QScale

Quantum technologies for extending the range of quantum communications

The QScale Project

09/2011 to 08/2014

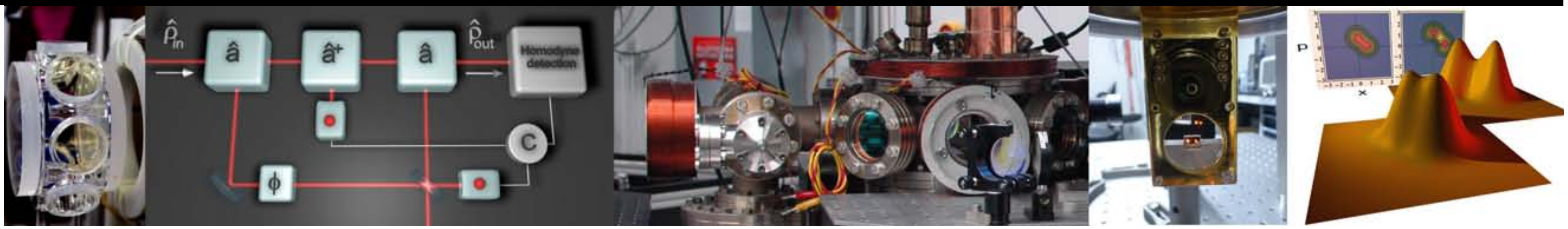
Coordinator: Julien Laurat

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

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

Istanbul, March 2014

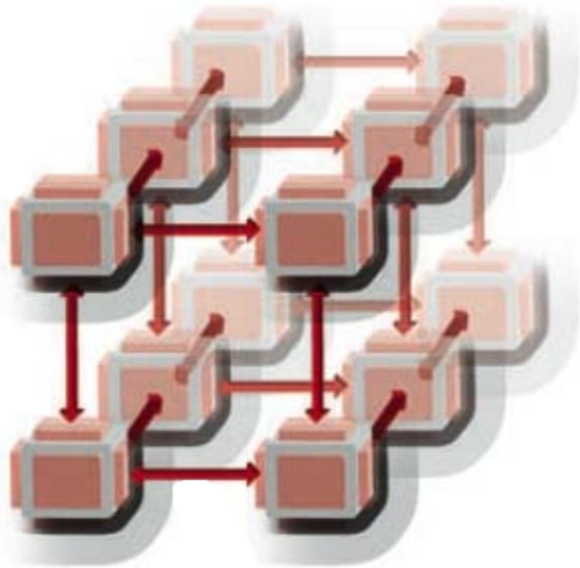
chist-era



The General Content of QScale

<u>Quantum node</u>
generate, process, store
quantum information locally

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

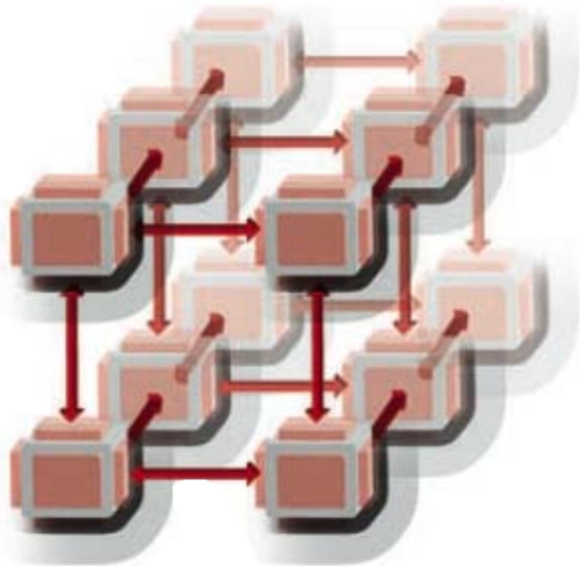


<u>Quantum channel</u>
transport / distribute
quantum information
over the entire network

The General Content of QScale

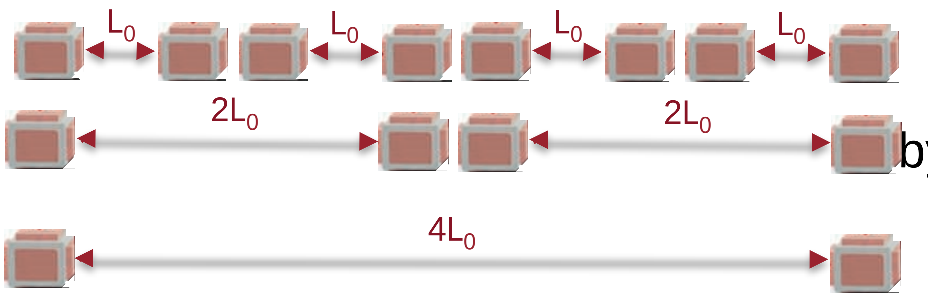
<u>Quantum node</u>
generate, process, store
quantum information locally

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



<u>Quantum channel</u>
transport / distribute
quantum information
over the entire network

One example: 'Quantum Repeater'



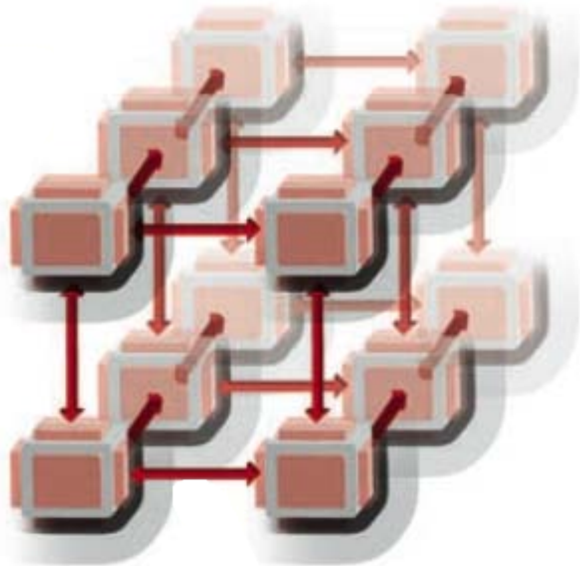
Entanglement Distribution
on distances larger than set
by the attenuation length of fibers

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

The General Content of QScale

<u>Quantum node</u>
generate, process, store
quantum information locally

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



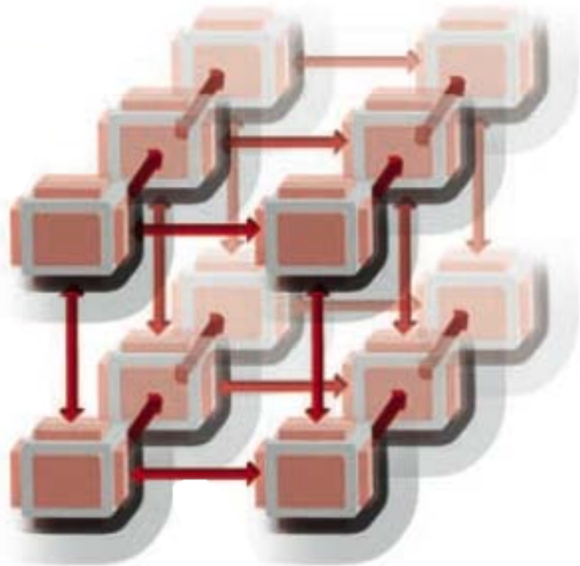
<u>Quantum channel</u>
transport / distribute
quantum information
over the entire network

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

The General Content of QScale

Quantum node
generate, process, store
quantum information locally



Quantum channel
transport / distribute
quantum information
over the entire network

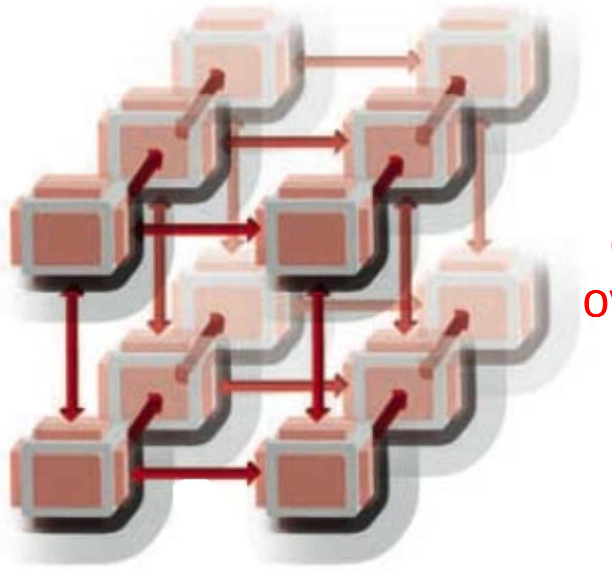
Scalable Q. Communication
Distributed Q. computing
Quantum resource sharing
Quantum simulation

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

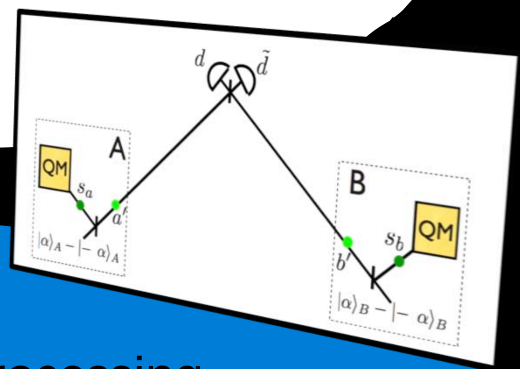
The General Content of QScale

<u>Quantum node</u>
generate, process, store
quantum information locally



<u>Quantum channel</u>
transport / distribute
quantum information
over the entire network

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

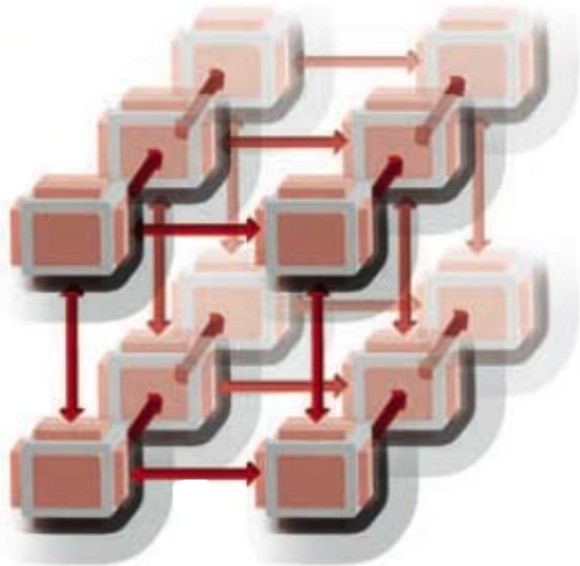


Implementation ?

- 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

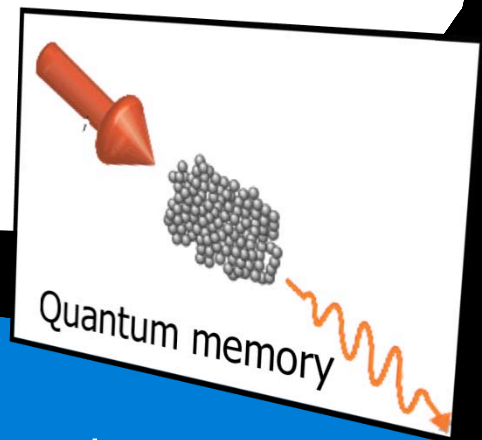
The General Content of QScale

Quantum node
generate, process, store
quantum information locally



Quantum channel
transport / distribute
quantum information
over the entire network

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

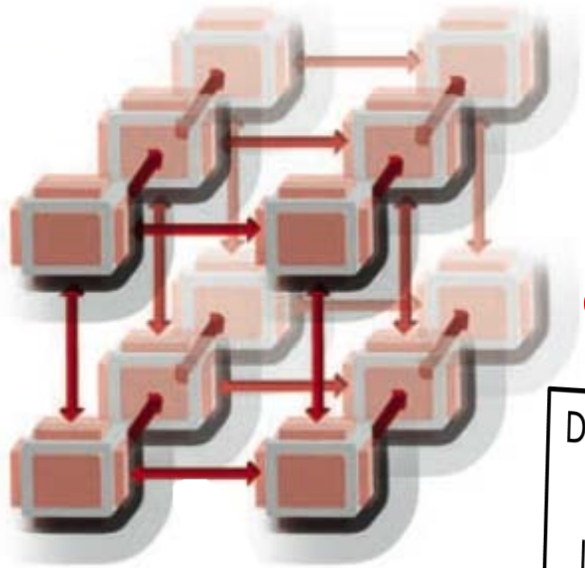


Implementation ?

- 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

The General Content of QScale

<u>Quantum node</u>
generate, process, store
quantum information locally



<u>Quantum channel</u>
transport / distribute
quantum information
over the entire network

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

Discrete/continuous encodings

Single photons, Squeezed light, Non-gaussian states,..

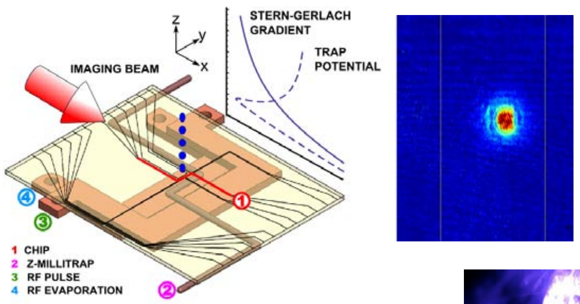
Doped crystals, cold and ultra-cold atoms, ion strings

Implementation ?

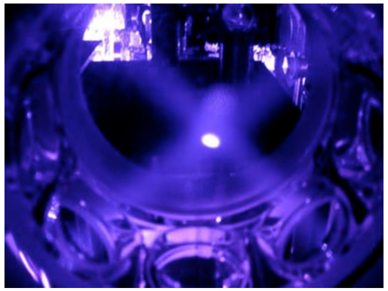
- Physical processes for reliable generation, processing, & transport of quantum states (including novel architectures)
- Quantum interfaces between matter and light
- Networks will be heterogeneous : Various kind of photonic carriers, of encodings and of material systems

The Tools of QScale

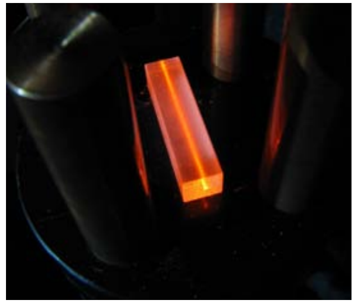
- Bose-Einstein Condensate on chip



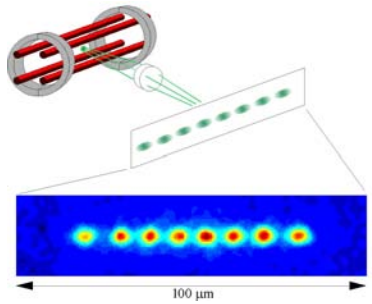
- Cold atoms in 2D-MOT and dipole trap



- Rare-earth ion doped crystals

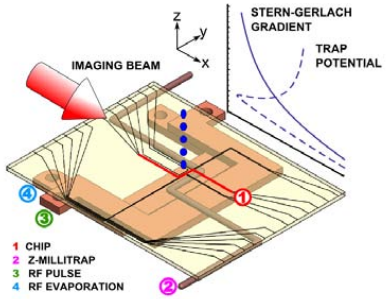


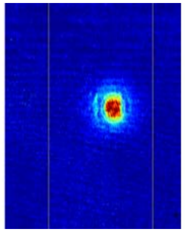
- Trapped ion strings



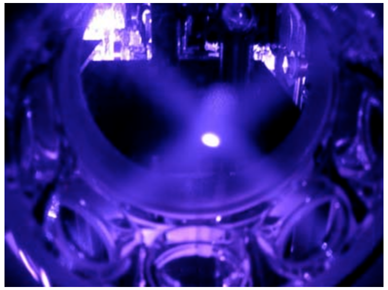
The Tools of QScale

- Bose-Einstein Condensate on chip

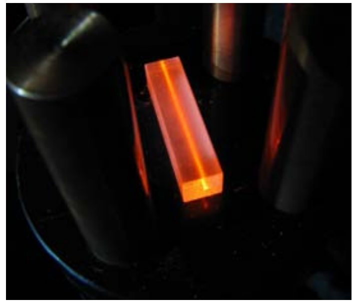




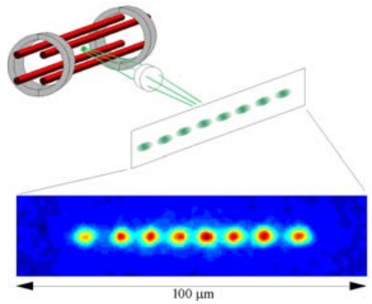
- Cold atoms in 2D-MOT and dipole trap



- Rare-earth ion doped crystals



- Trapped ion strings



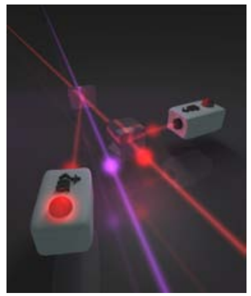
- Discrete degrees of freedom

  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

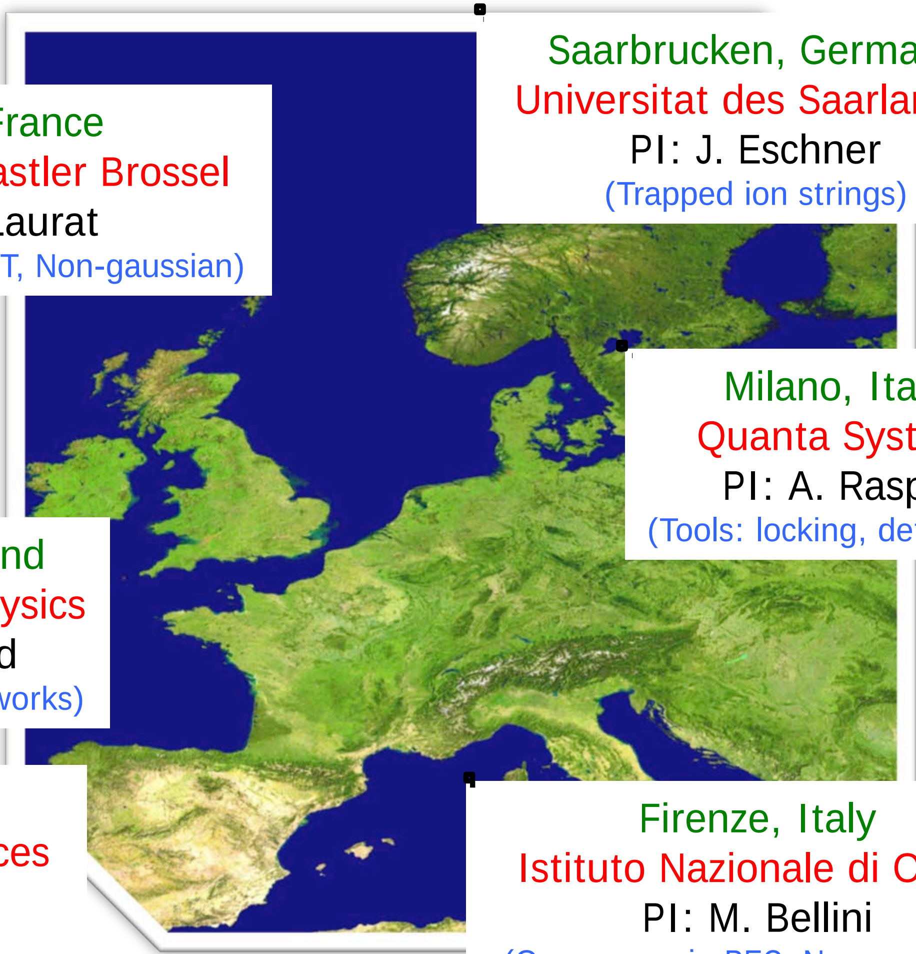
QScale

The QScale Consortium

5 academic partners
1 industrial partner

5 countries

Funding: ~1 M€
400 person months



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

Saarbrucken, Germany
Universitat des Saarlandes
PI: J. Eschner
(Trapped ion strings)

Milano, Italy
Quanta System
PI: A. Raspa
(Tools: locking, detection)

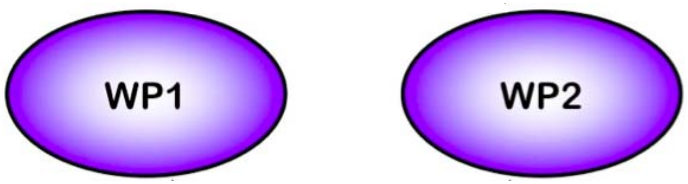
Geneva, Switzerland
Group of Applied Physics
PI: N. Sangouard
(Theory of quantum networks)

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)

QScale

QScale WorkPackages



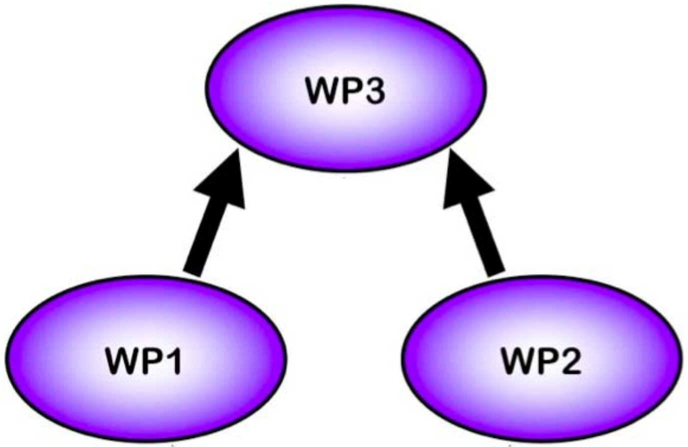
WP1: Photonic components for quantum architecture

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.

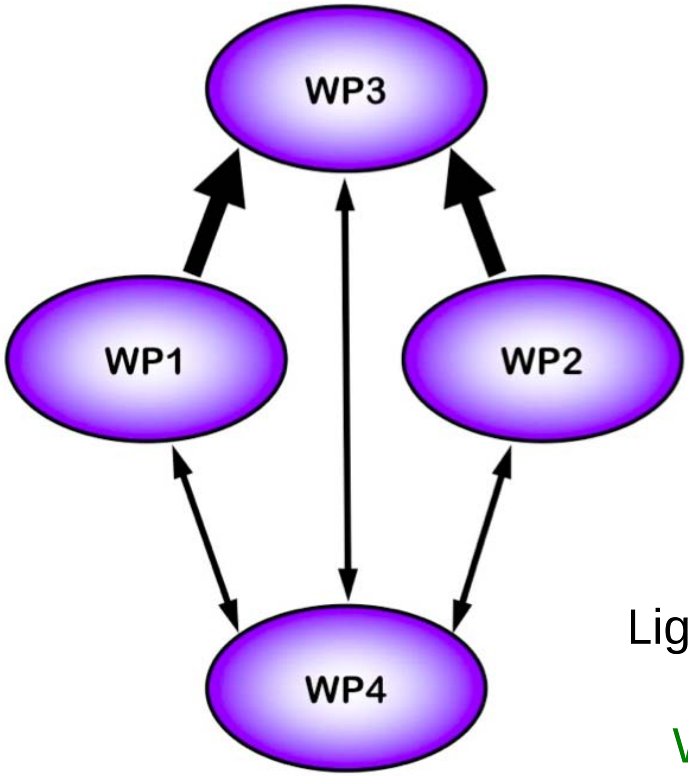
WP2: Controlling light-matter interfaces

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

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

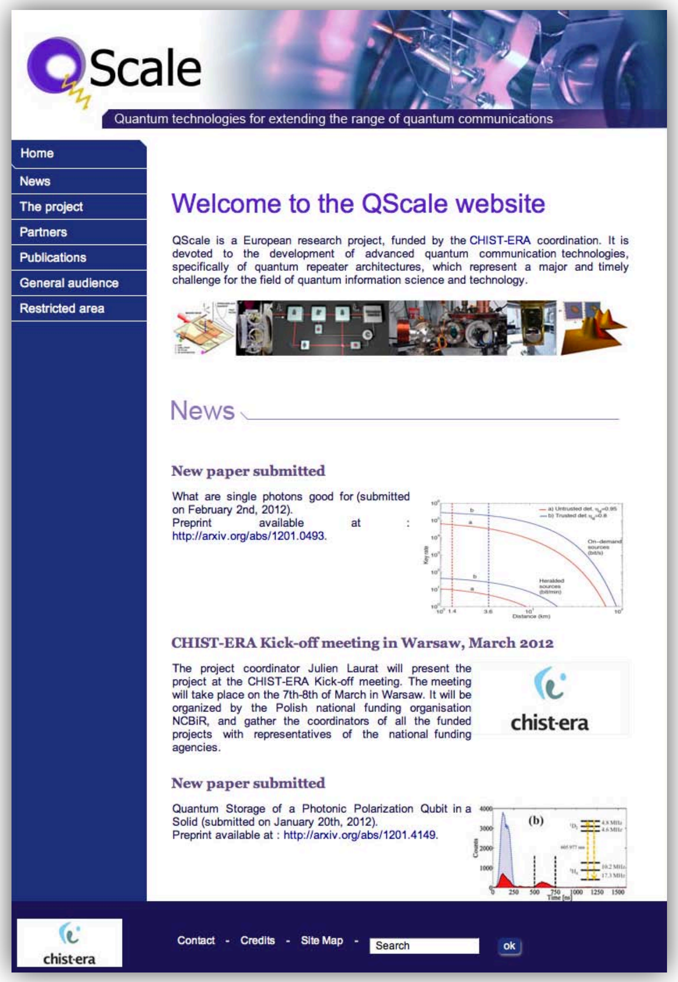
Investigating new architectures and characterization for operational repeaters (e.g. hybrid schemes, heralded qubit amplifier, deterministic operations, witnesses)

QScale

Quantum technologies for extending the range of quantum communications

QScale Website

- A website
  www.chistera-qscale.eu
  Partners, Workpackages
  Workshop programs
  Papers from the consortium
  General audience page



Kick-off Meeting in 2011

- Kick-off, Paris, October 2011
  25 researchers, 9 talks
  2 discussion sessions
  Presentation of the groups
  Consortium agreement validated

chist-era

"QScale: extending the range of quantum communications"

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

Location : Laboratoire Kasiter 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

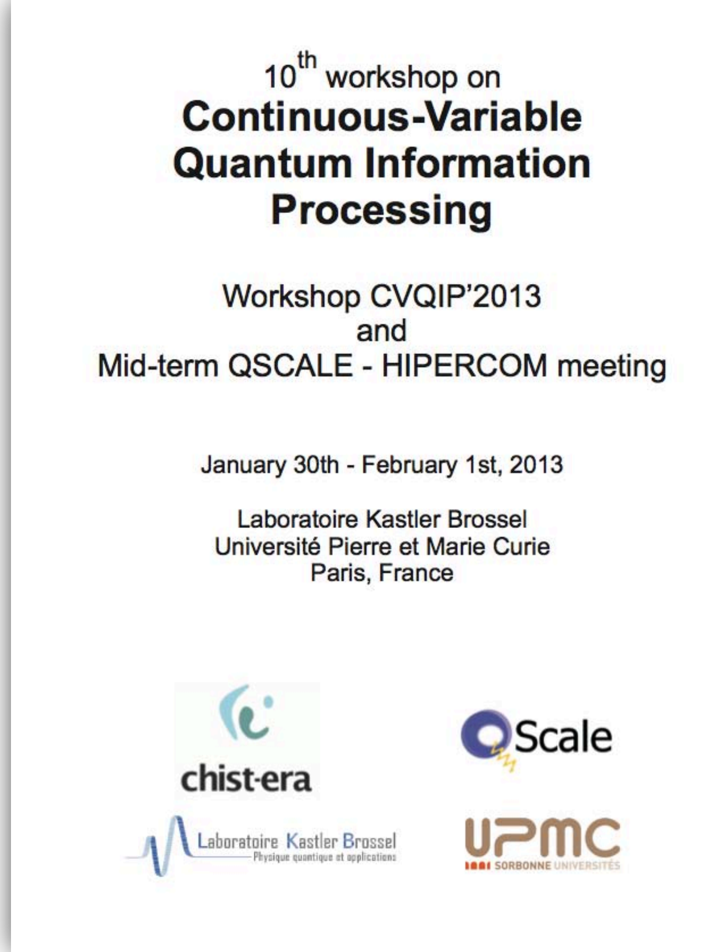
14:30-14:45	Introduction, J. Laurat (LKB)
14:45-15:30	Towards long-lived solid state quantum memories with spin wave storage, H. de Riedmatten (ICFO)
15:30-16:00	Towards quantum memories with cold atoms, P. Lombardi (INO)
16:00-16:30	Coffee Break
16:30-17:00	Towards the deterministic entanglement of 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 Maitre 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. Ferrario (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

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

chist-era
QScale
Laboratoire Kastler Brossel
Physique quantique et applications
UPMC
SORBONNE UNIVERSITÉS

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

Laboratoire Kastler Brossel — CNRS — UPMC Sorbonne Universités — QScale

"Informal Workshop on Atomic Ensembles"

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

Location : Laboratoire Kasiter 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	Introductive 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 Geoffrey 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)

Next 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

QScale 'Metrics'

- 31 papers in international peer-reviewed journals
  - 9 Physical Review Letters, 1 Nature Photonics
  - 5 'common' papers between QSCALE partners
- 75 contributions in international meetings and workshops

WP1: Photonic components for quantum architecture → 11 papers

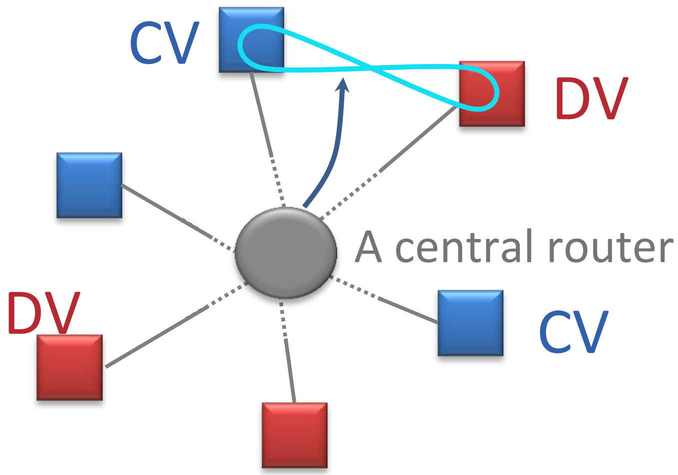
WP2: Controlling light-matter interfaces → 14 papers

WP3: Q. repeaters building blocks → 1 paper

WP4: Novel architectures and tools for repeaters → 5 papers

LKB and INO: A novel form of entanglement

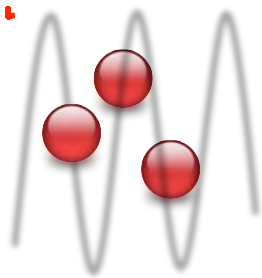
- A heterogeneous network



A resource for teleportation and encoding conversion

Opens the way to heterogeneous networks

LKB and INO
Hybrid Entanglement
A novel form of entanglement following two different strategies



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

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

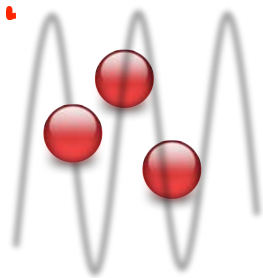
Hybrid entanglement between
particle-like and wave-like optical qubits

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

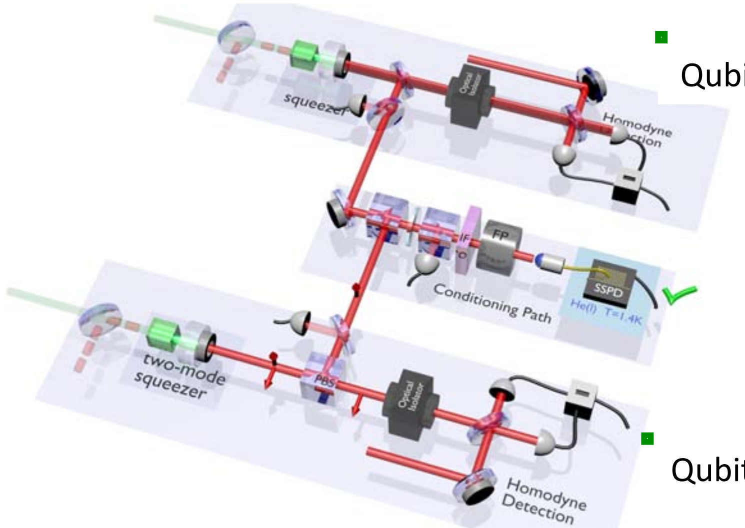
LKB and INO: A novel form of entanglement

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

LKB and INO
Hybrid Entanglement
A novel form of entanglement
following <u>two different strategies</u>



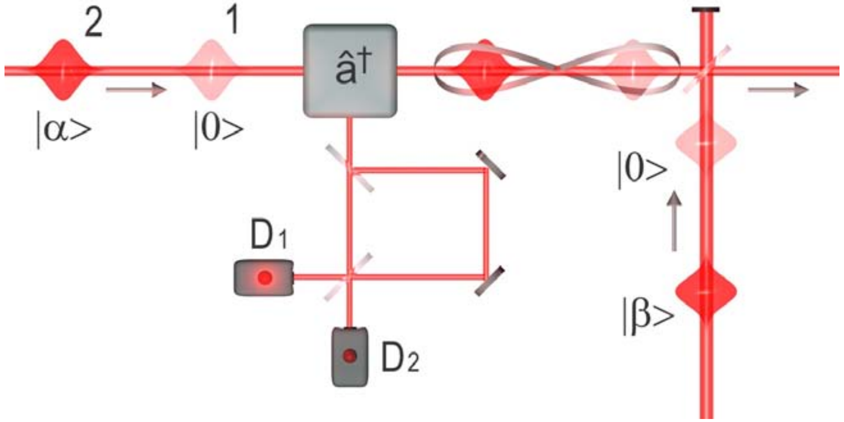
- Remote creation of hybrid entanglement between particle-like and wave-like optical qubits (CW)



- Qubit CV
- Qubit DV

LKB, arXiv: 1309.6191

- Entangling quantum and classical states of light (pulsed)



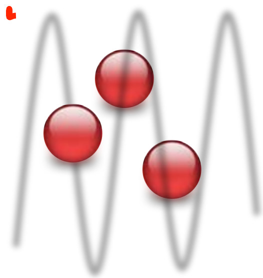
INO, arXiv: 1309.6192

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

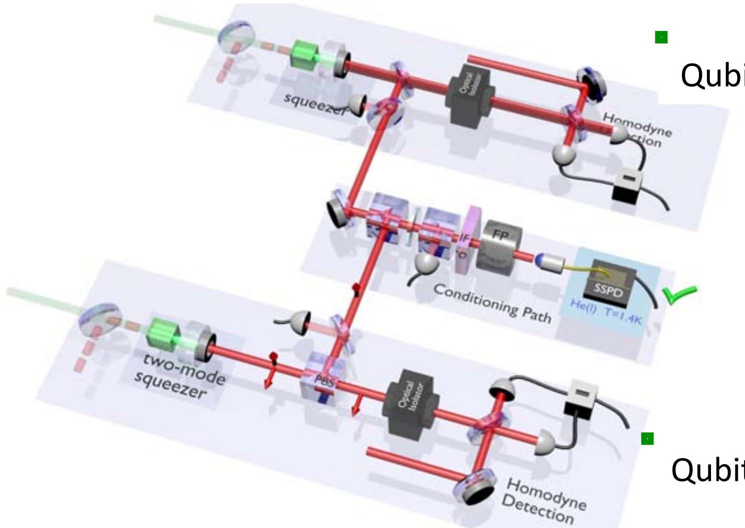
LKB and INO: A novel form of entanglement

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

LKB and INO
Hybrid Entanglement
A novel form of entanglement
following <u>two different strategies</u>

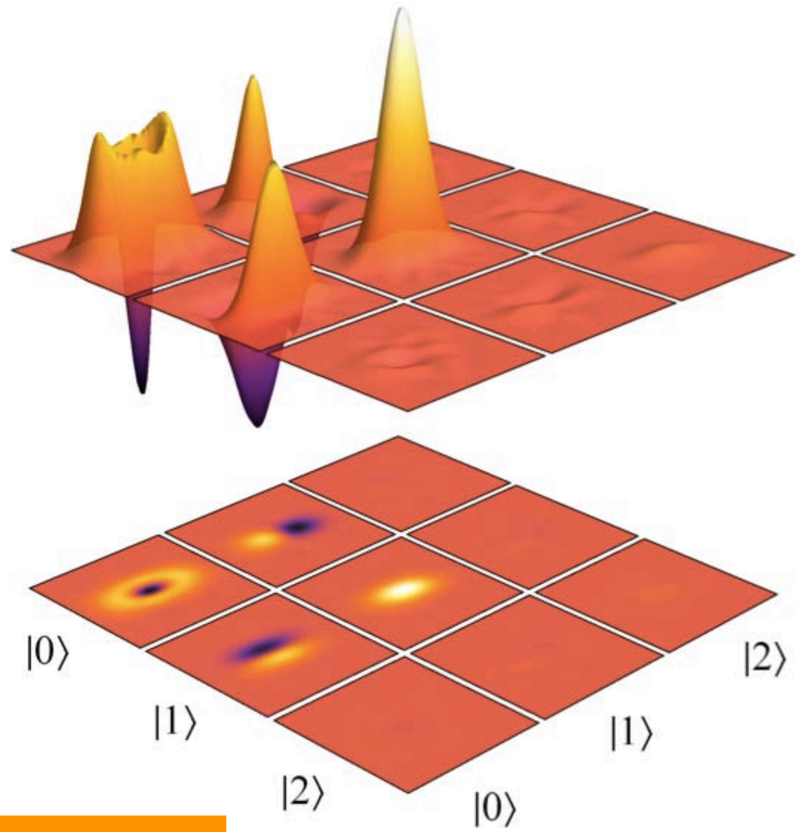


- Remote creation of hybrid entanglement between particle-like and wave-like optical qubits (CW)



- Qubit CV
- Qubit DV

LKB, arXiv: 1309.6191



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

ICFO: A compatible single-photon source

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

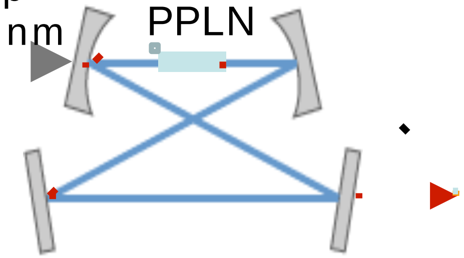
Ultranarrow-Band Photon-Pair Source Compatible with Solid State Quantum Memories and Telecommunication Networks

We report on a source of ultranarrow-band photon pairs generated by widely nondegenerate cavity-enhanced spontaneous down-conversion. The source is designed to be compatible with Pr^{3+} solid state quantum memories and telecommunication optical fibers, with signal and idler photons close to 606 nm and 1436 nm, respectively. Both photons have a spectral bandwidth around 2 MHz, matching the bandwidth of Pr^{3+} doped quantum memories. This source is ideally suited for long distance quantum communication architectures involving solid state quantum memories.

Phys. Rev. Lett. 110, 220502

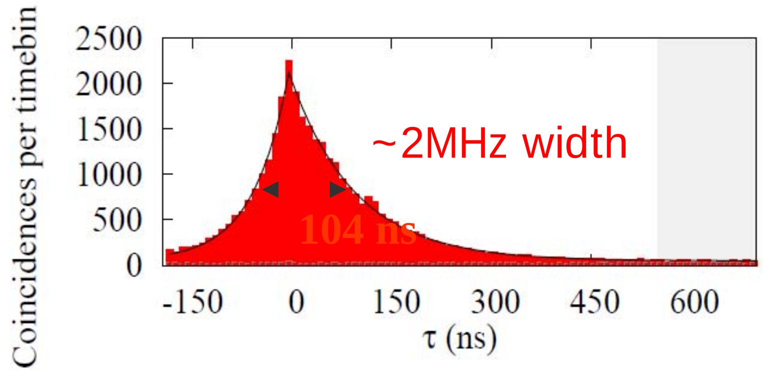
Pump @ 426 nm

PPLN



Signal @ 606 nm

Idler @ 1436 nm



First quantum light source compatible with spin-wave solid memory

Enters into WP1: single-photons compatible with quantum memories

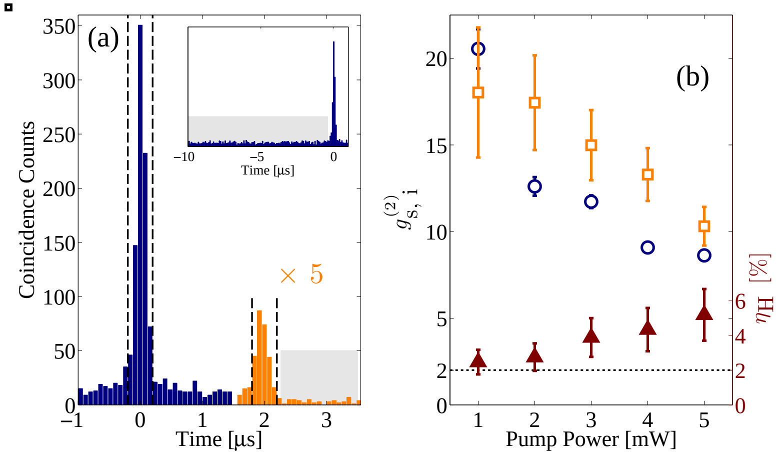
ICFO: Storage in doped crystal

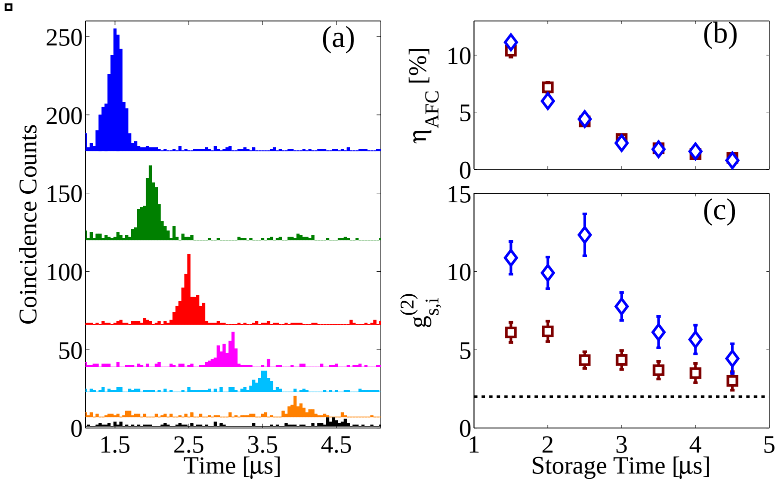
Storage of the non-classical light into Pr doped crystal

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 $Pr^{3+}:Y_2SiO_5$ 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 μs 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



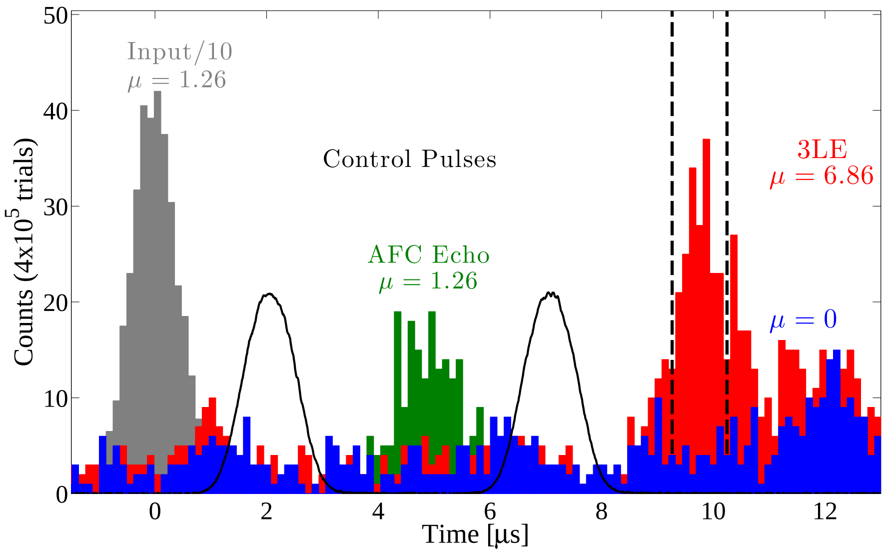


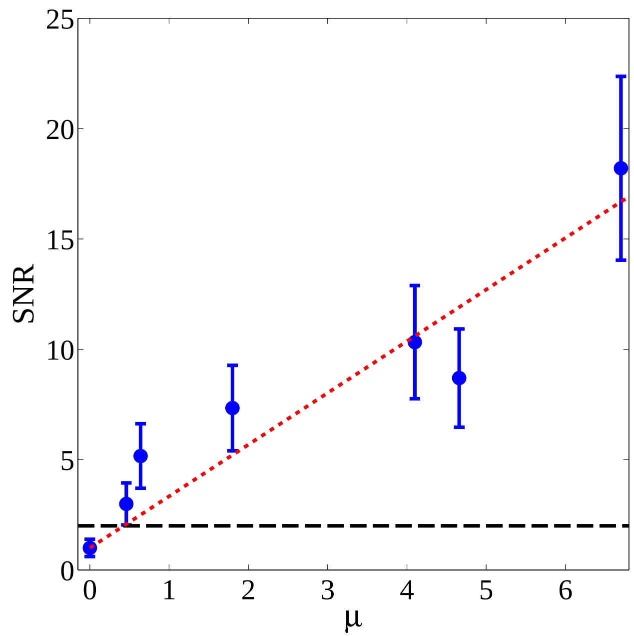
Quantum storage up to 4.5 µs

One milestone of WP3: tools developed in WP1 and WP2 are combined here

ICFO: Towards longer storage time

Storage of single-photon level pulses using spin-wave atomic frequency comb technique





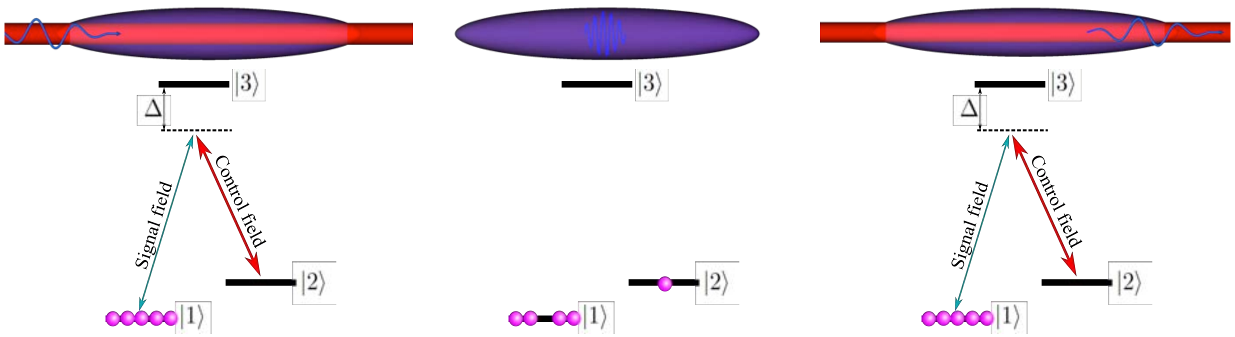
Signal to noise ratio of 2 is achieved for a level of 0.5 photon per pulse

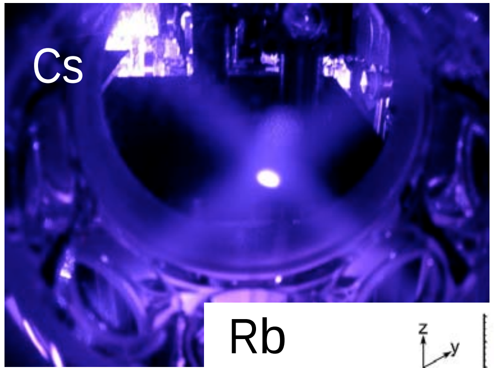
Enters into WP2: towards a long-lived storage of single-photons in doped crystal

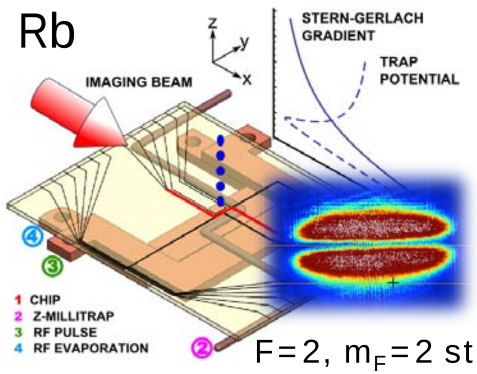
LKB and INO: EIT in atomic ensembles

EIT for quantum storage in large atomic ensembles

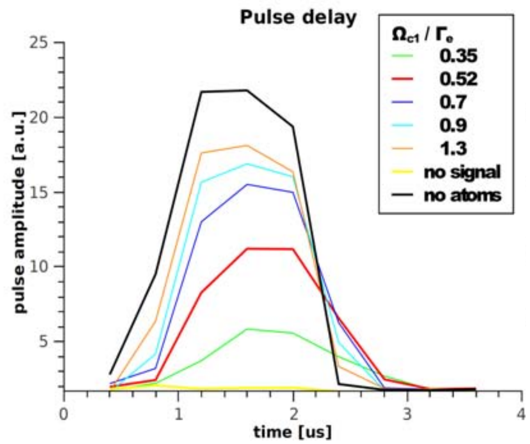
Two systems under study: large MOT (LKB) and BEC (INO)

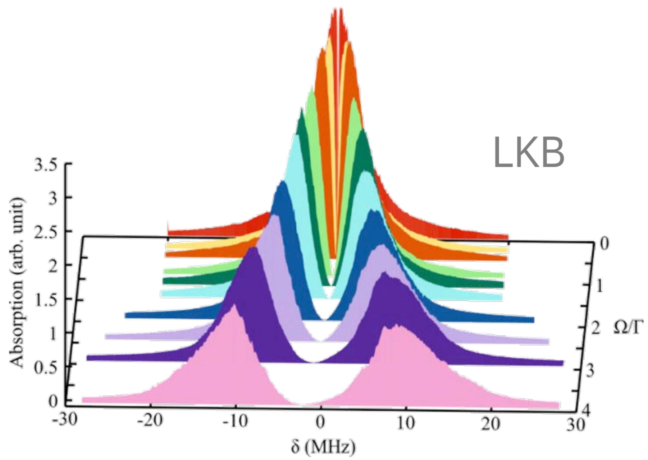






F=2, m_F=2 state





Phys. Rev. A 87, 013823 (2013)

Detailed investigation of EIT behavior in these systems

Enter into WP2: preparation of the atomic medium and memory optimization

LKB: Storage of qubit encoded in OAM

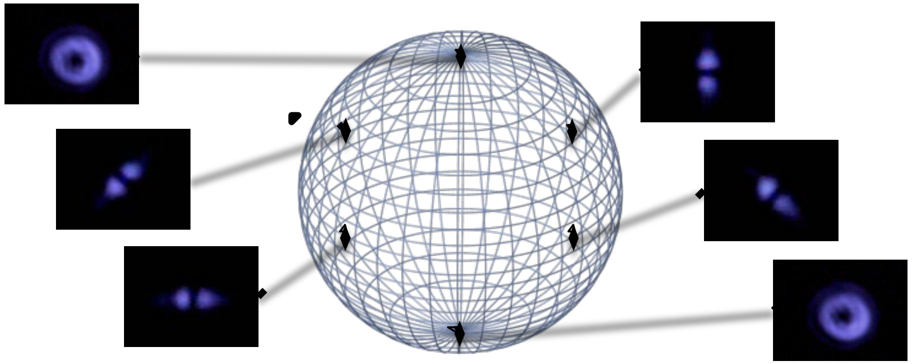
Qubit encoded in Orbital Angular Momentum superposition

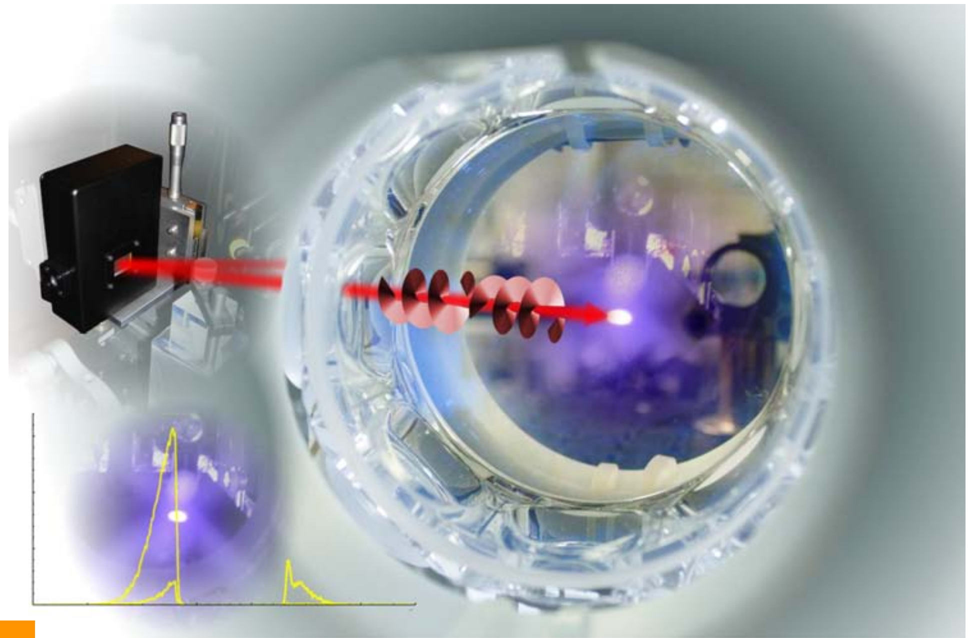
High-dimensional QIP

A quantum memory for orbital angular momentum photonic qubits

Among the optical degrees of freedom, the orbital angular momentum of light provides unique properties, including mechanical torque action with applications for light manipulation, enhanced sensitivity in imaging techniques and potential high-density information coding for optical communication systems. Recent years have also seen a tremendous interest in exploiting orbital angular momentum at the single-photon level in quantum information technologies. In this endeavor, here we demonstrate the implementation of a quantum memory for quantum bits encoded in this optical degree of freedom. We generate various qubits with computer-controlled holograms, store and retrieve them on demand using the dynamic electromagnetically-induced transparency protocol. We further analyse the retrieved states by quantum tomography and thereby demonstrate fidelities exceeding the classical benchmark, confirming the quantum functioning of our storage process. Our results provide an essential capability for future networks exploring the promises of orbital angular momentum of photons for quantum information applications.

Nature Photonics, AOP February 2014





Fidelity above 92%, beating any classical benchmark

Scalability: up to 100 modes

Enters into WP2: light-matter interfaces, towards high-capacity networks

INO: New proposal for Q. memories

A novel scheme for storing and retrieving frequency-entangled single-photons

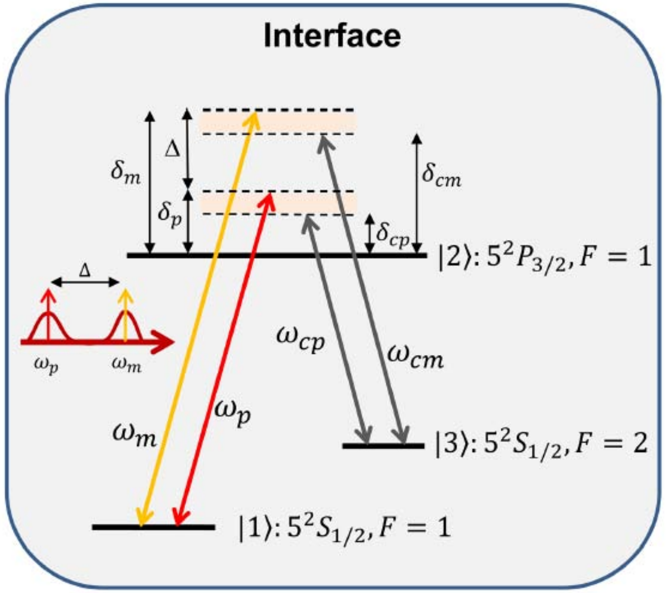
Harnessing the frequency degree of freedom

Manipulating frequency-bin entangled state in cold atoms

Optical manipulation of entanglement harnessing the frequency degree of freedom is important for encoding of quantum information. We here devise a phase-resonant excitation mechanism of an atomic interface where full control of a narrowband single-photon two-mode frequency entangled state can be efficiently achieved. We illustrate the working physical mechanism for an interface made of cold ^{87}Rb atoms where entanglement is well preserved from degradation over a typical 100 μm length scale of the interface and with fractional delays of the order of unity. The scheme provides a basis for efficient multi-frequency and multi-photon entanglement, which is not easily accessible to polarization and spatial encoding.

Sci. Rep. 4, 3941 (2014)

$$|\Phi_e\rangle = \frac{1}{\sqrt{2}}\left(|0_m,1_p\rangle + e^{i\phi_\eta}|1_m,0_p\rangle\right)$$



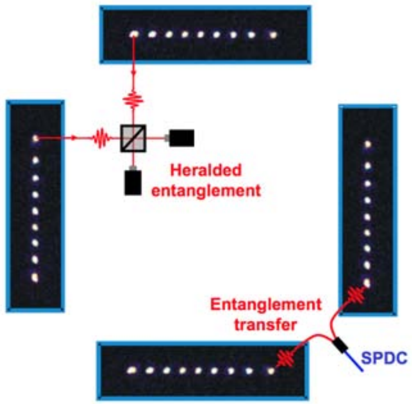
Using frequency encoded states in quantum networks, just like classical information has done from frequency multiplexing

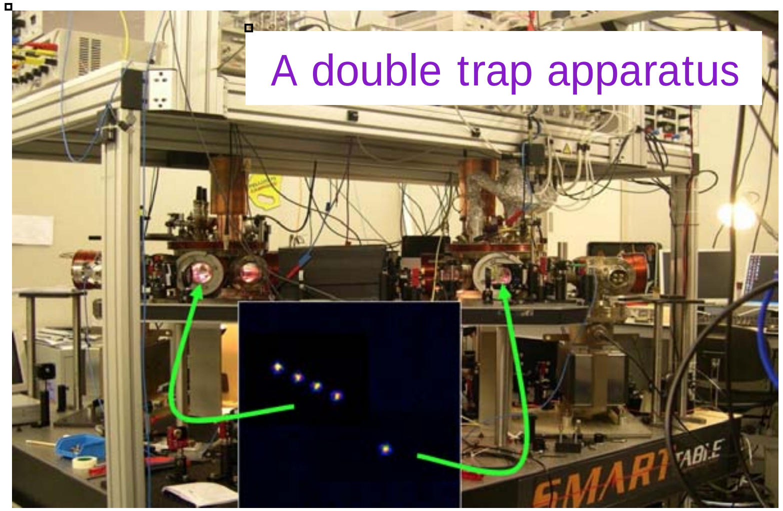
Enters into WP2: light-matter interfaces, towards high-capacity networks

Saarbrucken: Control of Ion Strings

Quantum network with ion strings

Enable a local processing widely developed for Q. computing





Two enabling works recently:

- A high rate source for single photons emitted from trapped ion
- Heralded interaction between distant ions

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

Saarbrucken: Heralded interaction

Making single-ions at remote place interact in a heralded fashion

▪

Heralded photonic interaction between distant single ions

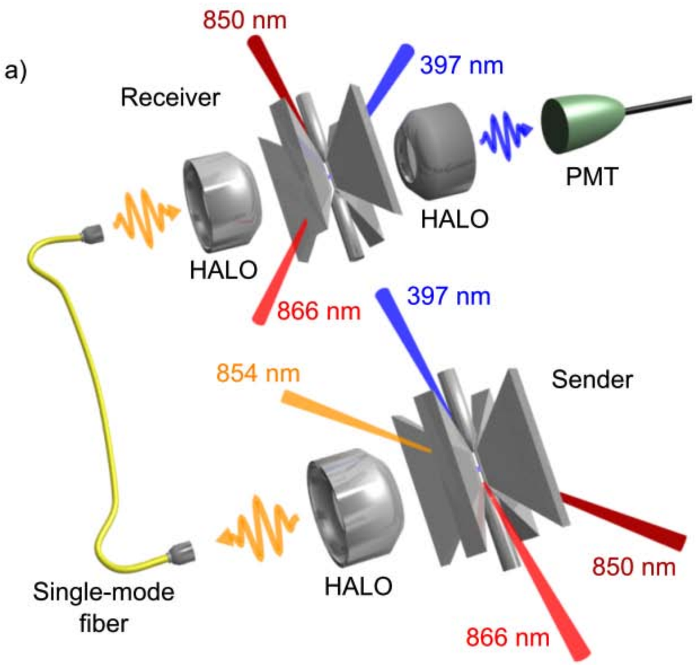
M. Schug[1,*] J. Huwer[1,2], C. Kurz[1], P. Müller[1], and J. Eschner[1]

[1] *Universität des Saarlandes, Experimentalphysik, Campus E2 6, 66123 Saarbrücken, Germany*

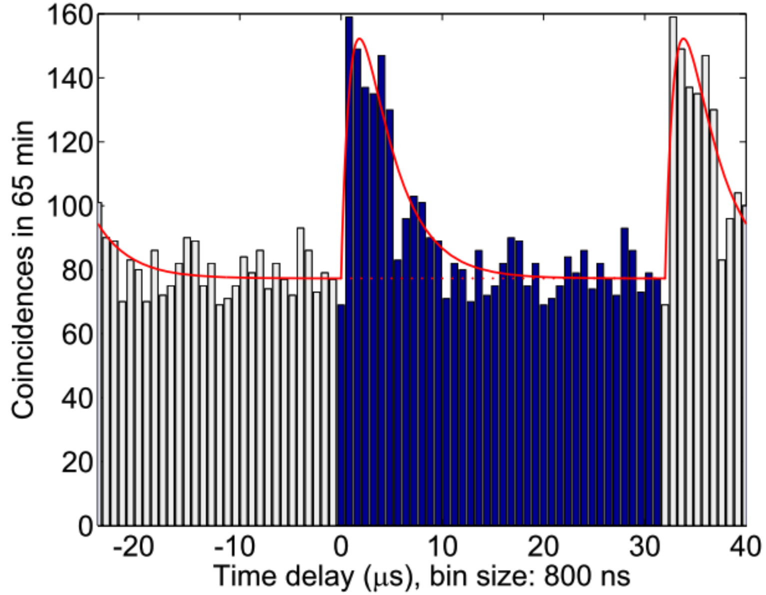
[2] *ICFO – The Institute of Photonic Sciences, Av. Carl Friedrich Gauss 3, 08860 Castelldefels (Barcelona), Spain*

(Dated: March 15, 2013)

We establish heralded interaction between two remotely trapped single $^{40}Ca^+$ ions through the exchange of single photons. In the sender ion, we release single photons with controlled temporal shape on the $P_{3/2}$ to $D_{5/2}$ transition and transmit them to the distant receiver ion. Individual absorption events in the receiver ion are detected by quantum jumps. For continuously generated photons, the absorption reduces significantly the lifetime of the long-lived $D_{5/2}$ state. For triggered single-photon transmission, we observe coincidence between the emission at the sender and quantum jump events at the receiver.



Phys. Rev. Lett. 110, 213603



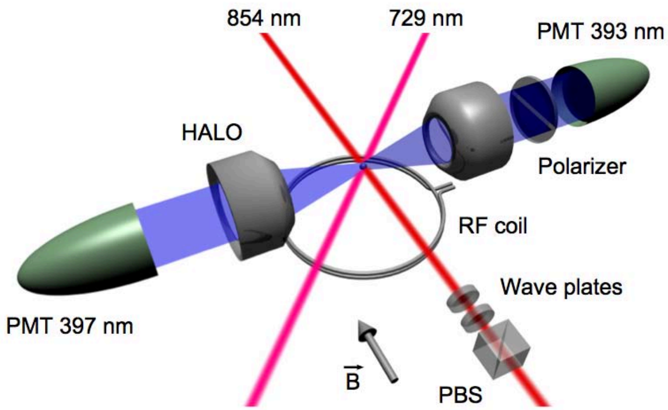
Triggered single photons are generated in one ion and transferred to another one at a distance. Absorption observed by quantum jumps

Saarbrucken: Quantum state transfer

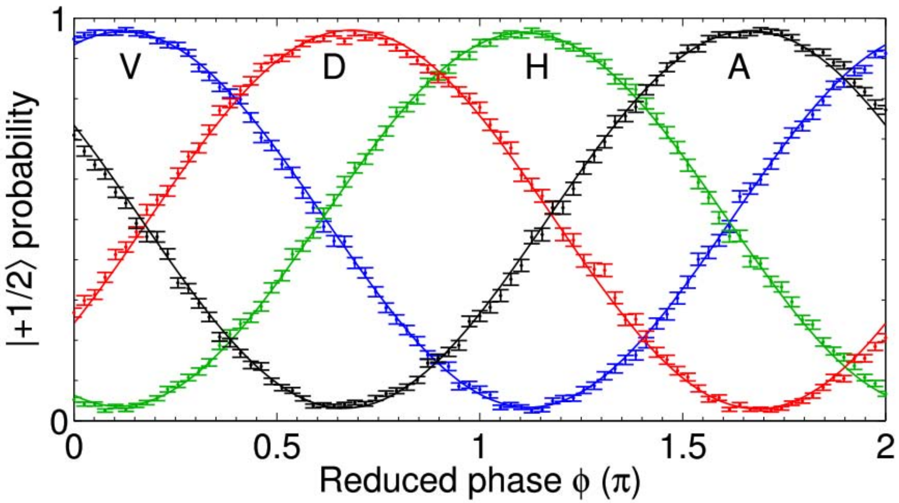
Quantum state conversion from a polarization-encoded photon to an ion

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.



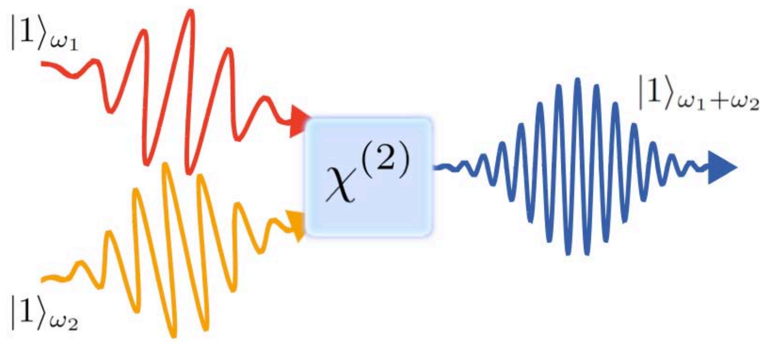
arXiv:1312.5995



- Fidelity of the mapping above 95%
  - Heralded process

Enters into WP2: enabling process for implementing WP3

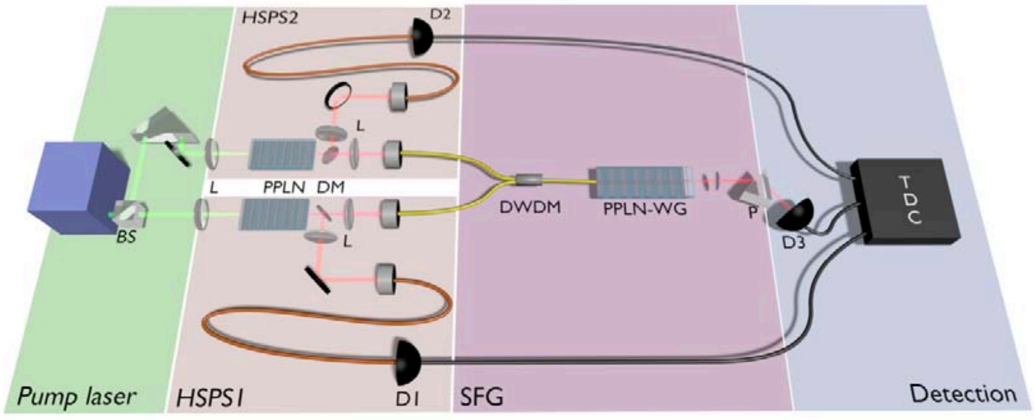
GAP: NL Interactions between single-photons



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

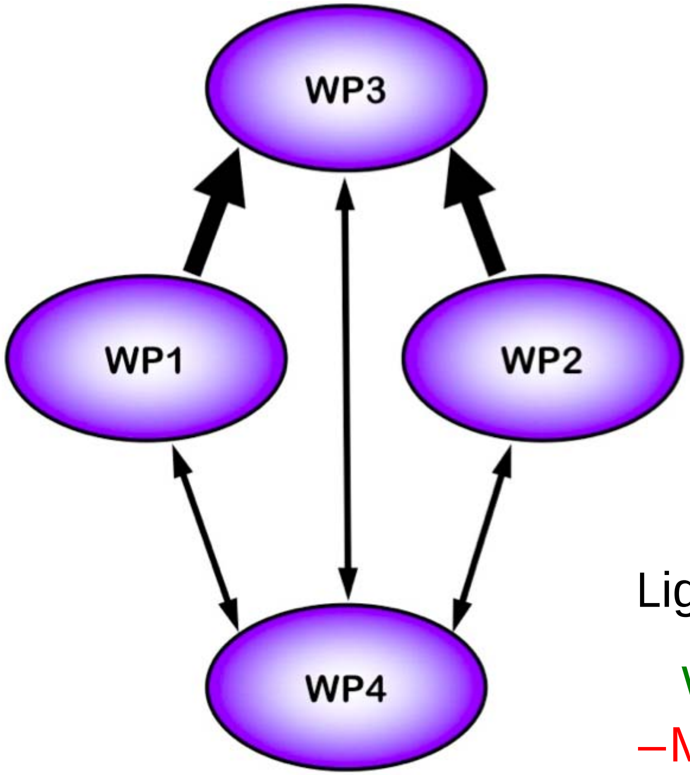
Detailed study with doped crystals led to an alternative implementation

Experimental work in progress, not initially planned in Qscale.



Enters into WP4: Towards more deterministic operations in a network

QScale WorkPackages



WP1: Photonic components for quantum architecture –Mostly achieved

Non-classical light and non-Gaussian operations.

WP2: Controlling light-matter interfaces –Many deliverables done, some delays

Memories in ensembles and control of ion strings.

WP3: Demonstration of Q. repeaters building blocks –In progress, mostly 3rd year

Light-matter, matter-matter entanglement, node processing

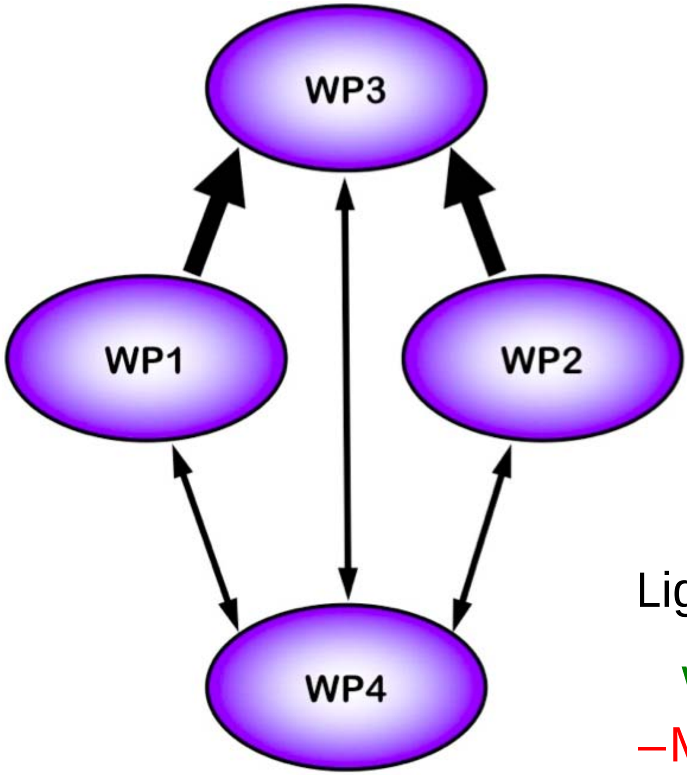
WP4: Novel architectures and tools for repeaters –Many deliverables done, no delays, new results not initially expected in the project

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

QScale

Quantum technologies for extending the range of quantum communications

QScale WorkPackages



WP1: Photonic components for quantum architecture –Mostly achieved

Non-classical light and non-Gaussian operations.

WP2: Controlling light-matter interfaces –Many deliverables done, some delays

Memories in ensembles and control of ion strings.

WP3: Demonstration of Q. repeaters building blocks –In progress, mostly 3rd year

Light-matter, matter-matter entanglement, node processing

WP4: Novel architectures and tools for repeaters –Many deliverables done, no delays, new results not initially expected in the project

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

- **Cost-neutral extension requested up to March 2015**

QScale

Quantum technologies for extending the range of quantum communications

QScale

Quantum technologies for extending the range of quantum communications

www.chistera-qscale.eu