Photonic quantum state transfer between a cold atomic gas and a crystal

Nicolas Maring, Pau Farrera, Kutlu Kutluer, Margherita Mazzera, Georg Heinze, and Hugues de Riedmatten

QPSA - Quantum photonics with solids and atoms

ICFO - The Institute of Photonic Sciences (Barcelona)

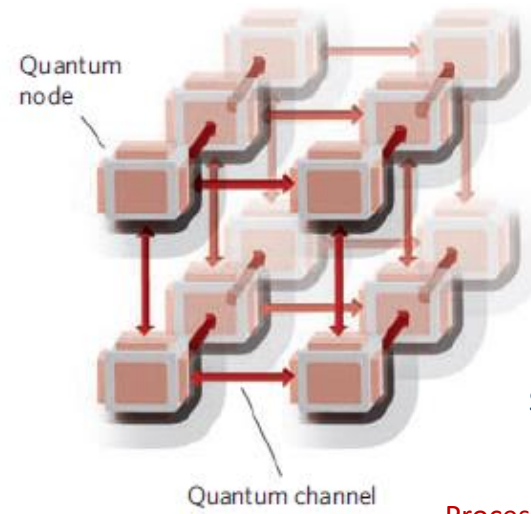
GDR IQFA 2017

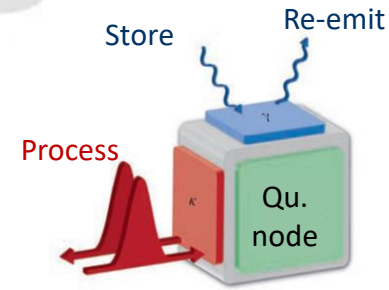
Motivation

Quantum Networks

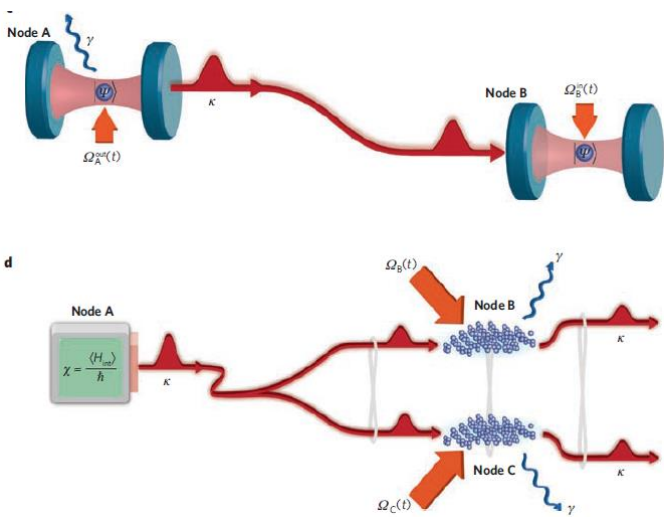
- Distributed Quantum Computing
- Quantum Communication / Cryptography
- Metrology / Sensing

H.J. Kimble, *The quantum internet*, Nature **453**, 1023 (2008).





Different Approaches:



- Cavity Systems
- Cold ensembles
- Trapped ions
- NV-centers
- Quantum dots
- Doped crystals
- …

Individual Advantages

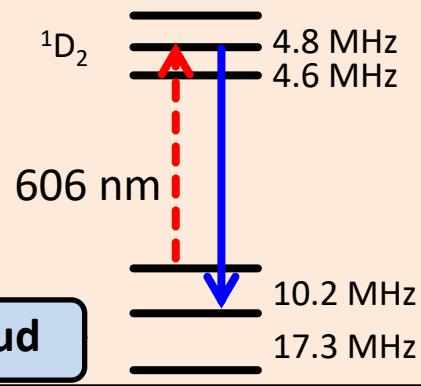
Heterogeneous Networks

T. Chanelière, D. N. Matsukevich, S. D. Jenkins, S.-Y. Lan, T. A. B. Kennedy & A. Kuzmich, Nature **438**, 833-836 (2005)
C. W. Chou, H. de Riedmatten, D. Felinto, S. V. Polyakov, S. J. van Enk & H. J. Kimble, Nature **438**, 828-832 (2005)
S. Ritter et al, Nature **484,** 195-200 (2012)

Photonic quantum state transfer between a cold atomic gas and a crystal

2 - Praseodymium doped-crystal

- Large number of stationary atoms with optical and spin transitions.
- Excellent coherent properties (T<4K).
- Static inhomogeneous broadening (~ GHz) which can be tailored.



Longest light storage (with bright pulses)

in the order of seconds, up to one minute

J.J. Longdell et. al., PRL **95**, 063601 (2005)

G. Heinze, et al, PRL **111**, 033601 (2013)

High storage and retrieval efficiency

Classical 76%, Quantum 69%

D. Schraft, et al., PRL **116**, 073602 (2016)

M.P. Hedges, et. al., Nature, **465** 1052, (2010)

1 - Rubidium cold atomic cloud

Emissive Quantum memory

Duan, Lukin, Cirac, Zoller, Nature, **414,** 413-418 (2001)

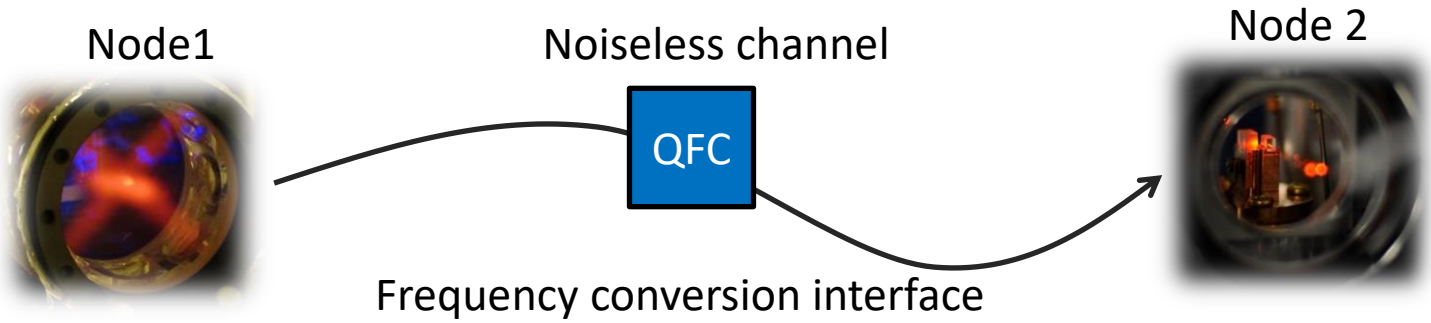
Tuneable single photon source

P. Farrera, et al. Nat. Com. **7**, 13556 (2016)

Quantum processing via Rydberg excitations

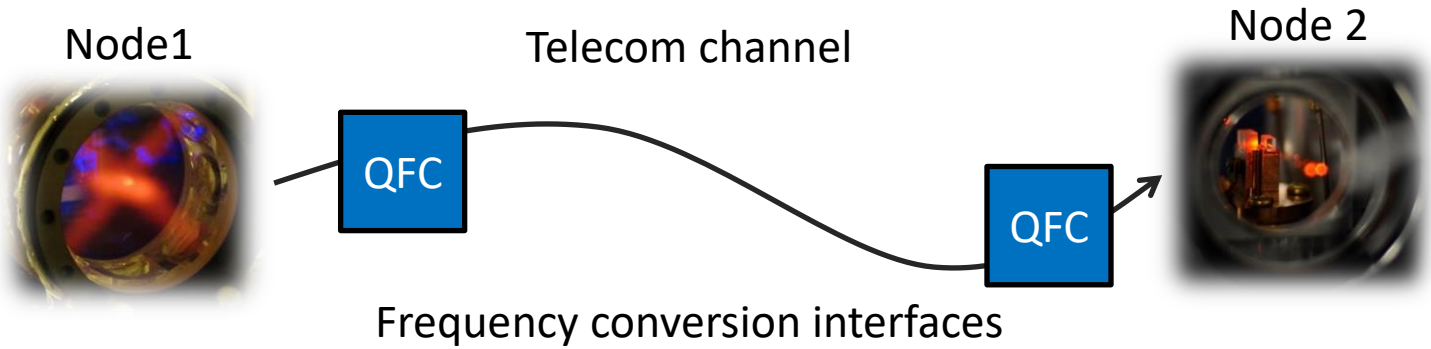
M. Saffman, Rev. Mod. Phys. **3,** 2313-2363 (2010)

Challenges



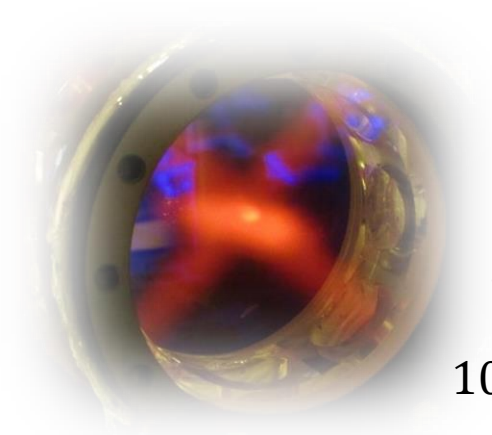
- Single photon interacts strongly with the two nodes – noise-free
- Wavelength and bandwidth matching (narrowband nodes)
- Preserve quantum superposition

Challenges



- Single photon interacts strongly with the two nodes – noise-free
- Wavelength and bandwidth matching (narrowband nodes)
- Preserve quantum superposition

Cold atomic cloud



^{87}Rb MOT

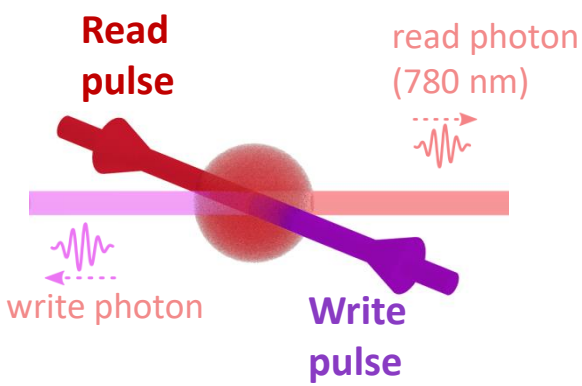
10^8 atoms

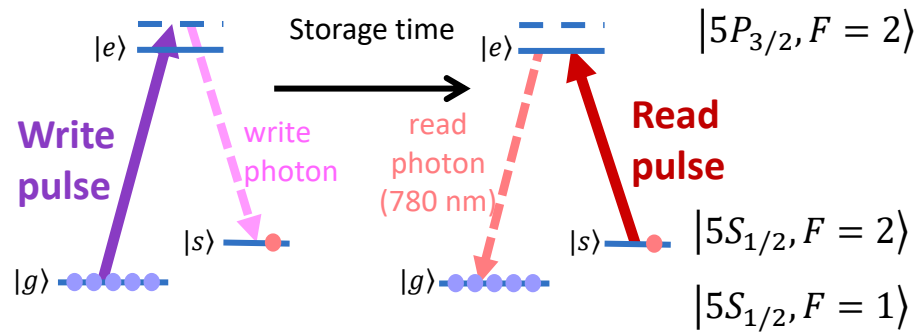
$T \sim 80\mu K$

NATURE | VOL 414 | 22 NOVEMBER 2001 **articles**

Long-distance quantum communication with atomic ensembles and linear optics

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



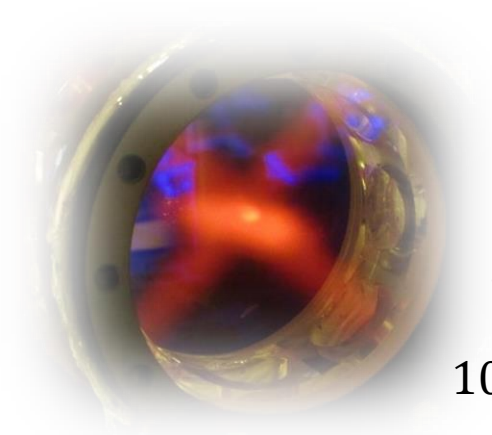


- Non-classically correlated photons
- Embedded storage

$$|\Psi\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} e^{i(\overrightarrow{k_W} - \overrightarrow{k_w})\overrightarrow{x_j}} |g_1 \dots s_j \dots g_N\rangle$$

"Spin-wave"

Cold atomic cloud



^{87}Rb MOT

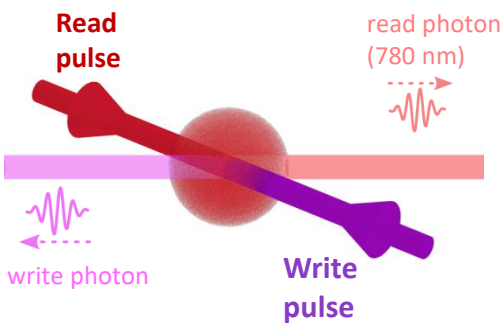
10^8 atoms

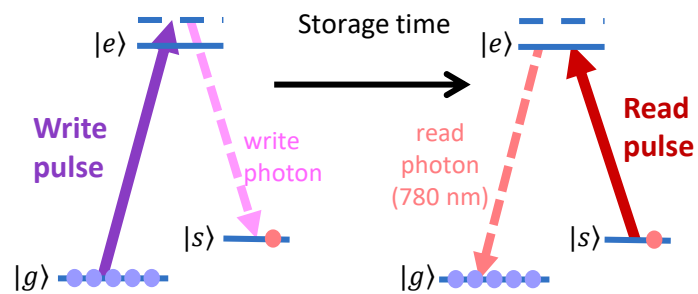
$T \sim 80\mu K$

NATURE | VOL 414 | 22 NOVEMBER 2001 **articles**

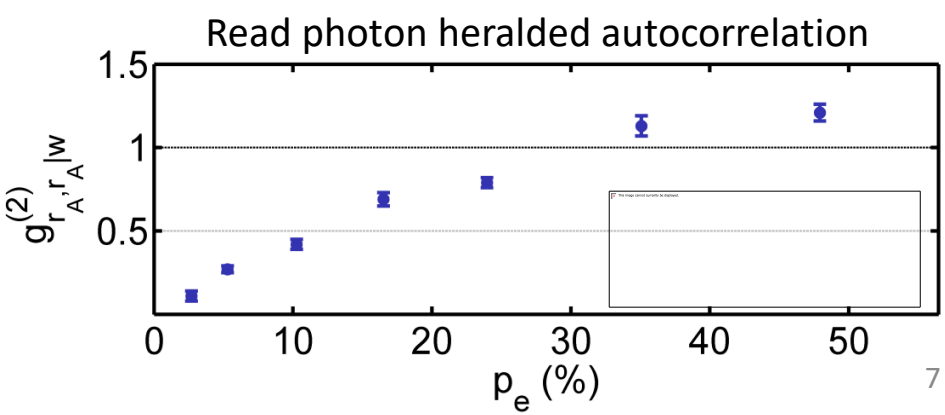
Long-distance quantum communication with atomic ensembles and linear optics

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

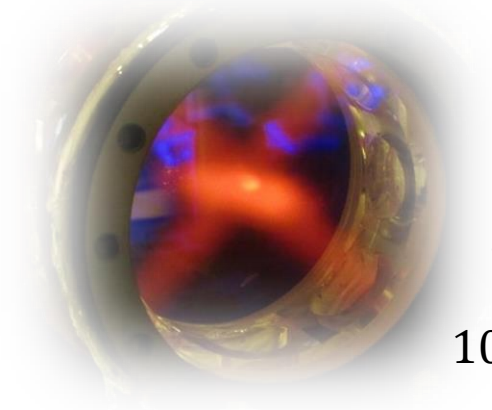




- Non-classically correlated photons
- Embedded storage



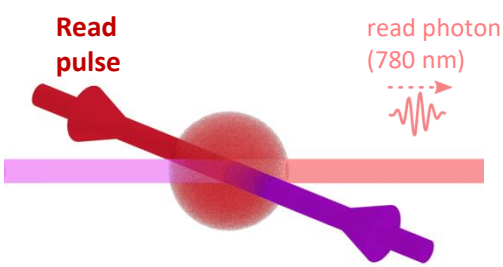
Cold atomic cloud



^{87}Rb MOT

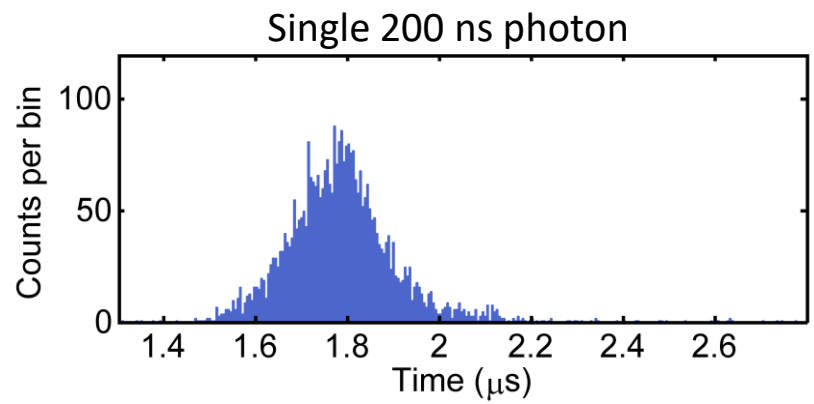
10^8 atoms

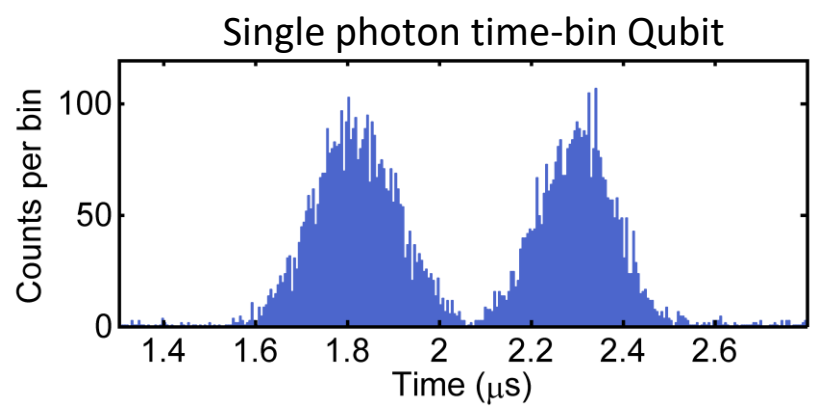
$T \sim 80\mu K$



- Non-classically correlated photons
- Embedded storage
- Ultra-narrow bandwidth

Tuneable bandwidth and waveform





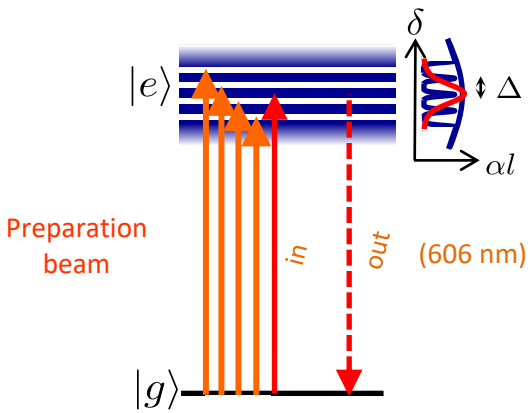
P. Farrera, G. Heinze, B. Albrecht, M. Ho, M. Chávez, C. Teo, N. Sangouard, H. de Riedmatten, Nat. Com. **7**, 13556 (2016)

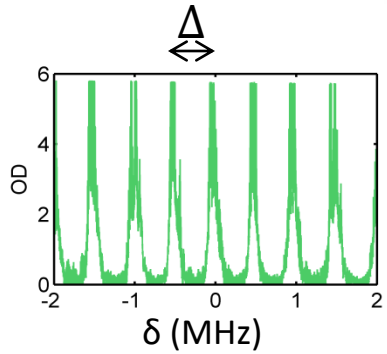
Rare-earth doped crystal

$Pr^{3+}:Y_2SiO_5$

$T \sim 3\ K$

Atomic Frequency Comb (AFC) protocol

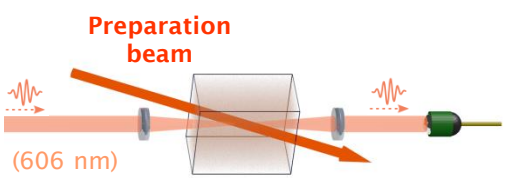




State after mapping

$$\sum_{k=1}^{N} c_k e^{-i\delta_k t} \left| g_1 g_2 \ldots e_k \ldots g_N \right\rangle$$

$$\delta_k = m_k \Delta \rightarrow e^{-i(m_k \Delta)t}$$



Collective, coherent emission in the forward mode (Photon echo-like)

Rephasing after $t_e = \frac{2\pi}{\Delta}$

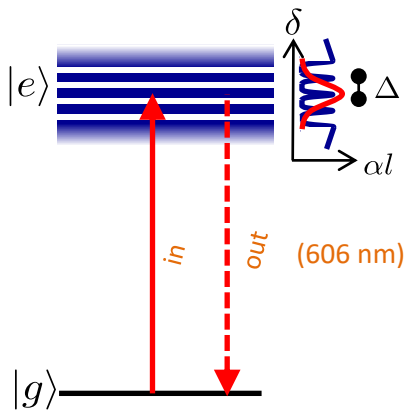
M. Afzelius, C. Simon, H. de Riedmatten, and N. Gisin, Phys.Rev.A 79, 052329 (2009)

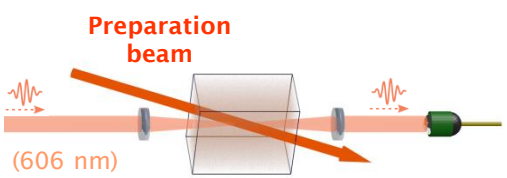
Rare-earth doped crystal

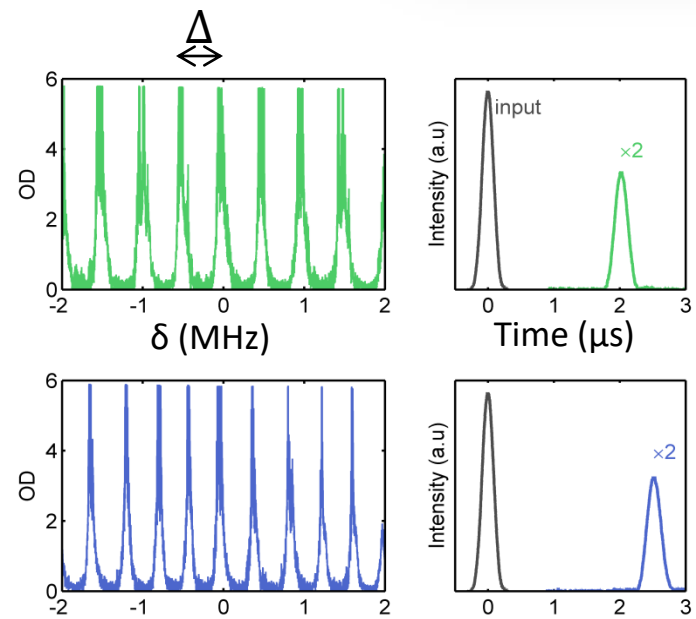
Pr^{3+}: YSO

T ~ 3 K

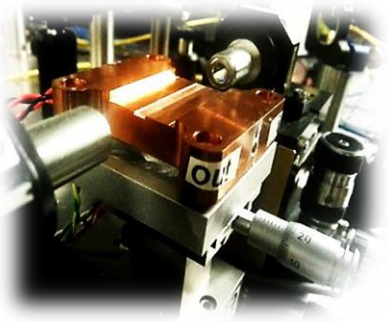
Atomic Frequency Comb (AFC) protocol





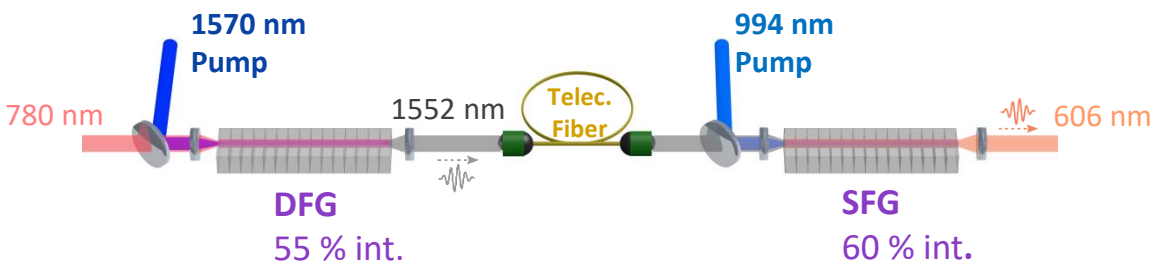


M. Afzelius, C. Simon, H. de Riedmatten, and N. Gisin, Phys.Rev.A 79, 052329 (2009)

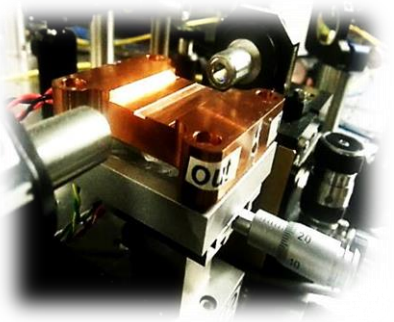


Quantum frequency conversion interface

Cascaded conversion

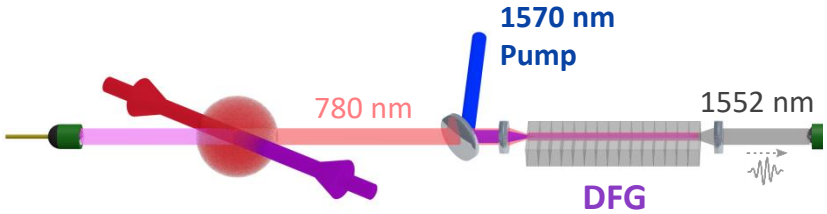


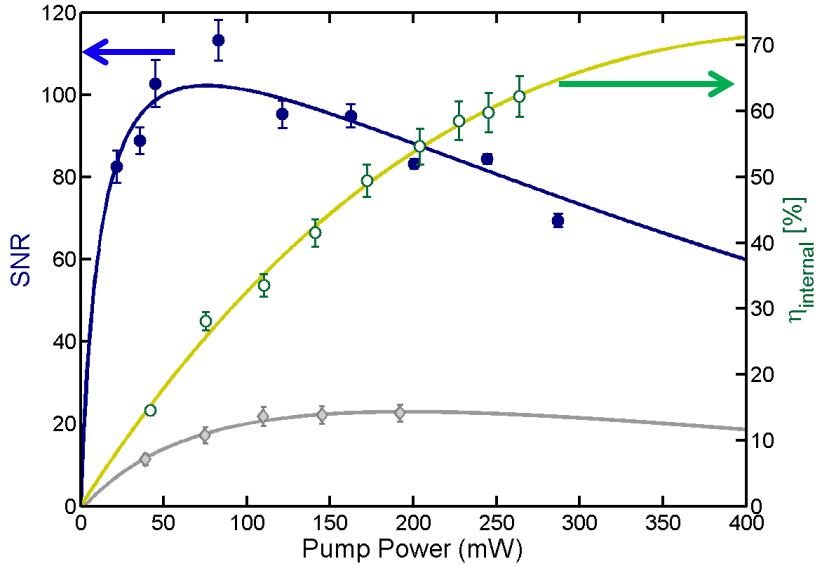
- 2 PPLN non-linear waveguides
- 1 % total conversion efficiency including all losses ($\eta_{opt} = 4\%$)
- Pump induced noise (Raman, parametric fluorescence)



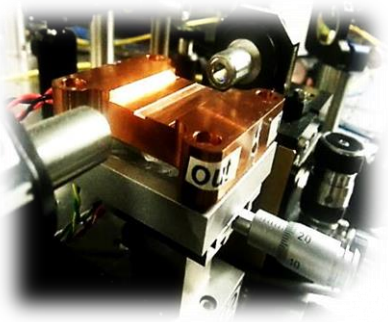
Quantum frequency conversion interface

Non-classical correlation preservation through conversion



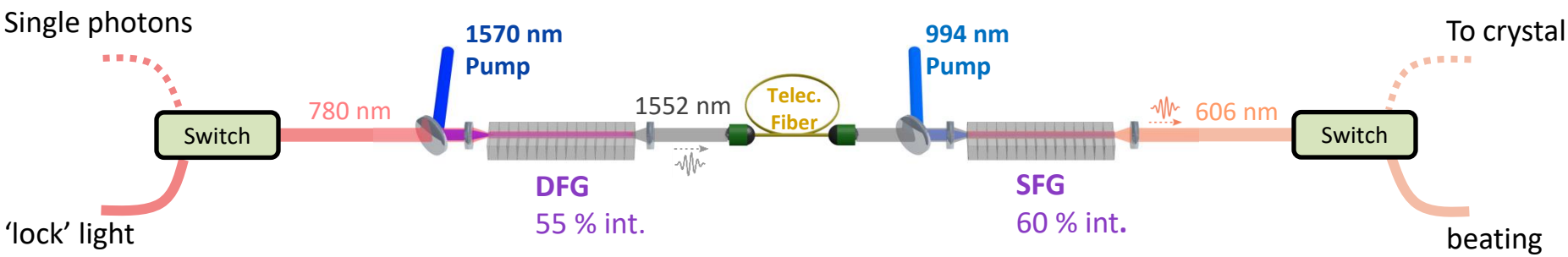


P. Farrera, N. Maring, G. Heinze, H. de Riedmatten, Optica 3, 1019 (2016)



Quantum frequency conversion interface

Cascaded conversion



- 2 PPLN non-linear waveguides
- 1 % total conversion efficiency including all losses ($\eta_{opt} = 4\%$)
- Pump induced noise (Raman, parametric fluorescence)
- Also used to lock the frequency of the converted light
  making sure the read photon in always resonant with the crystal

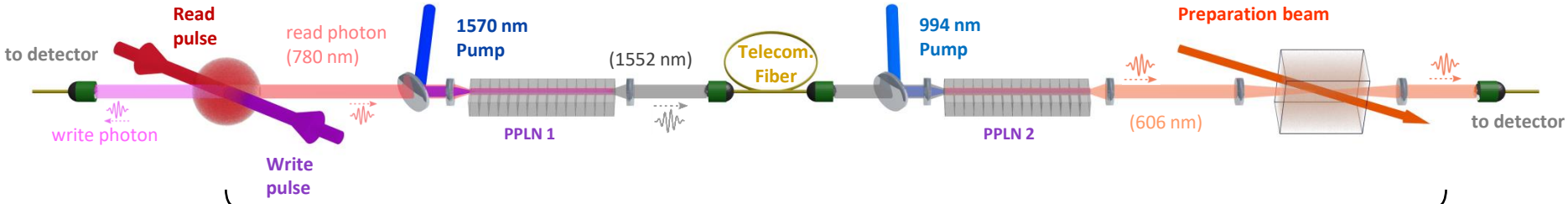
Pau Farrera

Georg Heinze

Full setup

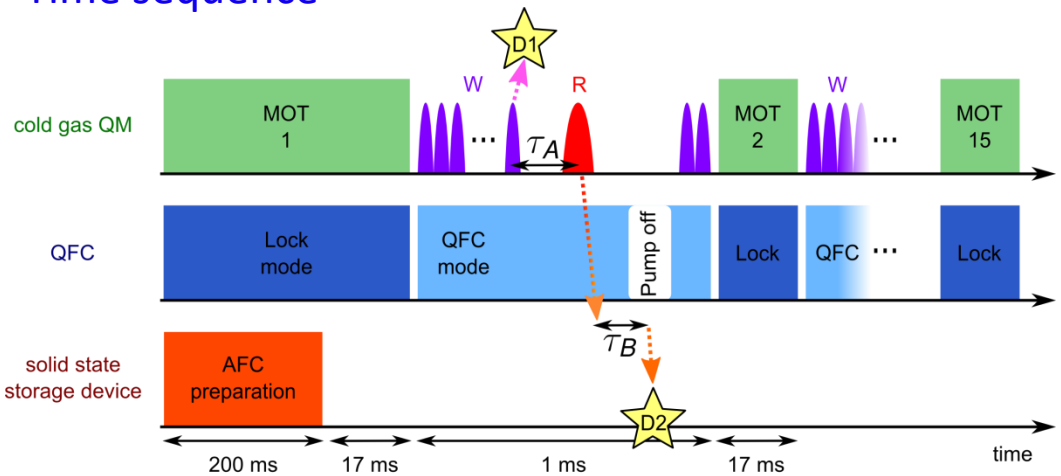
Margherita Mazzera

Kutlu Kutluer



10^{-3} probability of read photon retrieval

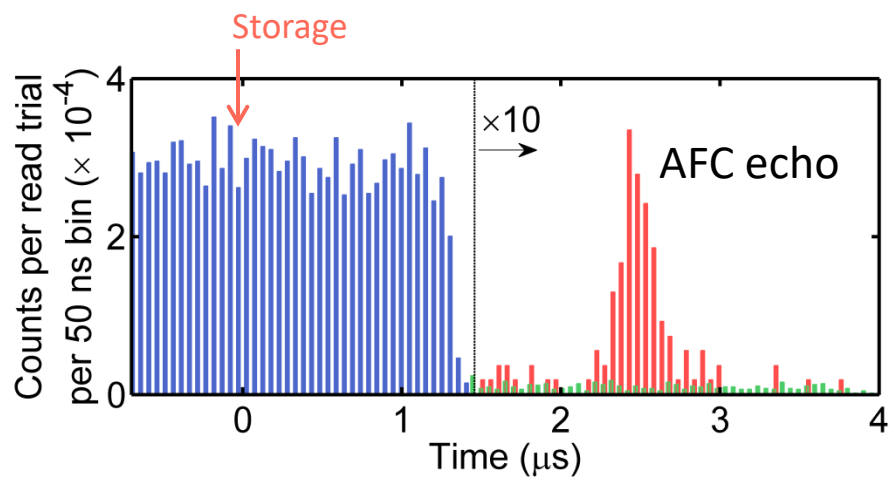
Time sequence



Results

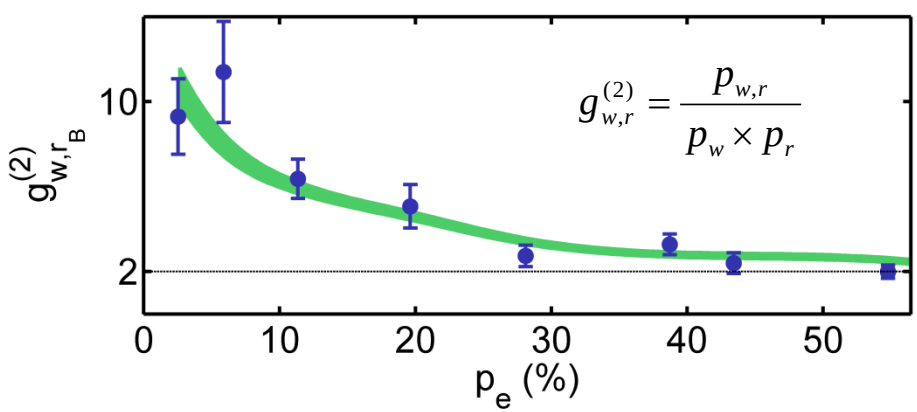
Photon generation, conversion and storage

$SNR = 17$

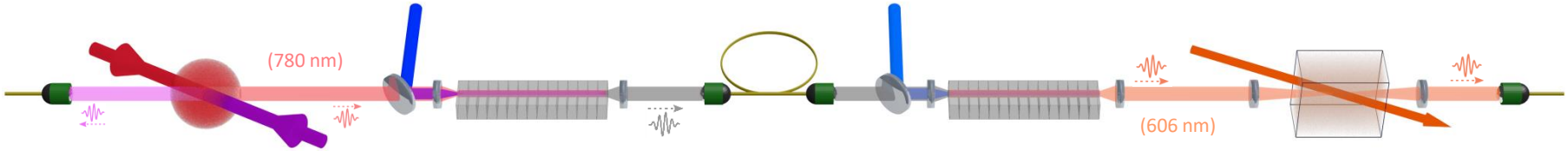


Preservation of quantum correlations

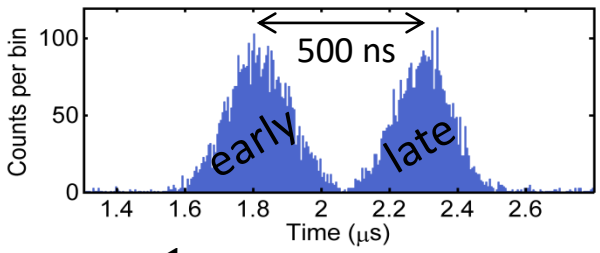
Single collective excitation is transfered from one to the other sytem via single photon



Time-bin qubit storage

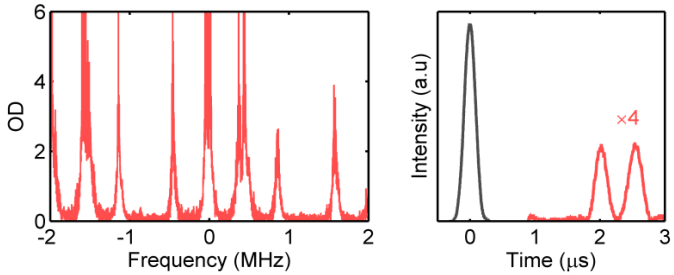


Read photon detected at the MOT



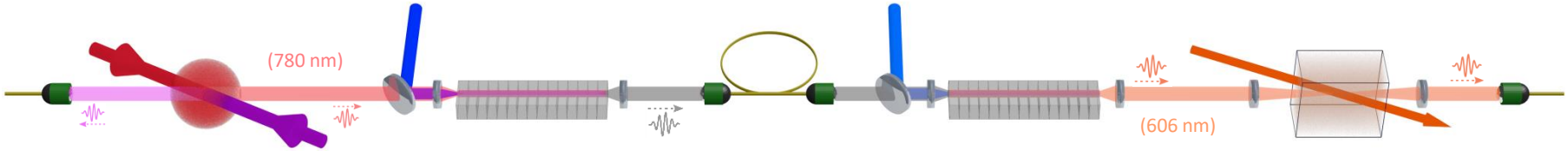
$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\text{early}\rangle + \mathrm{e}^{i\phi}|\text{late}\rangle)$$

Overlapping AFCs

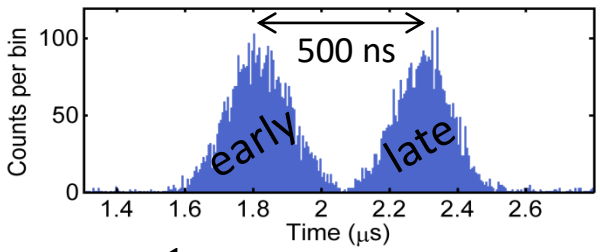


The memory acts as an interferometer

Time-bin qubit storage

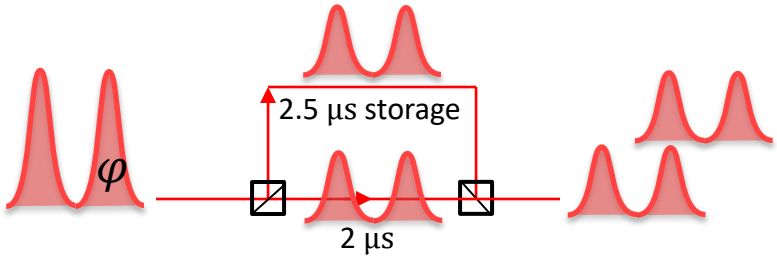


Read photon detected at the MOT



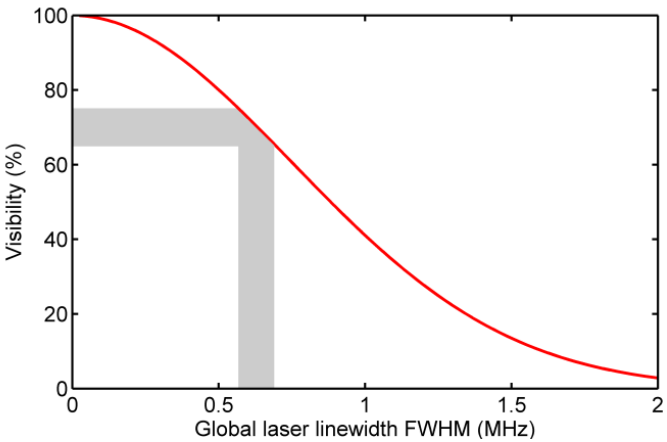
$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\text{early}\rangle + e^{i\phi}|\text{late}\rangle)$$

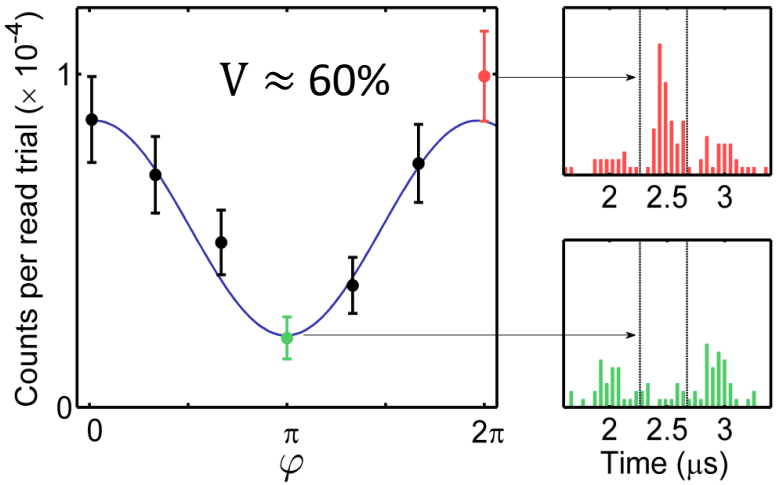
Overlapping AFCs



The memory acts as an interferometer

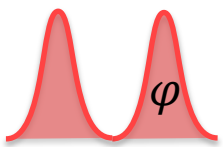
Preservation of coherence





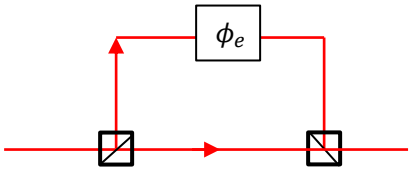
Time bin qubit analysis

Time-bin qubit



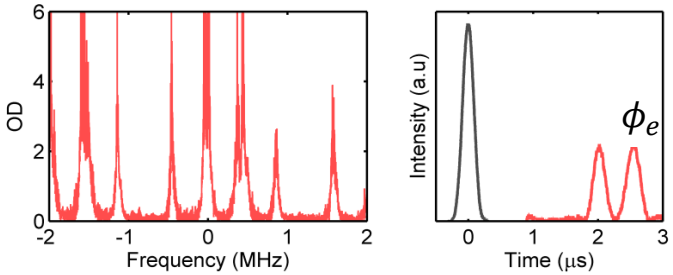
$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|\text{early}\rangle + e^{i\phi}|\text{late}\rangle)$$

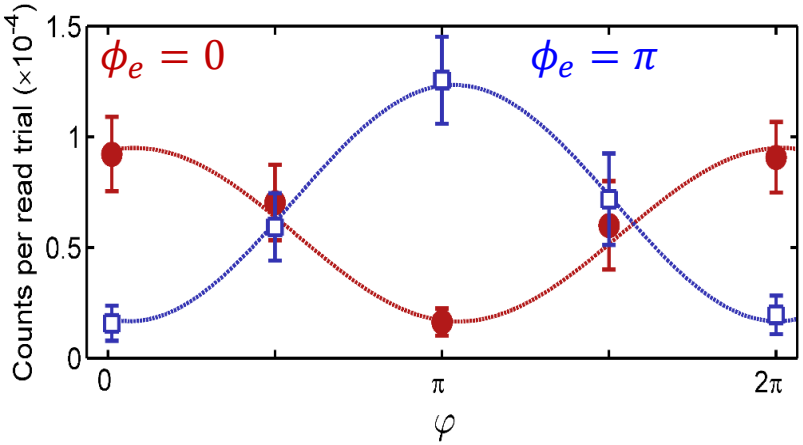
1. Prep. time-bin qubit
2. Convert & Store
3. **Tomography** (use AFC memory as analyser)



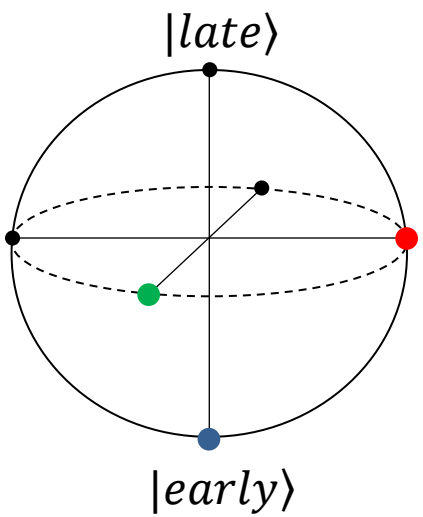
AFC echo phase shift $\phi_e = e^{i2\pi\delta/\Delta}$

δ: position of the comb
Δ: periodicity of the comb





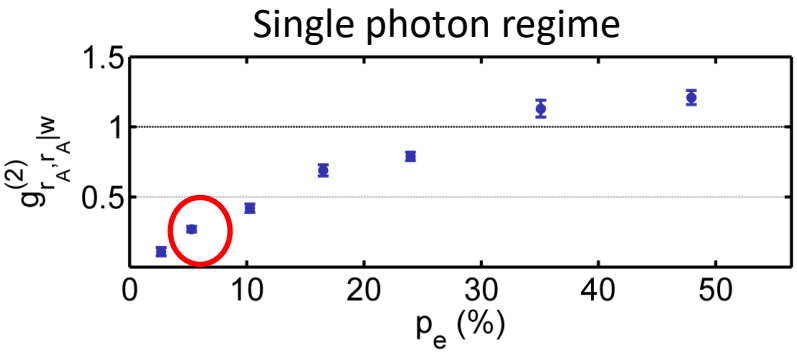
Time bin qubit tomography



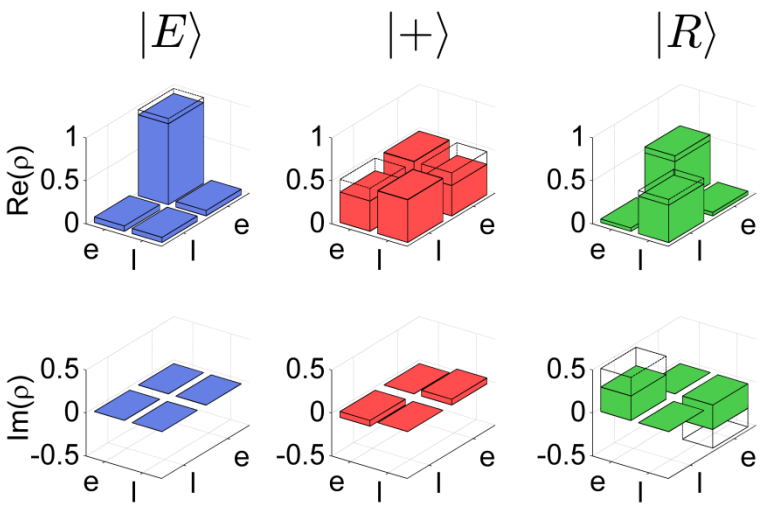
$$|E\rangle = |e\rangle$$

$$|+\rangle = \frac{1}{\sqrt{2}}(|e\rangle + |l\rangle)$$

$$|R\rangle = \frac{1}{\sqrt{2}}(|e\rangle + i|l\rangle)$$



$$\mathcal{F} = \langle\psi|\varrho|\psi\rangle = 85.8 \pm 3.3\%$$



N. Maring, P. Farrera, K. Kutluer, M. Mazzera, G. Heinze, and H. de Riedmatten, Nature 551, 485–488 (2017)

Conclusion

Proof of principle of interconnection between disparate quantum nodes

- Preservation of quantum correlations
- Faithful qubit transfer

Outlook

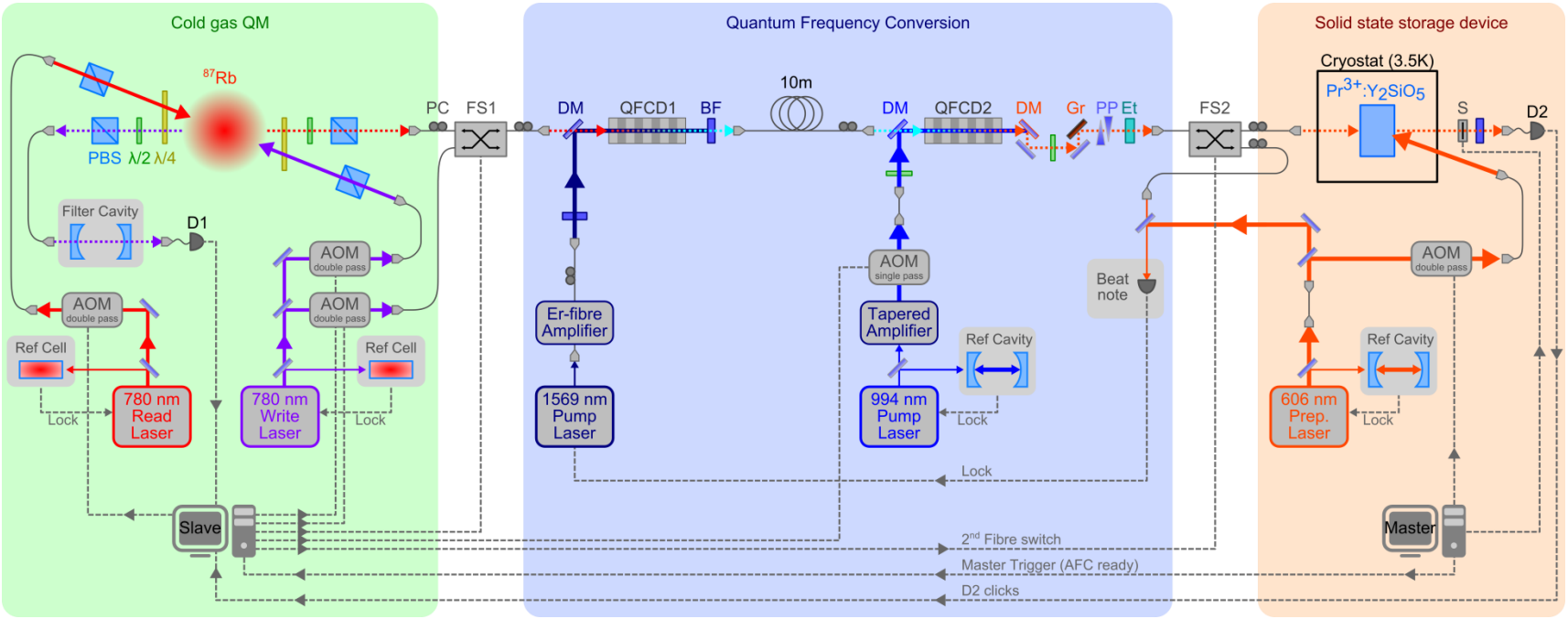
- Increase efficiency and on-demand storage time (spin wave storage in crystal)
- Heralded entanglement
- Platform to connect more systems through telecom wavelength

Hugues de Riedmatten

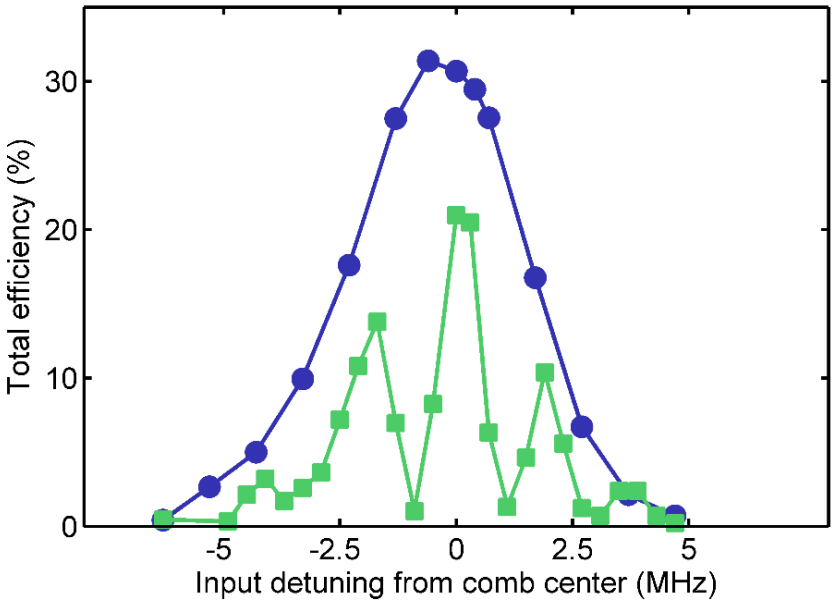

Chetan Deshmukh
Georg Heinze
Auxi Padrón
Daniel Rieländer
Nicolas Maring
Alessandro Seri
Bernardo Casabone
Andreas Lenhard
Emanuele Distante
Pau Farrera
David Paredes
Hugues de Riedmatten
Kutlu Kutluer
Margherita Mazzera
Dario Lago
QPSA
http://qpsa.icfo.es/
erc
GOBIERNO DE ESPAÑA
MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD
Fundació Privada CELLEX
EXCELENCIA SEVERO OCHOA

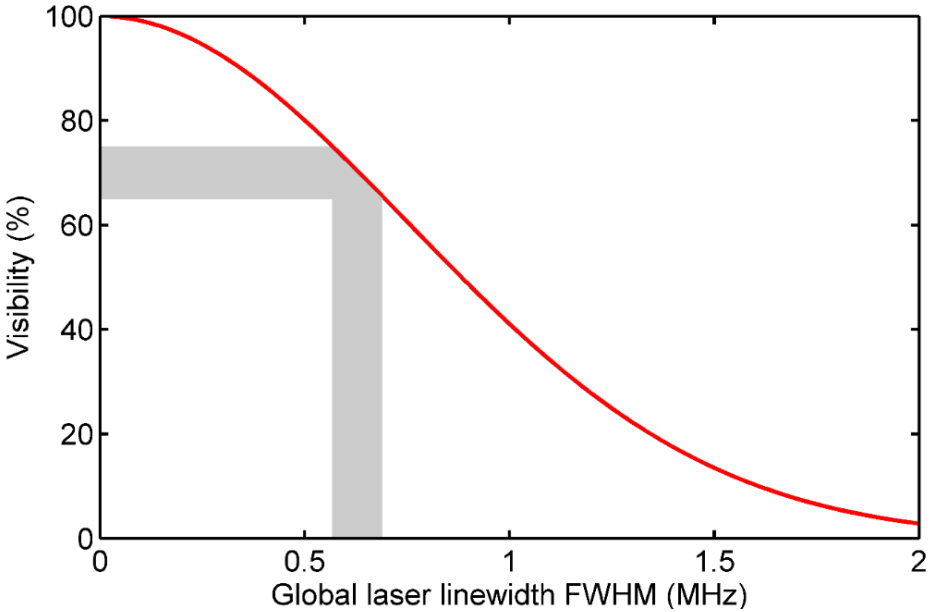
Thank you

Full setup

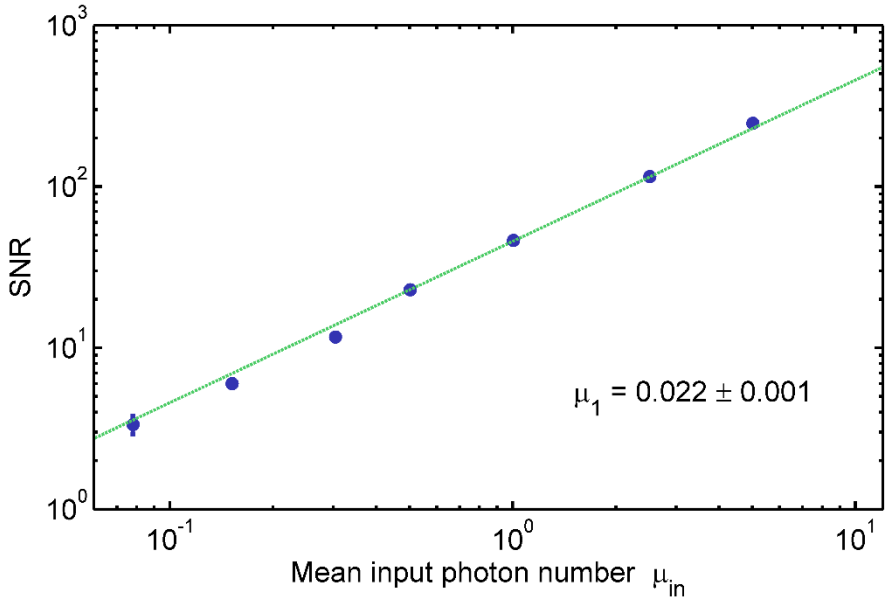

Cold gas QM
87Rb
PBS λ/2 λ/4
Filter Cavity
D1
AOM double pass
AOM double pass
AOM double pass
Ref Cell
Ref Cell
780 nm Read Laser
780 nm Write Laser
Lock
Lock
Slave
PC
FS1
Quantum Frequency Conversion
DM
QFCD1
BF
10m
DM
QFCD2
DM
Gr
PP
Et
Er-fibre Amplifier
1569 nm Pump Laser
AOM single pass
Tapered Amplifier
Ref Cavity
994 nm Pump Laser
Lock
Lock
Beat note
FS2
Solid state storage device
Cryostat (3.5K)
Pr3+:Y2SiO5
S
D2
AOM double pass
Ref Cavity
606 nm Prep. Laser
Lock
Master
2nd Fibre switch
Master Trigger (AFC ready)
D2 clicks

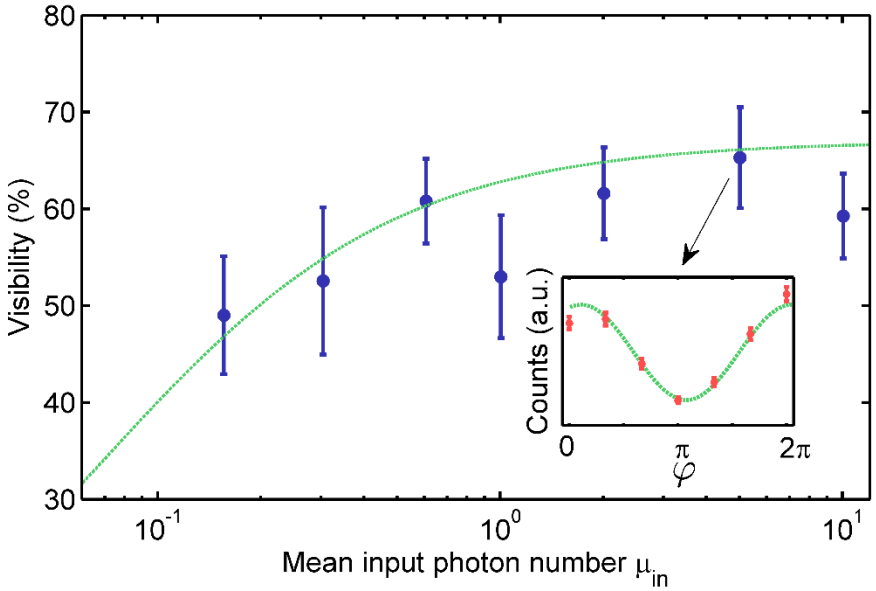
Frequency stability





Weak Coherent State Measurements





Storage time characterizations