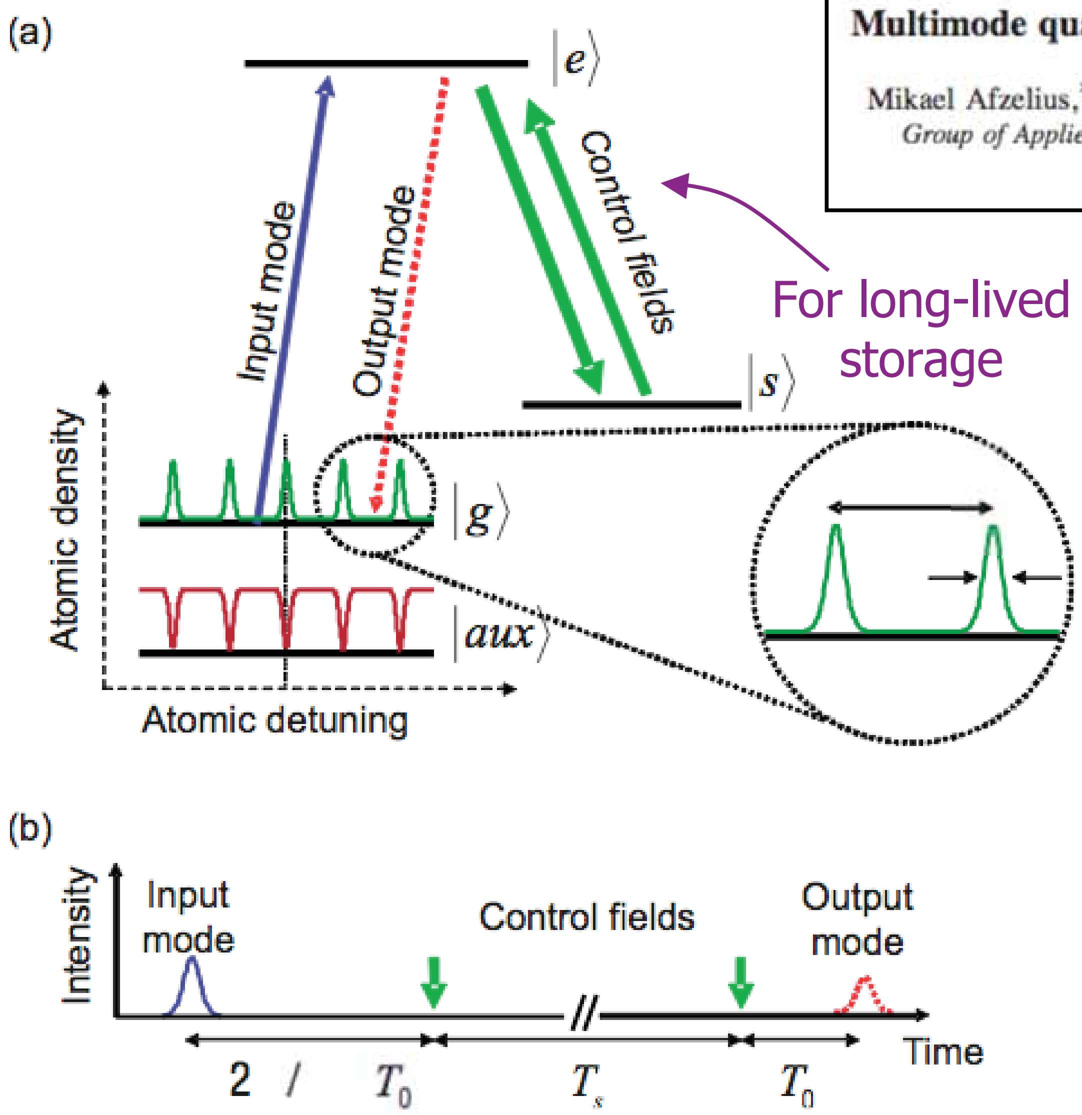

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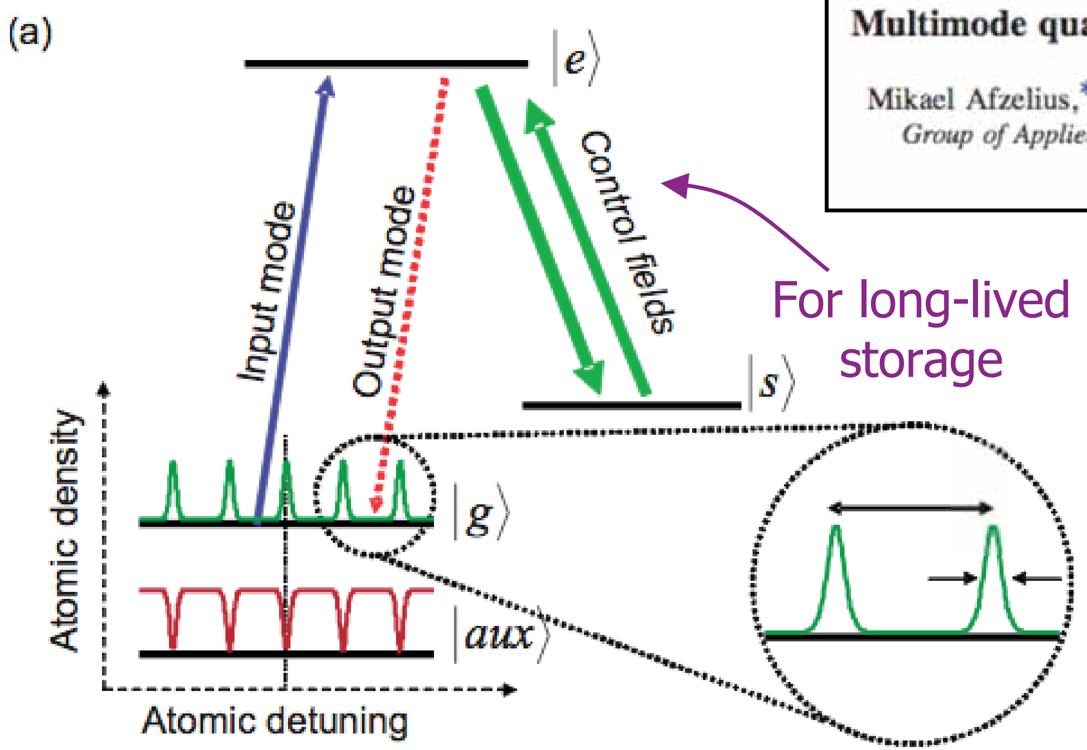

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Some advantages relative to CRIB:

- Better use of the optical depth (OD)
- Multimode capacity (only limited by the broadening while in CRIB number of modes scales with OD and in EIT it scales with √OD)

For instance : 1060 modes : M. Bonarota et al., Highly multimode storage in a crystal, NJP 13, 013013 (2010)

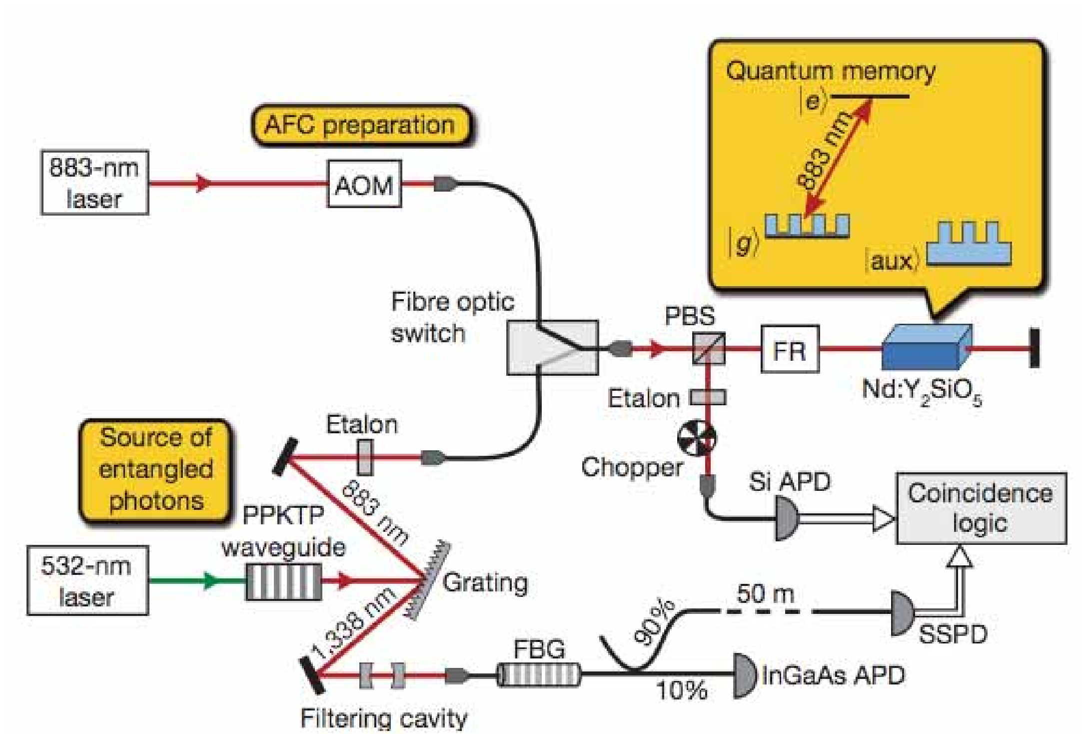
Atomic Frequency Comb (AFC)

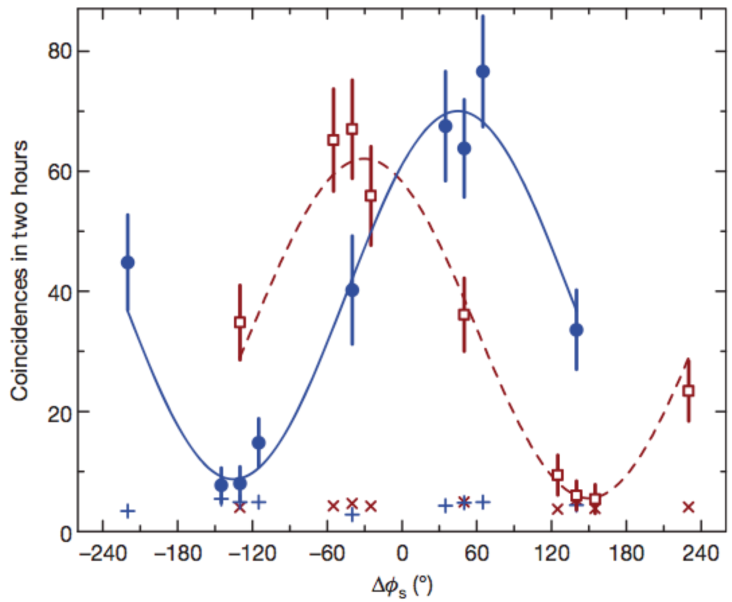
LETTER

doi:10.1038/nature09662

Quantum storage of photonic entanglement in a crystal

Christoph Clausen[1]*, Imam Usmani[1]*, Félix Bussières[1], Nicolas Sangouard[1], Mikael Afzelius[1], Hugues de Riedmatten[1,2,3] & Nicolas Gisin[1]



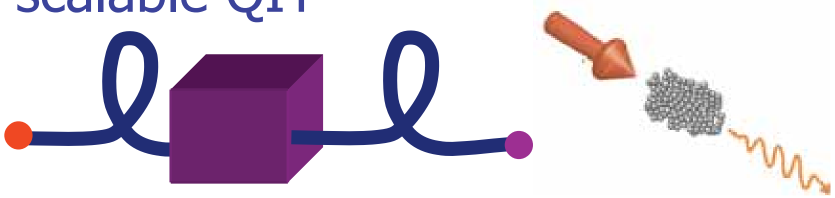


Bell violation S=2.65>2

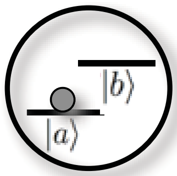
See other works in Orsay (Chanelière/Le Gouet), Lund (Kroll),…

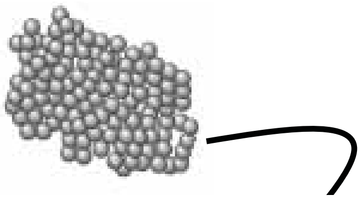
Summary

- Optical quanutm Memories for scalable QIT



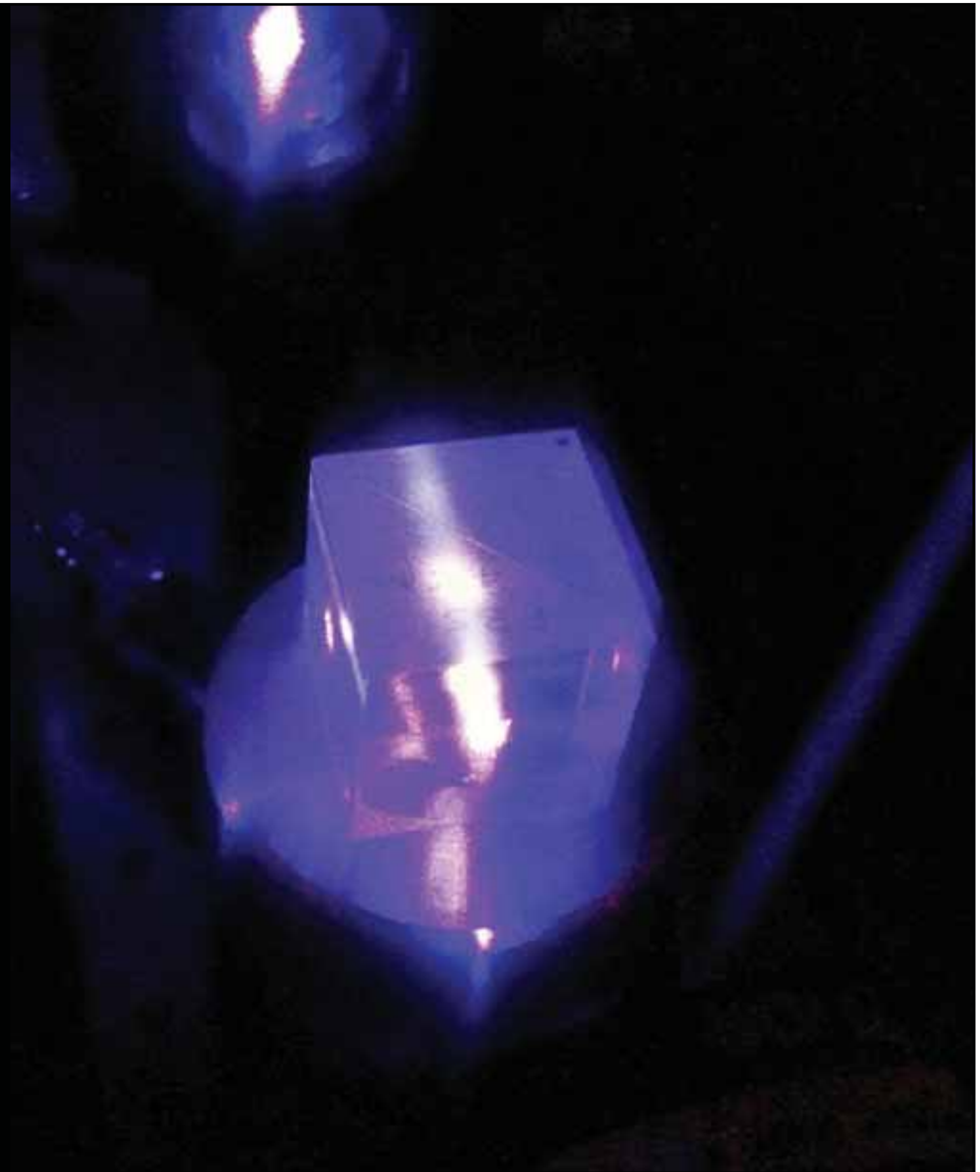
- Single-atom vs ensemble-based





Collective enhancement

- *DLCZ approach*
- *EIT-based memories*
- *Photon-echo techniques*



Some Reviews

Quantum interface between light and atomic ensembles
K. Hammerer et al., Rev. Mod. Phys. 82, 1041 (2010)

Optical quantum memories
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Quantum repeaters based on atomic ensembles and linear optics
N. Sangouard et al., Rev. Mod. Phys. 83, 33 (2011)

Photon-echo quantum memory in solid state systems
W. Tittel et al., Laser Photonics Review 4, 244 (2009)

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Open Postdoc positions in experimental quantum optics and quantum information

-Q. Memory
- Q. State Engineering

Feel free to contact me!