



Quantum technologies for extending the range of quantum communications

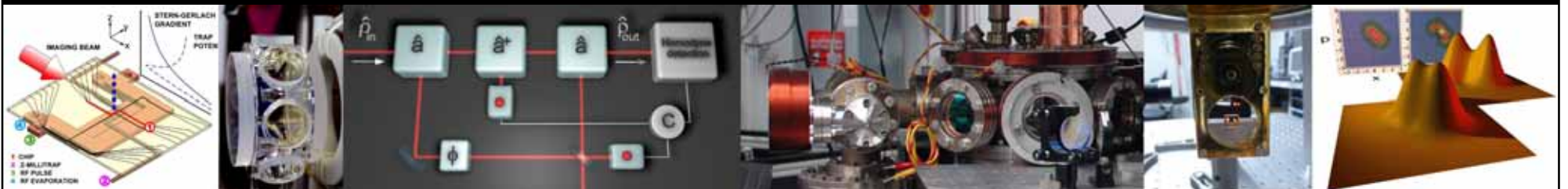
The QScale Project

Coordinator: Julien Laurat

**Laboratoire Kastler Brossel
Université P. et M. Curie
Ecole Normale Supérieure and CNRS**

**julien.laurat@upmc.fr
www.chistera-qscale.eu**

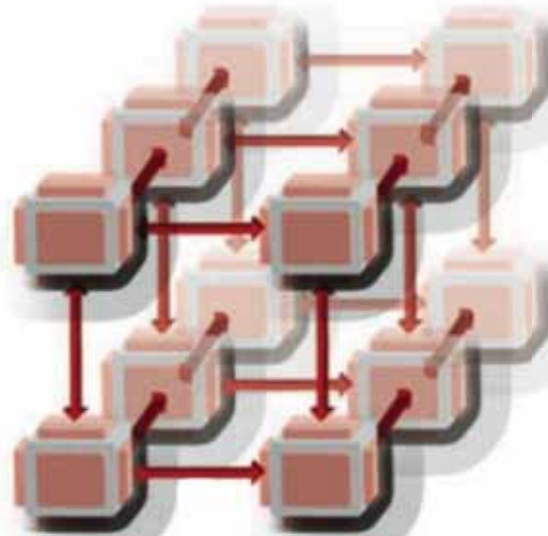
CHIST-ERA Kick-off Seminar, Warsaw, March 2012



The General Content of QScale

Quantum node

generate, process, store
quantum information locally



Quantum channel
transport / distribute
quantum information
over the entire network

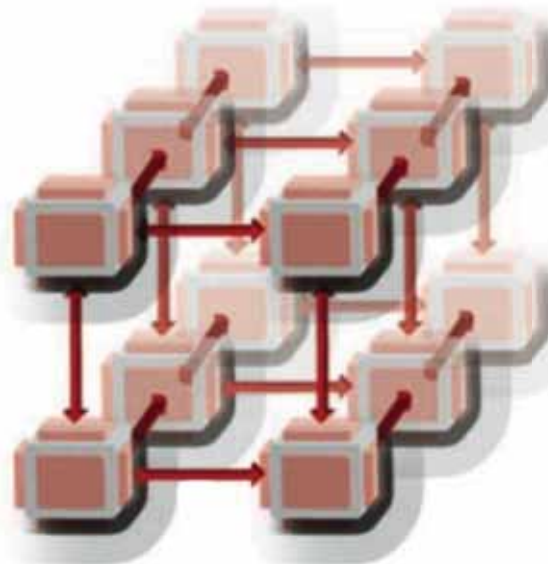
(from HJ Kimble, The Quantum Internet)

The General Content of QScale

Quantum node

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Scalable Q. Communication
Distributed Q. computing
Quantum resource sharing
Quantum simulation



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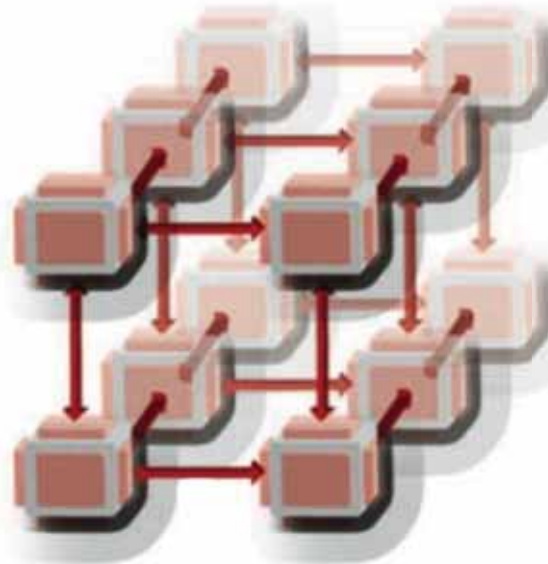
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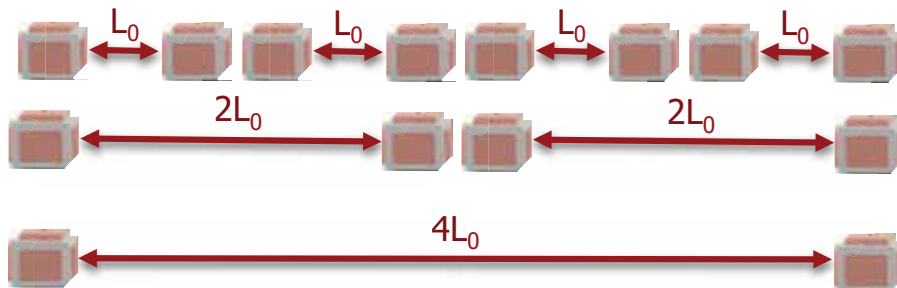
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One example: 'Quantum Repeater'



Entanglement Distribution
on distances larger than set
by the attenuation length of fibers

→ Long-distance Q. cryptography, Q. state transmission

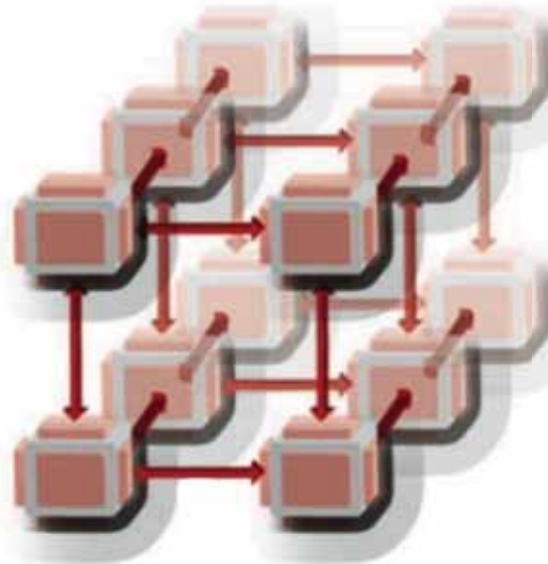
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Enters into Topic 3 of the QIFT call

focus on “Long distance quantum communications”

Overall objective

experimentally demonstrate ***photonic and atomic components***
enabling the development of quantum repeaters and their integration
into **quantum communication and processing networks**

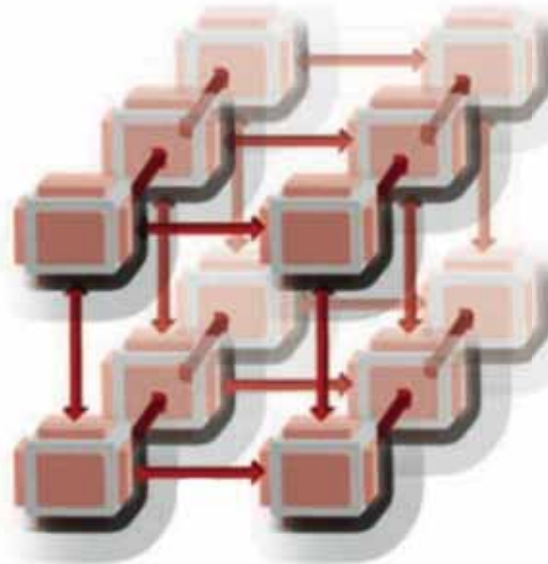
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Implementation ?

- Physical processes for reliable generation, processing, & transport of quantum states (including novel architectures)
 - Quantum interfaces between matter and light
- Networks will be heterogeneous : Various kind of photonic carriers, of encodings and of material systems

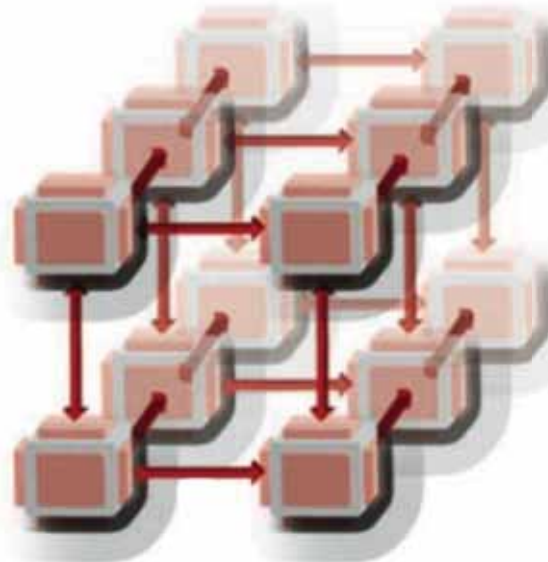
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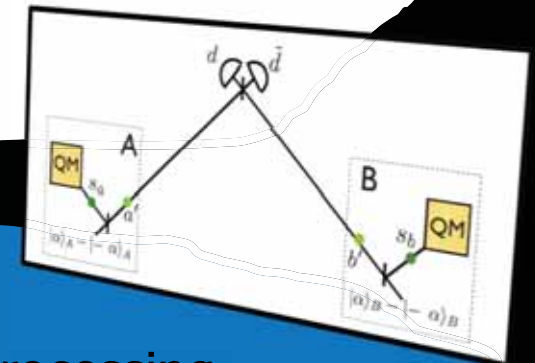
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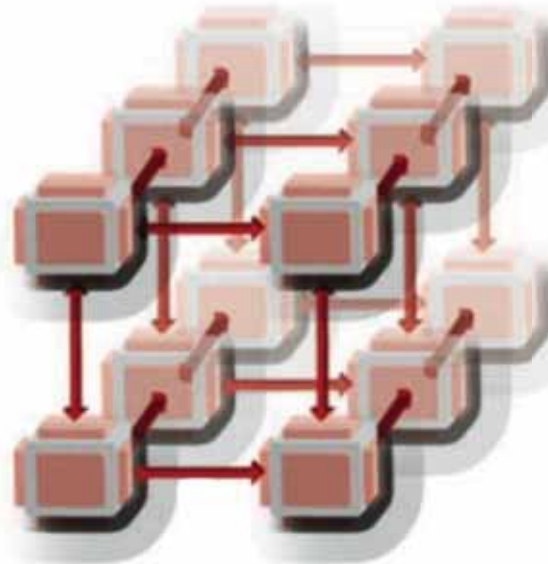
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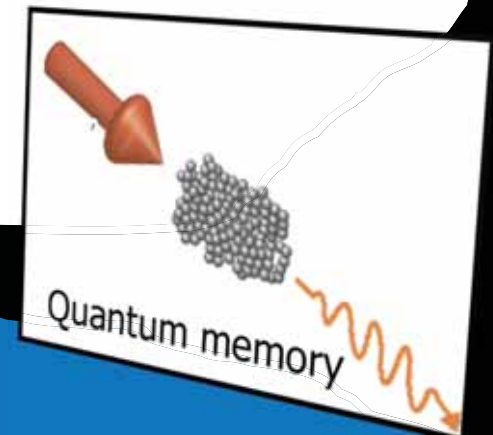
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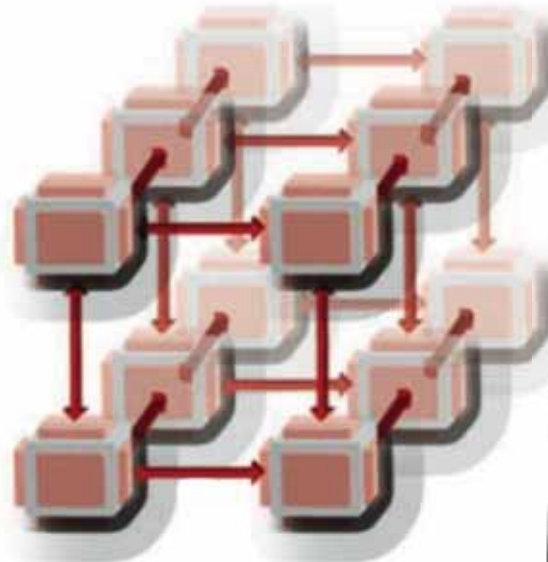
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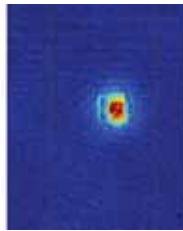
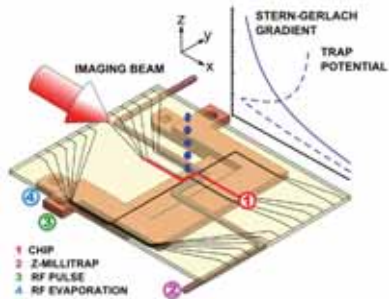
Discrete/continuous encodings
Single photons, Squeezed
light, Non-gaussian states,..
Doped crystals, cold and ultra-
cold atoms, ion strings

Implementation ?

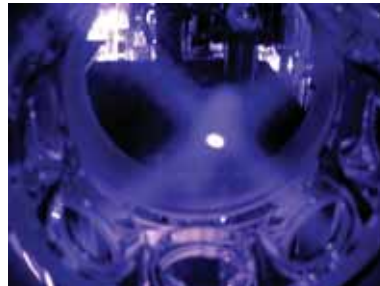
- Physical processes for reliable generation, processing, & transport of quantum states (including novel architectures)
 - Quantum interfaces between matter and light
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The Tools of QScale

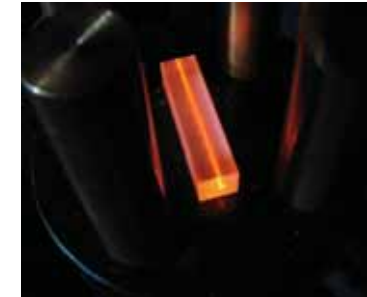
Bose-Einstein Condensate on chip



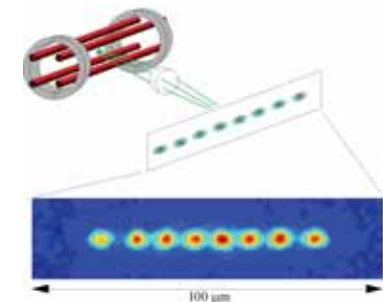
Cold atoms in 2D-MOT and dipole trap



Rare-earth ion doped crystals

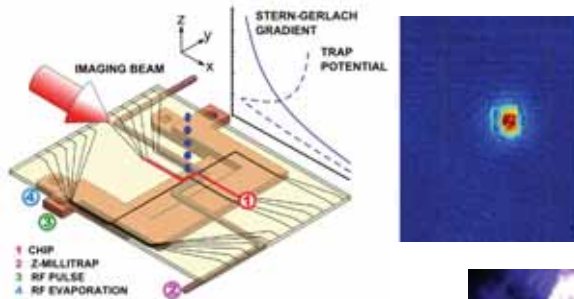


Trapped ion strings

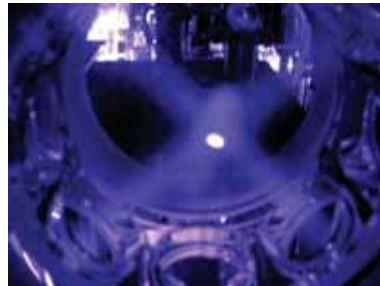


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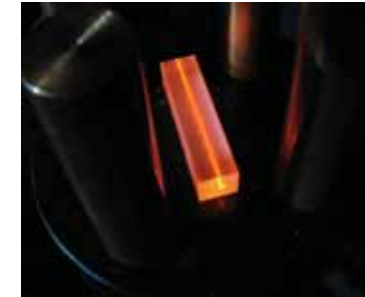
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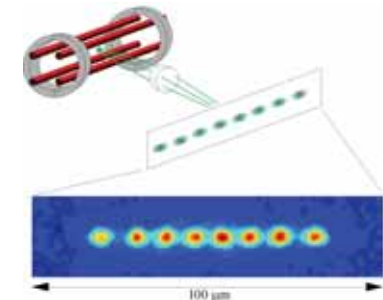
Cold atoms in 2D-MOT and dipole trap



Rare-earth ion doped crystals



Trapped ion strings



Discrete degrees of freedom

Polarization qubits
Single-photon entanglement
Involve photon counting

Continuous degrees of freedom

Quadrature measurements
Involve homodyne detection

Single photons

Gaussian Squeezed light and Entanglement

Non-Gaussian states Hybrid operations



The QScale Consortium

5 academic partners
1 industrial partner

5 countries

Funding: ~1 M€
400 person months



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Paris, France
Laboratoire Kastler Brossel
PI: J. Laurat
(Q. memory in MOT, Non-gaussian)

Saarbrücken, Germany
Universität des Saarlandes
PI: J. Eschner
(Trapped ion strings)

Milano, Italy
Quanta System
PI: F. Ferrario
(Tools: locking, detection)

Geneva, Switzerland
Group of Applied Physics
PI: N. Sangouard
(Theory of quantum networks)

Barcelona, Spain
Institute of Photonic Sciences
PI: H. de Riedmatten
(Q. memory in solids)

Firenze, Italy
Istituto Nazionale di Ottica
PI: M. Bellini
(Q. memory in BEC, Non-gaussian)

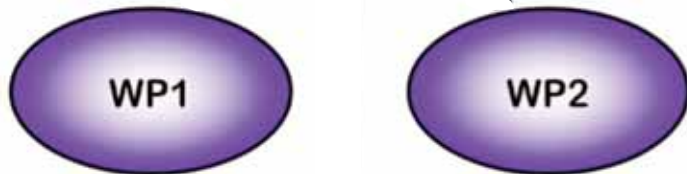


Quantum technologies for extending the range of quantum communications

QScale WorkPackages

WP1: Photonic components for quantum architecture

Developing sources of **non-classical light** compatible with memories and the ability to perform **non-Gaussian** operations.

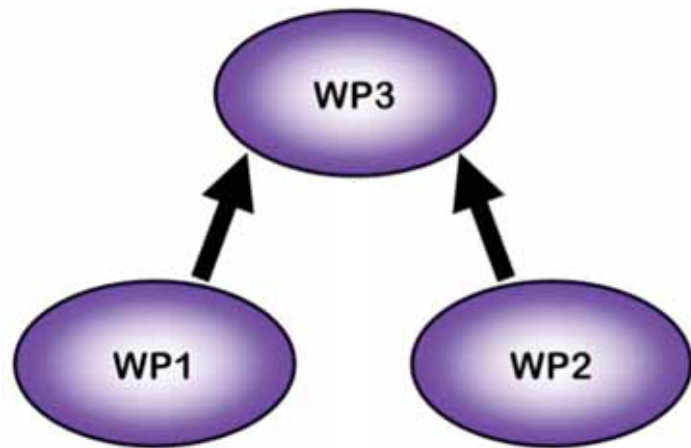


WP2: Controlling light-matter interfaces

Implementing long-lived and efficient quantum memories in **ensembles** (cold atoms, BEC on AtomChip, and rare-earth doped solid) and the synchronous control of photon emission by **trapped ion strings** leading to light-ion entanglement.



QScale WorkPackages



WP1: Photonic components for quantum architecture

Non-classical light and non-Gaussian operations.

WP2: Controlling light-matter interfaces

Memories in ensembles and control of ion strings.

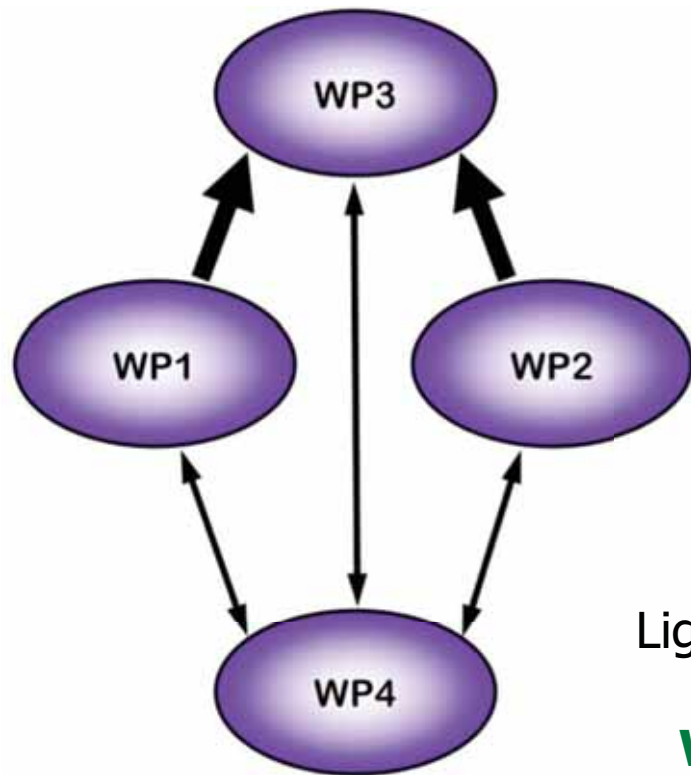
WP3: Demonstration of Q. repeaters building blocks

On-demand **matter-matter entanglement**, long-lived **light-solid** entanglement, local ion string processing and **teleportation between strings**



Quantum technologies for extending the range of quantum communications

QScale WorkPackages



WP1: Photonic components for quantum architecture

Non-classical light and non-Gaussian operations.

WP2: Controlling light-matter interfaces

Memories in ensembles and control of ion strings.

WP3: Demonstration of Q. repeaters building blocks

Light-matter, matter-matter entanglement, node processing

WP4: Novel architectures and tools for repeaters

Investigating new **architectures** and characterization for **operational repeaters** (e.g. hybrid schemes, heralded qubit amplifier, deterministic operations, witnesses)



Quantum technologies for extending the range of quantum communications



QScale Website On Line

A website

www.chistera-qscale.eu

Partners, Workpackages
Papers from the consortium
General audience page



Quantum technologies for extending the range of quantum communications

Kick-off Meeting

Kick-off, Paris, October 2011

25 researchers, 9 talks
2 discussion sessions



"QScale: extending the range of quantum communications"

Kick-off Meeting
Université Pierre et Marie Curie
Paris, 10-11 October 2011

Location : Laboratoire Kastler Brossel, Tower 23-13, 2nd floor
Université P. et M. Curie, 4 Place Jussieu
Metro: Jussieu (line 7 and 10)

Monday, October 10

Morning : Travel

- | | |
|-------------|---|
| 14:30-14:45 | Introduction, J. Laurat (LKB) |
| 14:45-15:30 | Towards long-lived solid state quantum memories with spin wave storage, H. de Riedmatten (ICFO) |
| 15:30-16:00 | Towards quantum memories with cold atoms, P. Lombardi (INO) |
| 16:00-16:30 | Coffee Break |
| 16:30-17:00 | Towards the deterministic entanglement of remote memories
L. Giner (LKB) |
| 17:00-17:30 | Non-Gaussian states and operations, O. Morin (LKB) |
| 17:30-18:00 | Non-Gaussian quantum state engineering, A. Zavatta (INO-CNR) |
| 18:00-18:30 | Discussion 1 |
| 20:00 | Dinner at "L'Atelier Maître Albert", 1 rue Maître Albert |

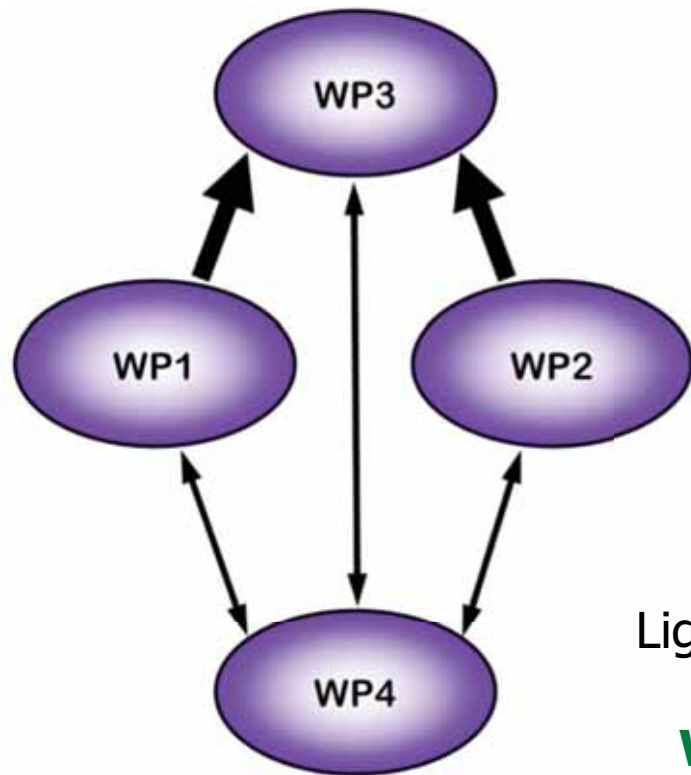
Tuesday, October 11

- | | |
|-------------|--|
| 9:15-10:00 | Emission and absorption of single photons by single atoms,
J. Eschner (UdS) |
| 10:00-10:30 | The first GAP projects within QScale
N. Sangouard (GAP) |
| 10:30-11:00 | Coffee Break |
| 11:00-11:45 | High End Laser Resonators, F. Ferraro (Quanta System) |
| 11:45-12h00 | Detector imperfections in photon pair source characterization,
Pavel Sekatski (GAP) |
| 12:15 | Lunch at the UPMC Restaurant "L'Ardoise" |
| 14:00-15:30 | Discussion 2 |



Quantum technologies for extending the range of quantum communications

QScale WorkPackages



WP1: Photonic components for quantum architecture

Non-classical light and non-Gaussian operations.

WP2: Controlling light-matter interfaces

Memories in ensembles and control of ion strings.

WP3: Demonstration of Q. repeaters building blocks

Light-matter, matter-matter entanglement, node processing

WP4: Novel architectures and tools for repeaters

Hybrid schemes, heralded qubit amplifier, deterministic operations, witnesses,...



Quantum technologies for extending the range of quantum communications

ICFO: Qubit Storage in a Solid

Polarization qubit storage by the Atomic Frequency Comb Technique

Quantum Storage of a Photonic Polarization Qubit in a Solid

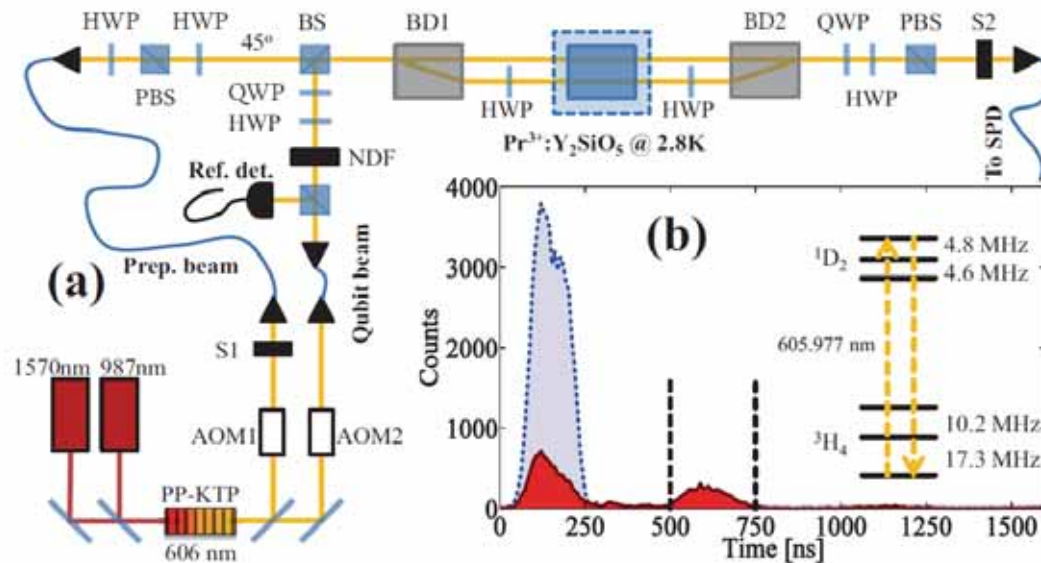
Mustafa Gündoğan,^{1,*} Patrick M. Ledingham,¹ Attaallah Almási,^{1,†} Matteo Cristiani,¹ and Hugues de Riedmatten^{1,2}

¹ICFO-Institut de Ciències Fotòniques, Mediterranean Technology Park, 08860 Castelldefels (Barcelona), Spain

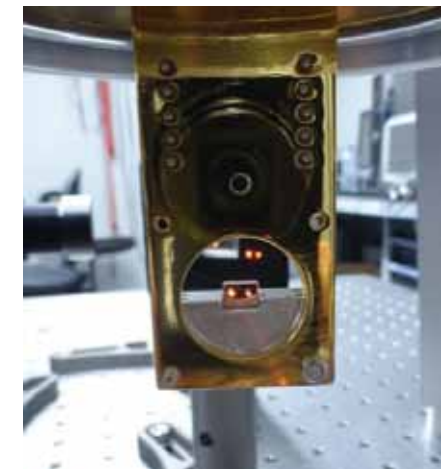
²ICREA-Institució Catalana de Recerca i Estudis Avançats, 08015 Barcelona, Spain

We report on the quantum storage and retrieval of photonic polarization quantum bits onto and out of a solid state storage device. The qubits are implemented with weak coherent states at the single photon level, and are stored for 500 ns in a praseodymium doped crystal with a storage and retrieval efficiency of 10 %, using the atomic frequency comb scheme. We characterize the storage by using quantum state tomography, and find that the average conditional fidelity of the retrieved qubits exceeds 95 % for a mean photon number $\mu = 0.4$. This is significantly higher than a classical benchmark, taking into account the Poissonian statistics and finite memory efficiency, which proves that our device functions as a quantum storage device for polarization qubits, even if tested with weak coherent states. These results extend the storage capabilities of solid state quantum memories to polarization encoding, which is widely used in quantum information science.

arXiv:1201.4149v2



Conditional fidelity above 95%, above classical benchmark

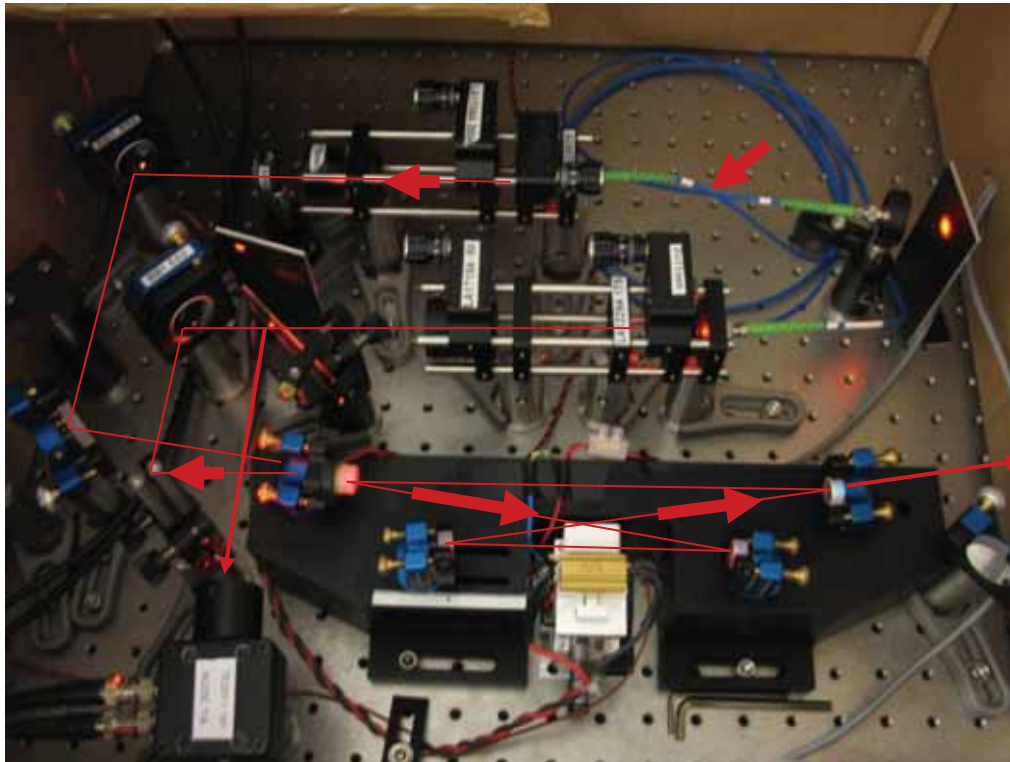
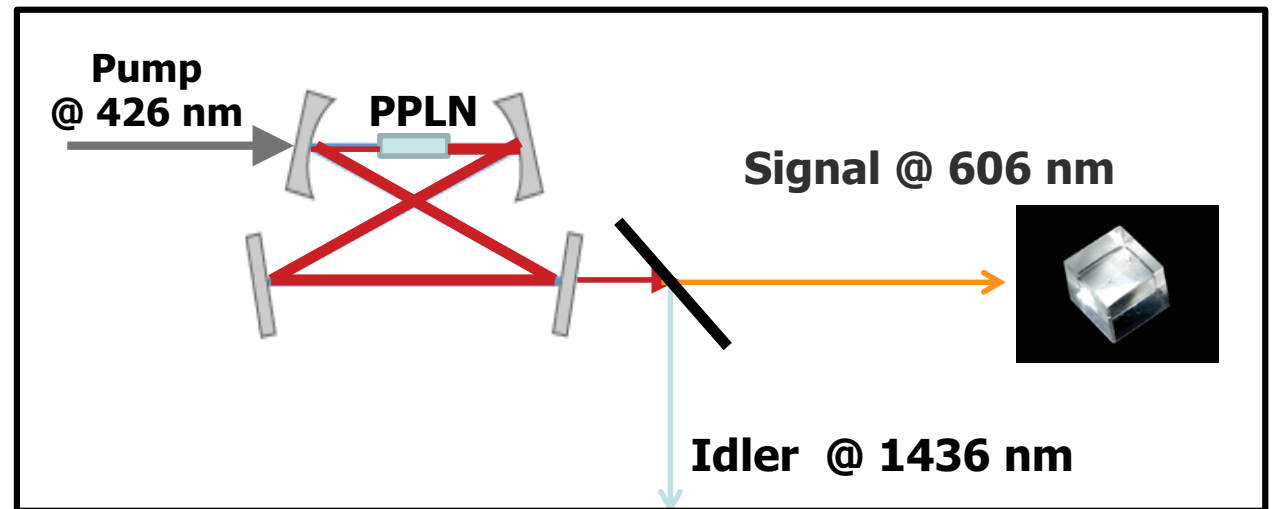


Cryogenically cooled
Pr³⁺:Y₂SiO₅

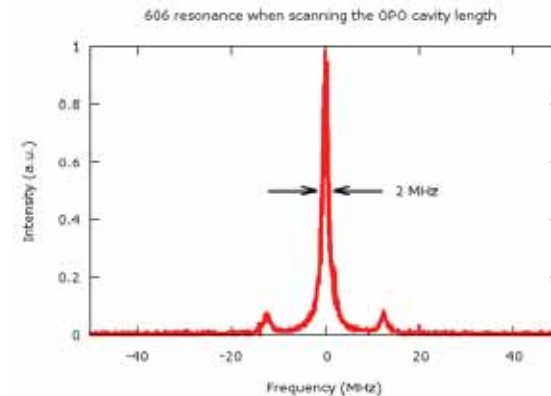
Next step for WP2: transferring the excitation to long-lived spin excitation

ICFO: A compatible single-photon source

Generation of ultra-narrow band photon pair compatible with Pr memory



Preliminary results



Next step for WP1: measuring the $g^2(0)$ and improving the emission rate and stability

GAP: Available Resources and their Uses

Usefulness of single-photons

Benchmarks for Q. communications

What are single photons good for?

Nicolas Sangouard and Hugo Zbinden
Group of Applied Physics, University of Geneva, 1211 Geneva 4, Switzerland
(Dated: February 3, 2012)

In a long-held preconception, photons play a central role in present-day quantum technologies. But what are sources producing photons one by one good for precisely? Well, in opposition to what many suggest, we show that single-photon sources are not helpful for point to point quantum key distribution because faint laser pulses do the job comfortably. However, there is no doubt about the usefulness of sources producing single photons for future quantum technologies. In particular, we show how single-photon sources could become the seed of a revolution in the framework of quantum communication, making the security of quantum key distribution device independent or extending quantum communication over many hundreds of kilometers. Hopefully, these promising applications will provide a guideline for researchers to develop more and more efficient sources, producing narrowband, pure and indistinguishable photons at appropriate wavelengths.

arXiv:1202.0493v1

Detector imperfections in photon-pair source characterization

P. Sekatski, N. Sangouard, F. Bussières, C. Clausen, N. Gisin, and H. Zbinden
Group of Applied Physics, University of Geneva, CH-1211 Geneva 4, Switzerland
(Dated: September 2, 2011)

We analyze how imperfections in single-photon detectors impact the characterization of photon-pair sources. We perform exact calculations to reveal the effects of multi-pair emissions and of noisy, non-unit efficiency, non photon-number resolving detections on the Cauchy-Schwarz parameter, on the second order auto-correlation and cross-correlation functions, and on the visibilities of both Hong-Ou-Mandel and Bell-like interferences. We consider sources producing either two-mode squeezed states or states with a Poissonian photon distribution. The proposed formulas are useful in practice to determine the impacts of multi-pair emissions and dark counts in standard tests used in quantum optics.

arXiv:1109.0194v1

Characterization of photon-pairs with realistic detectors that one has in the lab

Provides explicit formulas for usual quantum optics tests (HOM, cross-correlation,..) including detector parameters

Enters into WP4: How to characterize/optimize the available resources for efficient Q. communication protocols ?

GAP: Available Resources and their Uses

Detector imperfections in photon-pair source characterization

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arXiv:1109.0194v1

@ LKB

How realistic detectors influence the preparation of single-photon states ?

Characterization of photon-pairs with realistic detectors that one has in the lab

Provides explicit formulas for usual quantum optics tests (HOM, cross-correlation,..) including detector parameters

Effect of the heralding detector properties on the conditional generation of single-photon states

Virginia D'Auria, Olivier Morin, Claude Fabre and Julien Laurat

Laboratoire Kastler Brossel, Université Pierre et Marie Curie, Ecole Normale Supérieure, CNRS, Case 74, 4 place Jussieu, 75252 Paris Cedex 05, France
E-mail: julien.laurat@upmc.fr

Abstract. Single-photons play an important role in emerging quantum technologies and information processing. Apart from using single emitters, an efficient generation technique consists in preparing such states via a conditional measurement on photon-number correlated photons: the detection of a single-photon on one of the beam can herald the generation of a single-photon state on the other one. Such scheme strongly depends on the heralding detector properties, such as its quantum efficiency, its noise or its photon-number resolution ability. These performance parameters affect the preparation rate and the fidelity of the generated state. After reviewing the theoretical description of optical detectors and conditional measurements, and how both are here connected, we evaluate the effects of these properties and compare two kind of detectors, a conventional on/off detector and a time-multiplexed one.

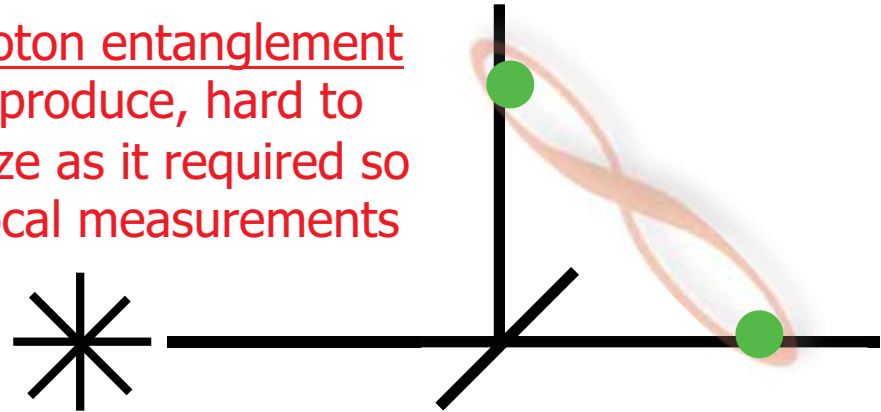
Enters into WP4: How to characterize/optimize the available resources for efficient Q. communication protocols ?

Witnessing Operational Q. Networks

GAP/LKB collaboration

Idea : a criterion for single photon entanglement using only local measurements

Single photon entanglement
easy to produce, hard to
characterize as it required so
far non-local measurements

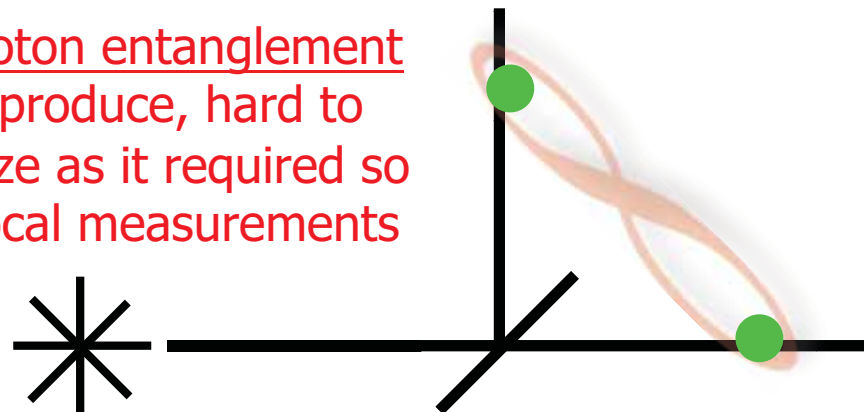


Witnessing Operational Q. Networks

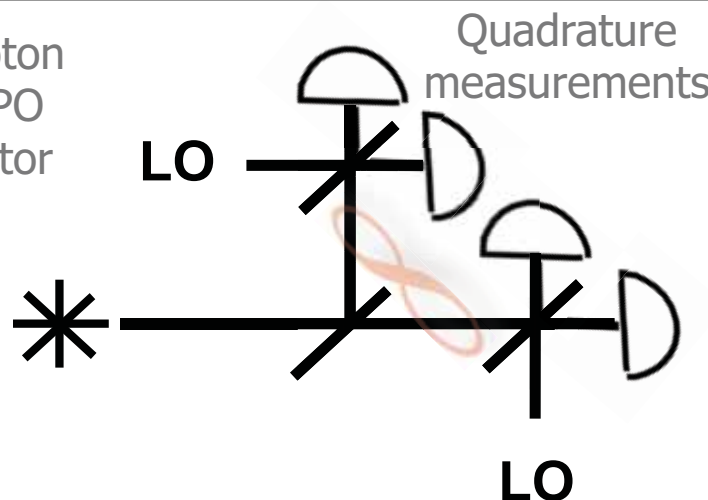
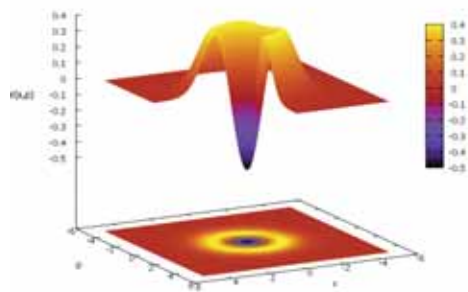
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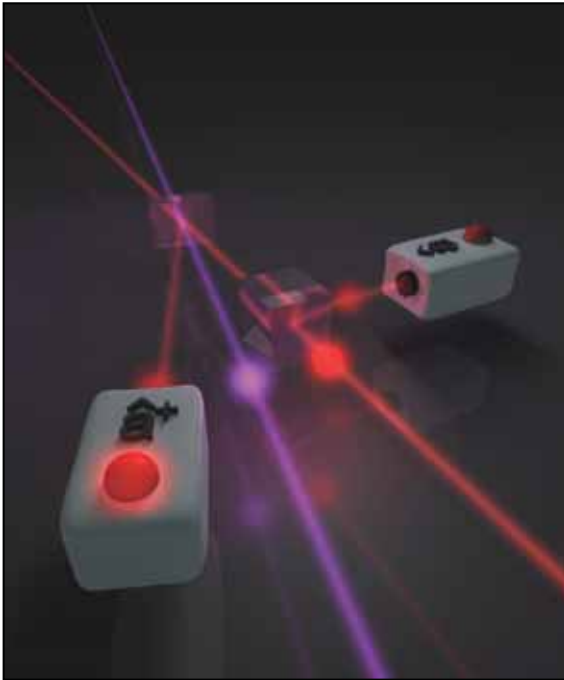
A ("very good") single-photon
generated with type-II OPO
and heralding SSPD detector



A witness proposed by GAP
and currently implemented
at LKB with only local
homodyne measurements

Enters into WP1 and WP4: Non-gaussian tasks and criteria
for networks operations, including hybrid networks

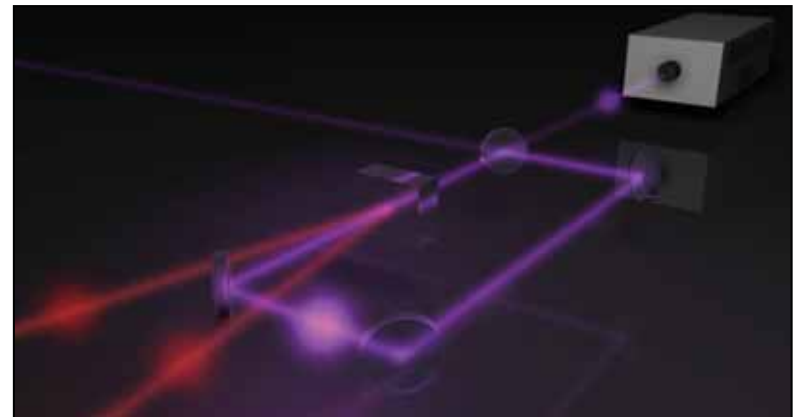
INO: A New Setup for Non-Gaussian task



Goal : Combination of photon addition and subtraction for multi-photon quantum state generation, CV qubit and entanglement purification

Requires a new setup with cavity enhancement of the non-linear effects and low-noise high-speed homodyne detection

A collaboration INO/QuantaSystem for developing these tools



Enters into WP1: Non-Gaussian toolbox for Q. state engineering

Q. Repeaters based on Qubit Amplifier

GAP/ICFO collaboration

Idea : using heralded qubit amplifier to generate **on-demand** entangled photon pairs and improve repeater scalability

Quantum repeaters based on heralded qubit amplifiers

Jiří Minář^{1,2}, Hugues de Riedmatten^{3,4}, and Nicolas Sangouard²

¹Centre for Quantum Technologies, National University of Singapore, 3 Science drive 2, Singapore 117543

²Group of Applied Physics, University of Geneva, CH-1211 Geneva 4, Switzerland

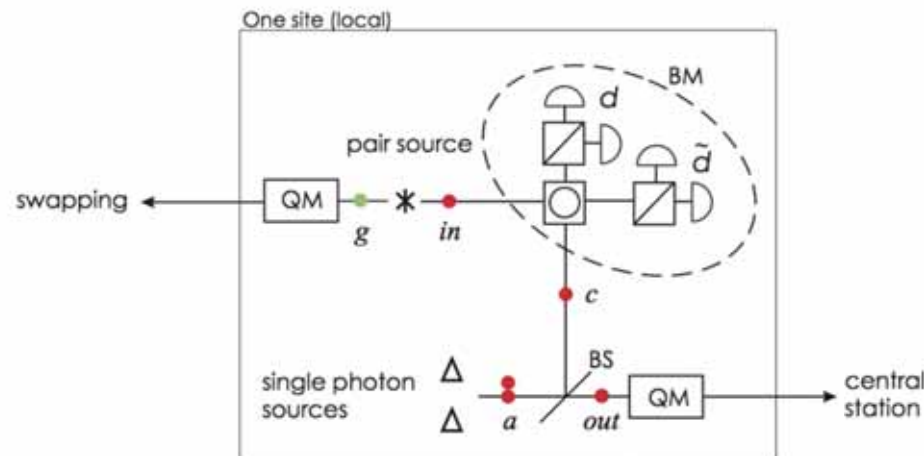
³ICFO-Institute of Photonic Sciences, Mediterranean Technology Park, E-08860 Castelldefels (Barcelona), Spain

⁴ICREA-Institució Catalana de Recerca i Estudis Avançats, E-08015 Barcelona, Spain

(Dated: November 23, 2011)

We present a quantum repeater scheme based on the recently proposed qubit amplifier [N. Gisin, S. Pironio and N. Sangouard, Phys. Rev. Lett. 105, 070501 (2010)]. It relies on an on-demand entangled-photon pair source which uses on-demand single-photon sources, linear optical elements and atomic ensembles. Interestingly, the imperfections affecting the states created from this source, caused e.g. by detectors with non-unit efficiencies, are systematically purified from an entanglement swapping operation based on a two-photon detection. This allows the distribution of entanglement over very long distances with a high fidelity, i.e. without vacuum components and multiphoton errors. Therefore, the resulting quantum repeater architecture does not necessitate final postselections and thus achieves high entanglement distribution rates. This also provides unique opportunities for device-independent quantum key distribution over long distances with linear optics and atomic ensembles.

arXiv:1111.5185v1, accepted in PRA



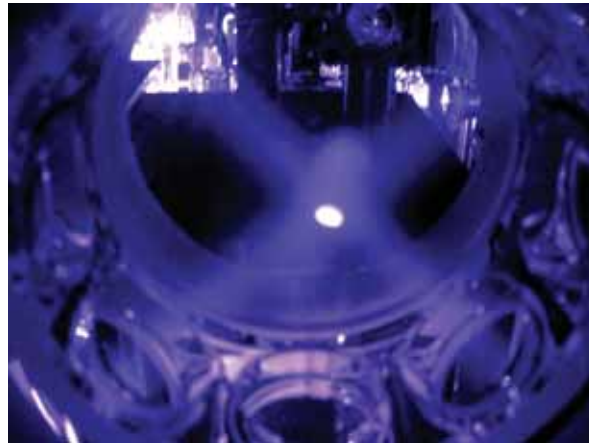
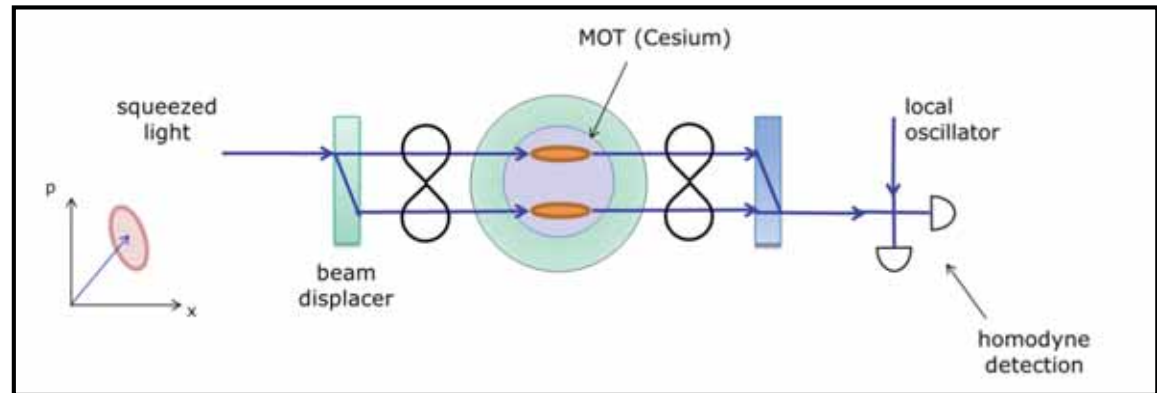
Show that the quality of the entanglement is preserved even after many swapping operations such that it does not require postselection as usually done in repeaters

Enters into WP4: Developing efficient protocols for Q. communications with a special emphasis on deterministic operations

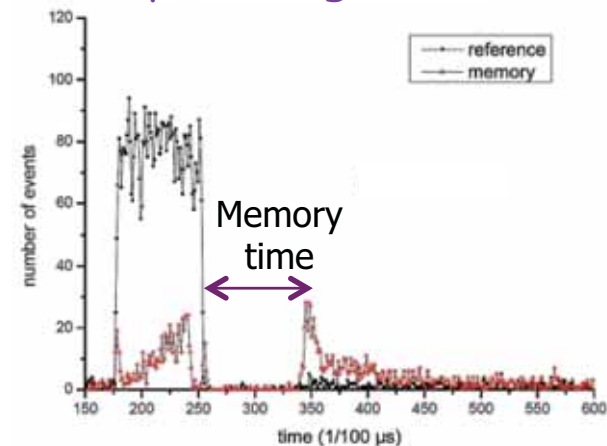
LKB: On-demand Matter Entanglement

Goal : Demonstrating the deterministic entanglement of two remote memories

Requires: large MOT for multiplexing, compatible source of squeezed light



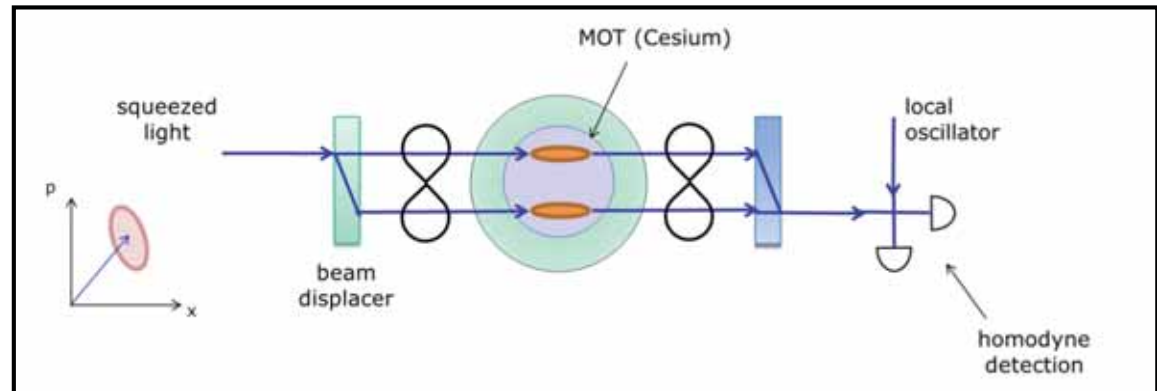
First results with weak coherent states
15% storage efficiency
20 μ s storage time



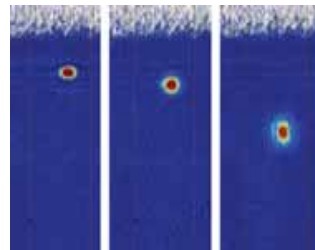
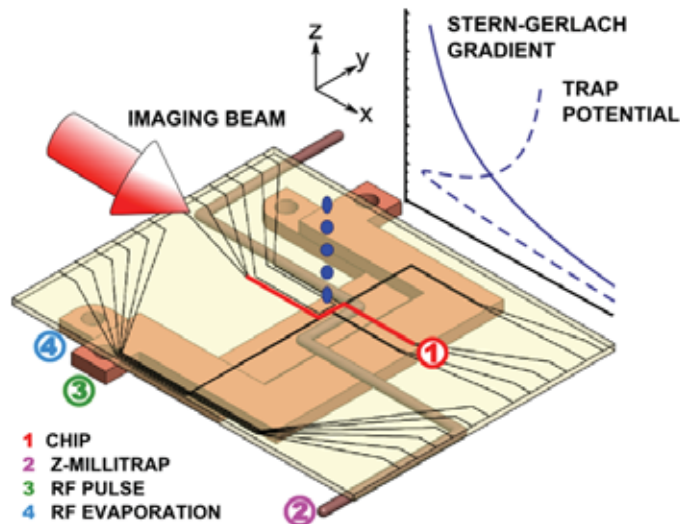
Optimization of the memory (WP2), Source of photonic entanglement (WP1), Transfer of deterministic entanglement to two memories (WP3)

INO: On-demand Matter Entanglement

Goal : Demonstrating the deterministic entanglement of two remote memories



Another system: Bose-Einstein Condensate



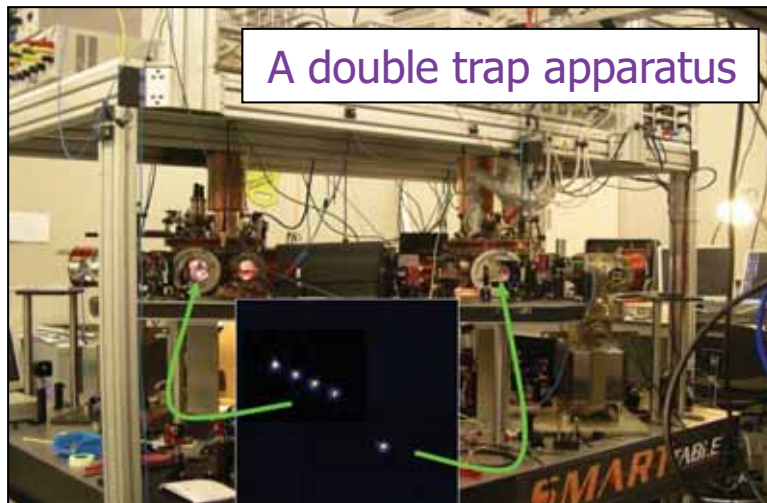
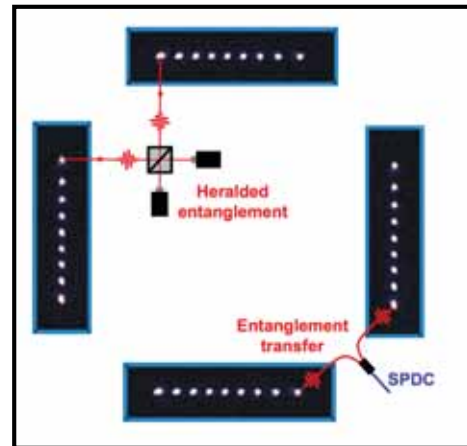
Storage of continuous-variable
on progress
Development of a double-trap

Optimization of the memory (WP1), Source of photonic entanglement (WP2), Transfer of deterministic entanglement to two memories (WP3)

Saarbrücken: Control of Ion Strings

Quantum network
with ion strings

Enable a local
processing widely
developed for Q.
computing

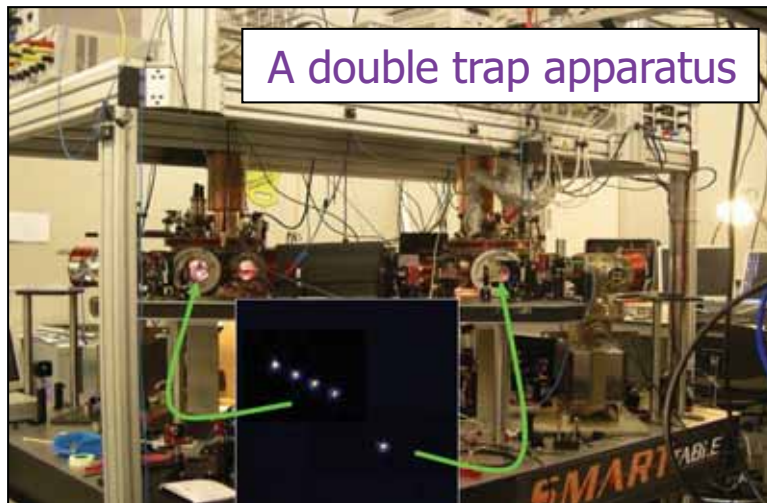
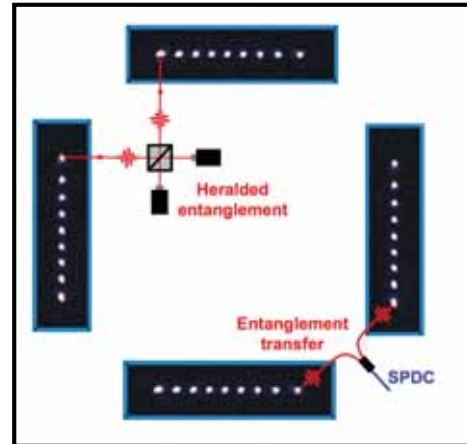


A double trap apparatus

Saarbrücken: Control of Ion Strings

Quantum network
with ion strings

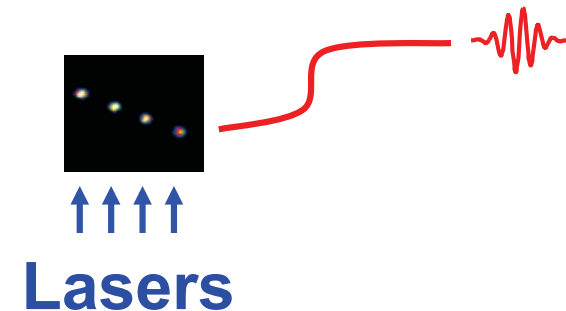
Enable a local
processing widely
developed for Q.
computing



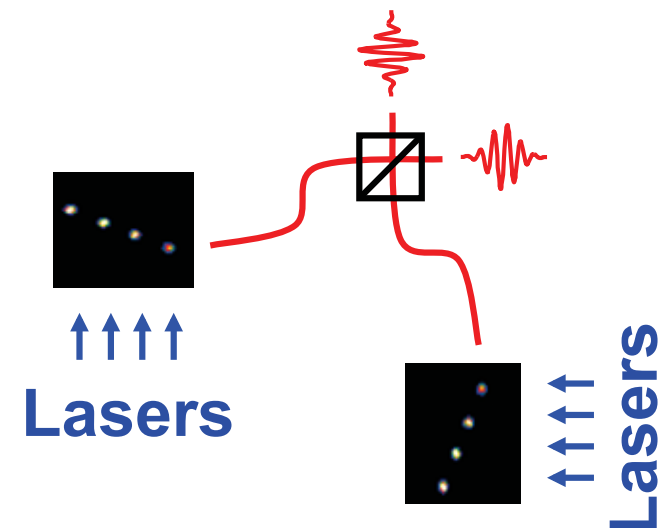
A double trap apparatus

Enters into WP2 and WP3: single-photon
emission from strings, remote ion-ion
entanglement, local operations on strings

Photon-conditioned gate



Remote gate





Quantum technologies for extending the range of quantum communications

Developing the atomic and photonic components enabling Q. repeaters and their integration into communication and processing networks

A strong partneship of researchers spanning a variety of material systems and optical carriers

Promising first results and collaborations

www.chistera-qscale.eu

