IV São Paulo School on light and cold atoms

Quantum networks with cold atoms

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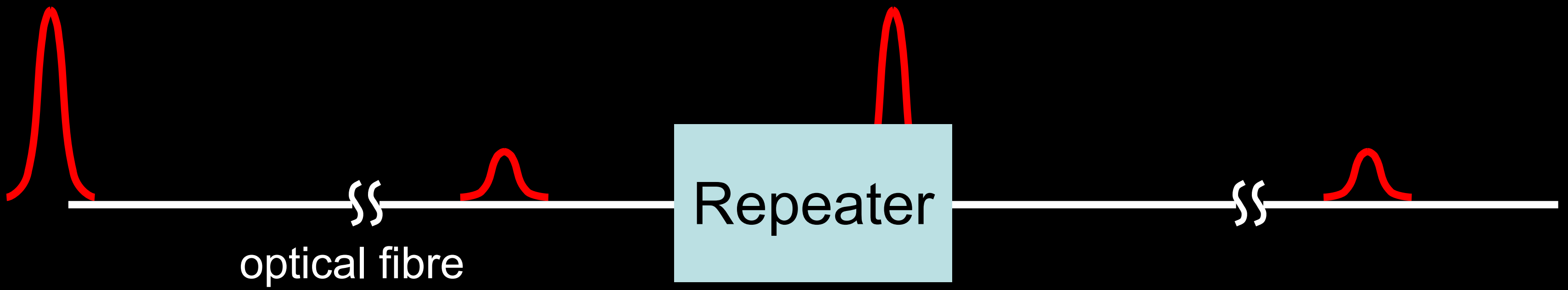
<u>**Part II**</u>

networks based on *atomic collective states*

extending the communication distance:

Repeater in Telecommunication



PROBLEM

A quantum state cannot be "amplified"

Current quantum cryptography technology limited to ~100 km

No Cloning

Perfect cloning machine $|A\rangle$ → $|A_0\rangle|s\rangle \rightarrow |A_s\rangle|ss\rangle$

Machine cloning vertical and horizontal polarization states of light →

$$|A_0\rangle|\updownarrow\rangle \rightarrow |A_{\text{vert}}\rangle|\updownarrow\updownarrow\rangle$$

$$|A_0\rangle|\leftrightarrow\rangle \rightarrow |A_{\text{hor}}\rangle|\leftrightarrows\rangle$$

$$|A_0\rangle(\alpha|\updownarrow\rangle+\beta|\leftrightarrow\rangle) \rightarrow \alpha|A_{\text{vert}}\rangle|\updownarrow\updownarrow\rangle+\beta|A_{\text{hor}}\rangle|\leftrightarrows\rangle$$

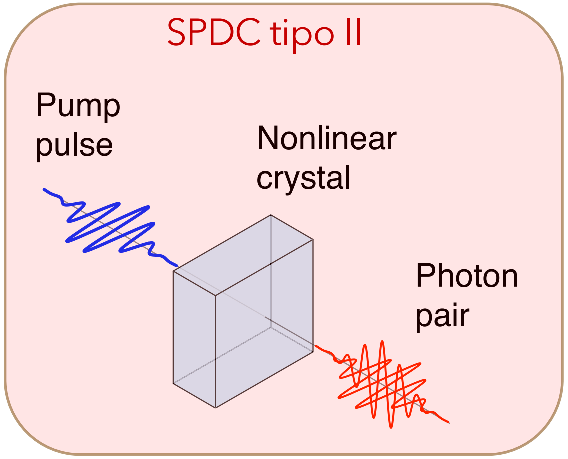
Ideal case → $\alpha|\updownarrow\updownarrow\rangle+\beta|\leftrightarrows\rangle \neq \alpha^2|\updownarrow\updownarrow\rangle+2^{1/2}\alpha\beta|\updownarrow\leftrightarrow\rangle+\beta^2|\leftrightarrows\rangle$

final state of a cloning procedure

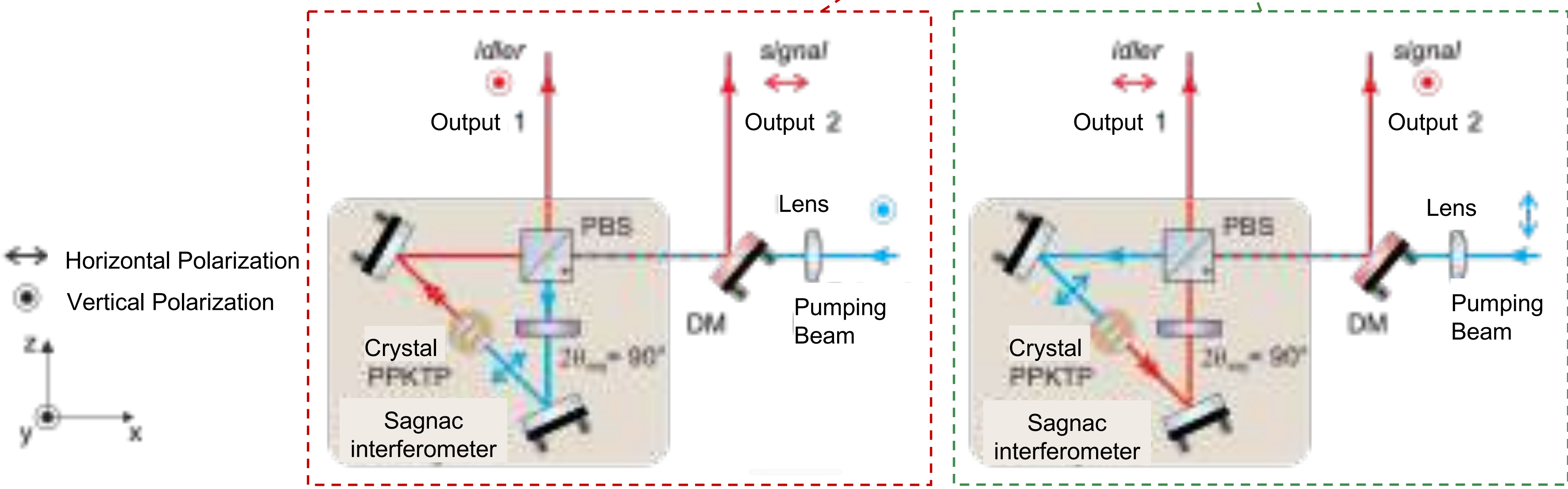
Moral of the story: it is possible to create a machine to clone specific states, but not a machine to clone an arbitrary superposition of states

Wooters & Zurek, Nature **229**, 802 (1982)

How to Create Entangled Photon Pairs



$$|\psi_{EPR}\rangle = \frac{1}{\sqrt{2}}(|x,y\rangle + |y,x\rangle)$$



Generation of Heralded Single Photons in Pure Quantum States, Peter J. Mosley (2007)
Route for absorption of individual ultrashort photons by an atomic medium, Alyson J. A. Carvalho (2020)

Quantum Teleportation

We call the process we are about to describe teleportation, a term from science fiction meaning to make a person or object disappear while an exact replica appears somewhere else.

Bennett et al., Phys. Rev. Lett. **70**, 1895 (1993)

Alice (2) and Bob (3) each have a particle of the entangled pair

$$|\Psi_{23}^{(-)}\rangle = \sqrt{\tfrac{1}{2}}\left(|\uparrow_2\rangle|\downarrow_3\rangle - |\downarrow_2\rangle|\uparrow_3\rangle\right)$$

Alice wants to transmit the state $|\phi_1\rangle$ to Bob:

$$|\phi_1\rangle = a\,|\uparrow_1\rangle + b\,|\downarrow_1\rangle$$

---

starting from the product:

$$|\Psi_{123}\rangle = \frac{a}{\sqrt{2}}\left(|\uparrow_1\rangle|\uparrow_2\rangle|\downarrow_3\rangle - |\uparrow_1\rangle|\downarrow_2\rangle|\uparrow_3\rangle\right) + \frac{b}{\sqrt{2}}\left(|\downarrow_1\rangle|\uparrow_2\rangle|\downarrow_3\rangle - |\downarrow_1\rangle|\downarrow_2\rangle|\uparrow_3\rangle\right)$$

we can make a change of base of the states with Alice to:

$$|\Psi_{12}^{(\pm)}\rangle = \sqrt{\tfrac{1}{2}}\left(|\uparrow_1\rangle|\downarrow_2\rangle \pm |\downarrow_1\rangle|\uparrow_2\rangle\right) \qquad |\Phi_{12}^{(\pm)}\rangle = \sqrt{\tfrac{1}{2}}\left(|\uparrow_1\rangle|\uparrow_2\rangle \pm |\downarrow_1\rangle|\downarrow_2\rangle\right)$$

in terms of this new basis, we can write:

$$|\Psi_{123}\rangle = \tfrac{1}{2}\left[|\Psi_{12}^{(-)}\rangle\left(-a|\uparrow_3\rangle - b|\downarrow_3\rangle\right) + |\Psi_{12}^{(+)}\rangle\left(-a|\uparrow_3\rangle + b|\downarrow_3\rangle\right) + |\Phi_{12}^{(-)}\rangle\left(a|\downarrow_3\rangle + b|\uparrow_3\rangle\right) + |\Phi_{12}^{(+)}\rangle\left(a|\downarrow_3\rangle - b|\uparrow_3\rangle\right)\right]$$

if Alice makes a measure whose eigenstates are given by this new base, the state $|\phi_3\rangle$ of Bob's particle becomes:

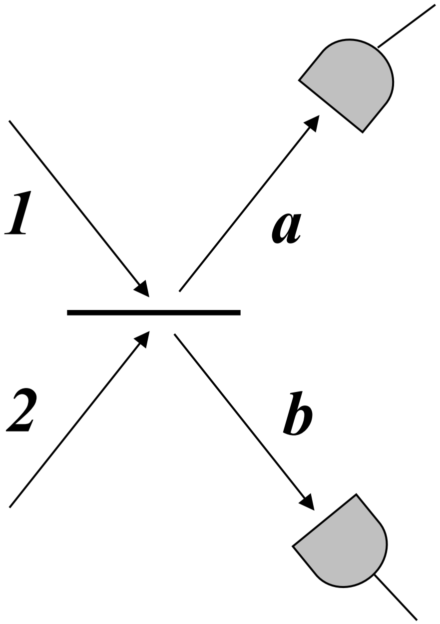
$$-|\phi_3\rangle \equiv -\begin{pmatrix} a \\ b \end{pmatrix} \quad \text{ou} \quad \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix}|\phi_3\rangle \quad \text{ou} \quad \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}|\phi_3\rangle \quad \text{ou} \quad \begin{pmatrix} 0 & -1 \\ 1 & 0 \end{pmatrix}|\phi_3\rangle$$

when Alice informs Bob of the result of her measurement, Bob can then apply a transformation to $|\phi_3\rangle$ and leave particle 3 in the original state $|\phi_1\rangle$

Bennett et al., Phys. Rev. Lett. **70**, 1895 (1993)

Base of Bell states $\Rightarrow$ $\left\{ |\Psi_{12}^{+}\rangle, |\Psi_{12}^{-}\rangle, |\Phi_{12}^{+}\rangle, |\Phi_{12}^{-}\rangle \right\}$

Example of a measure of a Bell Base eigenstate



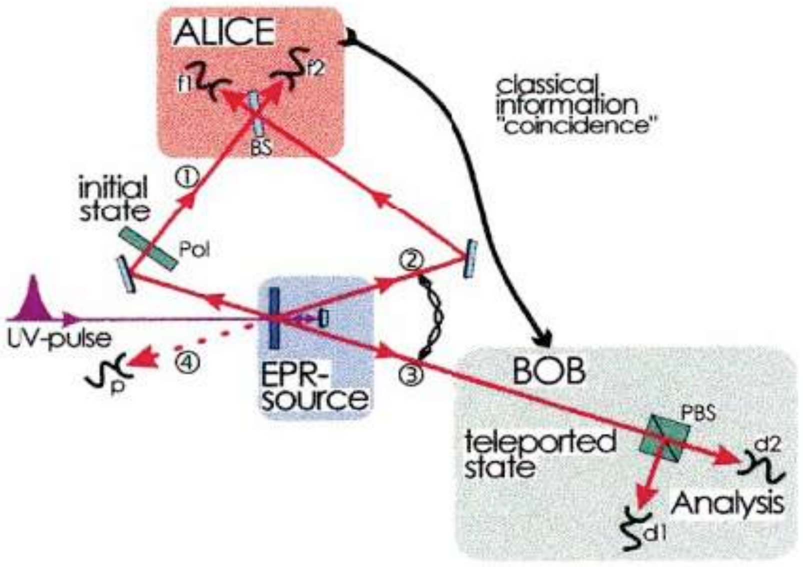
$$|\uparrow\rangle_1 \rightarrow \frac{1}{\sqrt{2}}(|\uparrow\rangle_a + i|\uparrow\rangle_b) \qquad |\uparrow\rangle_2 \rightarrow \frac{1}{\sqrt{2}}(|\uparrow\rangle_b + i|\uparrow\rangle_a)$$

$$\left\{ \begin{aligned} |\uparrow\rangle_1|\uparrow\rangle_2 &\rightarrow \frac{1}{2}(i|\uparrow\uparrow\rangle_a + i|\uparrow\uparrow\rangle_b + |\uparrow\rangle_a|\uparrow\rangle_b - |\uparrow\rangle_b|\uparrow\rangle_a) \\ &= \frac{i}{2}(|\uparrow\uparrow\rangle_a + |\uparrow\uparrow\rangle_b) \\ |\downarrow\rangle_1|\downarrow\rangle_2 &\rightarrow \frac{i}{2}(|\downarrow\downarrow\rangle_a + |\downarrow\downarrow\rangle_b) \\ |\uparrow\rangle_1|\downarrow\rangle_2 &\rightarrow \frac{1}{2}(i|\uparrow\downarrow\rangle_a + i|\uparrow\downarrow\rangle_b + |\uparrow\rangle_a|\downarrow\rangle_b - |\uparrow\rangle_b|\downarrow\rangle_a) \\ |\downarrow\rangle_1|\uparrow\rangle_2 &\rightarrow \frac{1}{2}(i|\uparrow\downarrow\rangle_a + i|\uparrow\downarrow\rangle_b + |\downarrow\rangle_a|\uparrow\rangle_b - |\uparrow\rangle_b|\downarrow\rangle_a) \end{aligned} \right.$$

$$\left\{ \begin{aligned} |\Psi_{12}^{+}\rangle &= \frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\downarrow\rangle_2 + |\downarrow\rangle_1|\uparrow\rangle_2) \rightarrow \frac{i}{\sqrt{2}}(|\uparrow\downarrow\rangle_a + |\uparrow\downarrow\rangle_b) \\ |\Psi_{12}^{-}\rangle &= \frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2) \rightarrow \frac{i}{\sqrt{2}}(|\uparrow\rangle_a|\downarrow\rangle_b - |\uparrow\rangle_b|\downarrow\rangle_a) \\ |\Phi_{12}^{+}\rangle &= \frac{1}{\sqrt{2}}(|\uparrow\rangle_1|\uparrow\rangle_2 + |\downarrow\rangle_1|\downarrow\rangle_2) \rightarrow \frac{i}{\sqrt{2}}(|\uparrow\uparrow\rangle_a + |\uparrow\uparrow\rangle_b + |\downarrow\downarrow\rangle_a + |\downarrow\downarrow\rangle_b) \\ |\Phi_{12}^{-}\rangle &= \frac{1}{\sqrt{2}}(|\uparrow_1\rangle|\uparrow_2\rangle - |\downarrow_1\rangle|\downarrow_2\rangle) \rightarrow \frac{i}{\sqrt{2}}(|\uparrow\uparrow\rangle_a + |\uparrow\uparrow\rangle_b - |\downarrow\downarrow\rangle_a - |\downarrow\downarrow\rangle_b) \end{aligned} \right.$$

Only state that leads to measures in a and b simultaneously

First experiment: Bouwmeester et al., Nature 390, 575 (1997)



Partial quantum teleportation
(probabilistic)

Alice's measure indicates only one of the states of the new base:

$$|\psi^-\rangle_{12} = \frac{1}{\sqrt{2}}\left(|\leftrightarrow\rangle_1|\updownarrow\rangle_2 - |\updownarrow\rangle_1|\leftrightarrow\rangle_2\right)$$

Teleportation occurs 25% of the time

Further measurements of full quantum teleportation (deterministic):

Furusawa et al., Science **282**, 706 (1998) → **coherent light beams**

Riebe et al., Nature **421**, 734 (2004)
Barret et al., Nature **421**, 737 (2004)
} **Ions**

Teleportation and Information

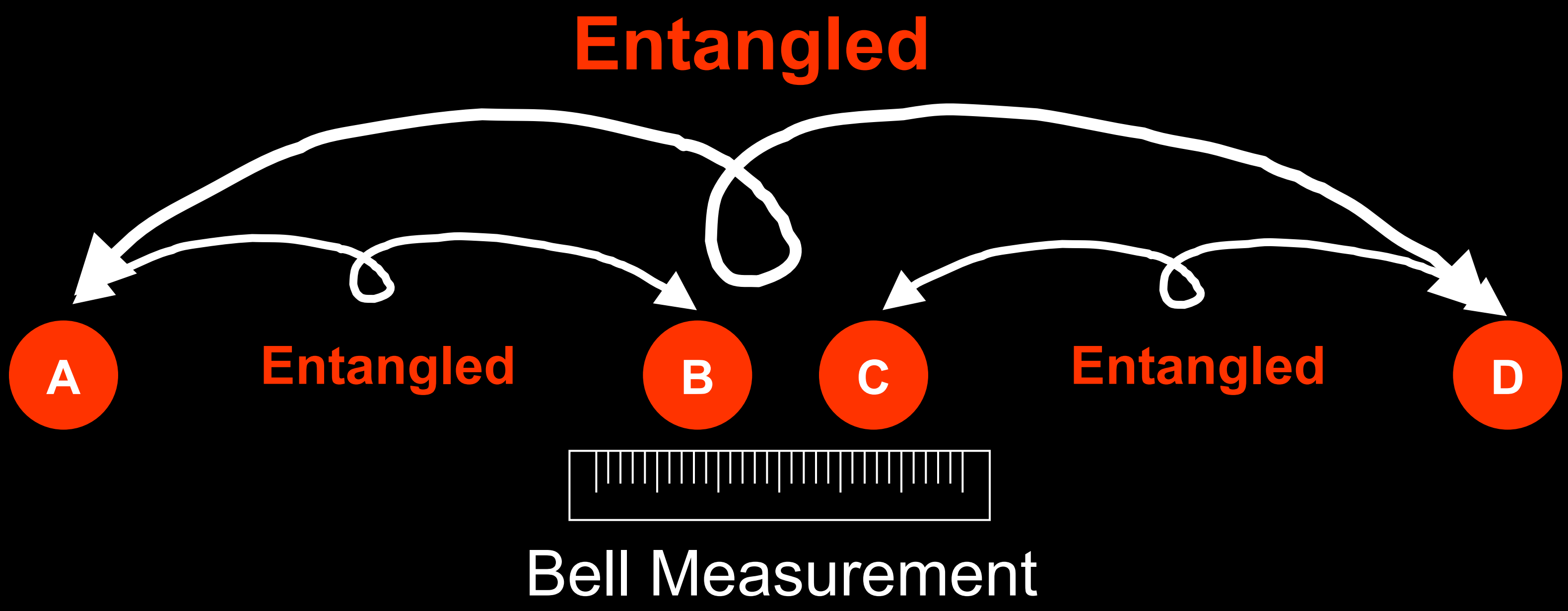
• Physical state cannot be cloned, but can be transferred to another system

• 1 entangled pair + classic communication channel → Faithful transmission of a qubit

• Decoupling of information into a purely quantum and a classical part → Entangled pairs can transmit the purely quantum part

Quantum entanglement as the basis for an "engineering" of quantum communication channels

Quantum Repeater
Entanglement Swapping



Scalability requires deterministic or signaled storage of quantum entanglement in distant locations

The Amazing DLCZ Protocol

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

articles

Long-distance quantum communication with atomic ensembles and linear optics

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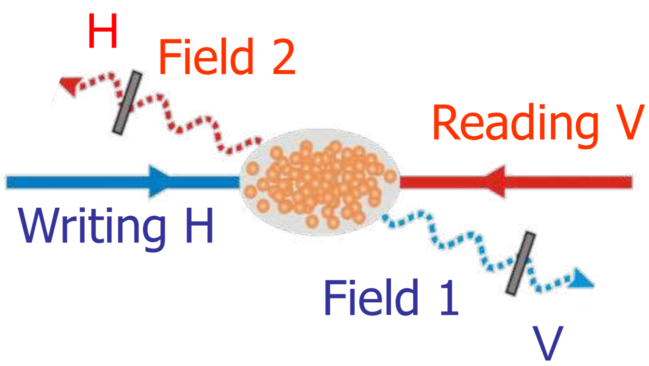
DLCZ

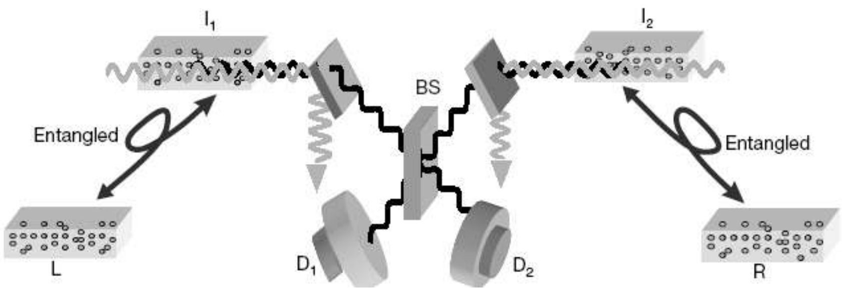
* *Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria*
† *Laboratory of Quantum Communication and Computation, USTC, Hefei 230026, China*
‡ *Physics Department and ITAMP, Harvard University, Cambridge, Massachusetts 02138, USA*

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.

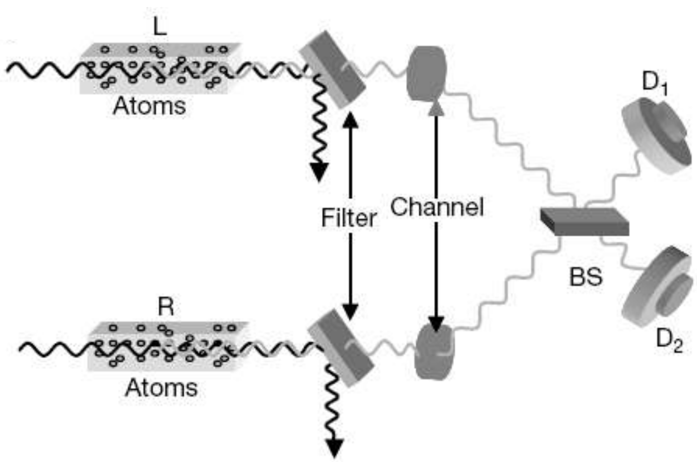
Source of photon pairs



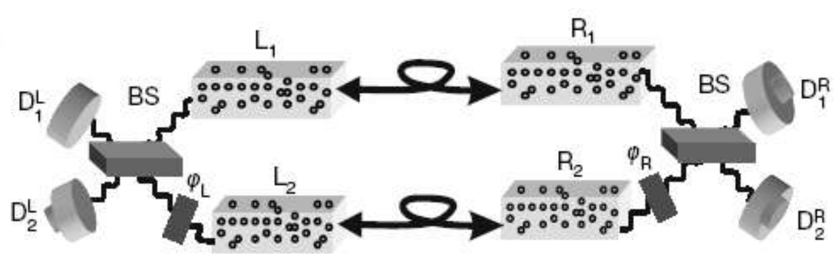
Entanglement Swapping



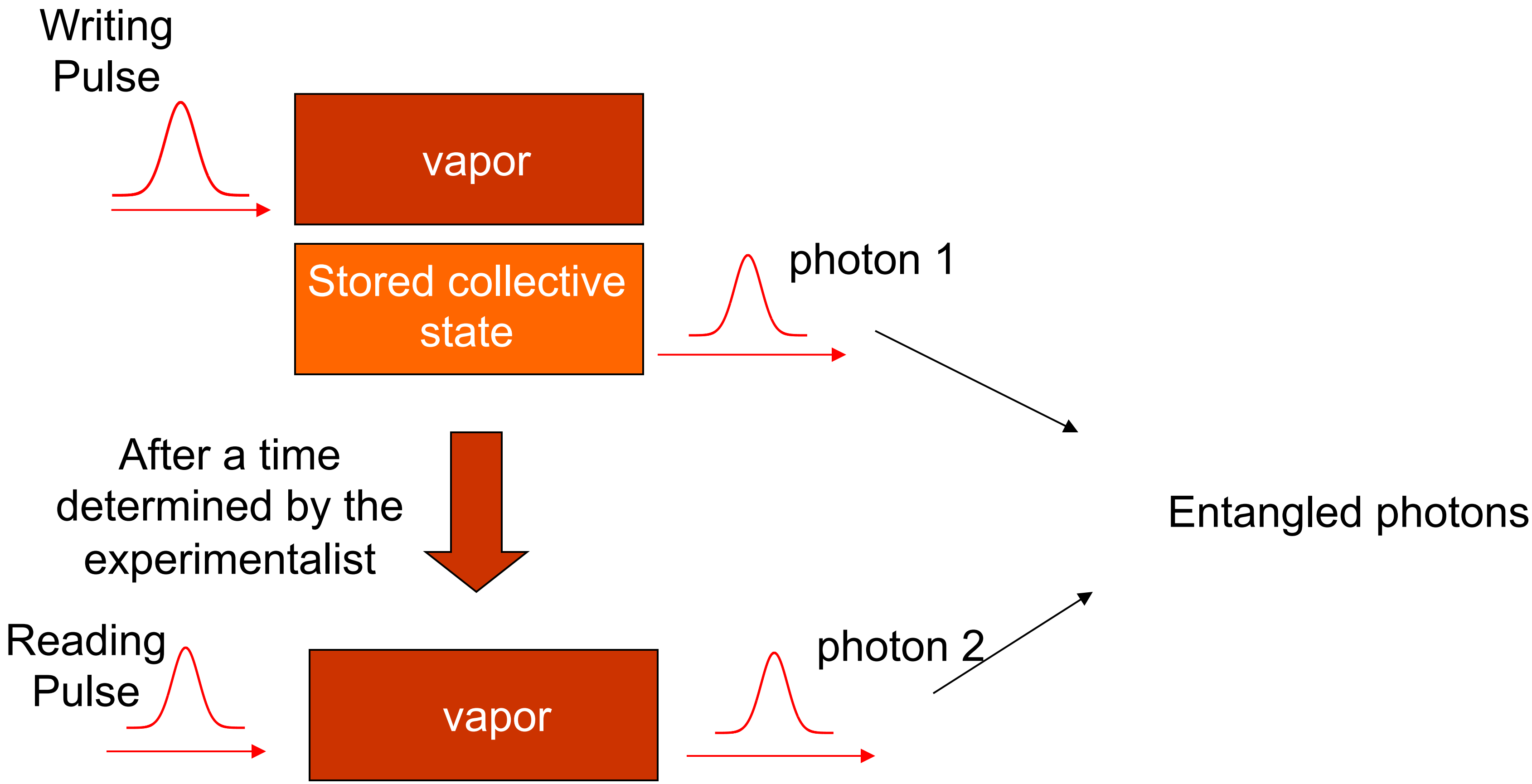
Entanglement between 2 ensembles



Quantum cryptography



Generation of the photon pair

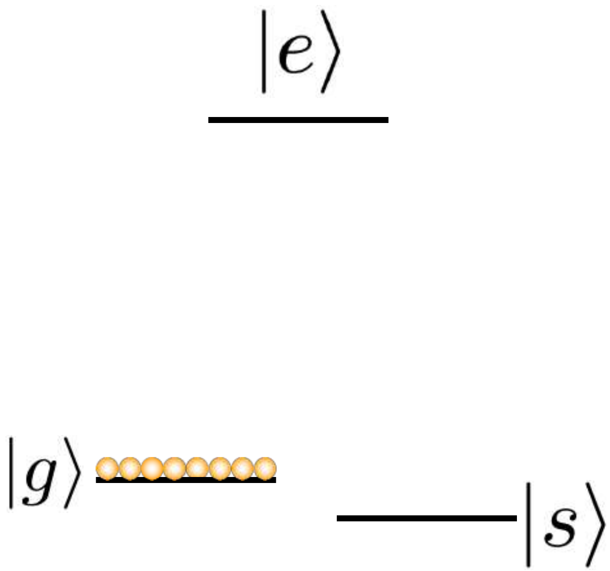


Possibility to wait before emitting the second photon → In a complex process it is not necessary to generate all photons simultaneously → scalability

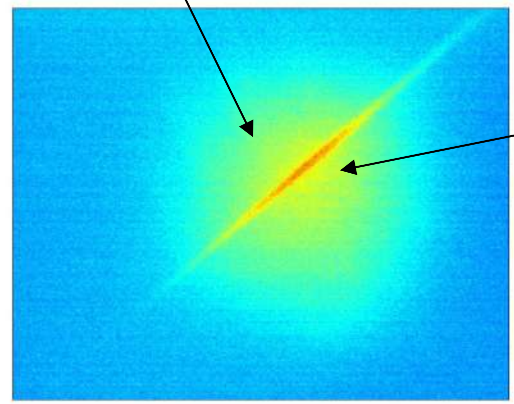
First implementation: Kuzmich et. al, Nature **423**, 731 (2003)

Basic requirement

- Large ensemble of atoms
- Λ-type level configuration

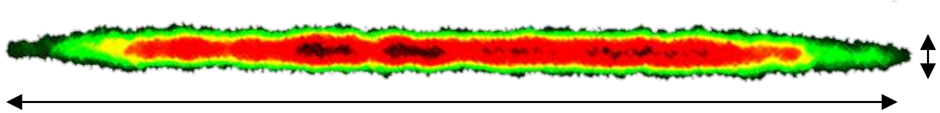


Cloud of cold atoms: trapped in a magneto-optical trap



Cylinder of atoms participating in the collective state

Typical Numbers

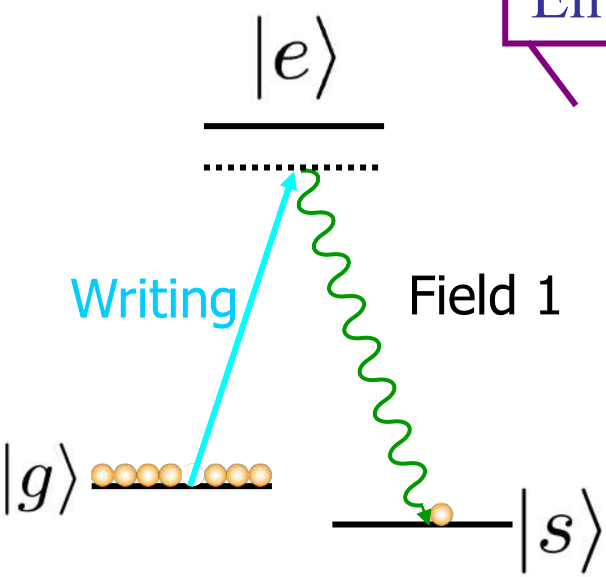


60 μm

3 mm

10^5 Cs atoms

Creating a single atomic excitation



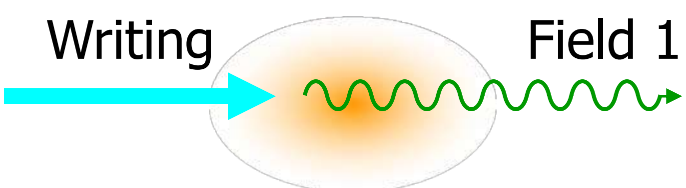
Entangled state between field 1 and ensemble

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

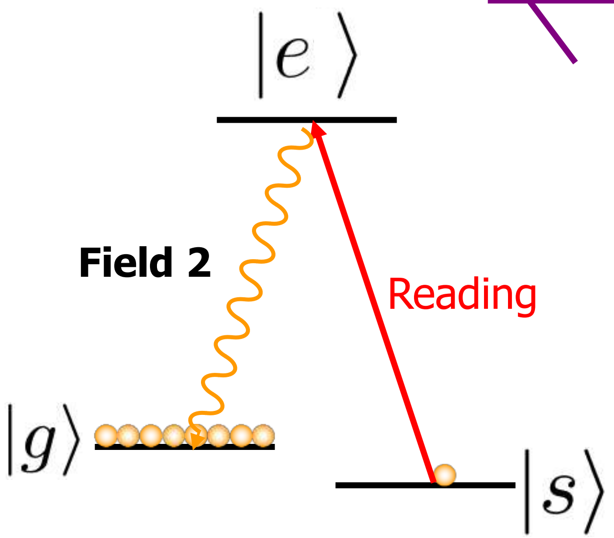
p : probability of excitation

$$|1_{atoms}\rangle \equiv \frac{1}{\sqrt{N_A}} \sum_{j=1}^{N_A} |g\rangle_1 \cdots |s\rangle_j \cdots |g\rangle_{N_A}$$

Collective atomic state



Extracting the excitation out of the meddium

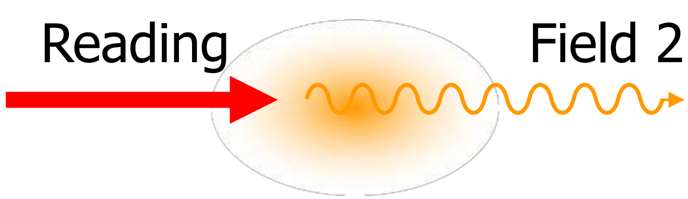


Entangled state between field 1 and ensemble

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

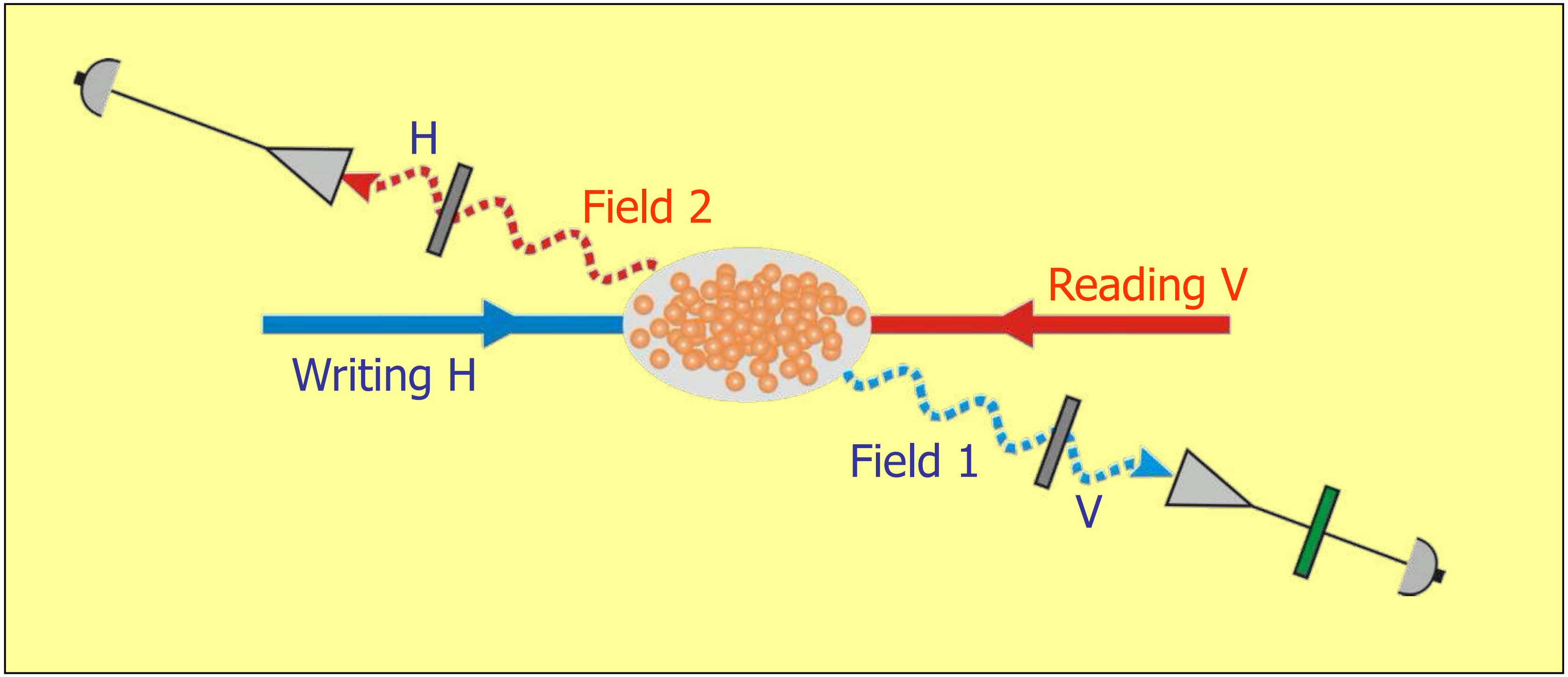
reading

$$|\psi_{12}\rangle = |0_1, 0_2\rangle + \sqrt{p}|1_1, 1_2\rangle + O(p)$$



Entangled state between fields 1 and 2

Experimental configuration

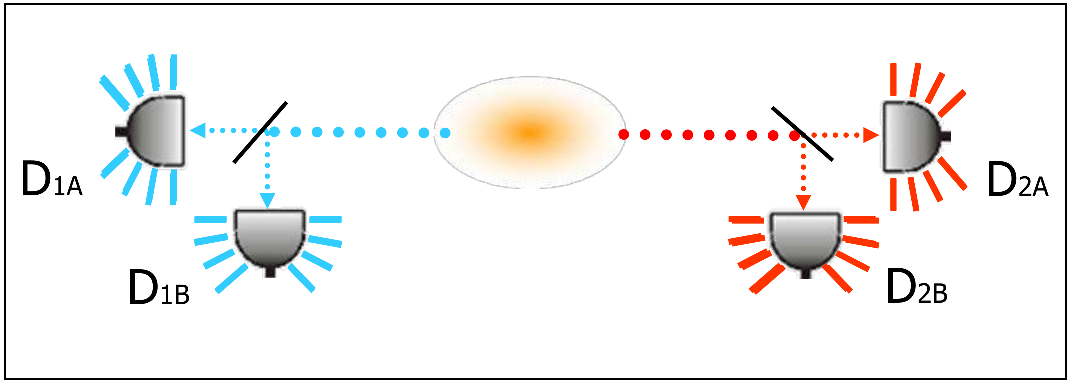


p_c : probability of one detection in 2 after one detection in 1

q_c : probability of having a photon in 2 at sample output, given a detection in 1

typically $p_c \approx 12\%$ ⟹ $q_c \approx 50\%$

Characterization of photon pairs



Probabilities of joint detections	Probabilities of simple detections
$p_{1,1}$	p_1
$p_{2,2}$	p_2
$p_{1,2}$	

Correlation functions

$$g_{1,1} \equiv p_{1,1} / p_1 \, p_1$$

$$g_{2,2} \equiv p_{2,2} / p_2 \, p_2$$

Normalized auto-correlation functions

$$g_{1,2} \equiv p_{1,2} / p_1 \, p_2$$

Normalized cross-correlation function

For classical fields:

$$(g_{1,2})^2 \leq g_{1,1} \, g_{2,2}$$

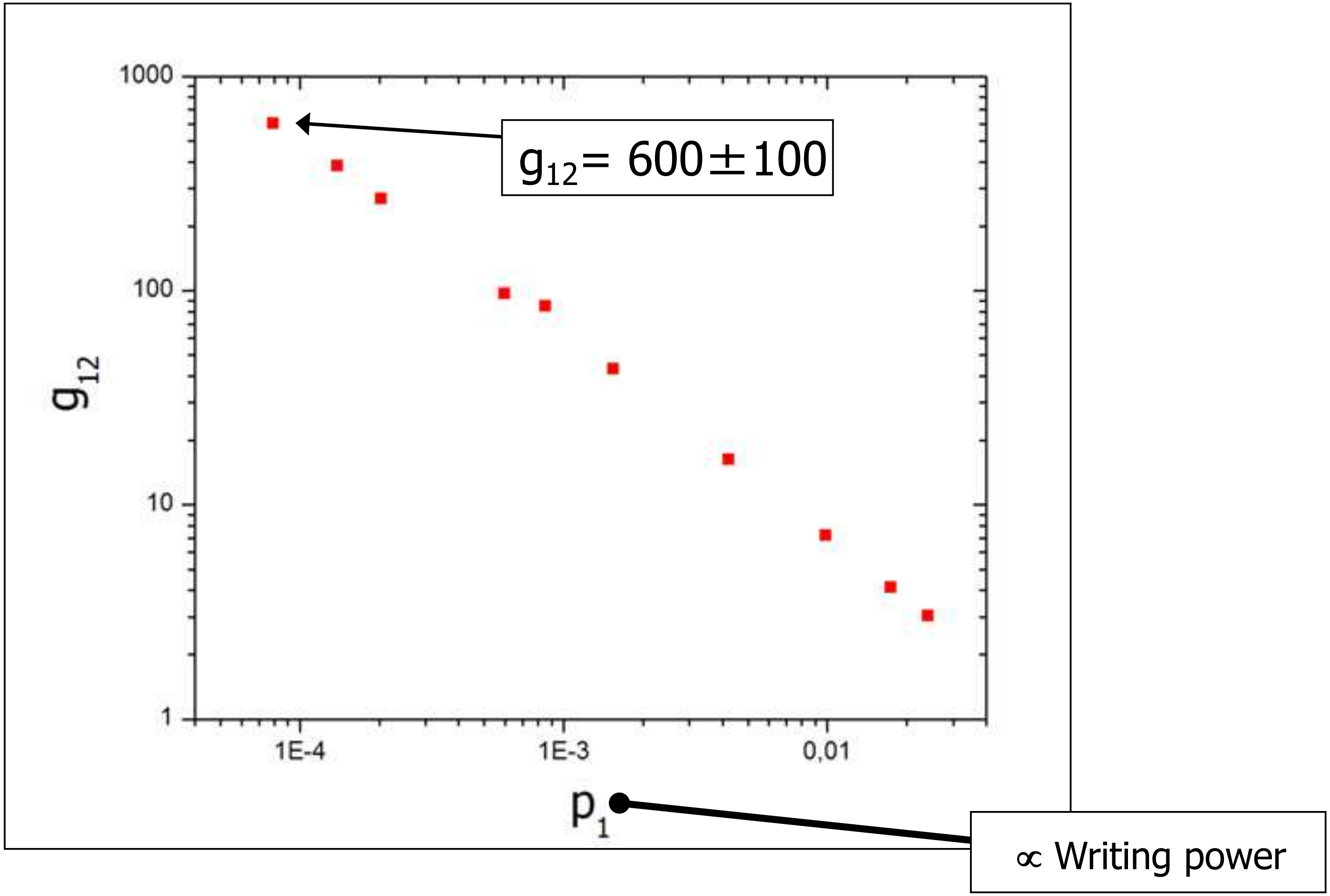
J. F. Clauser, PRD 9, 853 (1974)

For our system:

$$g_{1,1} \text{ e } g_{2,2} \leq 2$$

➔ **$g_{1,2}$ > 2 signals non-classical behavior**

Characterization of photon pairs



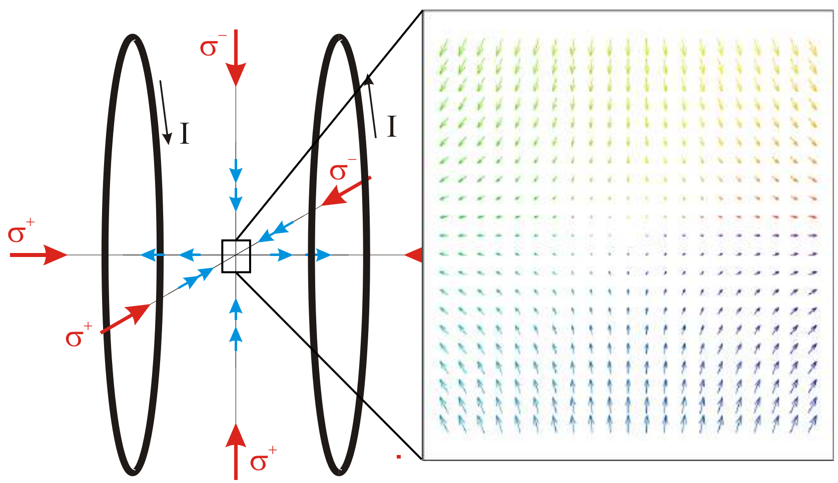
J. Laurat, H. de Riedmatten, D. Felinto, C.-W. Chou, E.W. Shomburg & H.J. Kimble, Opt. Express **14**, 6912 (2006)

First measure of g_{12} : g_{12} = 2.335 ± 0.014 [A. Kuzmich et. al., Nature **423** , 731 (2003)]

storage time

Excitation storage time

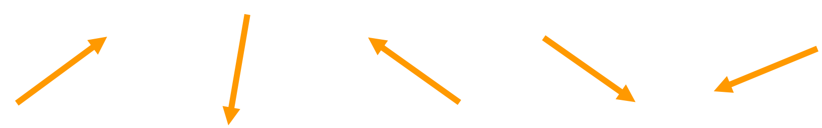
First source of decoherence: Quadrupole Magnetic Field



Each atom sees a different field: inhomogeneous broadening of the ground states

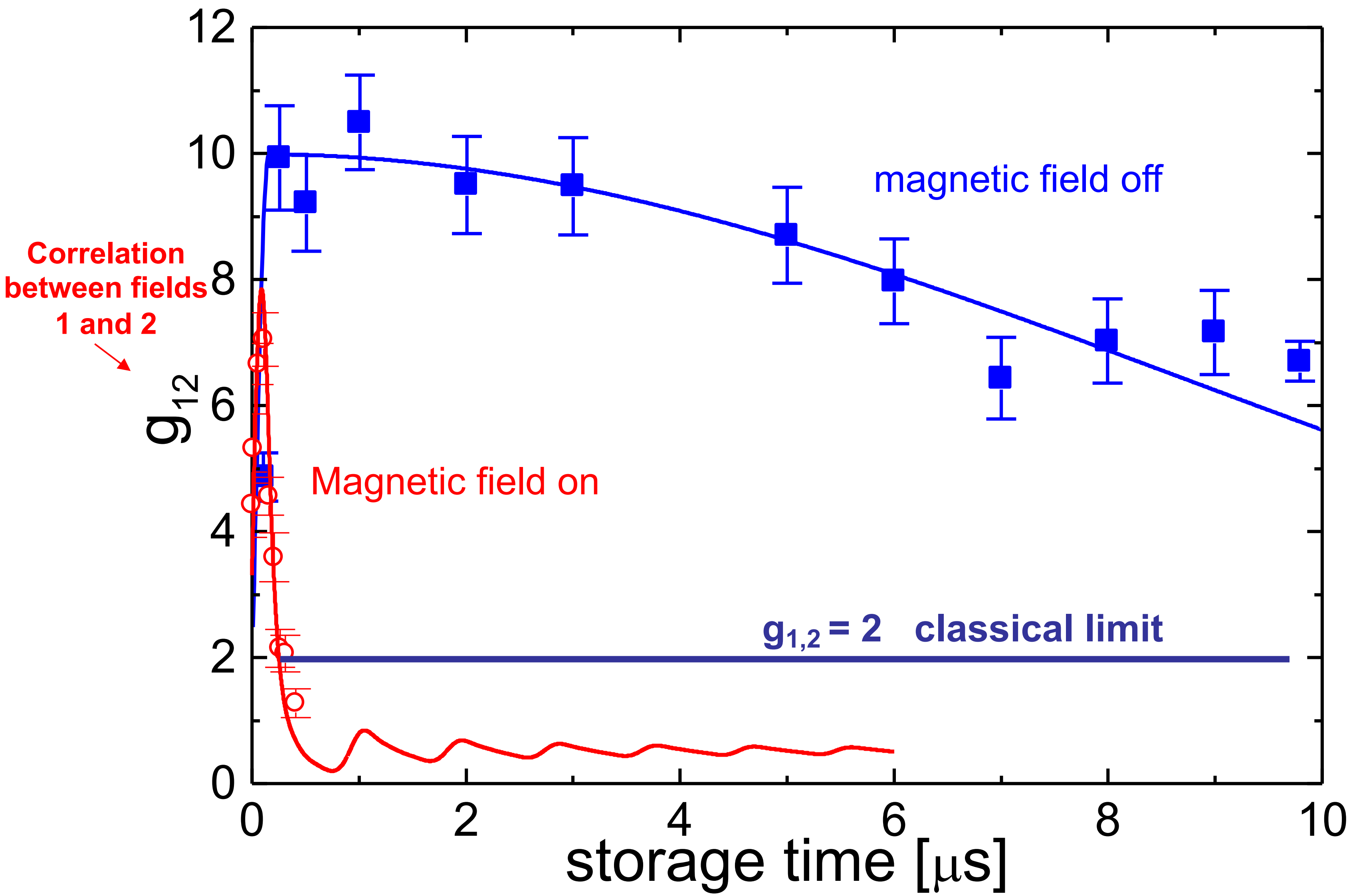
$$|1_{atoms}\rangle = \frac{1}{\sqrt{N_A}} \sum_{j=1}^{N_A} |g\rangle_1 \cdots |s\rangle_j \cdots |g\rangle_{N_A}$$

$$|1'_{atoms}\rangle = \frac{1}{\sqrt{N_A}} \sum_{j=1}^{N_A} e^{i\omega_j t} |g\rangle_1 \ldots |s\rangle_j \ldots |g\rangle_{N_A}$$



$$\boxed{\langle 1_{atoms} | 1'_{atoms} \rangle \rightarrow 0 \quad \textit{large } t}$$

Excitation storage time



D.Felinto, C. Chou, H.de Riedmatten, S.Polyakov, H.J.Kimble, Phys. Rev. A **72**, 053809 (2005)

Excitation storage time

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

PUBLISHED ONLINE: 7 DECEMBER 2008 | DOI: 10.1038/NPHYS1152

nature physics

Long-lived quantum memory

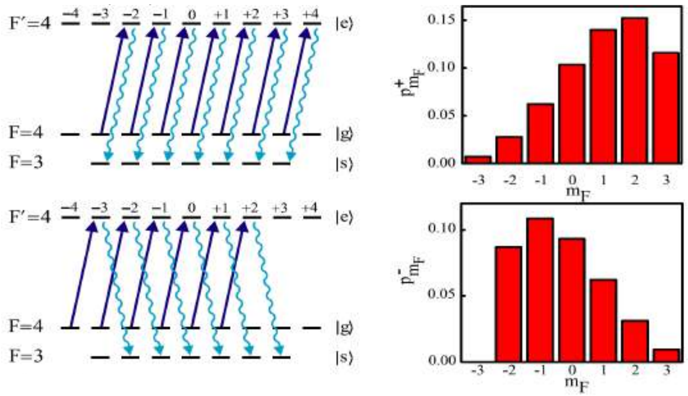
R. Zhao[1], Y. O. Dudin[1], S. D. Jenkins[1,2*], C. J. Campbell[1], D. N. Matsukevich[3], T. A. B. Kennedy[1] and A. Kuzmich[1]

Use of more sophisticated atomic traps (optical lattices) and magnetic field-insensitive states

Memory Lifetime: **1.0 – 6.0 ms**

Direct measurement of decoherence

Atoms-Field1 entanglement



For atoms initially in $|g, m_F\rangle$

$$\rho_{1a} = |0\rangle\langle 0| + |\Phi_{1a}\rangle\langle\Phi_{1a}|$$

$$|\Phi_{1a}\rangle = \sqrt{p}[\cos\eta_{m_F}|1_1^+, 1_a^+\rangle + \sin\eta_{m_F}|1_1^-, 1_a^-\rangle] + O(p)$$

$$\cos^2\eta_{m_F} = p^+_{m_F}/(p^+_{m_F} + p^-_{(m_F+2)})$$

For an initial incoherent distribution

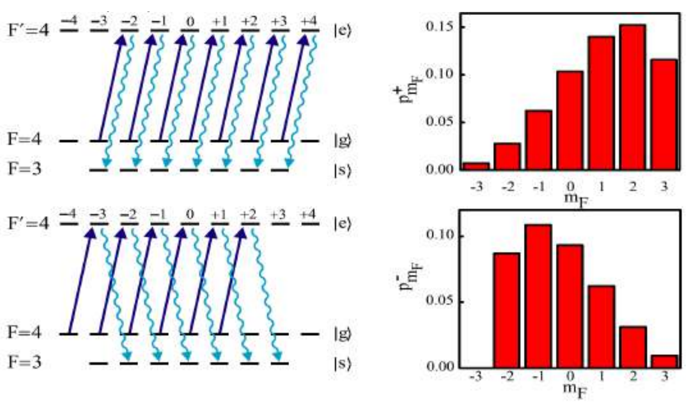
$$\cos^2\eta = \sum p^+_{m_F} / \sum (p^+_{m_F} + p^-_{m_F})$$

- If **field 1 is detected** in a superpostion state of σ+ and σ -, then the state of the excitation is projected into a coherent superposition of the mixed states shown above.
- **Goal :** persistency of this projection
- **Read pulse σ- :** qubit mapped to field 2 with polarization orthogonal to field 1. **Bell violation** between field 1 and field 2.

H. De Riedmatten et al., “Direct measurement of decoherence for entanglement between a photon and a stored excitation”, PRL **97**, 113603 (2006)

Direct measurement of decoherence

Atoms-Field1 entanglement



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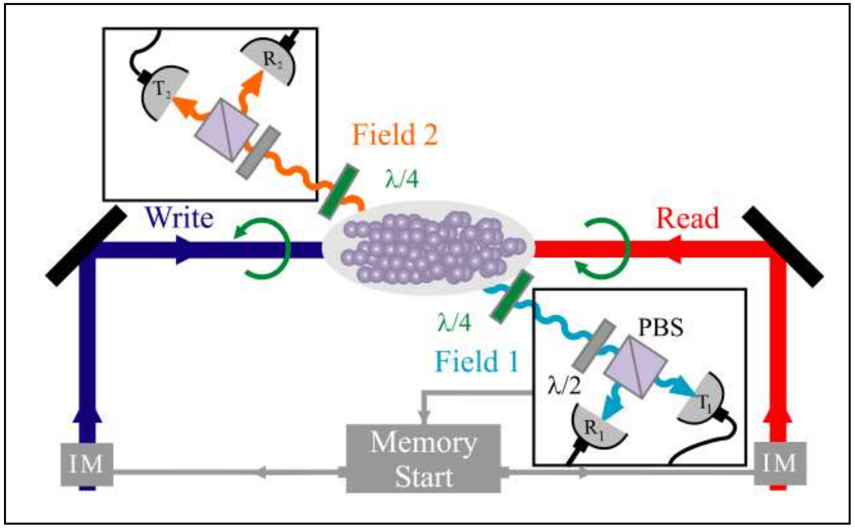
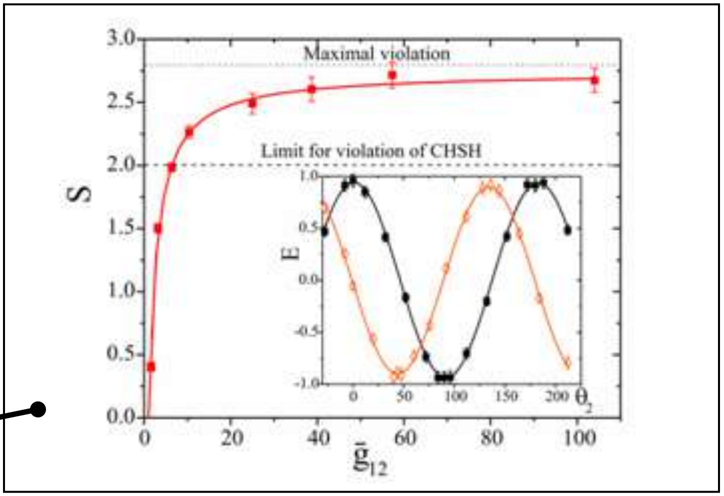
Setup



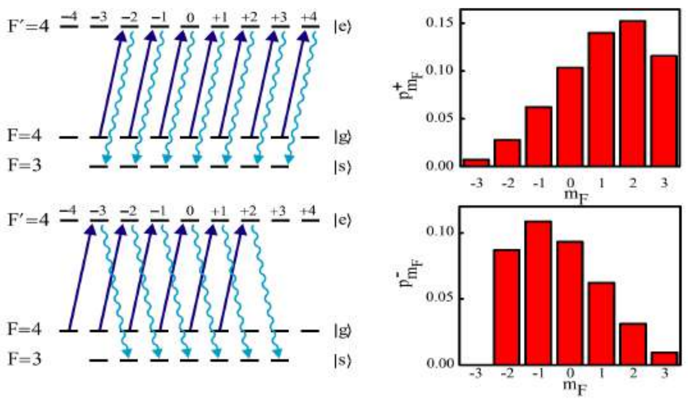


Short time, No logic

H. De Riedmatten et al., “Direct measurement of decoherence for entanglement between a photon and a stored excitation”, PRL **97**, 113603 (2006)

Direct measurement of decoherence

Atoms-Field1 entanglement



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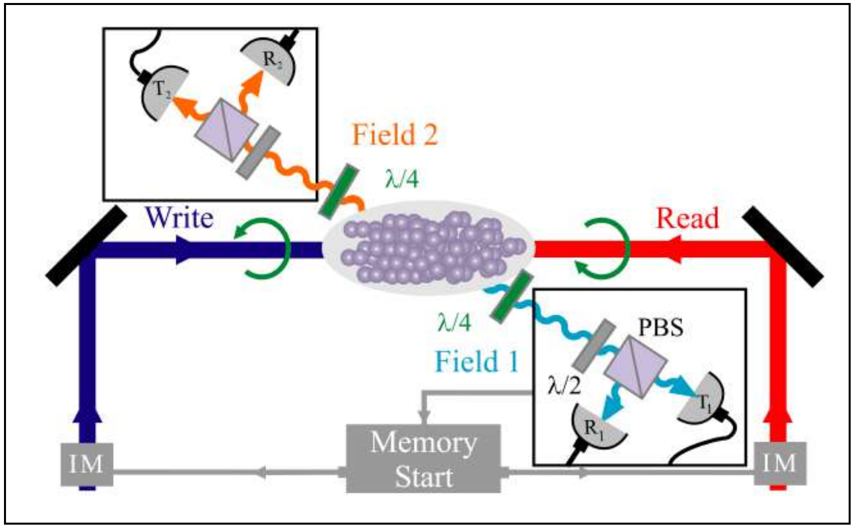
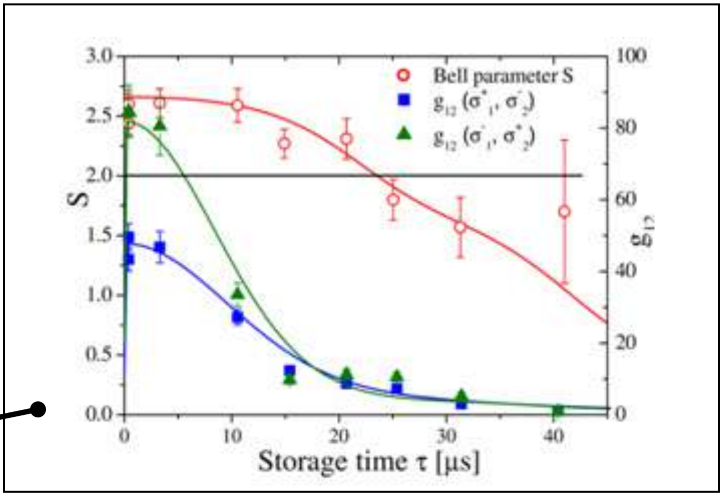
Setup



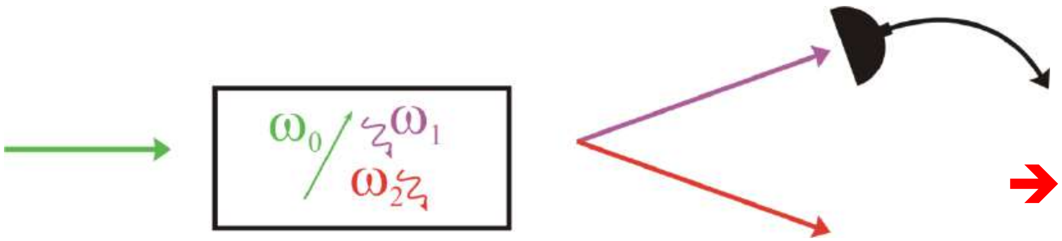


As a function of memory time,
Logic used

H. De Riedmatten et al., “Direct measurement of decoherence for entanglement between a photon and a stored excitation”, PRL **97**, 113603 (2006)

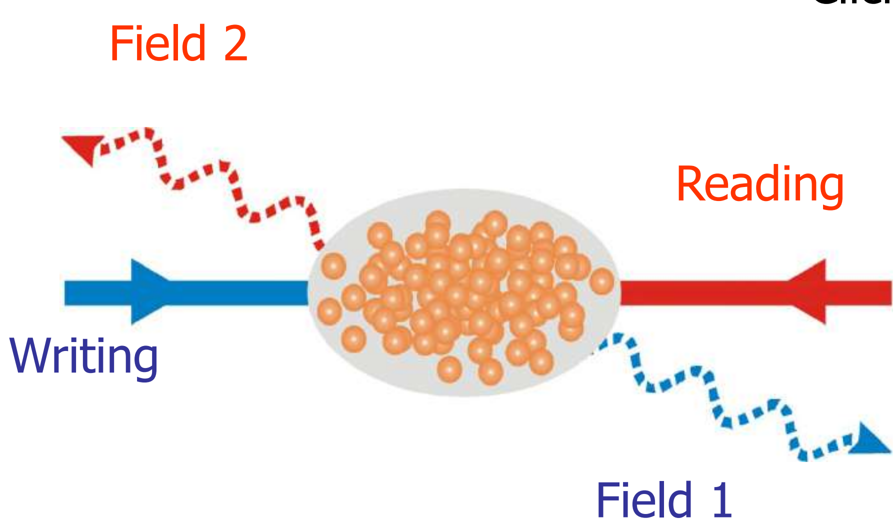
single photons with memory

Heralded generation of single photons



➔ heralded single photons

$$|\psi_{12}\rangle = |0_1, 0_2\rangle + \sqrt{p}|1_1, 1_2\rangle + O(p) \quad \xrightarrow[\text{Click!}]{} \quad |\psi_2\rangle = |1\rangle$$

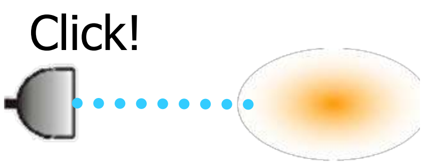


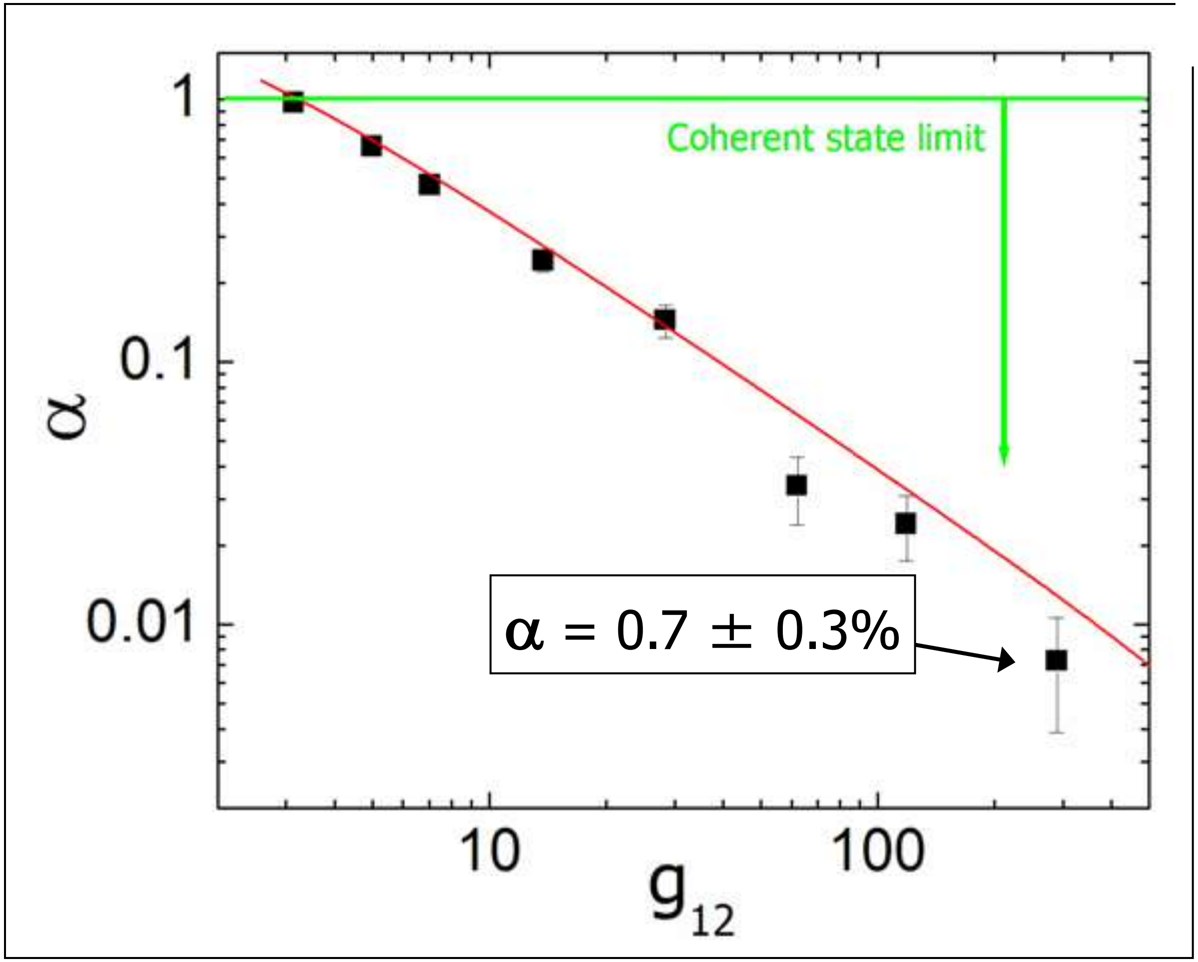
First implementation: Chou et. al, PRL **92**, 213601 (2004)

Heralded generation of single photons

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

α : degree of suppression of the two-photon component of the conditioned field 2





Heralded generation of single photons

PRL **97,** 013601 (2006) PHYSICAL REVIEW LETTERS week ending 7 JULY 2006

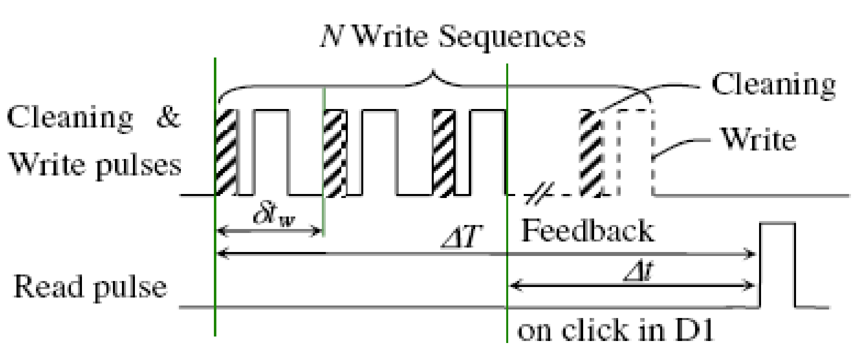
Deterministic Single Photons via Conditional Quantum Evolution

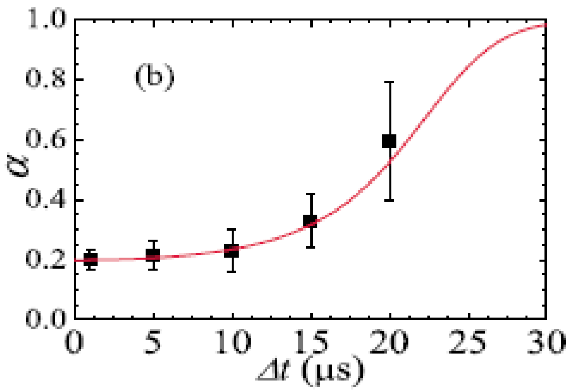
D. N. Matsukevich, T. Chanelière, S. D. Jenkins, S.-Y. Lan, T. A. B. Kennedy, and A. Kuzmich
School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332-0430, USA

PRL **97,** 173004 (2006) PHYSICAL REVIEW LETTERS week ending 27 OCTOBER 2006

Deterministic and Storable Single-Photon Source Based on a Quantum Memory

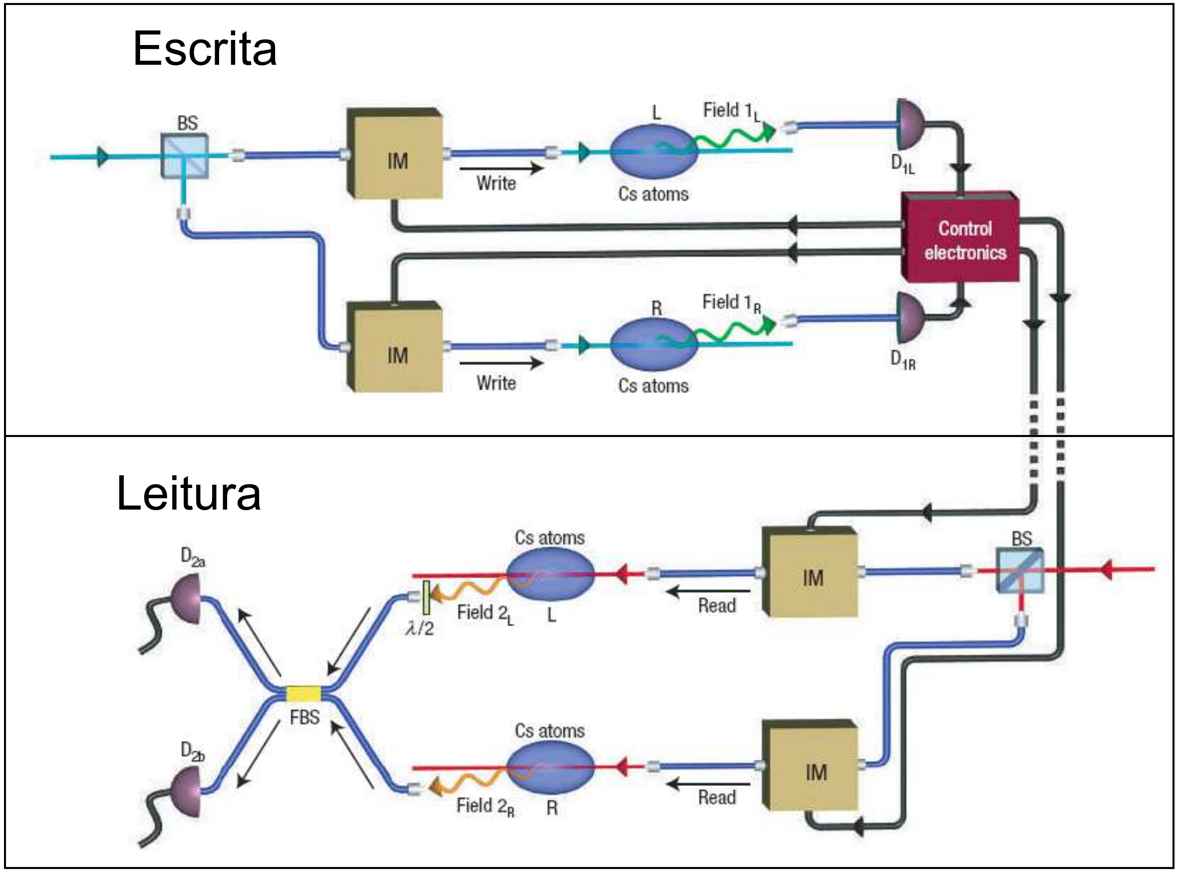
Shuai Chen,[1] Yu-Ao Chen,[1] Thorsten Strassel,[1] Zhen-Sheng Yuan,[1,2,*] Bo Zhao,[1]
Jörg Schmiedmayer,[1,3] and Jian-Wei Pan[1,2,†]
[1]*Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Philosophenweg 12, 69120 Heidelberg, Germany*



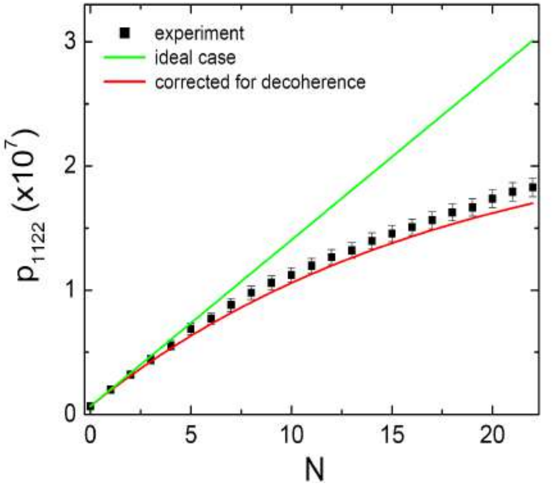


First use of memory for increased efficiency

Synchronization of two single-photon sources



Probability of detecting all 4 photons in one trial of the experiment



28-fold increase in p_{1122}!
(N=23, 12μs)

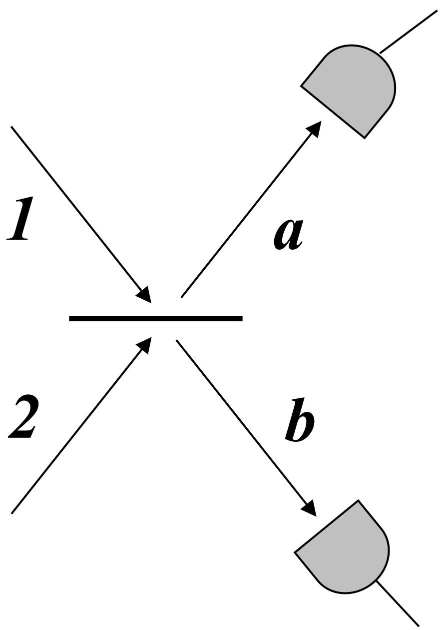
Felinto et. al, Nature Physics **2**, 844 (2006)

Hong-Ou-Mandel interference

VOLUME 59, NUMBER 18 PHYSICAL REVIEW LETTERS 2 NOVEMBER 1987

Measurement of Subpicosecond Time Intervals between Two Photons by Interference

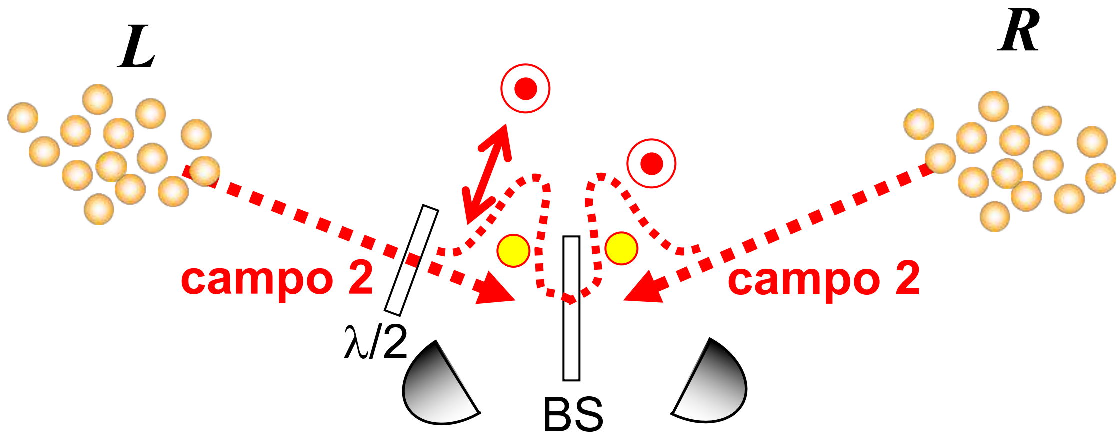
C. K. Hong, Z. Y. Ou, and L. Mandel
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627
(Received 10 July 1987)



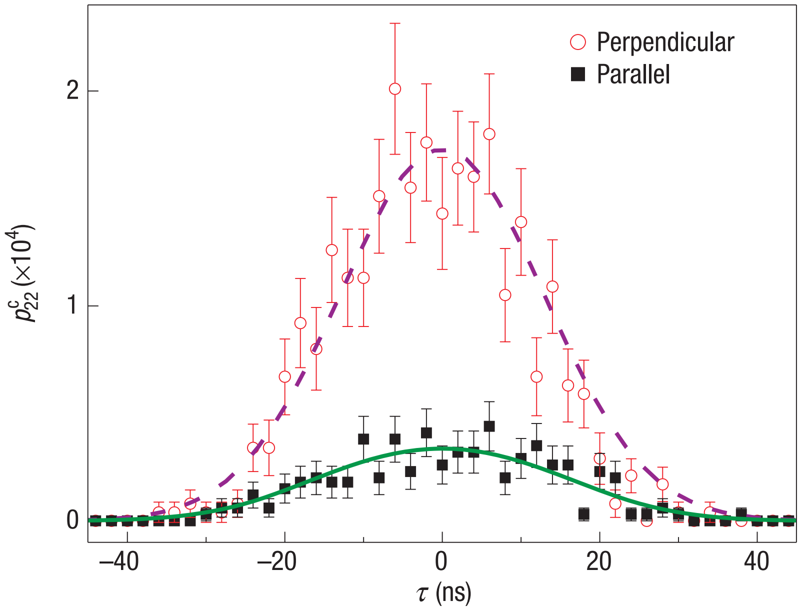
$$|\uparrow\rangle_1 \rightarrow \frac{1}{\sqrt{2}}(|\uparrow\rangle_a + i|\uparrow\rangle_b) \qquad |\uparrow\rangle_2 \rightarrow \frac{1}{\sqrt{2}}(|\uparrow\rangle_b + i|\uparrow\rangle_a)$$

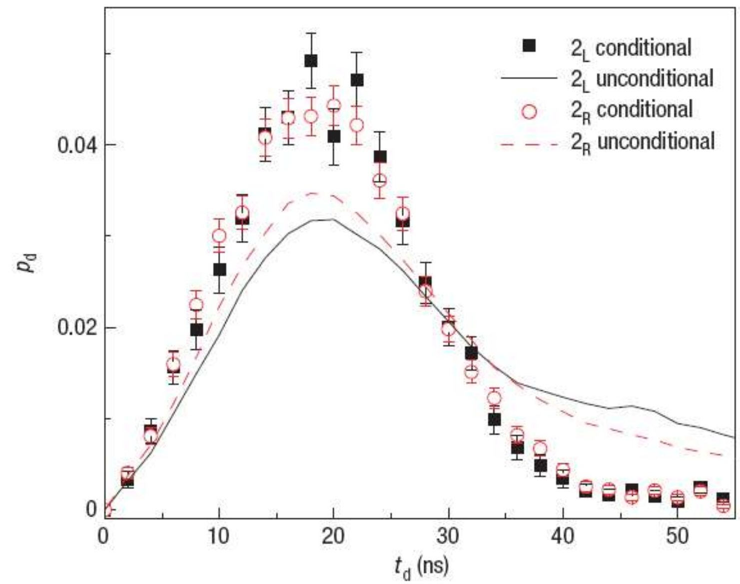
$$\begin{cases} |\uparrow\rangle_1|\uparrow\rangle_2 \rightarrow \frac{1}{2}(i|\uparrow\uparrow\rangle_a + i|\uparrow\uparrow\rangle_b + |\uparrow\rangle_a|\uparrow\rangle_b - |\uparrow\rangle_b|\uparrow\rangle_a) \\ \qquad = \frac{i}{2}(|\uparrow\uparrow\rangle_a + |\uparrow\uparrow\rangle_b) \\ |\downarrow\rangle_1|\downarrow\rangle_2 \rightarrow \frac{i}{2}(|\downarrow\downarrow\rangle_a + |\downarrow\downarrow\rangle_b) \end{cases}$$

Hong-Ou-Mandel interference



2 independent sources of single photons





D. Felinto et al., "Conditional control of the quantum states of remote atomic memories for Q. networking", Nature Physics **2**, 844 (2006)

Motivation*

46 © 2001 Macmillan Magazines Ltd NATURE | VOL 409 | 4 JANUARY 2001 | www.nature.com

articles

A scheme for efficient quantum computation with linear optics

E. Knill*, R. Laflamme* & G. J. Milburn†

* *Los Alamos National Laboratory, MS B265, Los Alamos, New Mexico 87545, USA*
† *Centre for Quantum Computer Technology, University of Queensland, St. Lucia, Australia*

Quantum computers promise to increase greatly the efficiency of solving problems such as factoring large integers, combinatorial optimization and quantum physics simulation. One of the greatest challenges now is to implement the basic quantum-computational elements in a physical system and to demonstrate that they can be reliably and scalably controlled. One of the earliest proposals for quantum computation is based on implementing a quantum bit with two optical modes containing one photon. The proposal is appealing because of the ease with which photon interference can be observed. Until now, it suffered from the requirement for non-linear couplings between optical modes containing few photons. Here we show that efficient quantum computation is possible using only beam splitters, phase shifters, single photon sources and photo-detectors. Our methods exploit feedback from photo-detectors and are robust against errors from photon loss and detector inefficiency. The basic elements are accessible to experimental investigation with current technology.

* Original proposal is hard to scale up due to rapid increase in required physical resources, but proposals along these lines have evolved since then.

Fock-State Superradiance

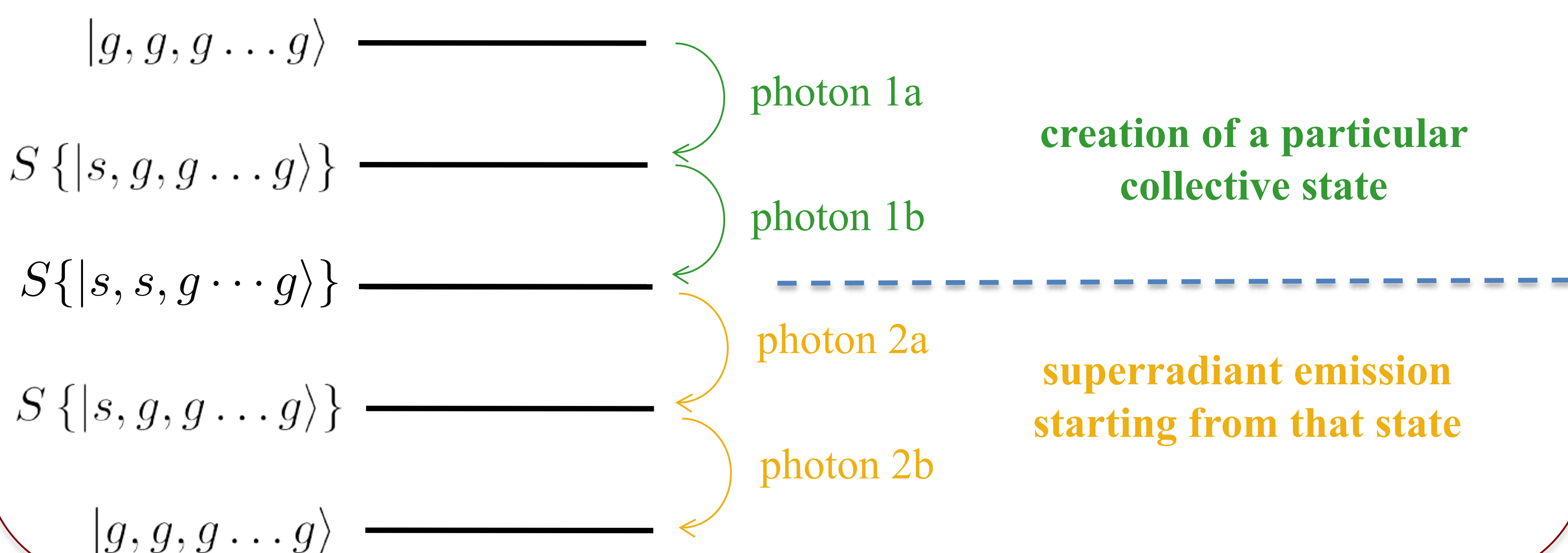
PHYSICAL REVIEW LETTERS **120,** 083603 (2018)

Experimental Fock-State Superradiance

L. Ortiz-Gutiérrez,[1] L. F. Muñoz-Martínez,[1] D. F. Barros,[2] J. E. O. Morales,[1] R. S. N. Moreira,[1] N. D. Alves,[1] A. F. G. Tieco,[1] P. L. Saldanha,[2] and D. Felinto[1,*]

Superradiant emission in a particular temporal and spatial mode with controlled number of excitations

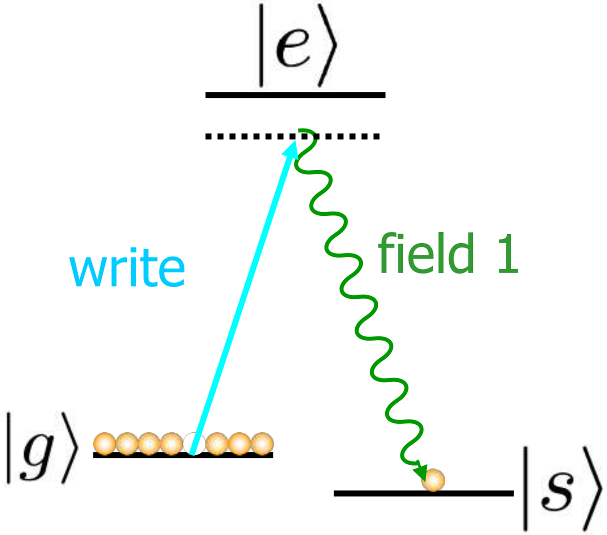
increased and controlled superradiance cascade



Fock-State Superradiance

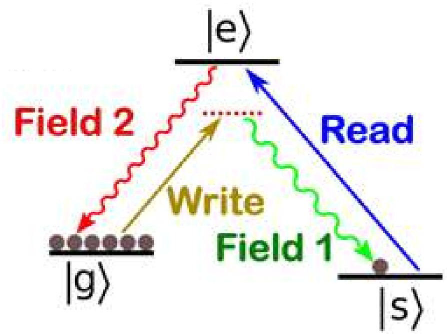
$$|\Psi_{a,1}\rangle = \sqrt{1-p}\sum_{n=0}^{\infty} p^{n/2}|n_a, n_1\rangle$$

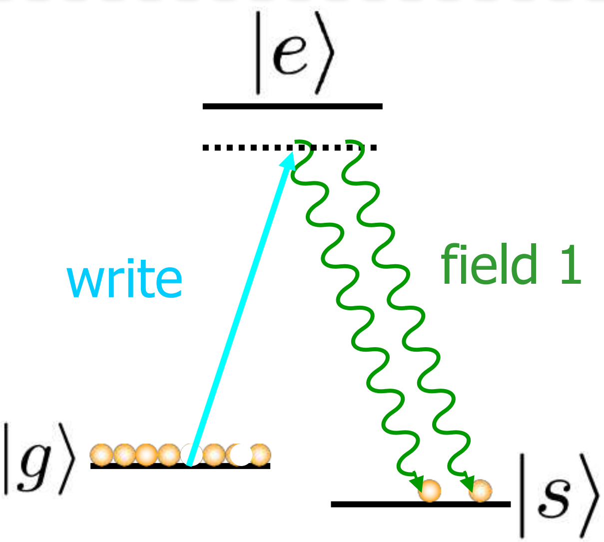
two-mode squeezed vacuum



1 click

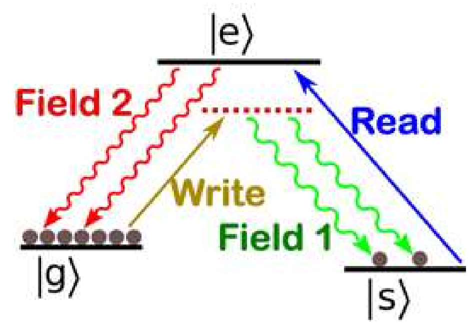
$$|\psi_1\rangle \propto |1_a\rangle + p^{1/2}|2_a\rangle + p|3_a\rangle + \cdots$$





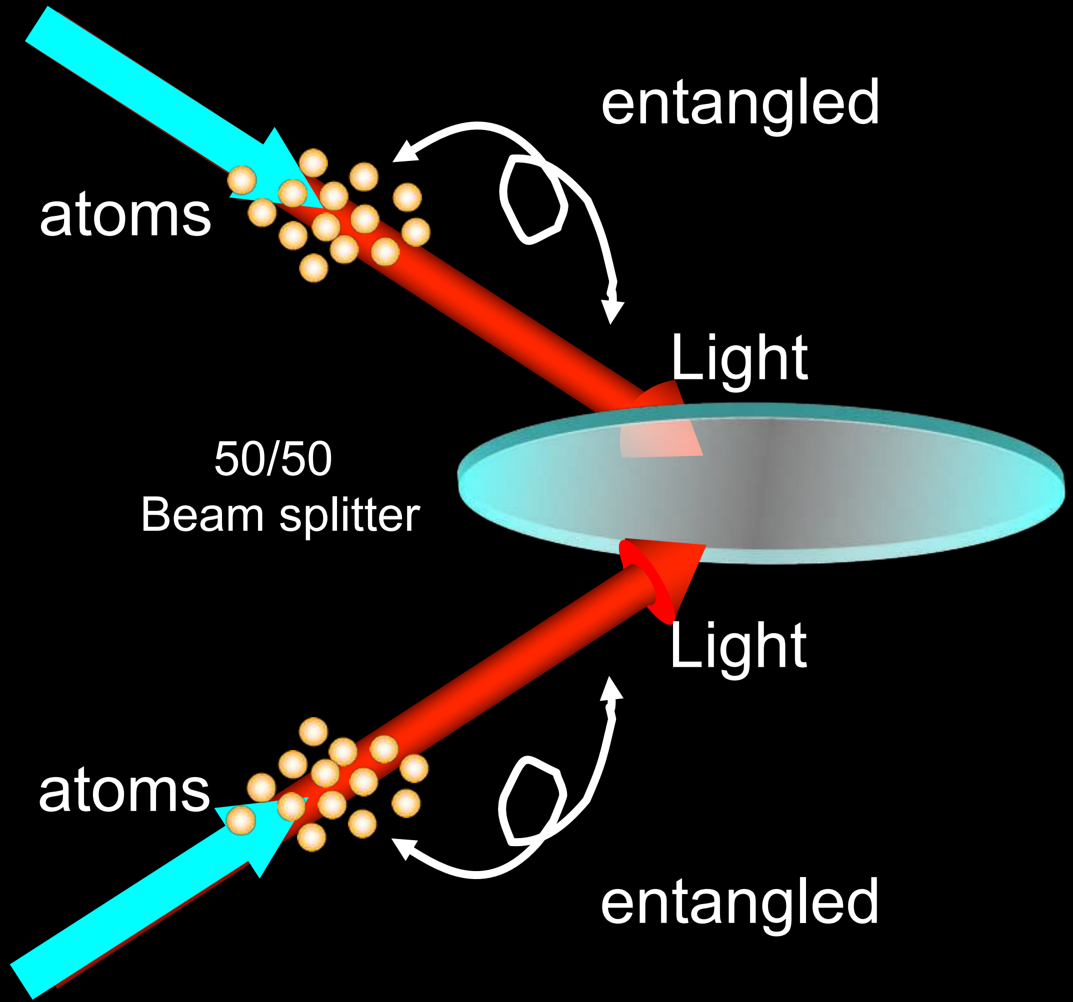
2 clicks

$$|\psi_2\rangle \propto |2_a\rangle + p^{1/2}|3_a\rangle + \cdots$$



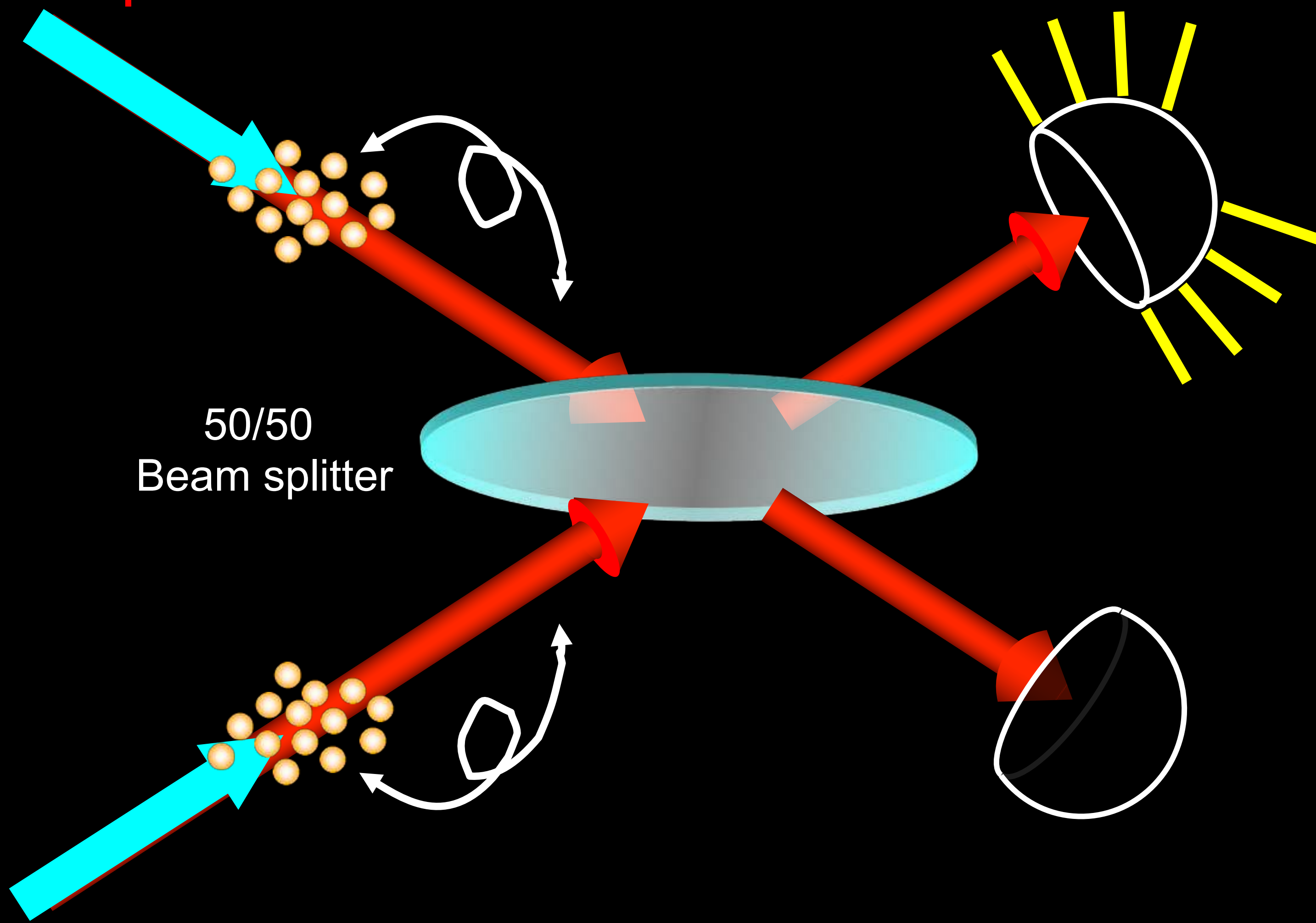
entangling distant memories

Entangling ensembles of atoms



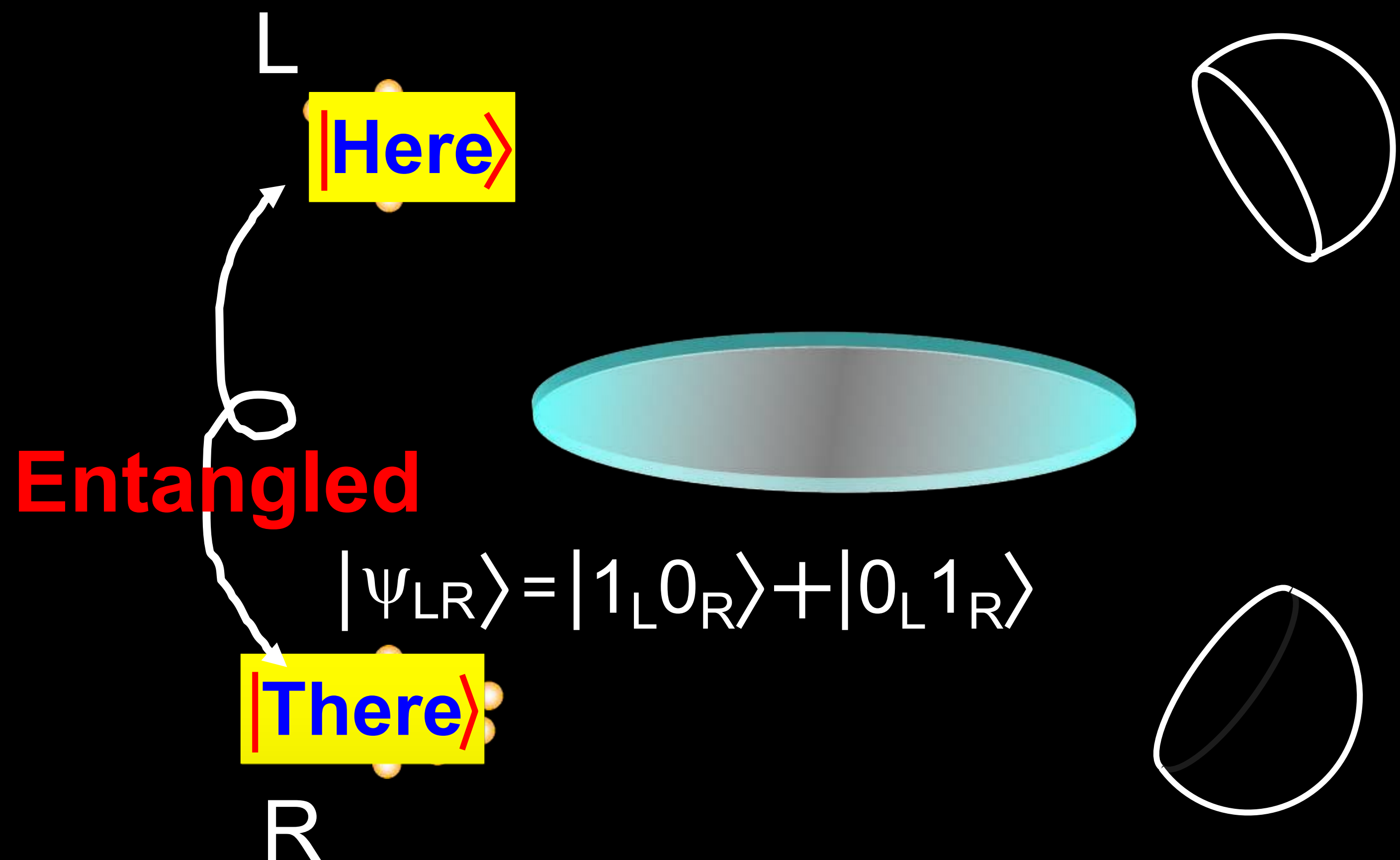
Entangling ensembles of atoms

1 photon detected ⇔ 1 atom transferred



Entangling ensembles of atoms

1 photon detected ⇔ 1 atom transferred



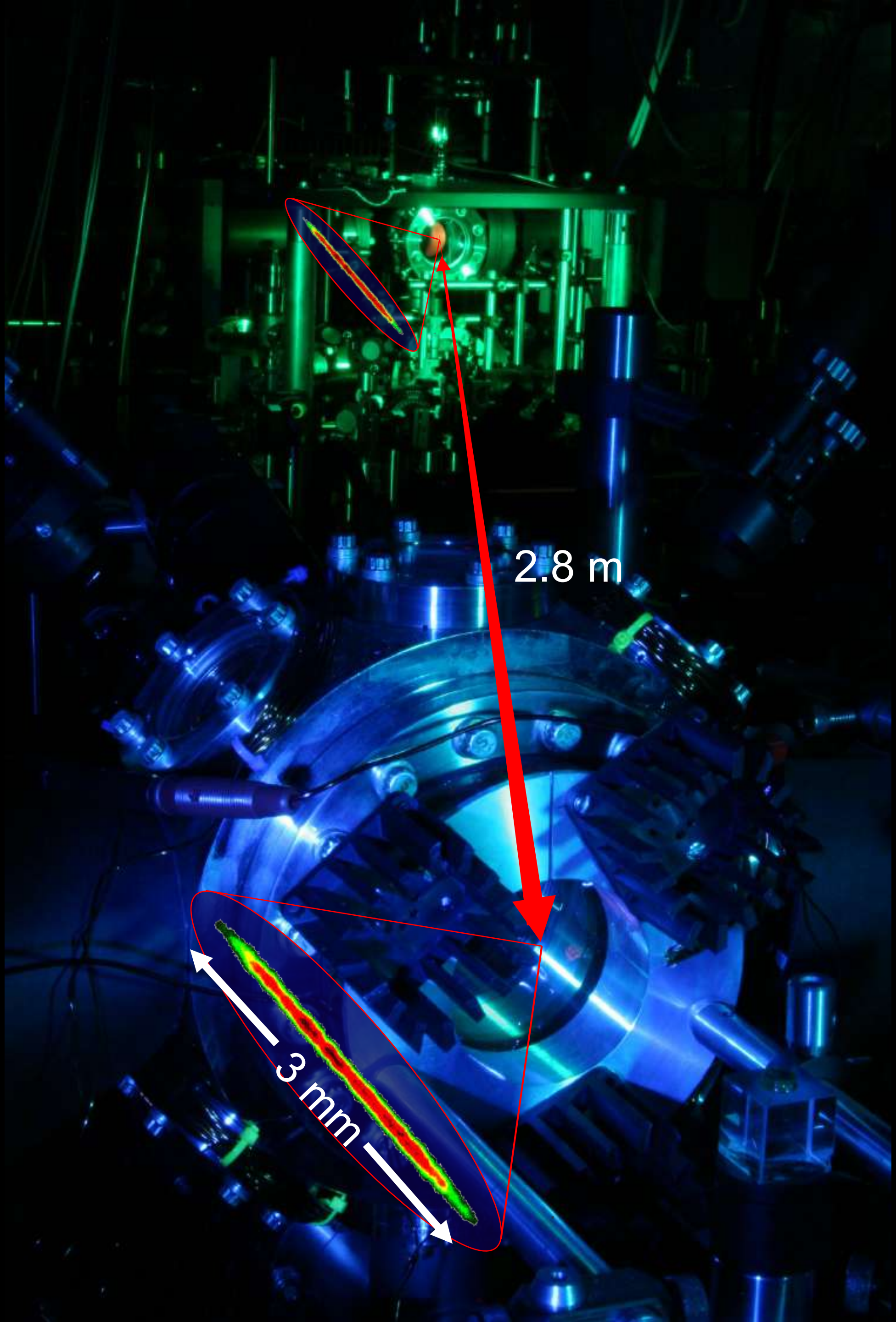
$|\text{Where?}\rangle = |\text{Here}\rangle + |\text{There}\rangle$

10^5 Cs atoms

3 mm long

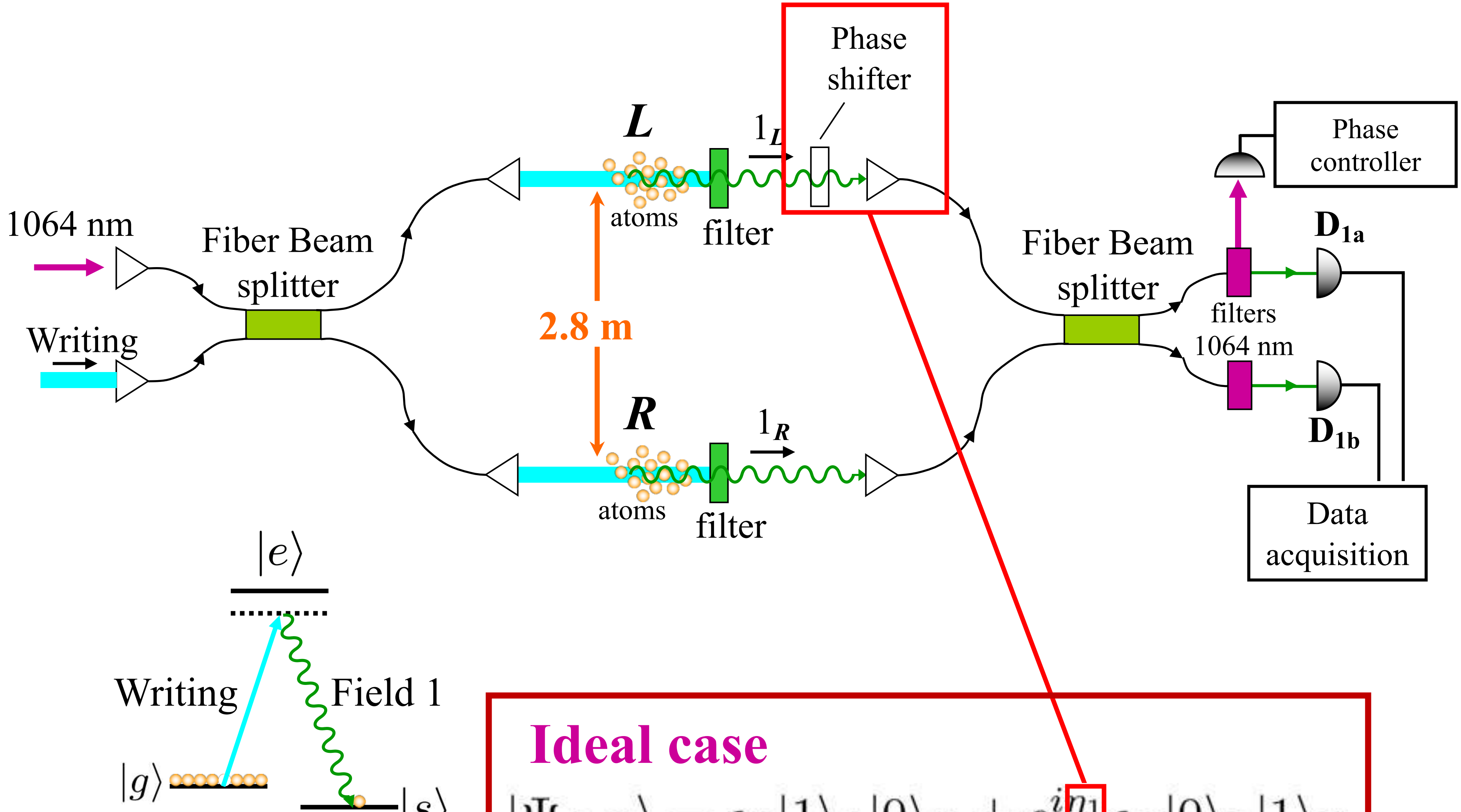
60 μm in diameter

separated by 2.8 m



Entangling 2 distant ensembles

C.-W. Chou, H. de Riedmatten, D. Felinto, S. Polyakov, S. Van Enk, H. J. Kimble Nature **438**, 828 (2005)



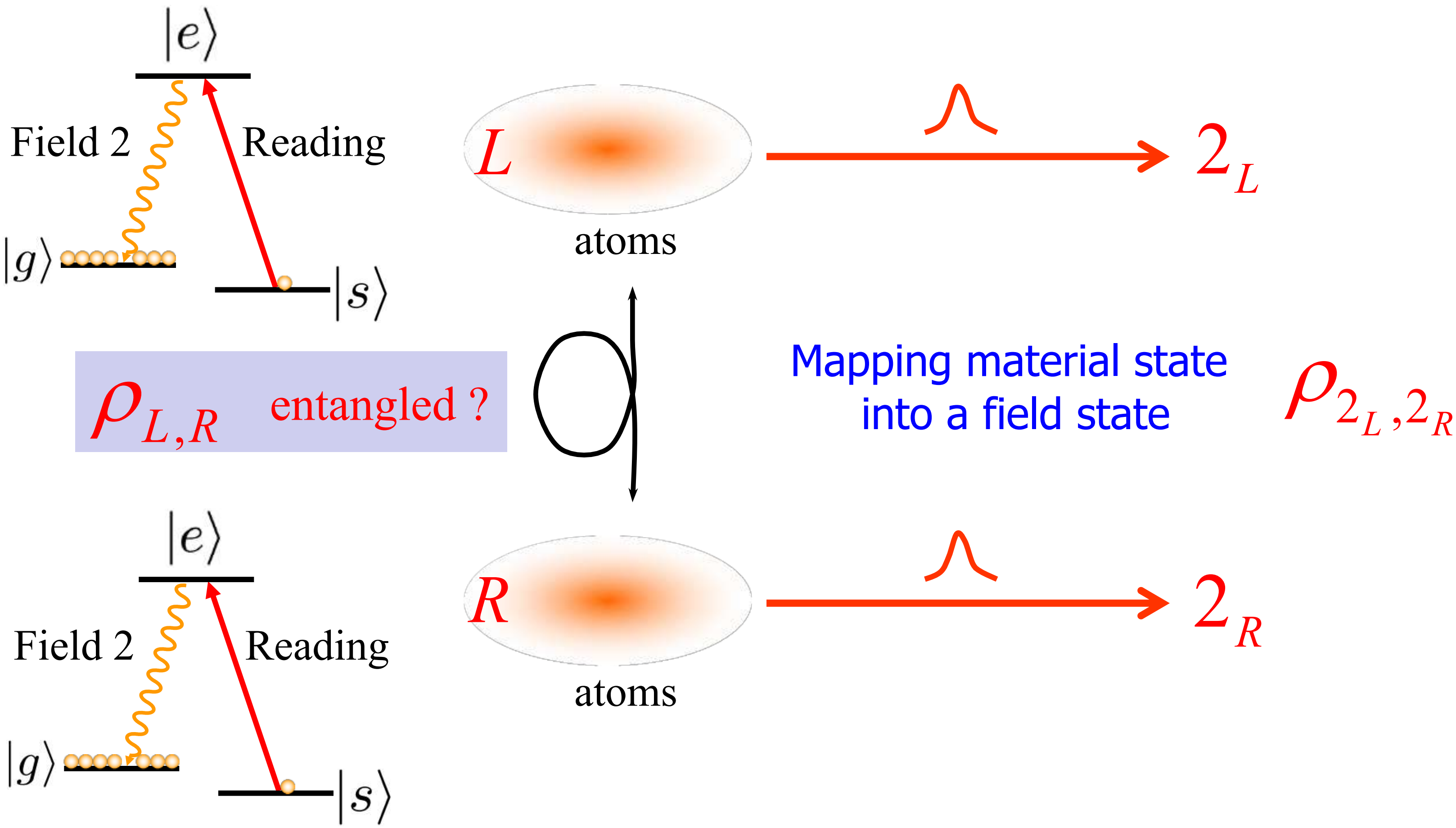
Ideal case

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

Entanglement is stored for 1 µs

The hard part: Operational Verification

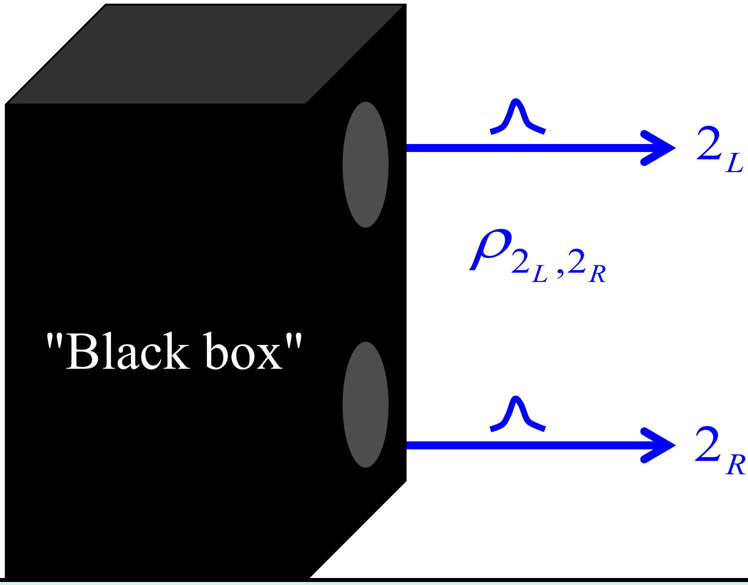
C.-W. Chou, H. de Riedmatten, D. Felinto, S. Polyakov, S. Van Enk, H. J. Kimble Nature **438**, 828 (2005)



Density matrix quantum state tomography $\rho_{2_L,2_R}$
to the fields $2_L, 2_R$

Model-independent protocol

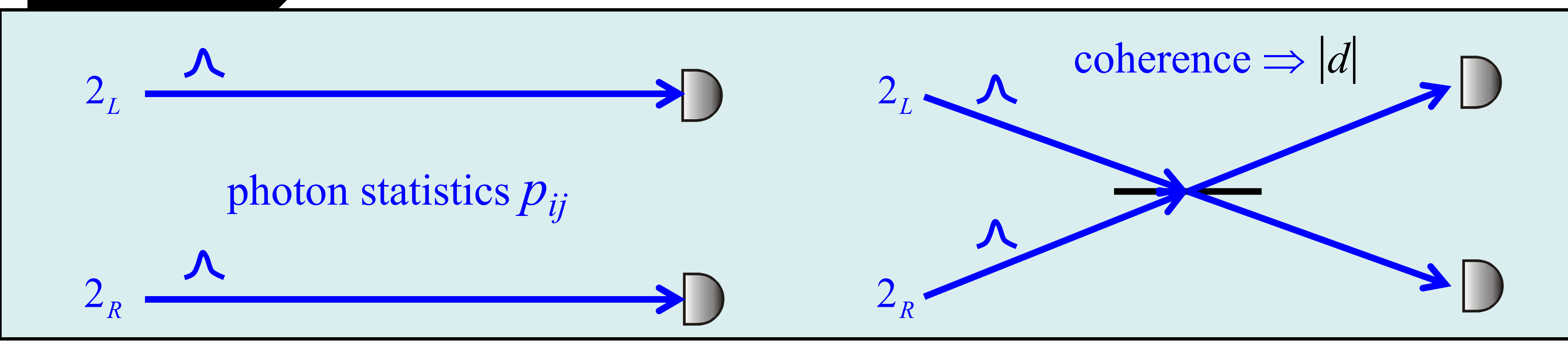
C.-W. Chou, H. de Riedmatten, D. Felinto, S. Polyakov, S. Van Enk, H. J. Kimble Nature **438**, 828 (2005)



Quantum state tomography

$$\tilde{\rho}_{2_L,2_R} = \frac{1}{\tilde{P}} \begin{pmatrix} p_{00} & 0 & 0 & 0 \\ 0 & p_{01} & d & 0 \\ 0 & d^* & p_{10} & 0 \\ 0 & 0 & 0 & p_{11} \end{pmatrix}$$

where $\tilde{P} = p_{00} + p_{01} + p_{10} + p_{11}$



Concurrence $C = \max(2|d| - 2\sqrt{(p_{00}p_{11})}, 0)/\tilde{P}$

$C > 0 \Rightarrow$ Entaglement of formation $E > 0$

W. K. Wootters, Phys. Rev. Lett. 80, 2245(1998)

Concurrence measures

C.-W. Chou, H. de Riedmatten, D. Felinto, S. Polyakov, S. Van Enk, H. J. Kimble Nature **438**, 828 (2005)

$$C = \max(2|d| - 2\sqrt{(p_{00}p_{11})}, 0)/\tilde{P}$$
$$\tilde{P} = p_{00} + p_{01} + p_{10} + p_{11}$$

$$\boxed{\begin{aligned} C_{1a}(\tilde{\rho}_{2_L,2_R}) &= (2.4 \pm 0.6) \times 10^{-3} > 0 \\ C_{1b}(\tilde{\rho}_{2_L,2_R}) &= (1.9 \pm 0.6) \times 10^{-3} > 0 \end{aligned}}$$

Fields
2_L e 2_R

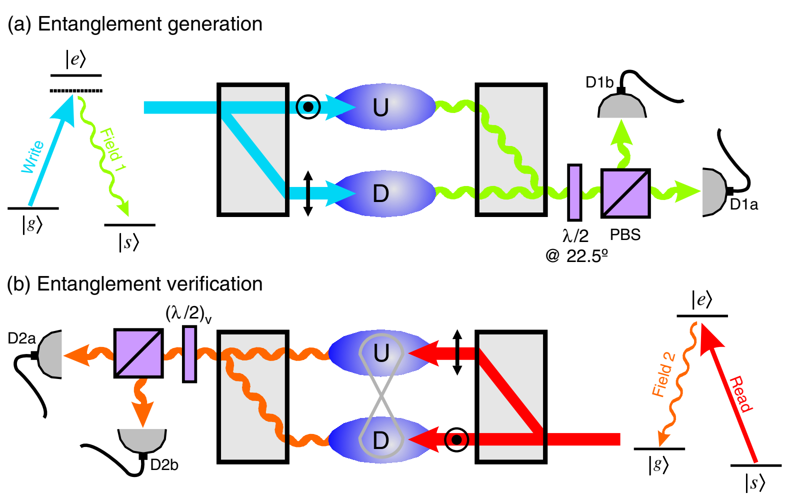
$C > 0 \Rightarrow$ entanglement of formation $E > 0$

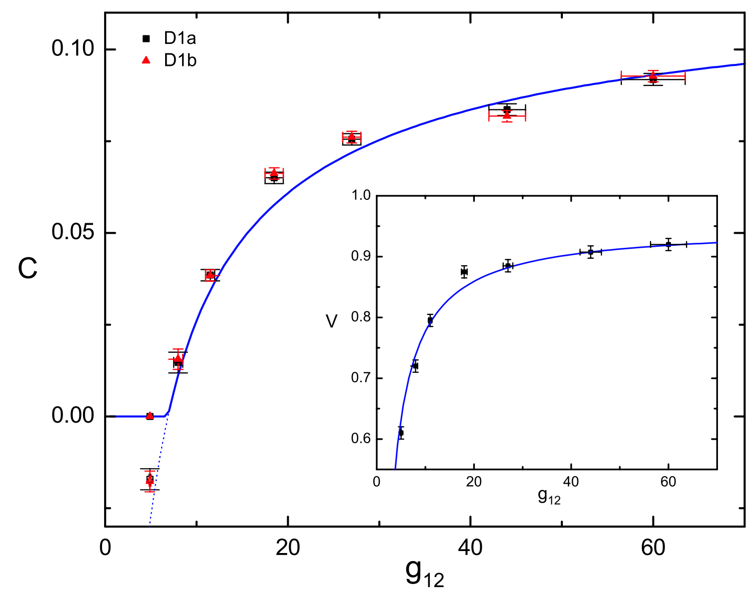
Fields 2_L and 2_R are entangled $\Rightarrow$ Ensembles L and R are entangled

$$\boxed{\text{C (atomic state) > C (Field state)>0}}$$

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

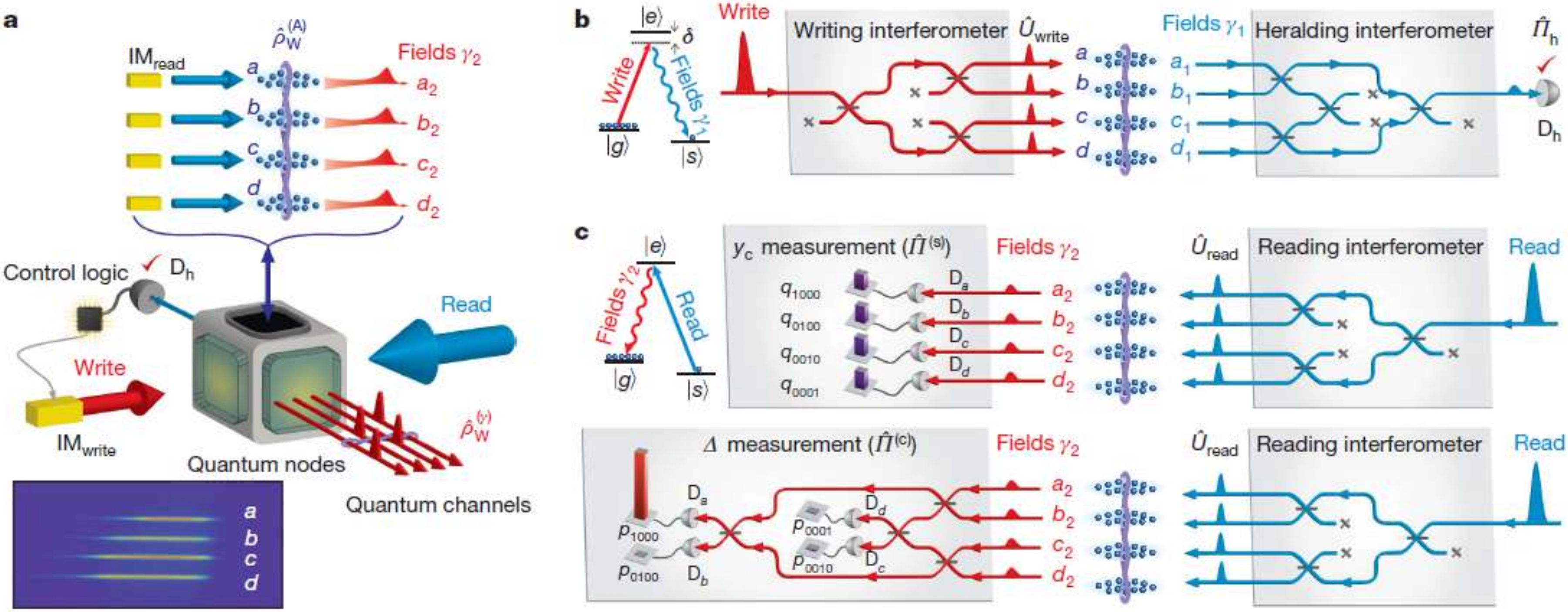
J. Laurat, K. S. Choi, H. Deng, C. W. Chou, and H. J. Kimble
Norman Bridge Laboratory of Physics 12-33, California Institute of Technology, Pasadena, California 91125, USA
(Received 26 May 2007; published 2 November 2007)





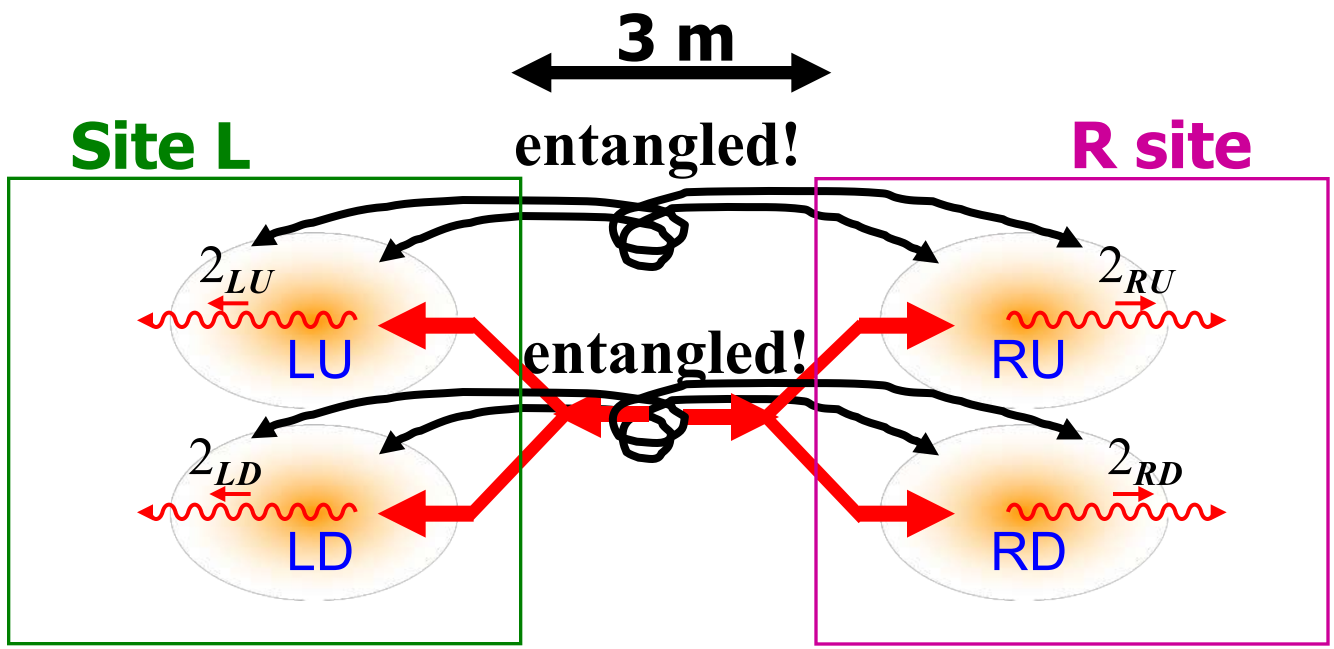
Entanglement of spin waves among four quantum memories

K. S. Choi[1], A. Goban[1], S. B. Papp[1]†, S. J. van Enk[2] & H. J. Kimble[1]



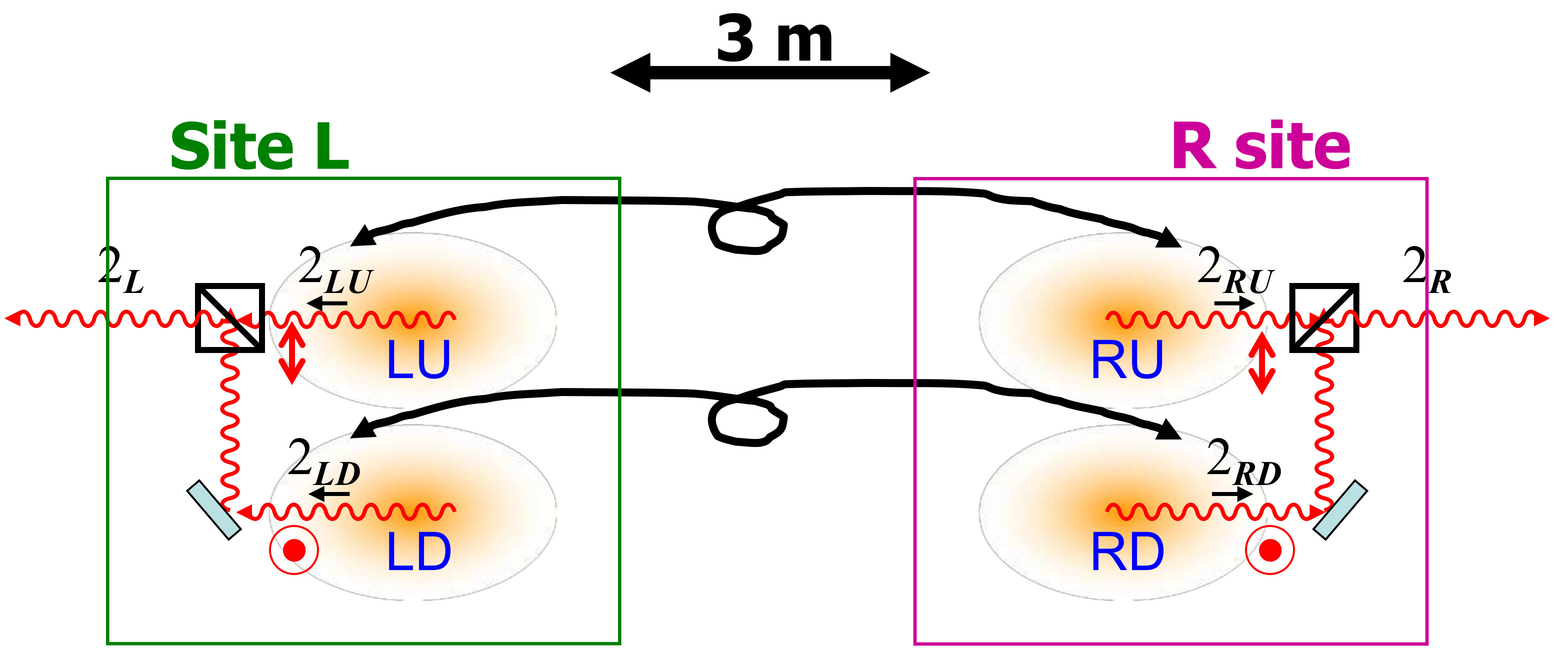
parallel pairs of entangled memories

Entanglement with 4 ensembles



- Memory usage increases the probability of state preparation by a factor of 30

Entanglement with 4 ensembles



Effective entangled state in polarization:

$$\frac{1}{\sqrt{2}}\left[|H\rangle_{2_L}|V\rangle_{2_R} + e^{i(\eta'_U-\eta'_D)}|V\rangle_{2_L}|H\rangle_{2_R}\right]$$

It can be used directly to perform cryptographic key exchange (also suggested by the DLCZ Protocol)

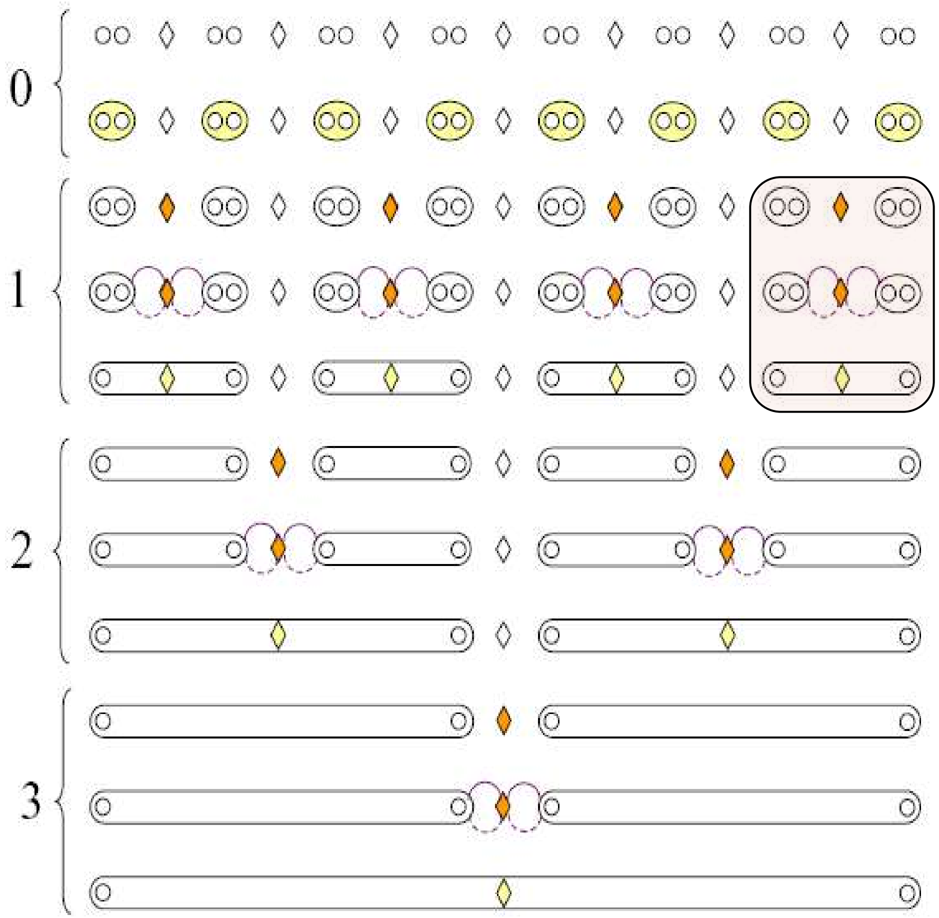
Implementation: Chou et. al, Science **316**, 1316 (2007) → Bell Inequality Violation (CHSH Type):

S = 2,6 $\pm$ 0,1 > 2

scaling up the system

Entanglement with 4 ensembles

Quantum repeater



Atomic Ensemble: ○

Entangled pair:

Control Station: ◊

"Entanglement Swap" Operation

Preliminary results: Laurat et. al, New J. Phys. 9, 207 (2007)

Objective: Extension of entanglement to arbitrary distances

DLCZ Protocol

PHYSICAL REVIEW A **84**, 062303 (2011)

Perspectives for laboratory implementation of the Duan-Lukin-Cirac-Zoller protocol for quantum repeaters

Milrian S. Mendes and Daniel Felinto
Departamento de Física, Universidade Federal de Pernambuco, 50670-901 Recife, PE-Brazil

(Received 3 October 2011; published 5 December 2011)

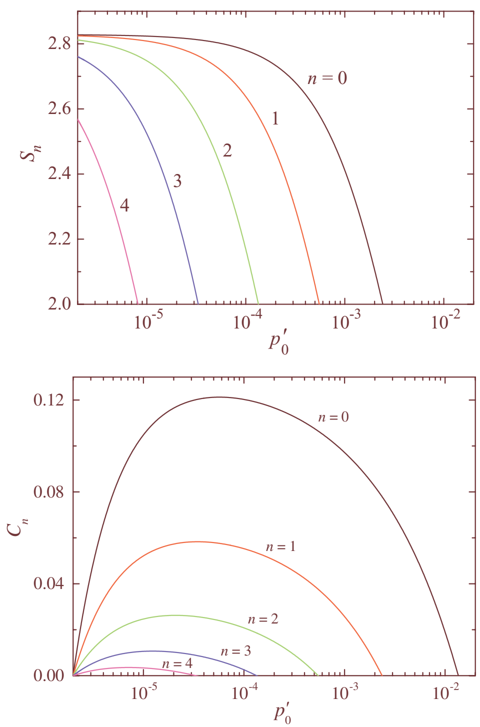
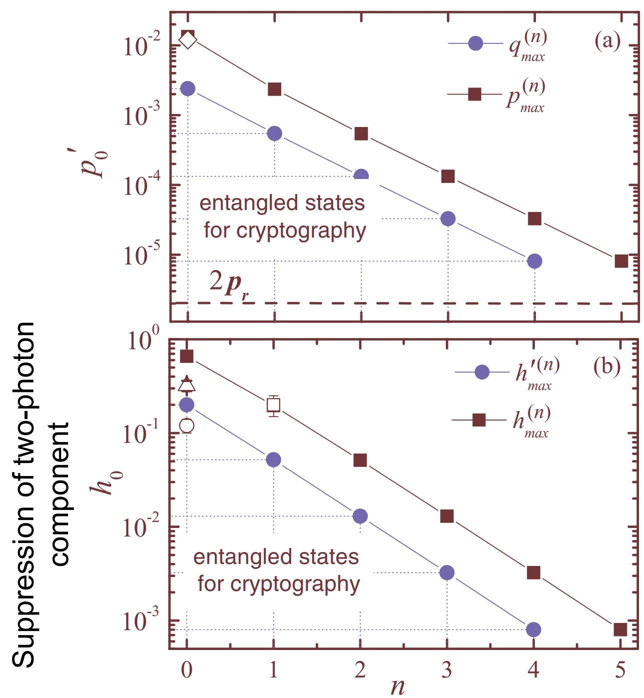
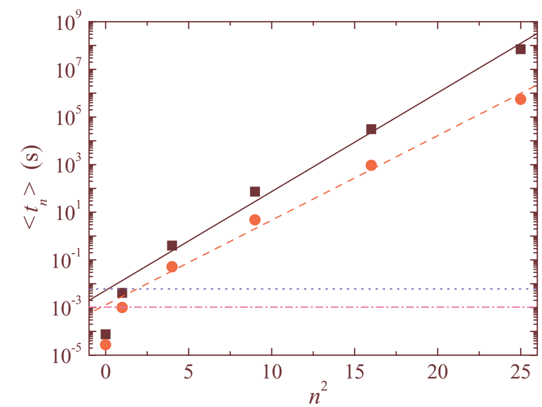


FIG. 5. (Color online) Concurrence as a function of the probability p'_0 to herald the storage of an entangled state for various numbers n of entanglement swapping stages. We employed here $n_p = 8$, and the other parameters were the same as in Fig. 4.



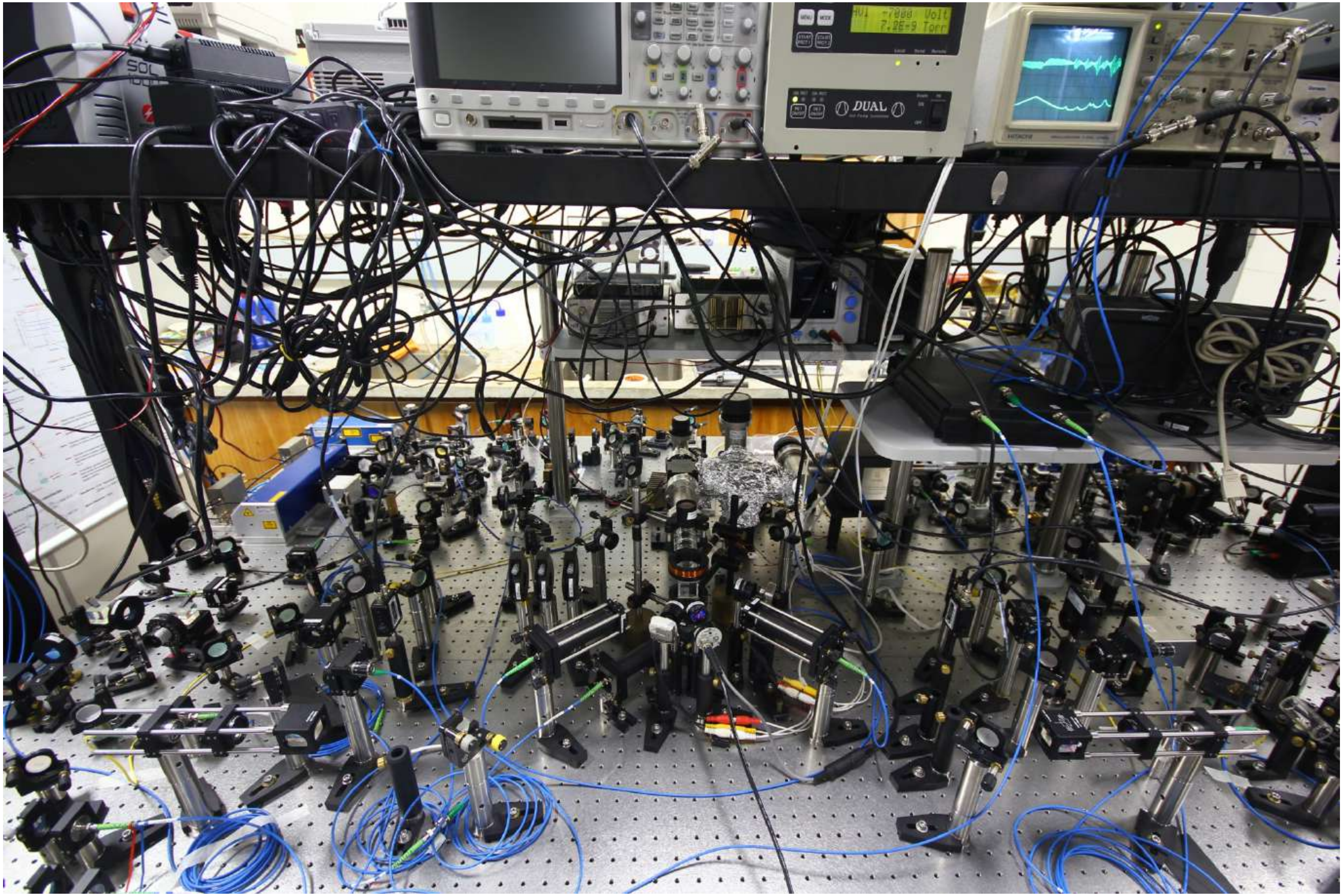
Same scalling as usual DLCZ protocol



1st experiments in Recife

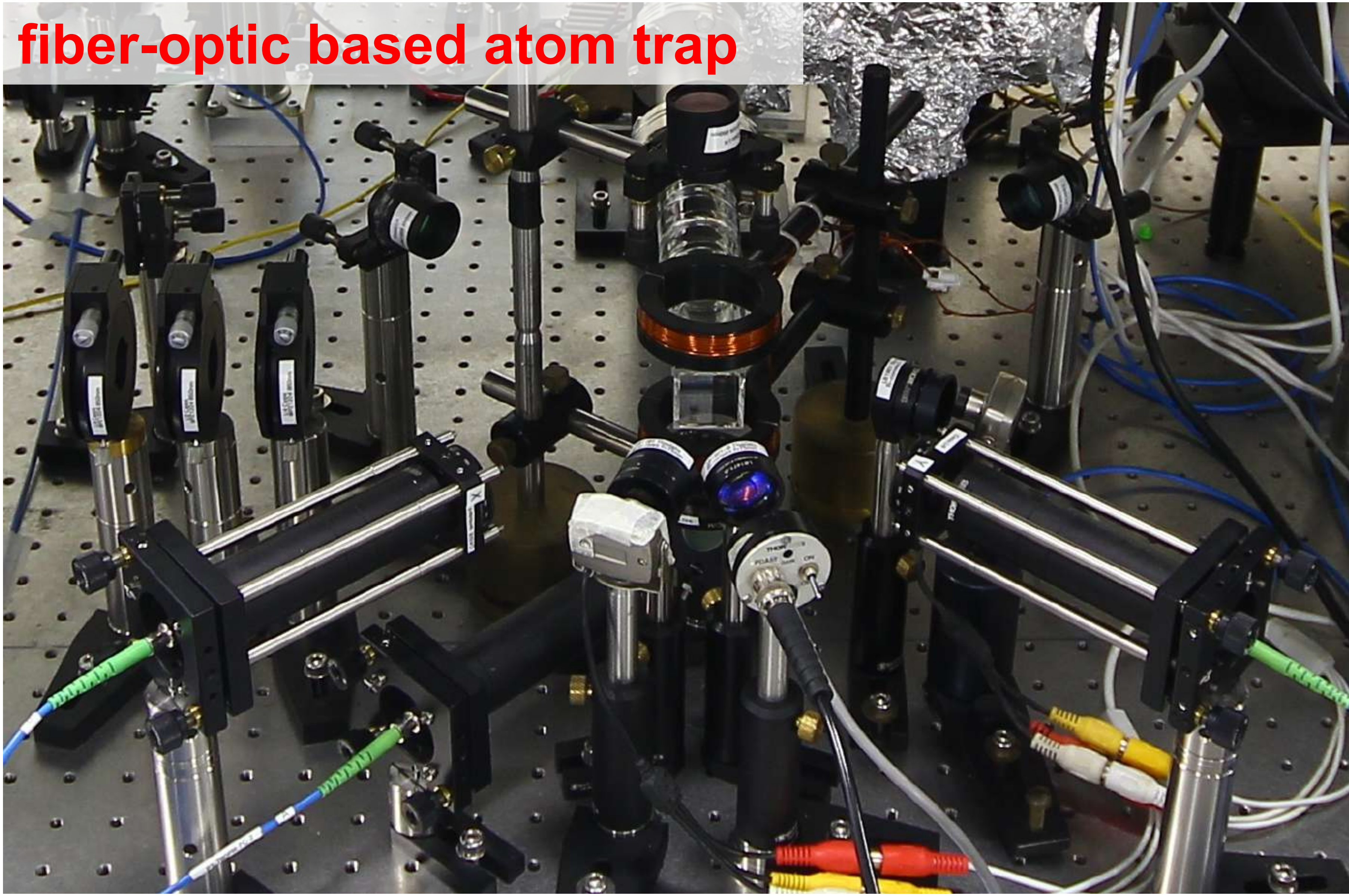
DLCZ setup at DF-UFPE

Cold Atoms Laboratory – collaboration with Prof. Tabosa



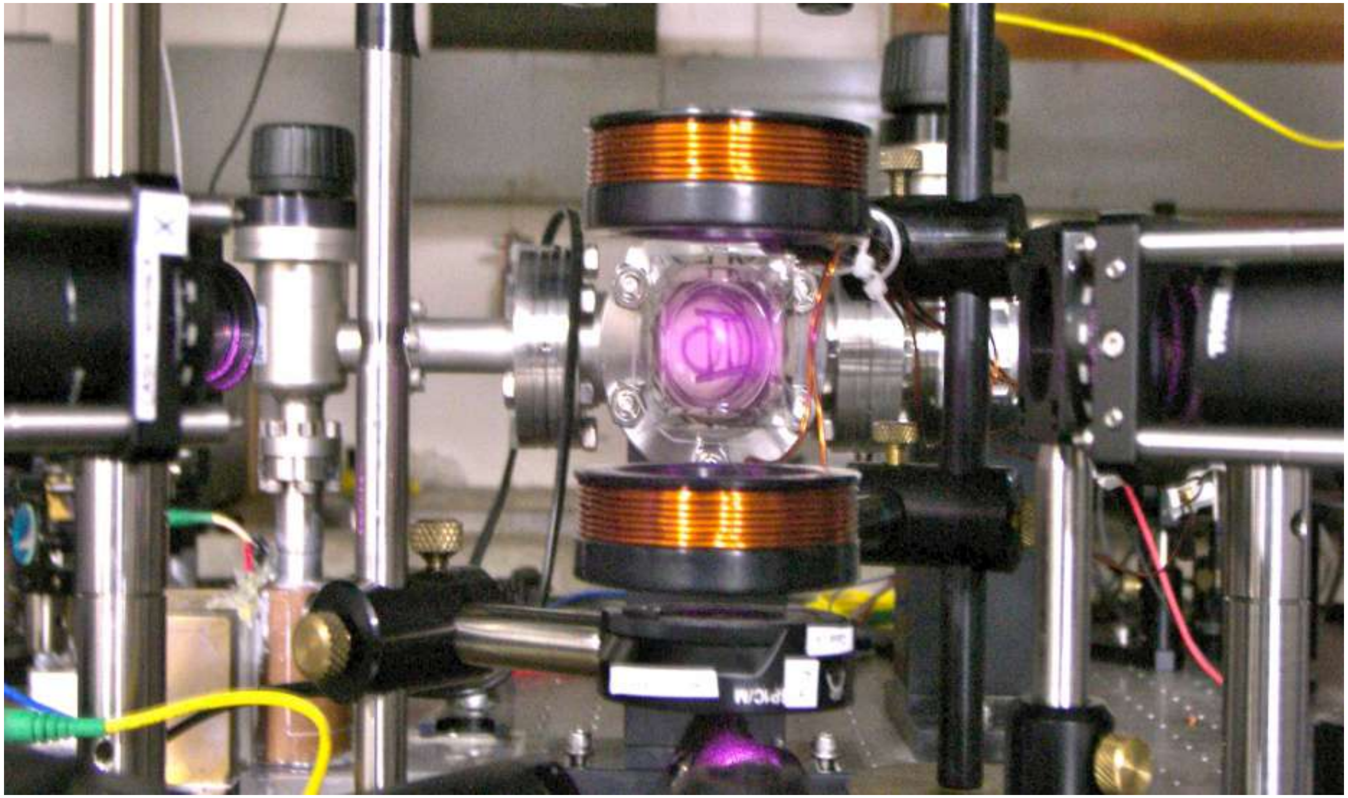
DLCZ setup at DF-UFPE

Cold Atoms Laboratory – collaboration with Prof. Tabosa

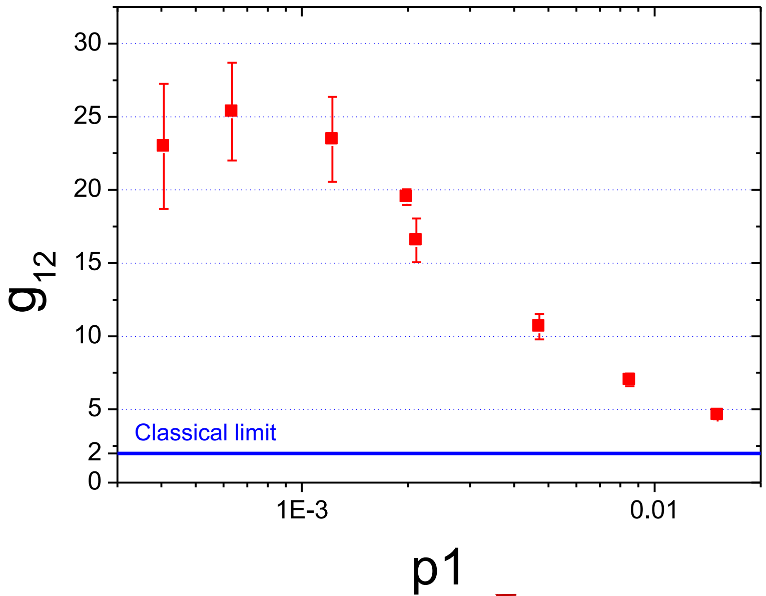


DLCZ setup at DF-UFPE

Cold Atoms Laboratory – collaboration with Prof. Tabosa



Quantum regime



For classical fields:

$$R = g_{12}^{2} / (g_{11} g_{22}) \leq 1$$

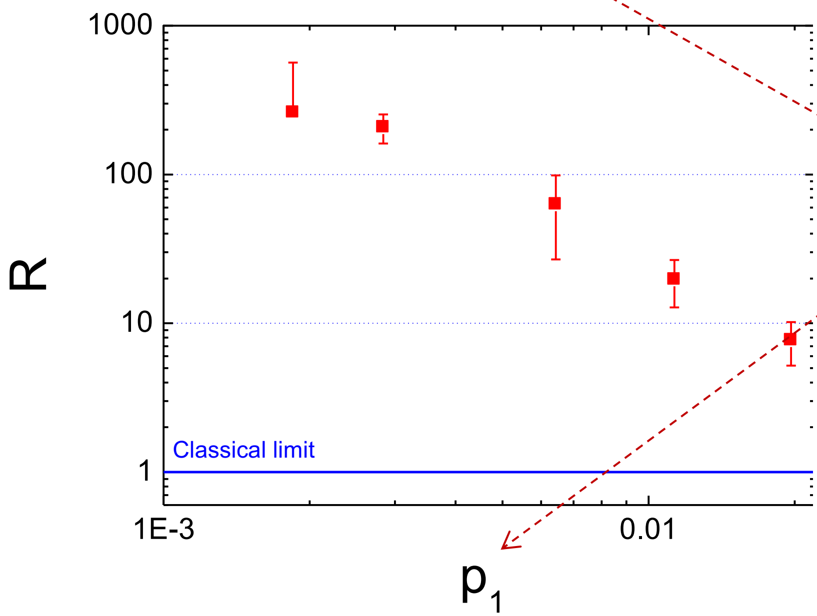
$g_{11} \equiv$ Auto-correlation function, field 1

$g_{22} \equiv$ Auto-correlation function, field 2

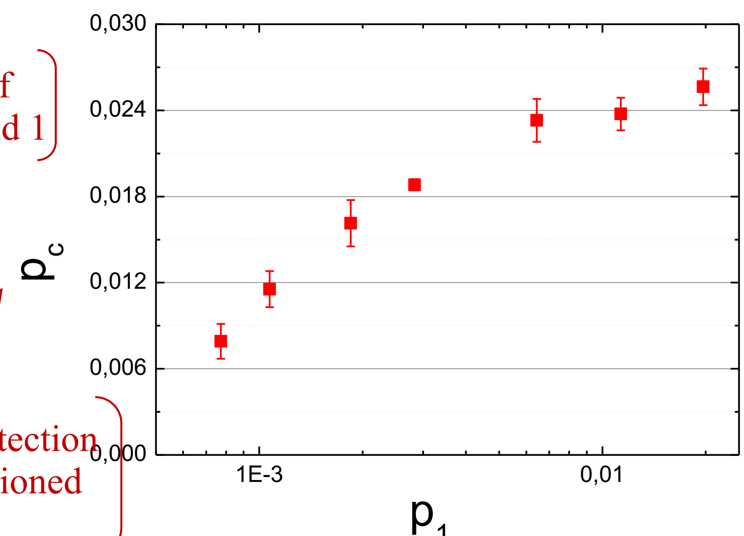
$g_{12} \equiv$ Cross-correlation function

for our system g_{11} , $g_{22} \leq 2$

$g_{12} > 2$ also indicates quantum regime



Probability of detection in field 1



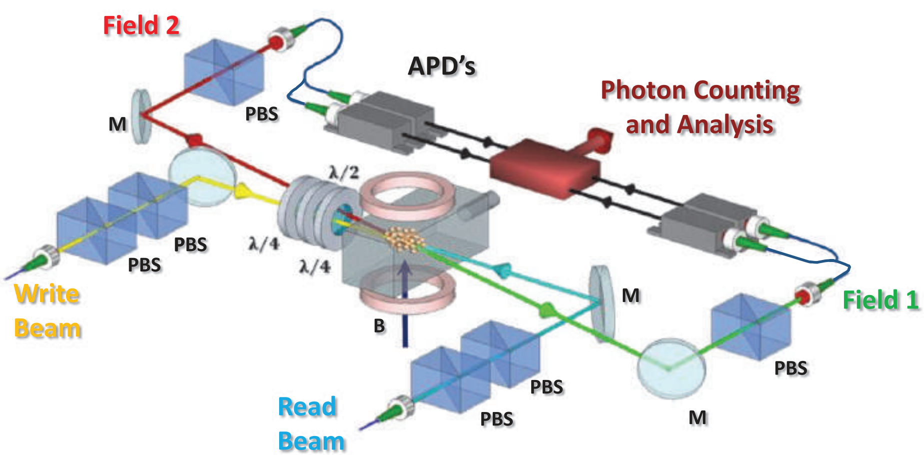
Probability of detection in field 2 conditioned in field 1

1st published experimental work (2013)

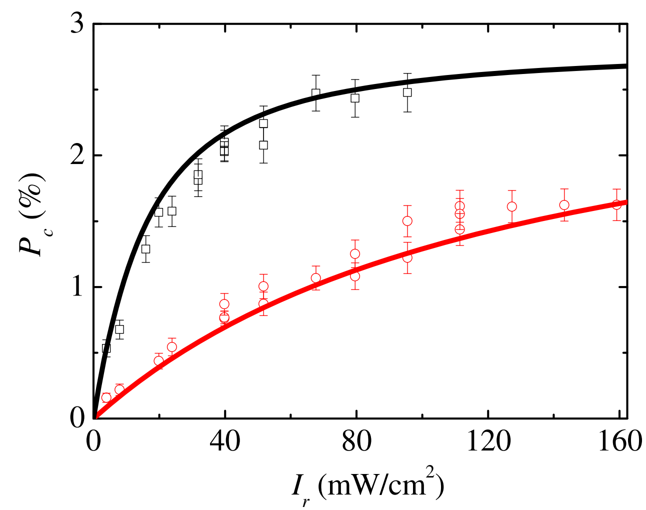
New Journal of Physics
The open access journal for physics

Dynamics of the reading process of a quantum memory

Milrian S Mendes[1], Pablo L Saldanha[1,2], José W R Tabosa[1] and Daniel Felinto[1,3]



- New theory of first principles for the reading process.
- First comparison with experiments



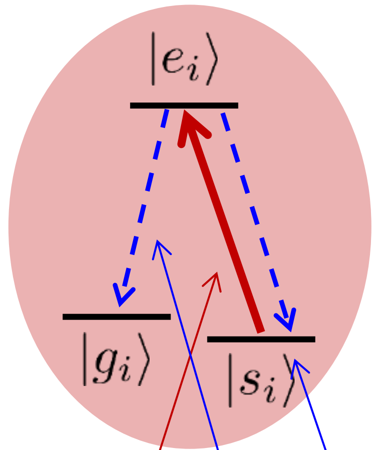
- It highlighted the role of the superradiance effect in the problem

Mendes et al, New J. Phys. **15**, 075030 (2013)

Theory for wavepacket of the extracted photon (P. Saldanha)

atomic ensemble

$$\sum_{i=1}^{N}$$



initial state after detection in field 1

$$|\Psi(0)\rangle = \sum_i \overbrace{A_i(0)|s_i,0\rangle}^{\text{atom } i \text{ in } |\text{s}\rangle,\ \text{others in } |\text{g}\rangle,\ \text{no photons}} \underbrace{e^{i(\vec{k}_w-\vec{k}_1)\cdot\vec{r}_i}}_{\text{Phase spcacial grid}}$$

Temporal evolution

$$\hat{H} = \hat{H}_0 + \hat{H}_1 + \underbrace{\hat{H}_2 + \hat{H}_3}$$

Free Hamiltonian, atoms and fields

Interaction with reading field

Interaction with vacuum modes

$$|\Psi(t)\rangle = \sum_i e^{i(\vec{k}_w-\vec{k}_1)\cdot\vec{r}_i}\left[A_i(t)|s_i,0\rangle + B_i(t)\overbrace{|e_i,0\rangle}^{\text{atom } i \text{ in} |\text{e}\rangle,\ \text{others in } |\text{g}\rangle,\ \text{no photons}}\right]$$

$$+ \int d^3k\, C_{\mathbf{k}}(t)\underbrace{|g,1_{\mathbf{k}}\rangle}_{\text{atoms in } |\text{g}\rangle\ +\ 1 \text{ photon}} + \sum_i \int d^3k\, D_{i,\mathbf{k}}(t)\underbrace{|s_i,1_{\mathbf{k}}\rangle}_{\text{atom } i \text{ in} |\text{s}\rangle,\ \text{others in} |\text{g}\rangle,\ +\ 1 \text{ photon}}$$

wavepacket of photon 2

$$\psi_2(t) \propto \int d\omega_k\, e^{-i\omega_k t}\,[\lim_{t'\to\infty} C_{\mathbf{k}}(t')]$$

Mendes et al, New J. Phys. **15**, 075030 (2013)

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Single-photon superradiance in cold atoms

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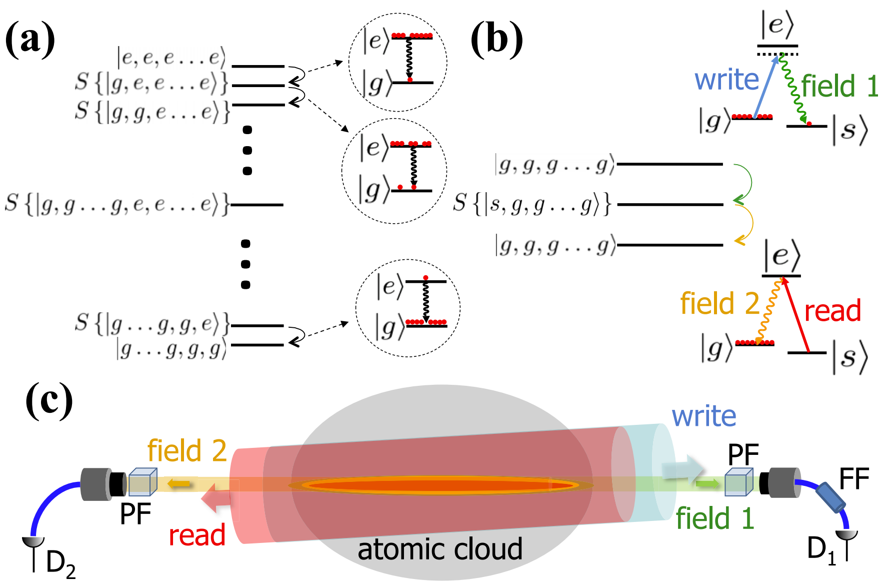

photon wavepacket

$$\frac{p_c(t)}{P_c} = \frac{\chi\Gamma\Omega^2\Delta t\, e^{-\chi\Gamma t/2}}{\left(\Omega^2 - \frac{\chi^2\Gamma^2}{4}\right)} \sin^2\left(\sqrt{\Omega^2 - \frac{\chi^2\Gamma^2}{4}}\,\frac{t}{2}\right)$$

$$\chi = 1 + \frac{N}{w_0^2 k_2^2}$$