



Quantum technologies for extending the range of quantum communications

The QScale Project

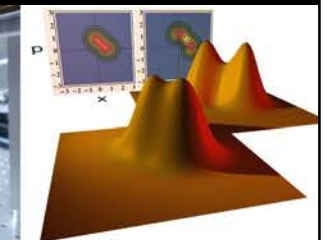
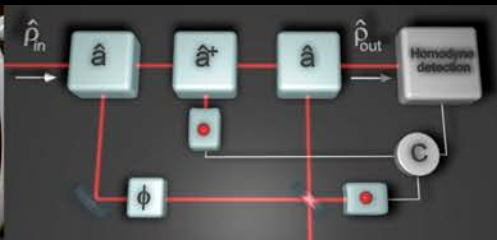
09/2011 to 03/2015

Coordinator: Julien Laurat

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

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

Madrid, Final review meeting, March 2015

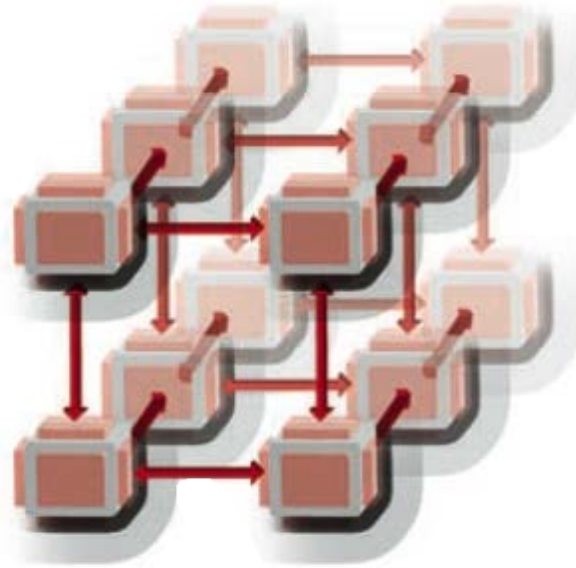


The General Content of QScale

Quantum node

generate, process, store
quantum information locally

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



Quantum channel
transport / distribute
quantum information
over the entire network

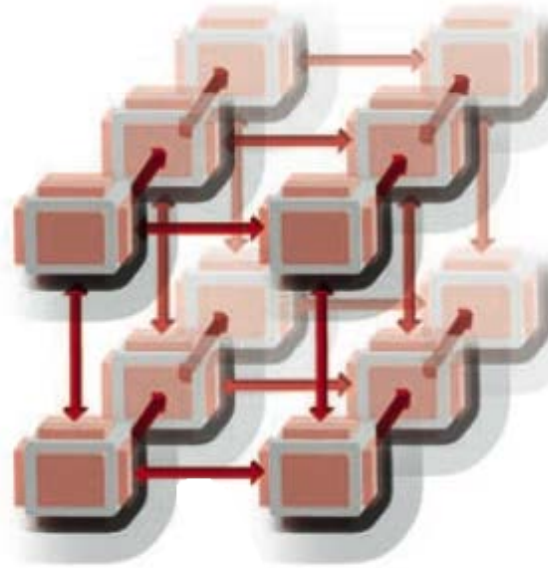
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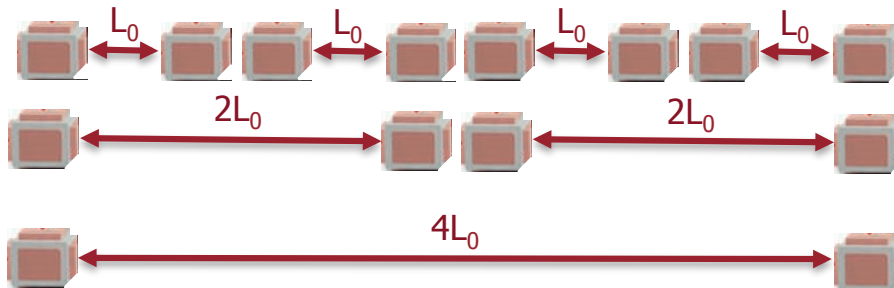
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One example: 'Quantum Repeater'



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

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

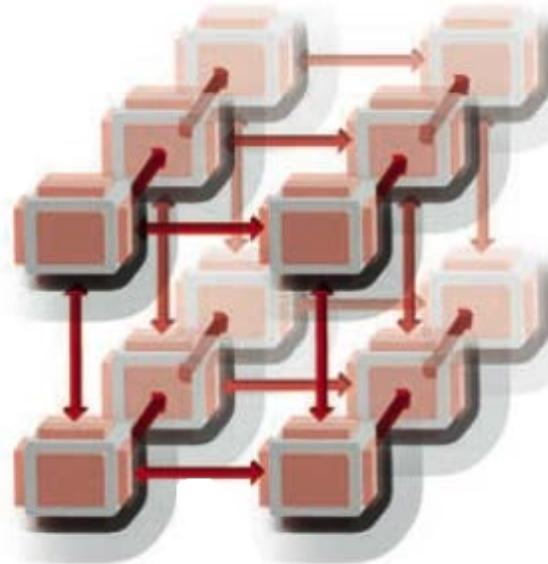
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Enters into Topic 3 of the QIFT call

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**

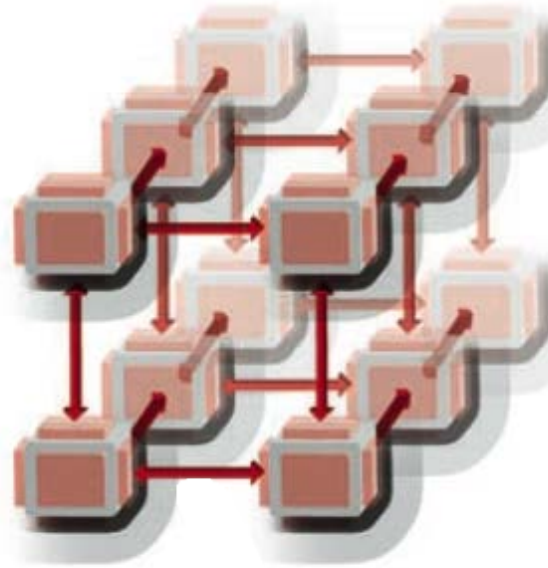
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Implementation ?

- 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

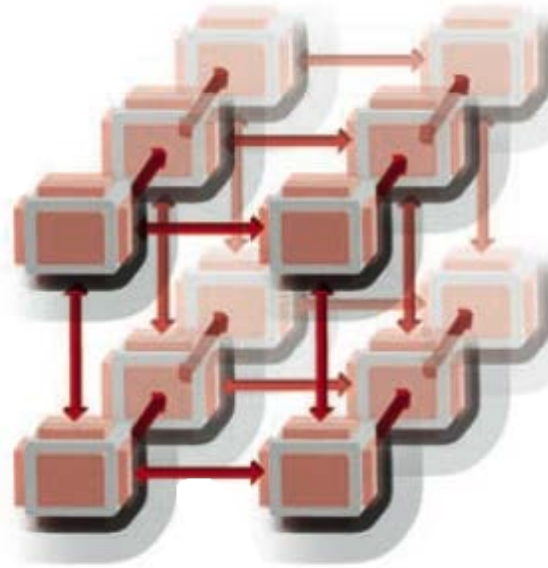
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Quantum node

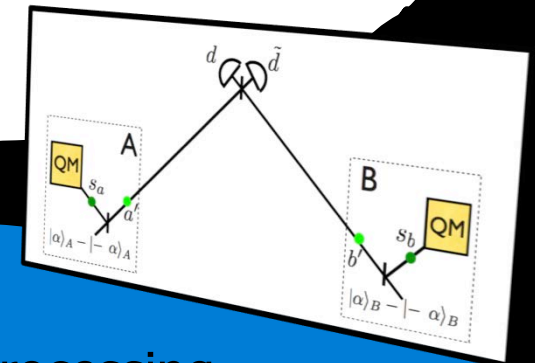
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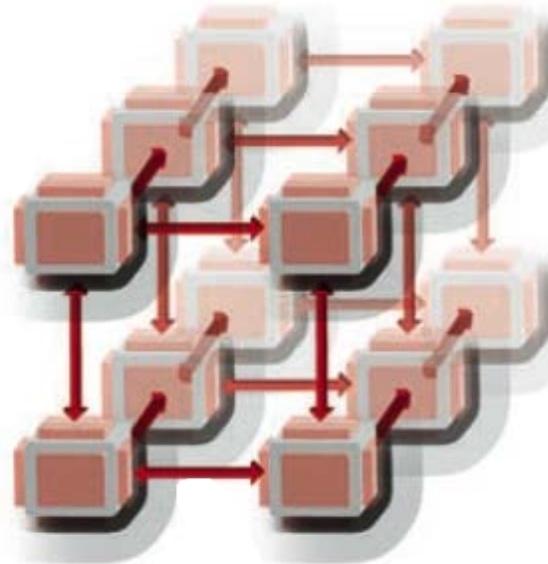
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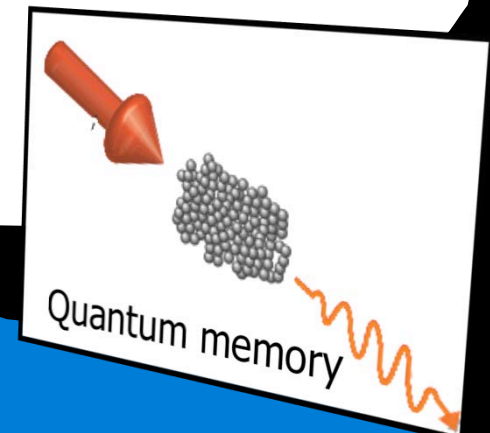
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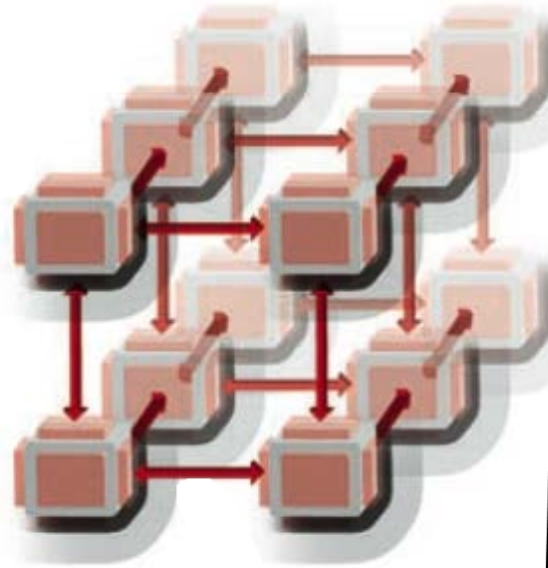
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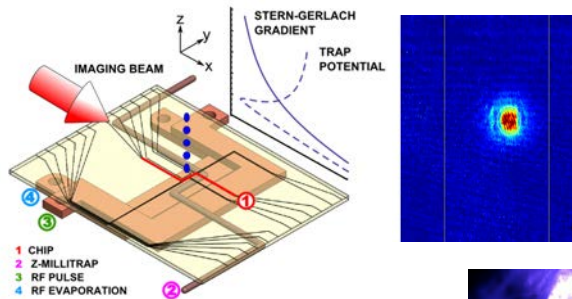
Discrete/continuous encodings
Single photons, Squeezed
light, Non-gaussian states,..
Doped crystals, cold and ultra-
cold atoms, ion strings

Implementation ?

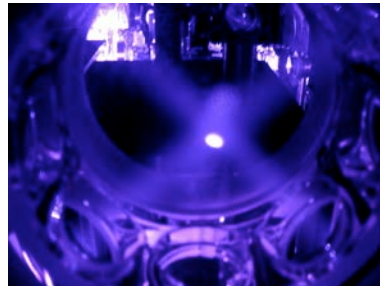
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 - Quantum interfaces between matter and light
- Networks will be heterogeneous : Various kind of photonic carriers, of encodings and of material systems

The Tools of QScale

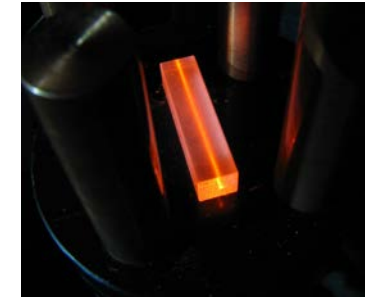
Bose-Einstein Condensate on chip



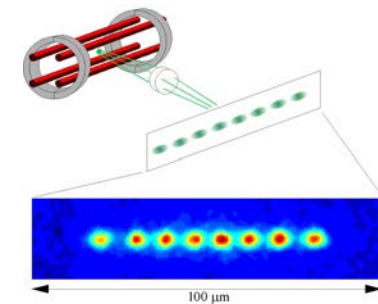
Cold atoms in 2D-MOT and dipole trap



Rare-earth ion doped crystals

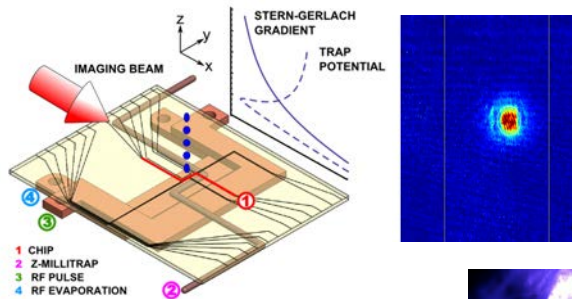


Trapped ion strings

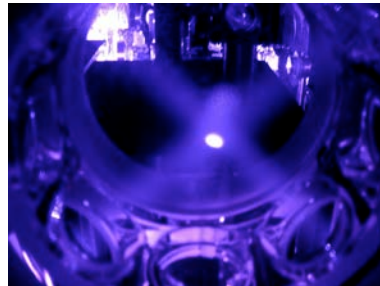


The Tools of QScale

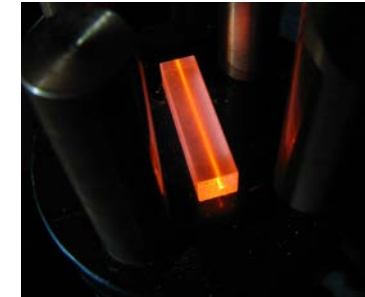
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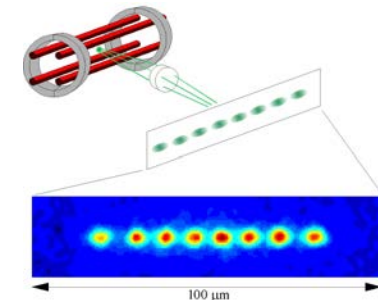
Cold atoms in 2D-MOT and dipole trap



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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Funding: ~1 M€
400 person months

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: A. Raspa
(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)

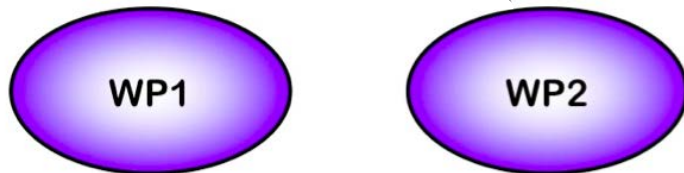


Quantum technologies for extending the range of quantum communications

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.

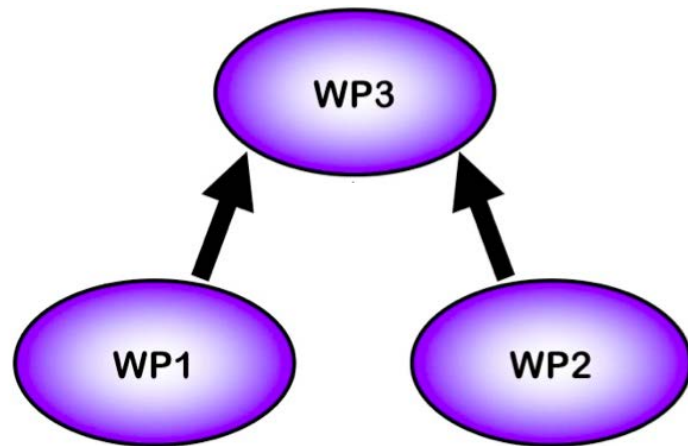


WP2: Controlling light-matter interfaces

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

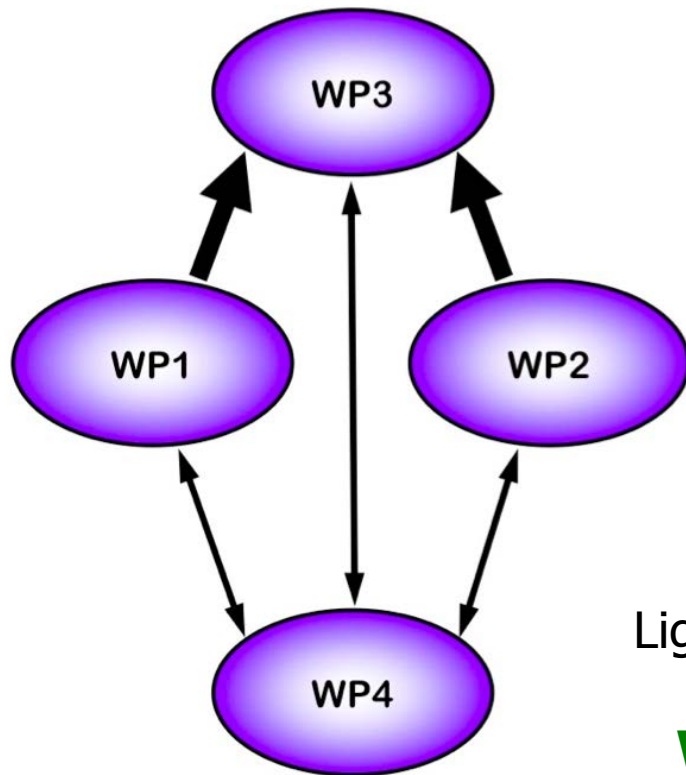
On-demand **matter-matter entanglement**, long-lived **light-solid** entanglement, local ion string processing and **teleportation between strings**



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)



QScale Website

A website

www.chistera-qscale.eu

Partners, Workpackages
Workshop programs
Papers from the consortium
General audience page



The screenshot shows the QScale website homepage. At the top is the QScale logo and the tagline "Quantum technologies for extending the range of quantum communications". A navigation menu on the left includes links to Home, News, The project, Partners, Publications, General audience, and Restricted area. The main content area features a "Welcome to the QScale website" message, a brief description of the project, a "News" section with a "New paper submitted" announcement about single photons, and a "CHIST-ERA Kick-off meeting in Warsaw, March 2012" announcement. The footer includes the CHIST-ERA logo, contact information, and a search bar.

QScale
Quantum technologies for extending the range of quantum communications

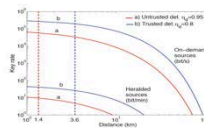
Home
News
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Restricted area

Welcome to the QScale website

QScale is a European research project, funded by the CHIST-ERA coordination. It is devoted to the development of advanced quantum communication technologies, specifically of quantum repeater architectures, which represent a major and timely challenge for the field of quantum information science and technology.

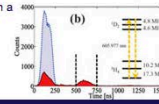
News

New paper submitted
What are single photons good for (submitted on February 2nd, 2012).
Preprint available at : <http://arxiv.org/abs/1201.0493>.



CHIST-ERA Kick-off meeting in Warsaw, March 2012
The project coordinator Julien Laurat will present the project at the CHIST-ERA Kick-off meeting. The meeting will take place on the 7th-8th of March in Warsaw. It will be organized by the Polish national funding organisation NCBR, and gather the coordinators of all the funded projects with representatives of the national funding agencies.

New paper submitted
Quantum Storage of a Photonic Polarization Qubit in a Solid (submitted on January 20th, 2012).
Preprint available at : <http://arxiv.org/abs/1201.4149>.



Contact - Credits - Site Map - Search



Quantum technologies for extending the range of quantum communications

Kick-off Meeting in 2011

Kick-off, Paris, October 2011

25 researchers, 9 talks

2 discussion sessions

Presentation of the groups

Consortium agreement validated



"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

Mid-term meeting January 2013

Paris

January 30, 31 and February 1st 2013

Hipercom and QScale together

70 researchers

27 talks + administrative session

9 invited speakers from outside the consortiums

New collaborations emerged

10th workshop on
**Continuous-Variable
Quantum Information
Processing**

Workshop CVQIP'2013
and
Mid-term QSCALE - HIPERCOM meeting

January 30th - February 1st, 2013

Laboratoire Kastler Brossel
Université Pierre et Marie Curie
Paris, France



Quantum technologies for extending the range of quantum communications

Focus meeting in November 2013

Paris
November 5 and 6, 2013

"Informal Workshop on Atomic Ensembles"

30 researchers

Including 13 researchers from Qscale groups

A focus workshop on a hot topic of Qscale

Different approaches compared



"Informal Workshop on Atomic Ensembles"

Université Pierre et Marie Curie
Paris, 5-6 November 2013

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

Tuesday, November 5

Morning : Travel

- 14:15-14:30 Introductory Remarks, J. Laurat (LKB)
- 14:30-15:15 Light storage protocols in atomic ensembles: a modest fundamental review, T. Chanelière (LAC)
- 15:15-16:00 Quantum storage of heralded single photons in solid state atomic ensembles, H. de Riedmatten (ICFO)
- 16:00-16:30 Coffee Break
- 16:30-17:15 Photonic interactions in Rydberg atomic ensembles, A. Ourjoumtsev (IOGS)
- 17:15-18:00 Lab tour and discussions
- 20:00 Dinner at "La mosquée de Paris", 39 rue Geoffroy Saint-Hilaire

Wednesday, November 6

- 9:00-9:45 A reversible quantum memory for OAM photonic qubits, L. Veissier (LKB)
- 9:45-10:30 Towards scalable photonic processing with quantum memories, J. Nunn (Oxford)
- 10:30-11:00 Coffee Break
- 11:00-11:45 Photon localization and cooperative effects in cold atomic clouds, L. Bellando (INLN)



Quantum technologies for extending the range of quantum communications

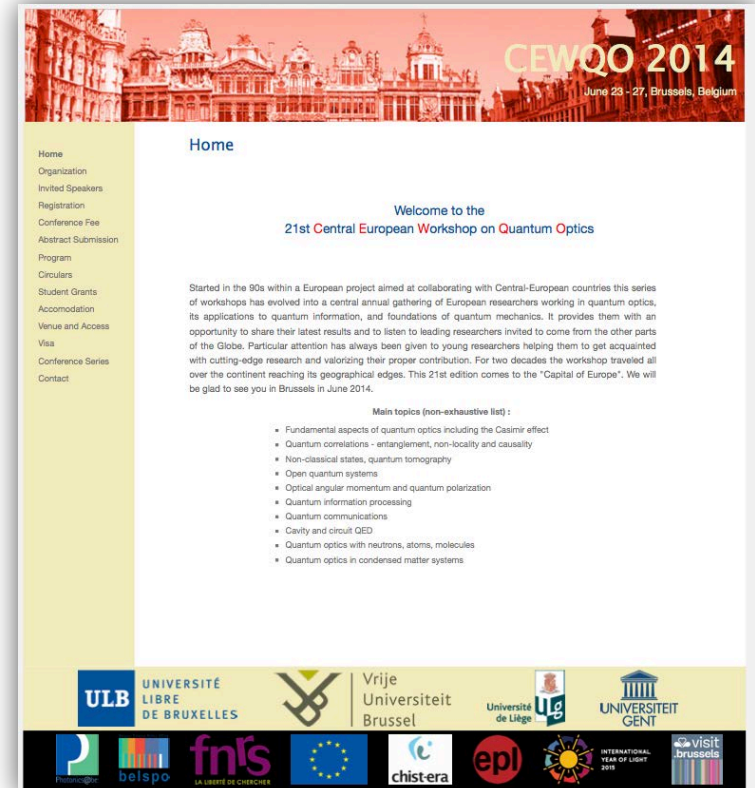
Last meeting: June 2014

**Brussels, during CEWQO 2014
23-27 June 2014**

Hipercom and QScale together again

One afternoon session for each project
+ two invited speakers from Qscale
in the plenary sessions

Dissemination towards the whole QIP community



Quantum technologies for extending the range of quantum communications

QScale 'Metrics'

46 papers in international peer-reviewed journals

10 Physical Review Letters, 3 Nature Photonics, 3 Nature Com.

5 'common' papers between QSCALE partners

117 contributions in international meetings and workshops

3 book chapters, 3 popularization articles, General audience conf

WP1: Photonic components for quantum architecture → 18 papers

WP2: Controlling light-matter interfaces → 17 papers

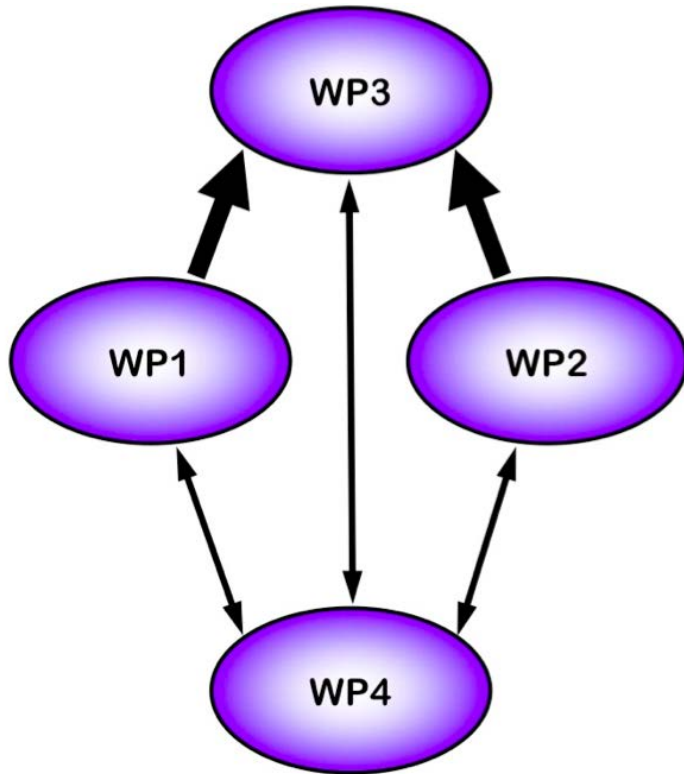
WP3: Q. repeaters building blocks → 4 papers

WP4: Novel architectures and tools for repeaters → 7 papers



Quantum technologies for extending the range of quantum communications

QScale WorkPackages



WP1: Photonic components for quantum architecture –All delivered, additional works
Non-classical light and non-Gaussian operations.

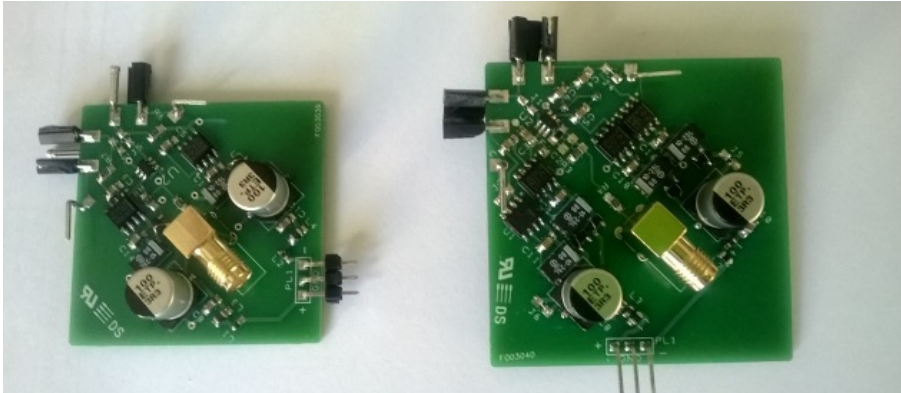
WP2: Controlling light-matter interfaces
Most of deliverables, two delayed
Memories in ensembles and control of ion strings.

WP3: Demonstration of Q. repeaters building blocks Results presented today

WP4: Novel architectures and tools for repeaters
–All deliverables done, new results not initially expected in the project, large collaboration
New architectures and characterization for operational repeaters



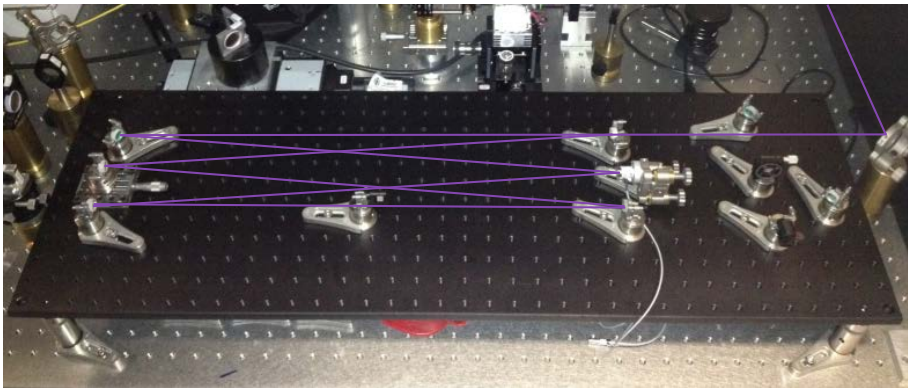
INO and QuantaS: industrial developments



Industry-standard, purpose-driven development and engineering of advanced devices for quantum optics experiments

Initially delayed, not reported before

Ultrafast, time-domain, homodyne detectors



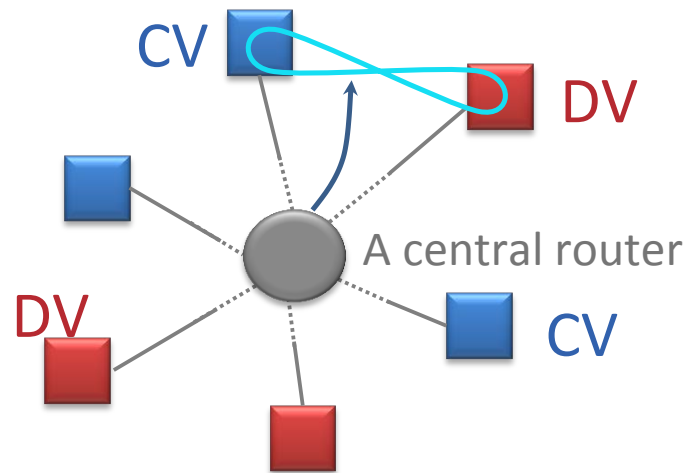
Will enable more efficient quantum state generation and characterization

Pulsed UV pump enhancement in a cavity

WP1 : Collaboration INO and Italian industrial partner – Development of electronics board

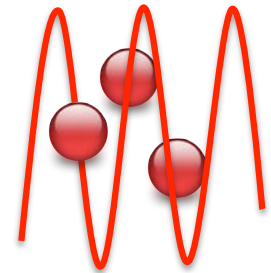
LKB and INO: A novel form of entanglement

A heterogeneous network



Opens the way to
heterogeneous networks and
computational basis mapping

Hybrid Entanglement
A novel form of entanglement
following two different strategies



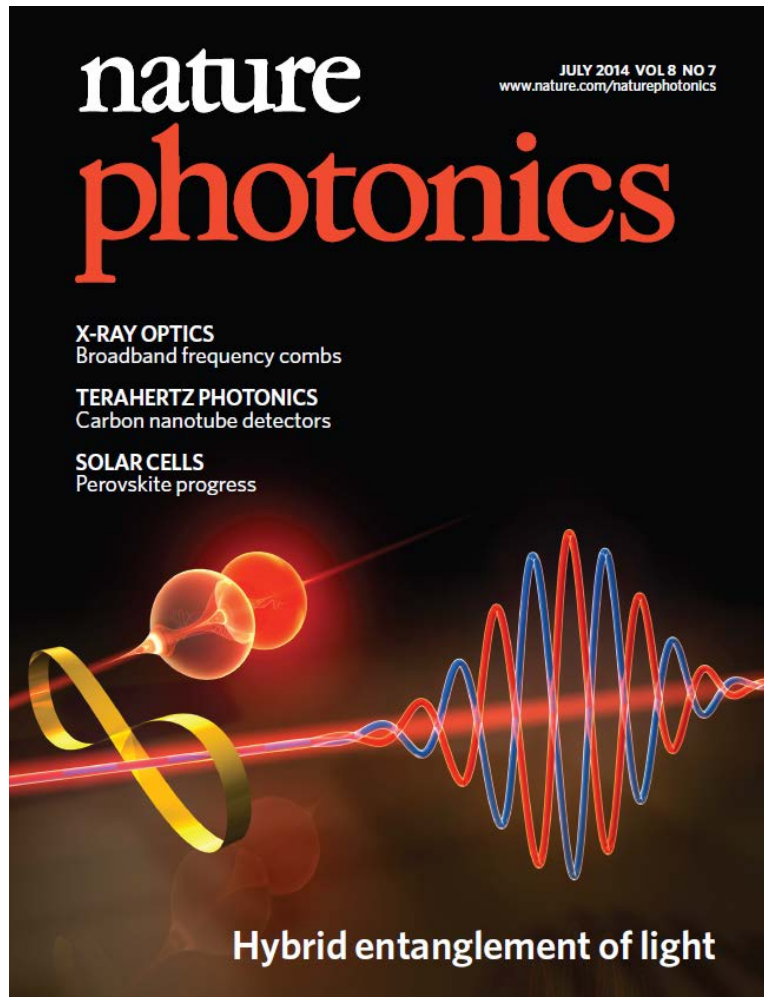
Alice and Bob working with different
encodings, i.e. CV or DV

$$|0\rangle_A |\alpha\rangle_B + |1\rangle_A |-\alpha\rangle_B$$

Hybrid entanglement between
particle-like and wave-like optical qubits

WP1 and WP4: Non-gaussian toolbox and Hybrid
approach for network operations and architectures

LKB and INO: A novel form of entanglement



Nature Photonics 8, 564 (2014)

Nature Photonics 8, 570 (2014)

Press release by ANR and MIUR

Covered by many medias, newspapers,
La Repubblica, websites...

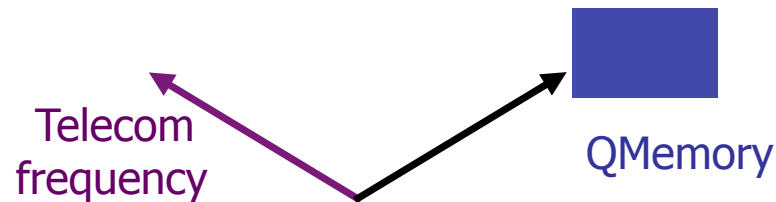
Cited among the 10 best Italian science
achievements of 2014 by Citta della Scienza

An example of work not fully planned at the
beginning of the project but that emerges from
the first developed capabilities

WP1 and WP4: Non-gaussian toolbox and Hybrid
approach for network operations and architectures

ICFO: Storage in doped crystal

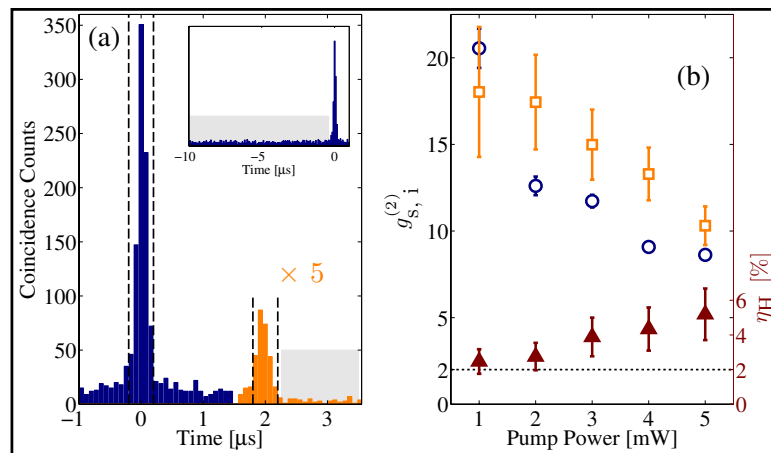
Storage of the single-photons
into Pr doped crystal



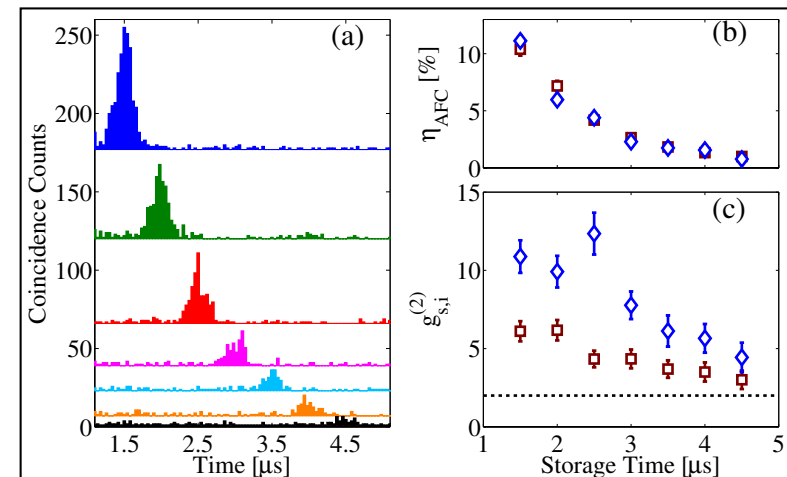
Quantum Storage of Heralded Single Photons in a Praseodymium-Doped Crystal

We report on experiments demonstrating the reversible mapping of heralded single photons to long-lived collective optical atomic excitations stored in a $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ crystal. A cavity-enhanced spontaneous down-conversion source is employed to produce widely nondegenerate narrow-band (≈ 2 MHz) photon pairs. The idler photons, whose frequency is compatible with telecommunication optical fibers, are used to herald the creation of the signal photons, compatible with the Pr^{3+} transition. The signal photons are stored and retrieved using the atomic frequency comb protocol. We demonstrate storage times up to $4.5 \mu\text{s}$ while preserving nonclassical correlations between the heralding and the retrieved photon. This is more than 20 times longer than in previous realizations in solid state devices, and implemented in a system ideally suited for the extension to spin-wave storage.

Phys. Rev. Lett. 112, 040504



Quantum storage up to $4.5 \mu\text{s}$

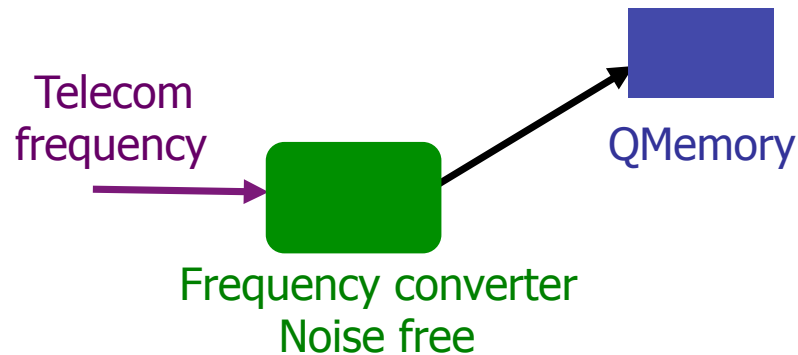


A quantum node
compatible with telecom photons

tools developed in WP1 and
WP2 are combined here

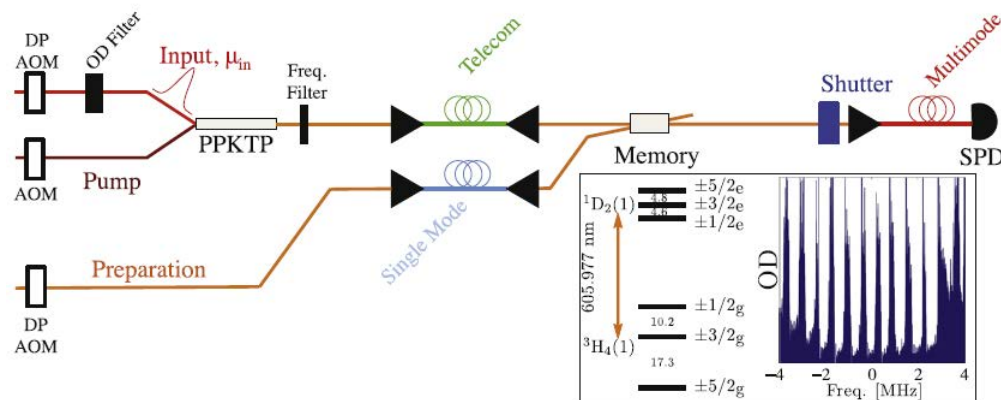
ICFO: Storage of up-converted photons

Storage of the single-photons
into Pr doped crystal



Storage of up-converted telecom photons

We report on an experiment that demonstrates the frequency up-conversion of telecommunication wavelength single-photon-level pulses to be resonant with a $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$ crystal. We convert the telecom photons at 1570 nm to 606 nm using a periodically-poled potassium titanyl phosphate nonlinear waveguide. The maximum device efficiency (which includes all optical loss) is inferred to be $\eta_{\text{dev}}^{\text{max}} = 22 \pm 1\%$ (internal efficiency $\eta_{\text{int}} = 75 \pm 8\%$) with a signal to noise ratio exceeding 1 for single-photon-level pulses with durations of up to 560 ns. The converted light is then stored in the crystal using the atomic frequency comb scheme with storage and retrieval efficiencies exceeding $\eta_{\text{AFC}} = 20\%$ for pre-determined storage times of up to 5 μs . The retrieved light is time delayed from the noisy conversion process allowing us to measure a signal to noise ratio exceeding 100 with telecom single-photon-level inputs. These results represent the first demonstration of single-photon-level optical storage interfaced with frequency up-conversion.



New Journal of Physics 16, 113021 (2014)

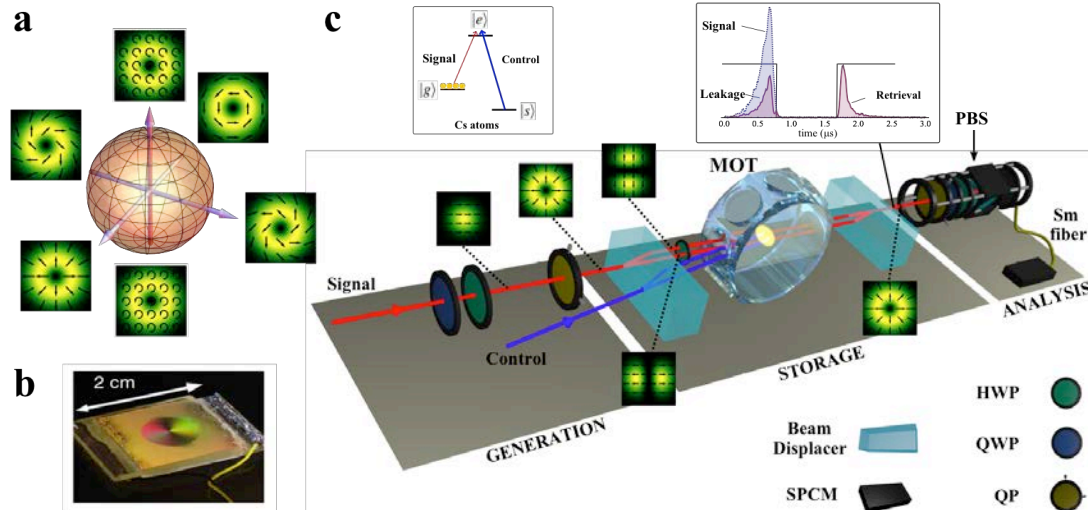
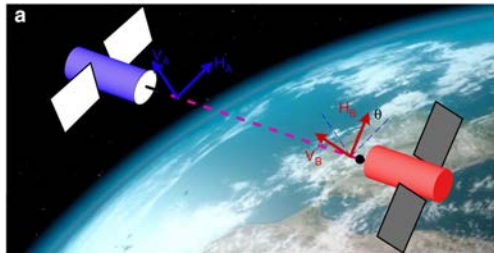
Outperforms (efficiency, storage time) the
previous absorptive telecom memory at
the single photon level

A quantum node
compatible with telecom photons

LKB: A memory for structured light

Quantum information encoded in
vector beams of light

A multiple-degree-of-freedom
quantum memory



Storage and retrieval of vector beams of light
in a multiple-degree-of-freedom quantum memory

The full structuration of light in the transverse plane, including intensity, phase and polarization, holds the promise of unprecedented capabilities for applications in classical optics as well as in quantum optics and information sciences. Harnessing special topologies can lead to enhanced focusing, data multiplexing or advanced sensing and metrology. Here we experimentally demonstrate the storage of such spatio-polarization-patterned beams into an optical memory. A set of vectorial vortex modes is generated via liquid crystal cell with topological charge in the optic axis distribution, and preservation of the phase and polarization singularities is demonstrated after retrieval, at the single-photon level. The realized multiple-degree-of-freedom memory can find applications in classical data processing but also in quantum network scenarios where structured states have been shown to provide promising attributes, such as rotational invariance.

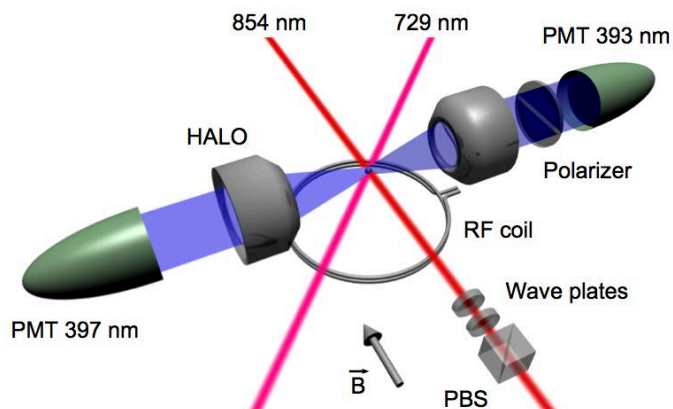
Under Review

Storage ~ 30%
Offers a universal quantum
memory for structured light
and rotationally-invariant qubits

Enters into WP3: Multiplexed quantum
memories in a network

Saarbrücken: Quantum state transfer

Quantum state
conversion from a
polarization-encoded
photon to an ion

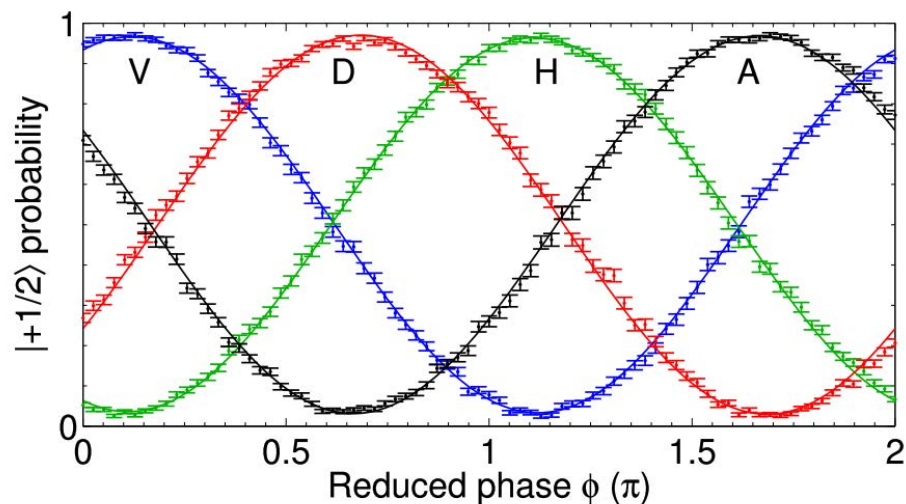


- Fidelity of the mapping above 95%
- Heralded process

High-fidelity heralded photon-to-atom quantum state transfer

Quantum network combines the benefits of quantum systems regarding secure information transmission and calculational speed-up by employing quantum coherence and entanglement to store, transmit, and process information. A promising platform for implementing such a network are atom-based quantum memories and processors, interconnected by photonic quantum channels. A crucial building block in this scenario is the conversion of quantum states between single photons and single atoms through controlled emission and absorption. Here we present an interface for photon-to-atom quantum state conversion, whereby the polarization state of an absorbed single photon is mapped onto the spin state of a single absorbing atom with >95% fidelity, while successful conversion is heralded by a single emitted photon. Heralding high-fidelity conversion without affecting the converted state is a main experimental challenge, in order to make the transferred information reliably available for further operations. Other approaches employ optical resonators or a deep parabolic mirror, but results so far have been inherently probabilistic with overall fidelities below 10%. We circumvent this limitation by our heralding protocol. We record >80/s successful quantum state transfer events out of 18,000/s repetitions.

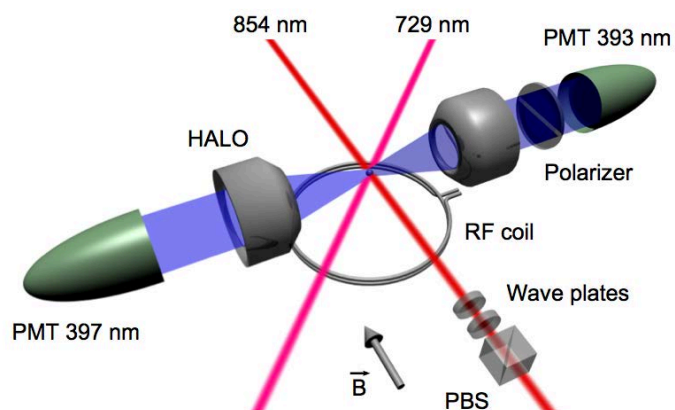
Nature Communications 5, 5527 (2014)



A very flexible interface ion-light interface
for bi-directional state transfer

Saarbrücken: Quantum state transfer

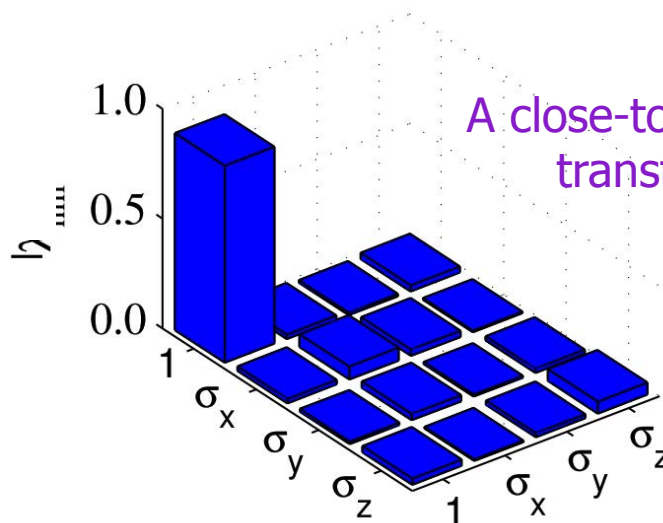
The other way round
atom-to-photon state
conversion



Ion-photon quantum interface for state mapping and entanglement

We realized a flexible, programmable interface for quantum state conversion between photons and atoms. Depending on its mode of operation, it serves as photon-to-atom quantum state converter or for its inverse, i.e. atom-to-photon state conversion, as well as for the generation of entangled atom-photon pairs, or for single-photon frequency conversion. The interface comprises single-ion gate operations conditioned on an absorbed or emitted photon.

In preparation



A very flexible interface ion-light interface
for bi-directional state transfer

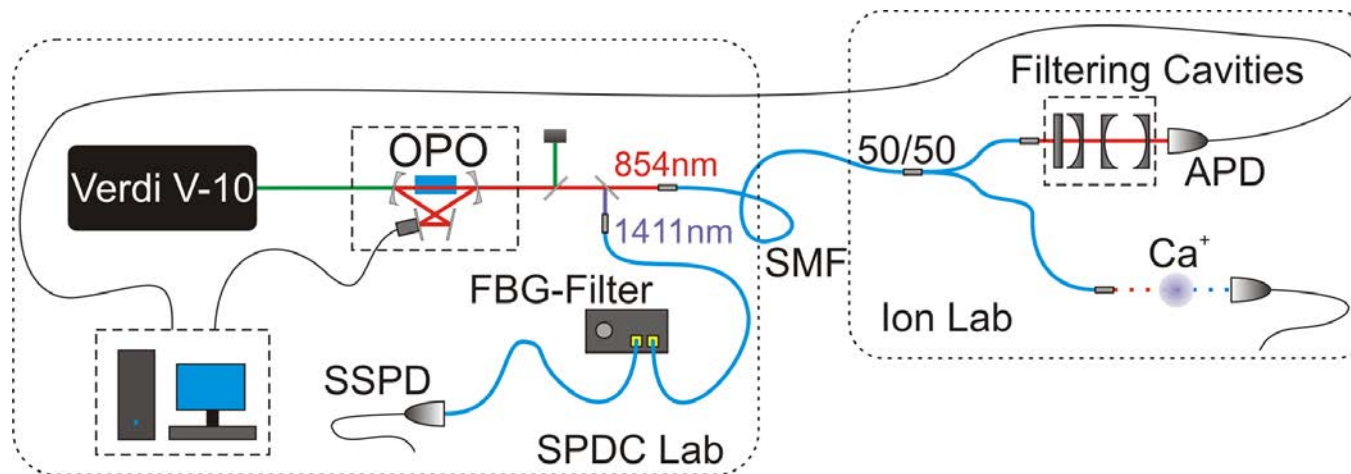
Saarbrücken: telecom-coupled ion

Absorption a telecom photon into a single-ion

Telecom heralded single-photon absorption by a single ion

We present, characterize, and apply a photonic quantum interface between the near infrared and telecom spectral regions. A singly resonant optical parametric oscillator (OPO) operated below threshold generates high-rate narrowband photon pairs; the signal photons are tuned to resonance with an atomic transition in Ca^+ , while the idler photons are at telecom wavelength. Quantum interface operation is demonstrated through the absorption of a single photon by a single trapped ion, heralded by a telecom photon.

In preparation



Telecom-heralded single photon are absorbed by the single-trapped ion

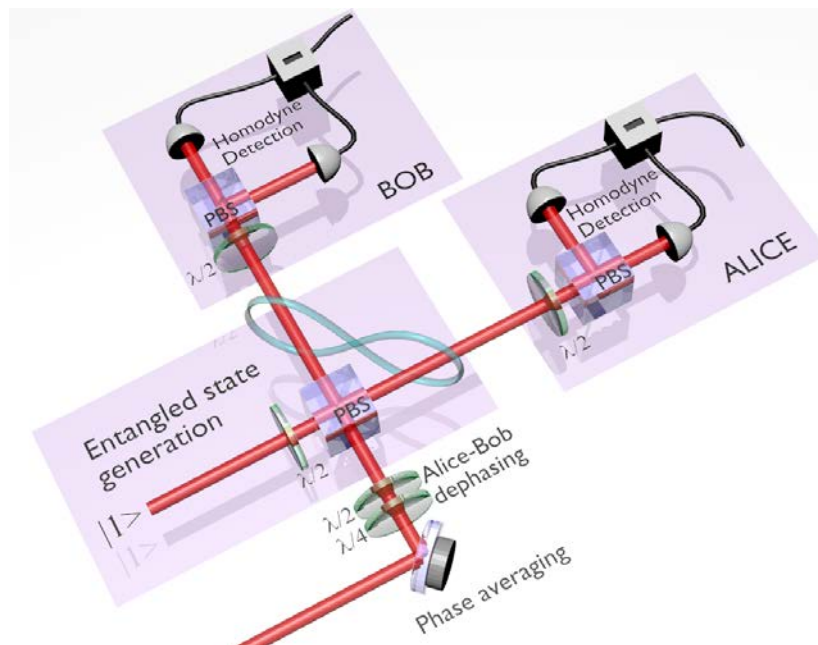
Enters into WP3: coupling ion to a telecom network

GAP - LKB: Witnessing Operational Networks

A witness for single-photon entanglement using only local homodyne measurements

Witnessing single-photon entanglement with local homodyne measurements: analytical bounds and robustness to losses

Single-photon entanglement is one of the primary resources for quantum networks, including quantum repeater architectures. Such entanglement can be revealed with only local homodyne measurements through the entanglement witness presented in [Morin *et al.* Phys. Rev. Lett. **110**, 130401 (2013)]. Here, we provide an extended analysis of this witness by introducing analytical bounds and by reporting measurements confirming its great robustness with regard to losses. This study highlights the potential of optical hybrid methods, where discrete entanglement is characterized through continuous-variable measurements.



Physical Review Letters 100, 130401 (2013)
New Journal of Physics 16, 103035 (2014)

Robustness demonstrated
up to 80 km of telecom fibers

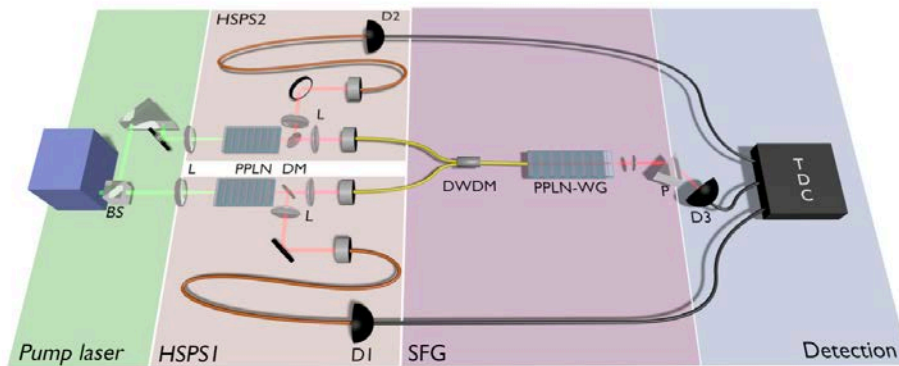
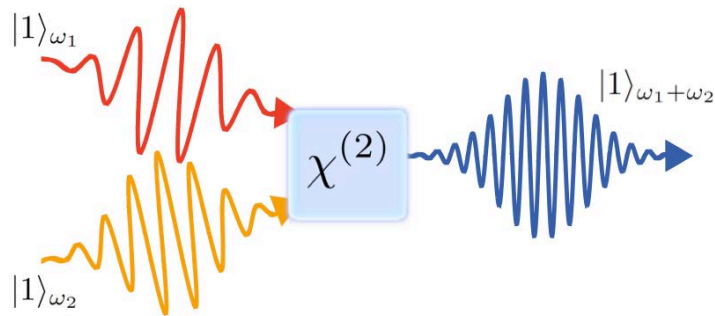
Well-suited for a large-scale networks

Enters into WP4: Verifying the functionality of a quantum network

GAP: NL Interactions between single-photons

Sum-frequency generation
between heralded single-
photons at telecom
frequencies

Non-linear interactions between two heralded single-photons
Physical Review Letters 113, 173601 (2014)



Detailed study with doped crystals led
to an alternative implementation

➔ First demonstration with waveguide

Enters into WP4: Towards more deterministic
operations in a network



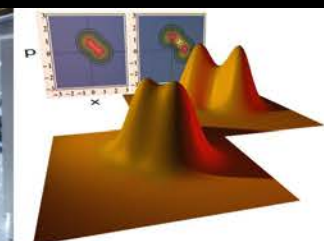
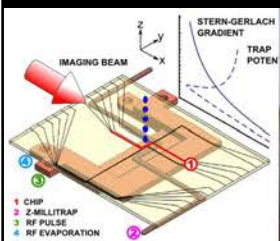
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