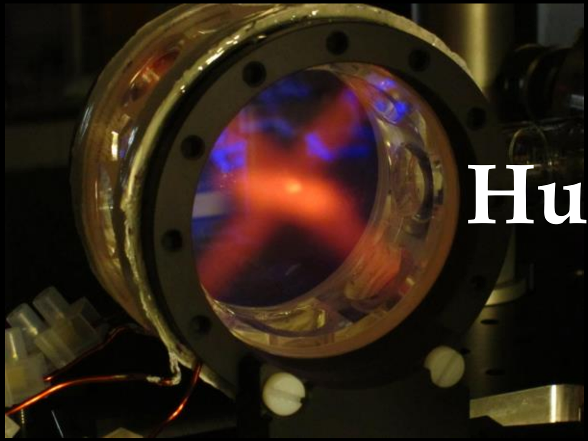
Quantum Nodes for Quantum Repeaters



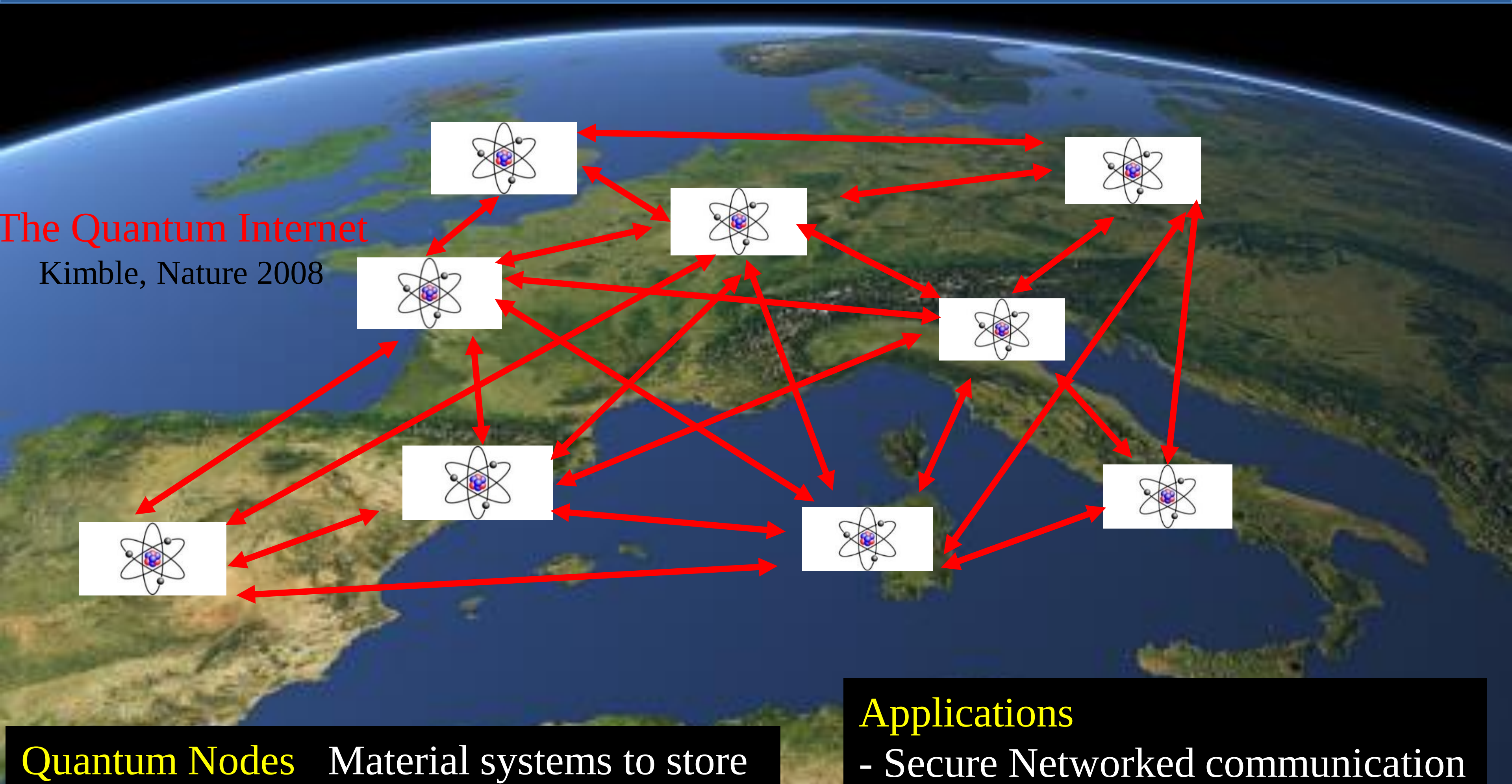
Hugues de Riedmatten

ICFO-The Institute of Photonic Sciences

ICREA- Catalan Institute for Research and Advanced studies

Quantum Science Seminar, January 14th 2021

Quantum information networks

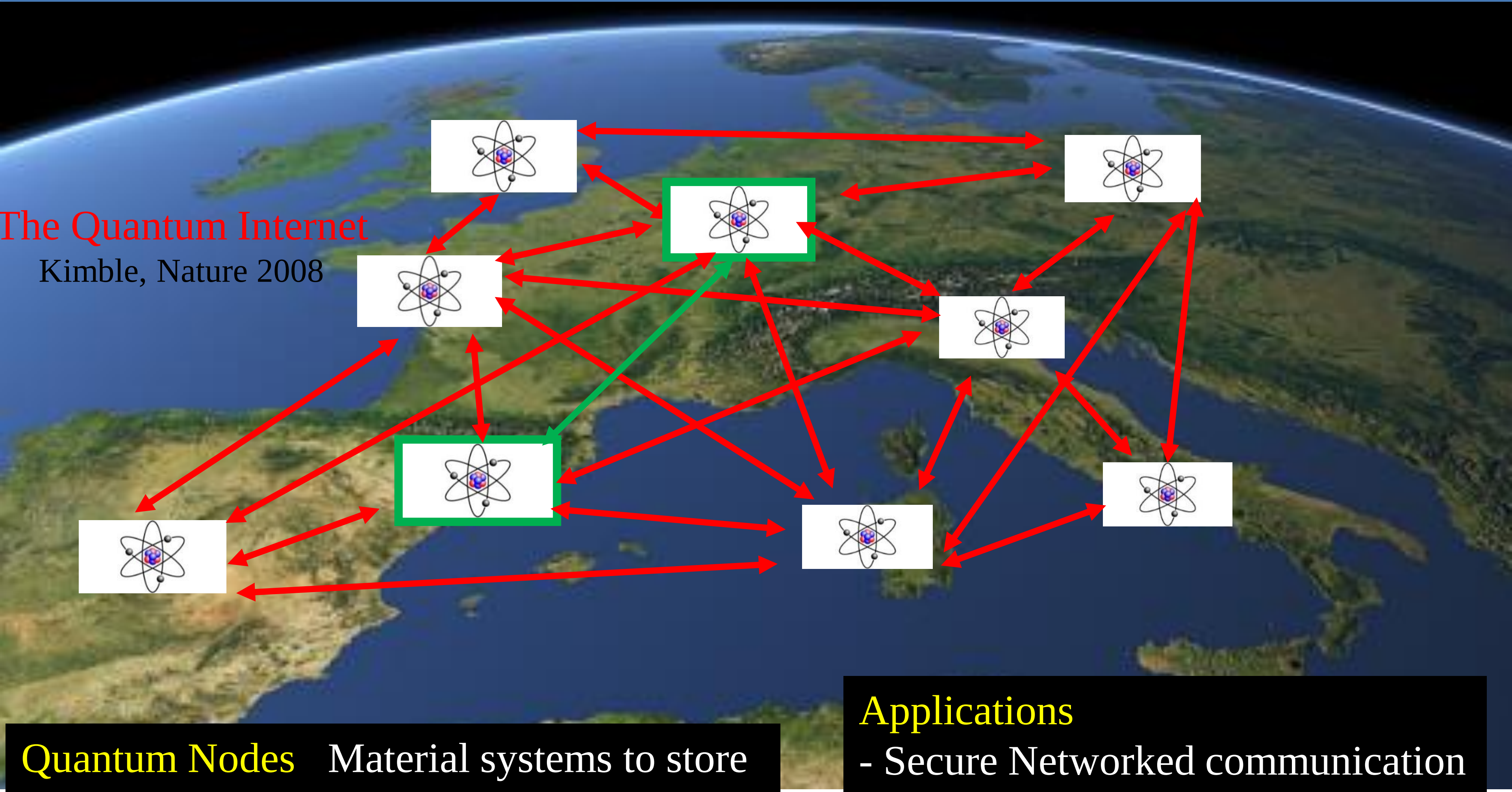


The Quantum Internet
Kimble, Nature 2008

Quantum Nodes Material systems to store and process QI
Quantum Channels Optical fibers to distribute QI

Applications
- Secure Networked communication
- Distributed quantum computing
- Secure cloud Quantum Computing
- Clock synchronozation

Quantum information networks



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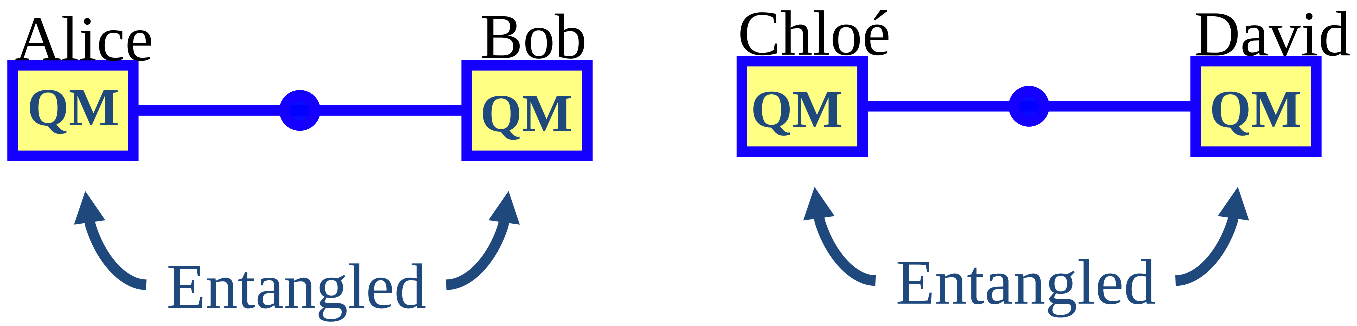
Long distance Quantum Communication with Quantum Repeaters



Create entanglement independently for each link.

H.J. Briegel W.Dur, J.I. Cirac, P.Zoller, PRL **81**, 5932 (1998)
L.M. Duan, M.D. Lukin, J.I. Cirac, P.Zoller, Nature **414**, 413 (2001)
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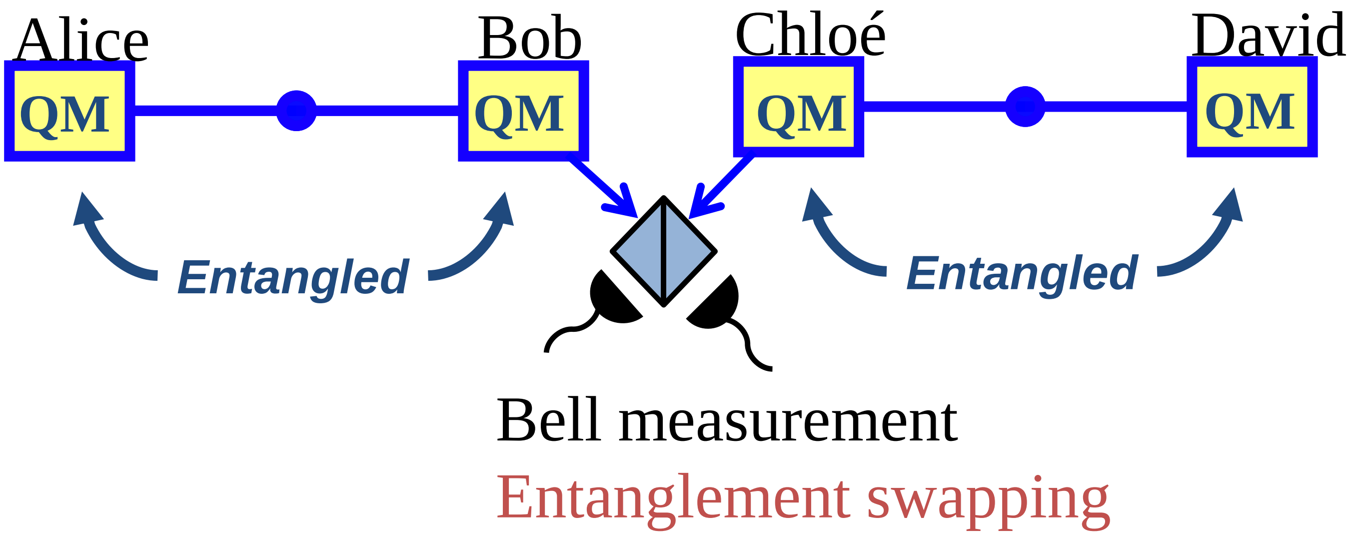
Long distance Quantum Communication with Quantum Repeaters



Create entanglement independently for each link.

Extend by entanglement swapping.

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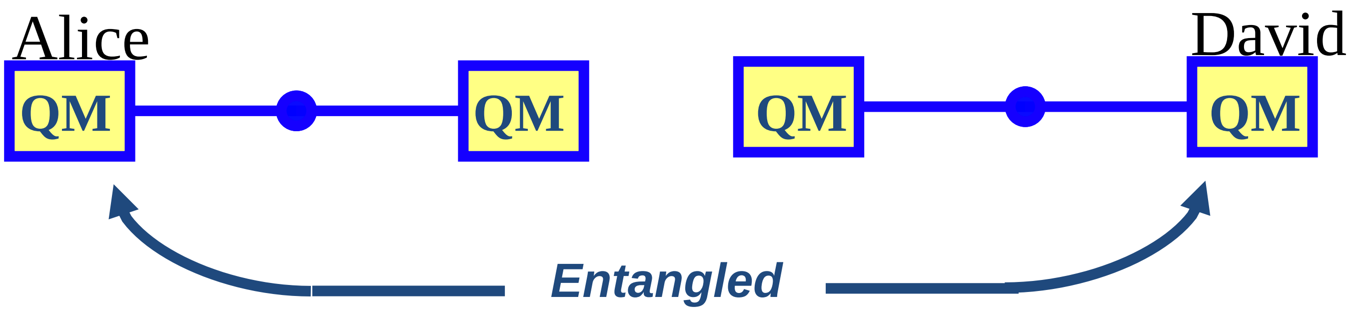
Long distance Quantum Communication with Quantum Repeaters



Create entanglement independently for each link.

Extend by entanglement swapping.

Requires heralded creation and storage of entanglement

H.J. Briegel W.Dur, J.I. Cirac, P.Zoller, PRL **81**, 5932 (1998)
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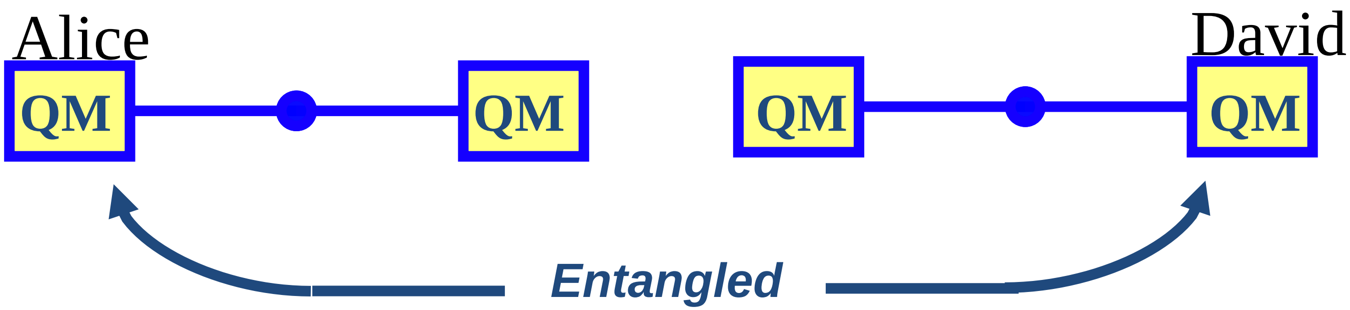
Long distance Quantum Communication with Quantum Repeaters



Other new protocols not based on heralded entanglement and quantum memories. Require more advanced capabilities

Create entanglement independently for each link.

Extend by entanglement swapping.

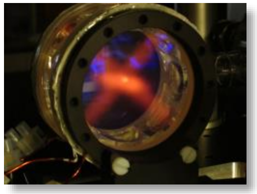
Requires heralded creation and storage of entanglement

H.J. Briegel W.Dur, J.I. Cirac, P.Zoller, PRL **81**, 5932 (1998)
L.M. Duan, M.D. Lukin, J.I. Cirac, P.Zoller, Nature **414**, 413 (2001)
N. Sangouard, C. Simon, H. de Riedmatten and N. Gisin, Rev. Mod. Phys. **83**, 33–80 (2011)

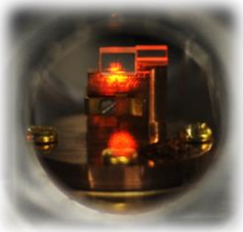
Outline

- **Quantum repeater nodes**

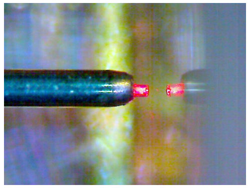
- **Ensemble-based memories and sources based on cold atomic gases**



- **Entanglement of Solid-State quantum memories**

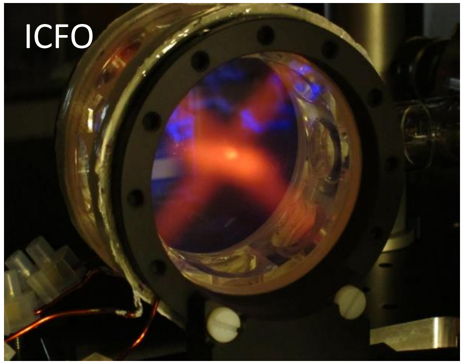


- **Towards quantum nodes with single rare-earth ions in solids**

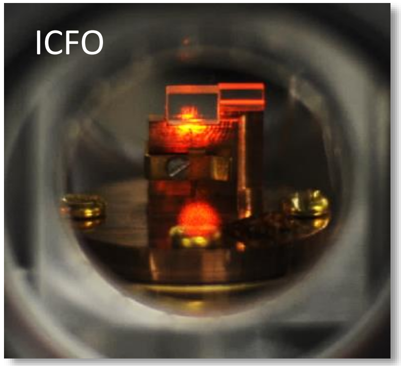


Quantum Nodes: Candidates

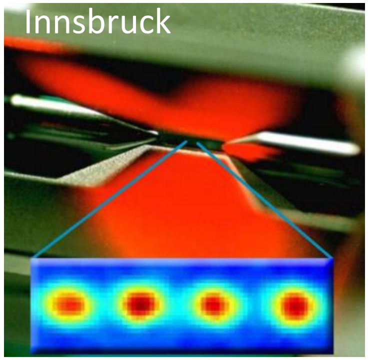
Cold/hot atomic gases



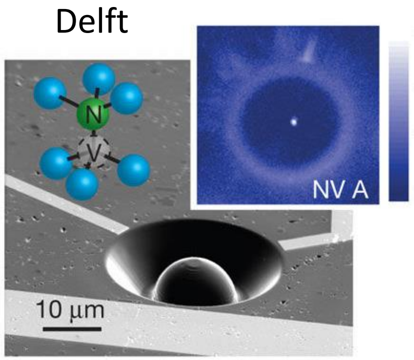
Rare earth doped crytals



single trapped atoms/ions,



Color Centers

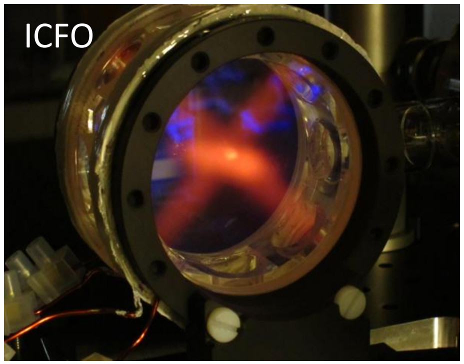


Quantum nodes requirements:

- Efficient interface and entanglement between photonic and matter qubits
- Long-lived qubit storage
- Compatibility with telecom fibers
- Multiqubit register (multiplexing)
- Quantum logic between local qubits

Quantum Nodes: Candidates

Cold/hot atomic gases



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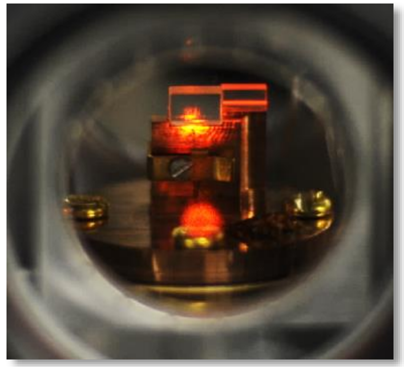

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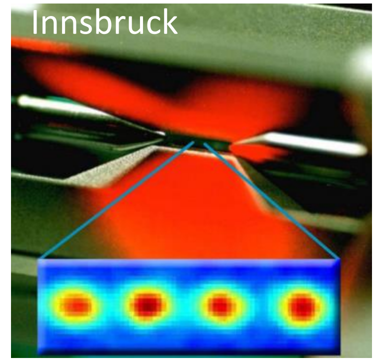
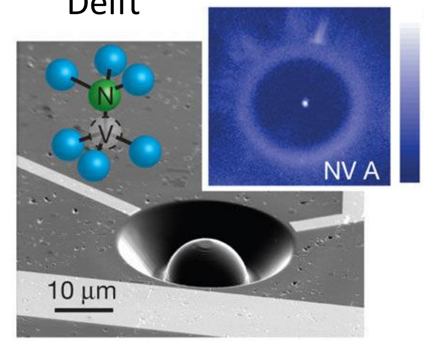


Color Centers

Delft



Ensemble based:

- Easy collective efficient light-matter interaction without cavity:
- Collective enhancement

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

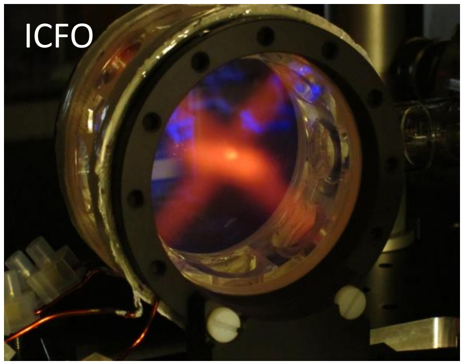
- Multiplexing quantum info

Single emitters

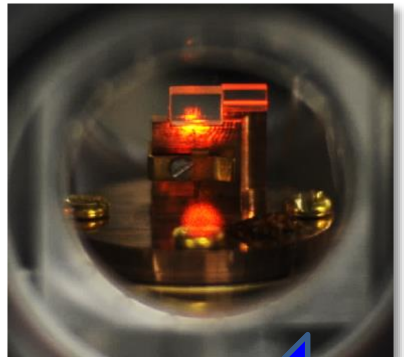
- Strong interaction between qubits Quantum Logic !
- Need cavity

Quantum Nodes: Candidates

Cold/hot atomic gases



Rare earth doped crytals



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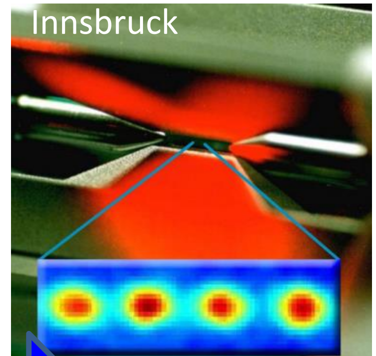

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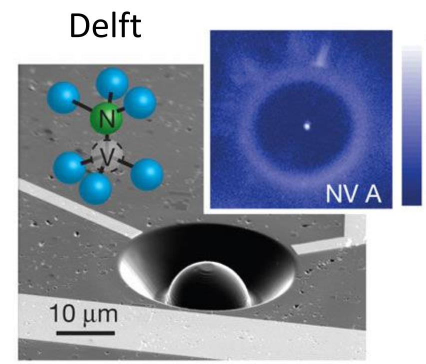

Ensemble based:

- Easy collective e
interaction with

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- Multiplexing quantum info

on between qubits

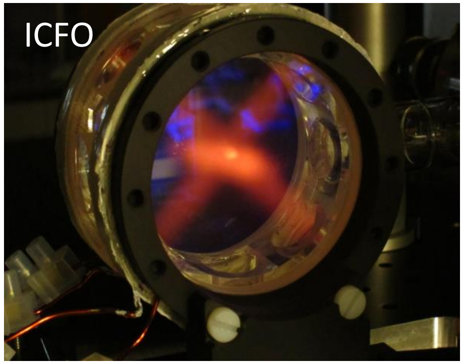
t !

- Need cavity

Strong Incentive for heterogeneous quantum network nodes Combining all capabilities

Quantum Nodes: Candidates

Cold/hot atomic gases



Rare earth
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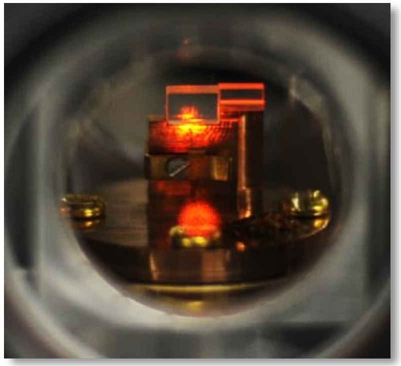

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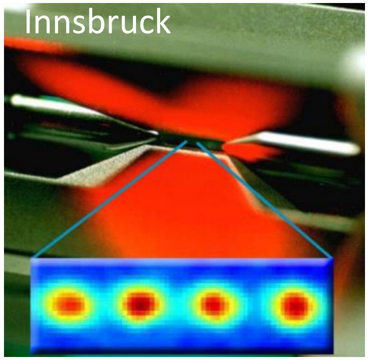

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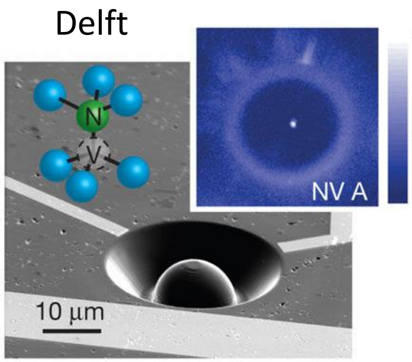
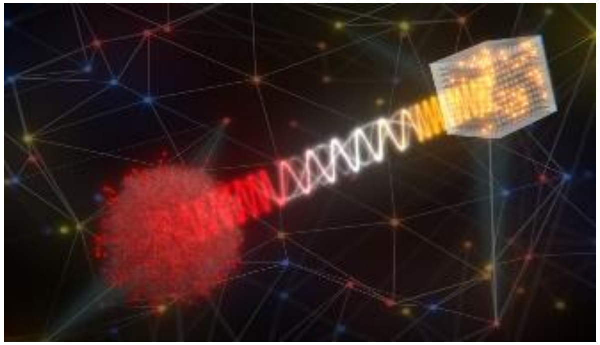


Quantum Communication between disparate quantum nodes



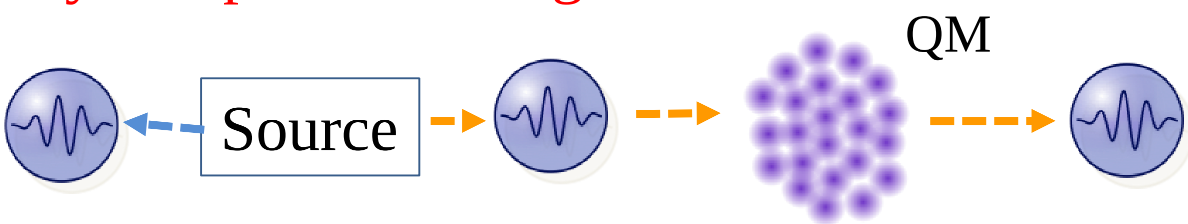
N. Maring, P. Farrera, K. Kutluer,
M. Mazzera, G. Heinze, and H. de Riedmatten,
Nature **551**,485 (2017)

Quantum Technology for Quantum Repeaters

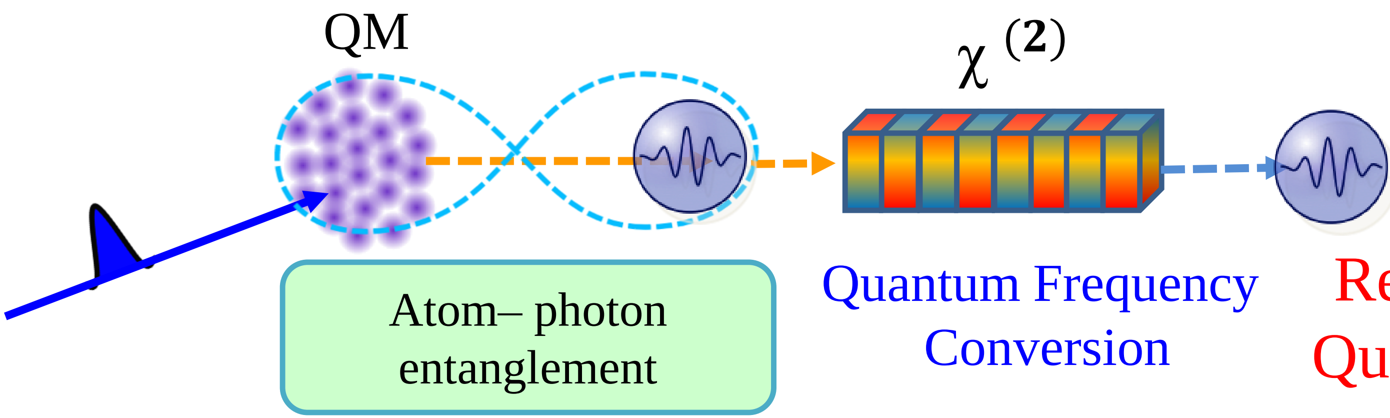
Quantum Memory

- Efficiency >90 %
- Storage time : 500 us-500 ms
- >1000 modes

Memory compatible entanglement source



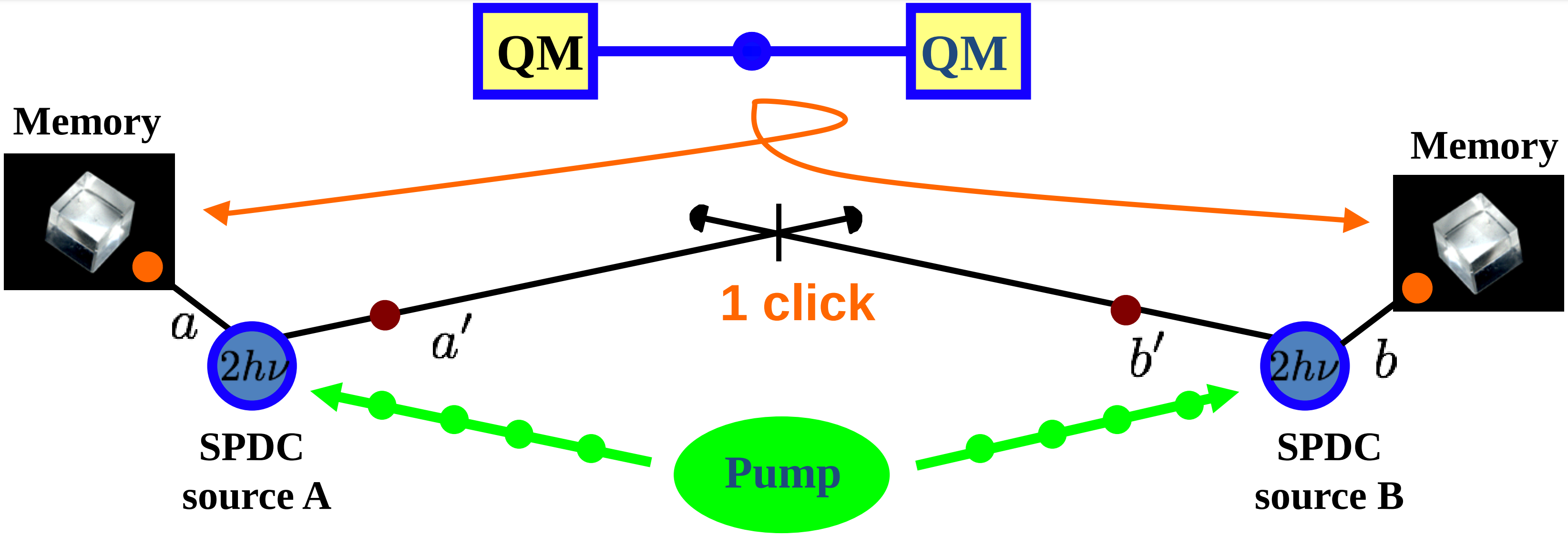
Read-Write Quantum Memory



Read (emissive) Quantum Memory

So far, mostly probabilistic sources. Challenge: deterministic sources

Heralded entanglement of absorptive QMs



$$\left(1+\sqrt{\frac{p}{2}}(a^\dagger a'^\dagger + b^\dagger b'^\dagger) + O(p)\right)|0\rangle$$

Initial state

$$|\Phi_{AB}\rangle = \frac{1}{\sqrt{2}}(a^\dagger e^{i\phi_A} + b^\dagger e^{i\phi_B})|0\rangle$$

Conditional state (one click!)

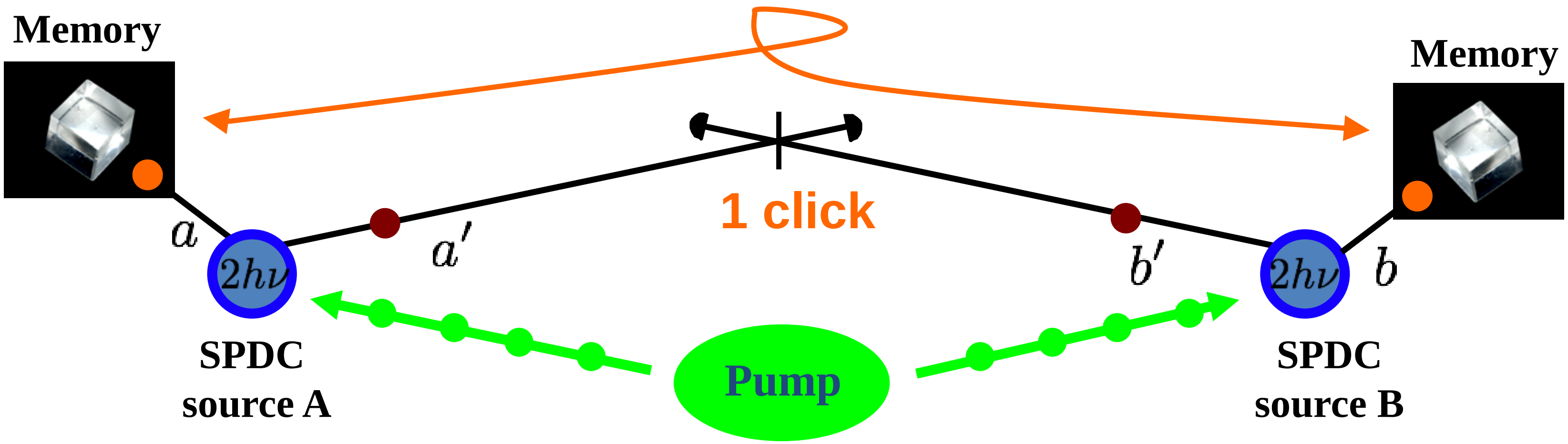
$$|\Phi_{AB}\rangle = \frac{1}{\sqrt{2}}(|1\rangle_A|0\rangle_B + e^{i\phi_{AB}}|0\rangle_A|1\rangle_B)$$

$$\phi_{AB} = \phi_B - \phi_A$$

Heralded entangled state of remote QM

C. Simon, H. de Riedmatten, M.Afzelius, N. Sangouard, H. Zbinden and N. Gisin, PRL **98**, 190503 (2007)

Heralded entanglement of absorptive QMs



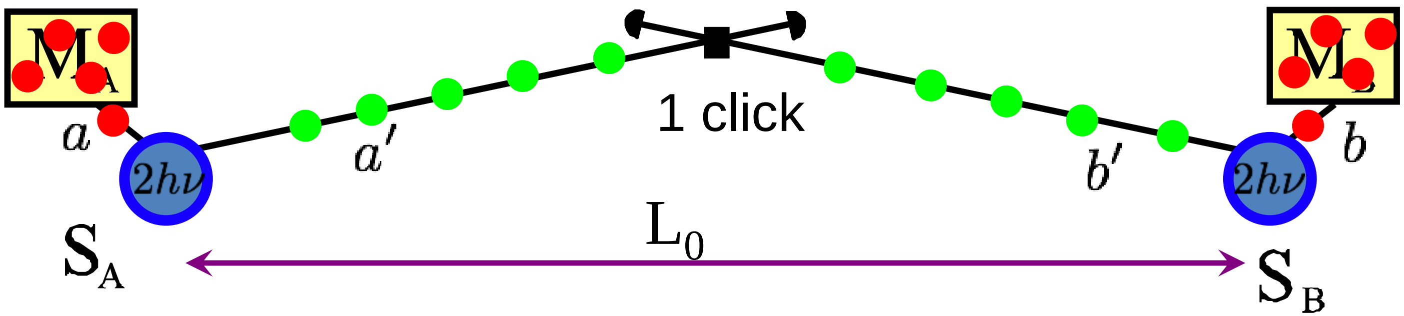
- Similar as DLCZ scheme

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

- Wavelength optimization
- Temporal multiplexing

C. Simon, H. de Riedmatten, M.Afzelius, N. Sangouard, H. Zbinden and N. Gisin, PRL **98**, 190503 (2007)

Heralded entanglement generation between remote multimode memories



Conventional (single mode) memory: have to wait time L_0/c before trying again. (Ex. For 100 km, L_0/c=500 us, R=2 kHz)

$$P_0 = p\eta_{L_0}\eta_D$$

Low success probability! (Typ. 10^{-3} - 10^{-4})

Memories that can store N modes.

N attempts per time interval L_0/c

$$P_0^{(N)} = 1-(1-P_0^{(1)})^N \approx N P_0^{(1)}$$

(N > 1000 possible)

Speedup by factor of N.

C. Simon, H. de Riedmatten, M. Afzelius, N. Sangouard, H. Zbinden and N. Gisin, Phys. Rev. Lett. 98, 190503 (2007)

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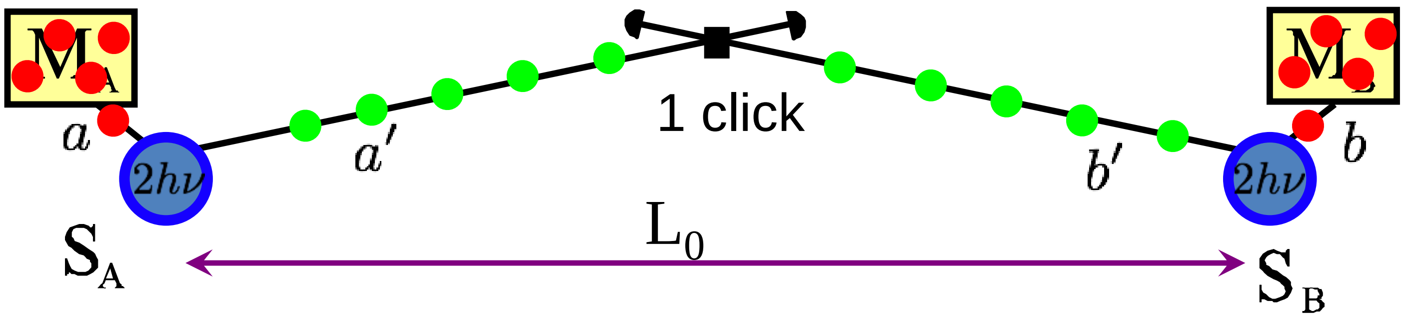


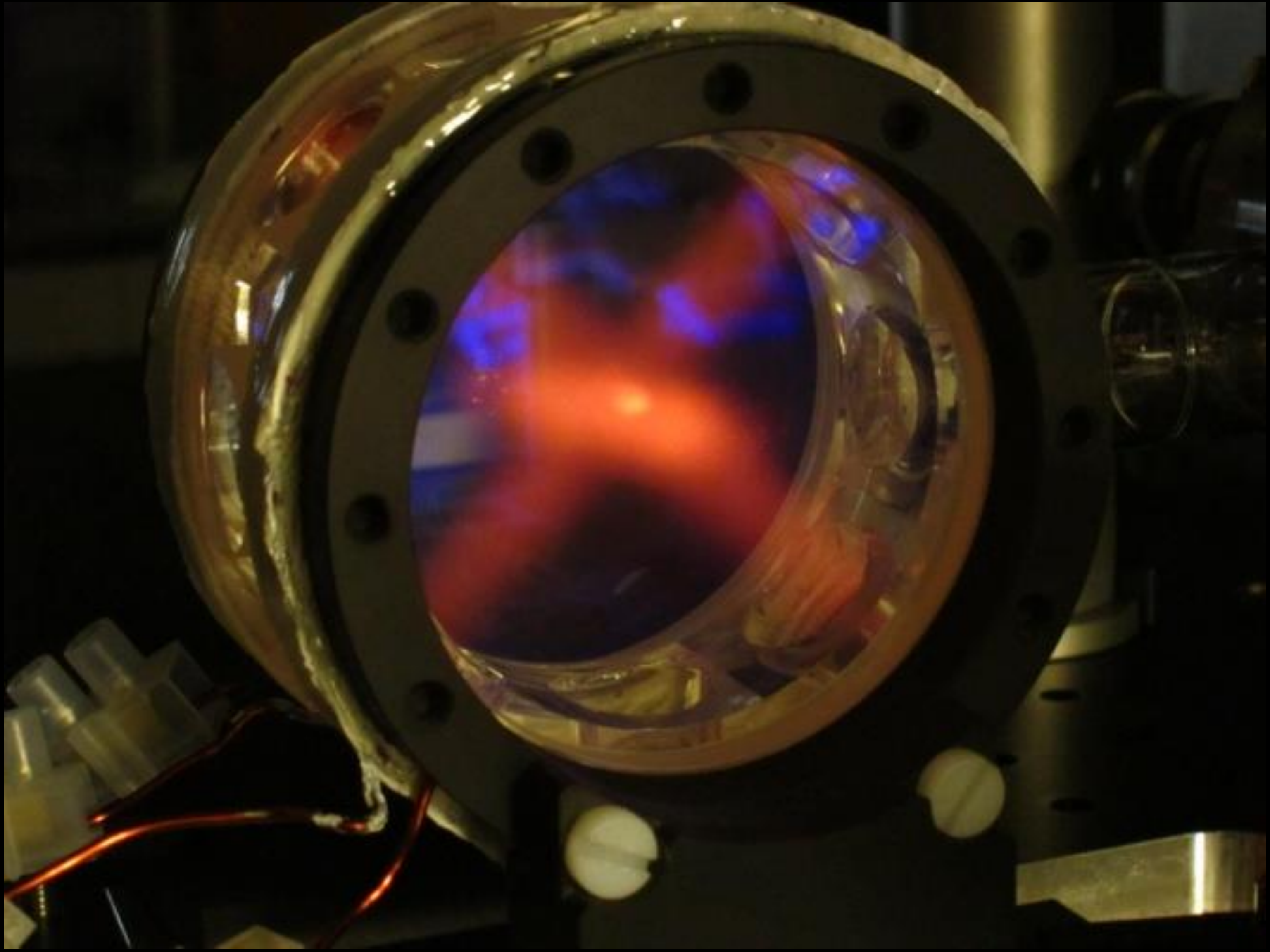
Conventional (single mode) memory: have to wait time L_0/c before trying again.
(Ex. For 100 km, L_0/c=500 us, R=2 kHz)

System requirements

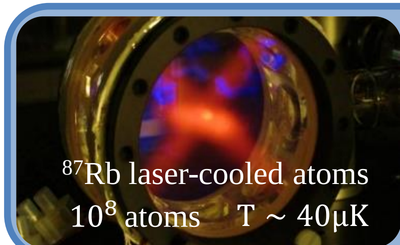
- minimum storage time>L_0/c
- Photon pair source compatible with memory and fiber network
- store N distinguishable modes (time, frequency, space)
- selective read-out
- preserve the phase of each mode

C. Simon, H. de Riedmatten, M. Afzelius, N. Sangouard, H. Zbinden and N. Gisin,
Phys. Rev. Lett. 98, 190503 (2007)

Cold atomic ensemble quantum memories



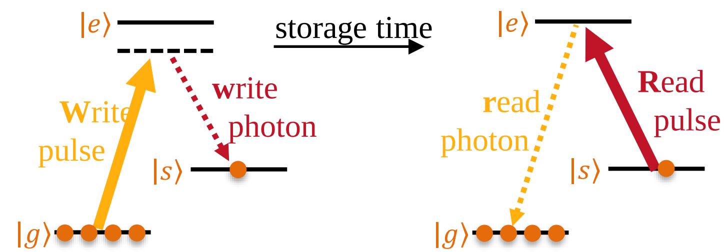
The DLCZ quantum memory



articles

Long-distance quantum communication with atomic ensembles and linear optics

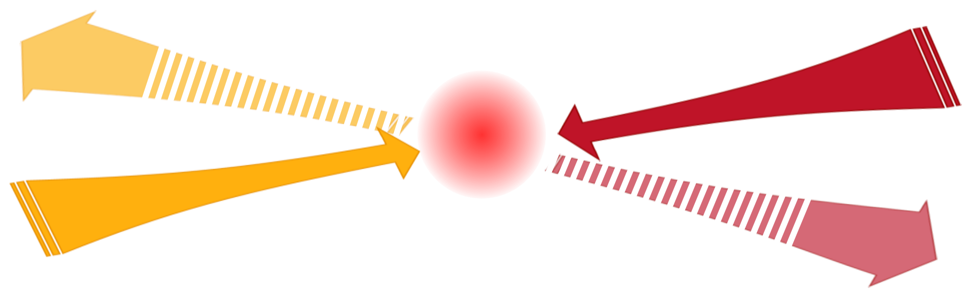
L.-M. Duan*†, M. D. Lukin‡, J. I. Cirac* & P. Zoller*



Entangled two-mode squeezed state

$$|\Psi\rangle_{\text{write,atoms}} = |00\rangle_{wa} + \sqrt{p}\,|11\rangle_{wa} + O(p)$$

$$|\Psi\rangle_{\text{write,read}} = |00\rangle_{wr} + \sqrt{p}\,|11\rangle_{wr} + O(p)$$



On detection of a *single photon*, state collapses to .

$$\vec{k}_r + \vec{k}_w - \vec{k}_W - \vec{k}_R = 0$$

$$\vec{k}_W = -\vec{k}_R \Rightarrow \vec{k}_r = -\vec{k}_w$$

Phase matching

$$|1_a\rangle = \frac{1}{\sqrt{N_a}} \sum_{j=1}^{N_a} e^{-i\omega_j t} e^{i(\vec{k}_W - \vec{k}_w)\vec{x}_j} |g\rangle_1 \ldots |s\rangle_j \ldots |g\rangle_{N_a}$$

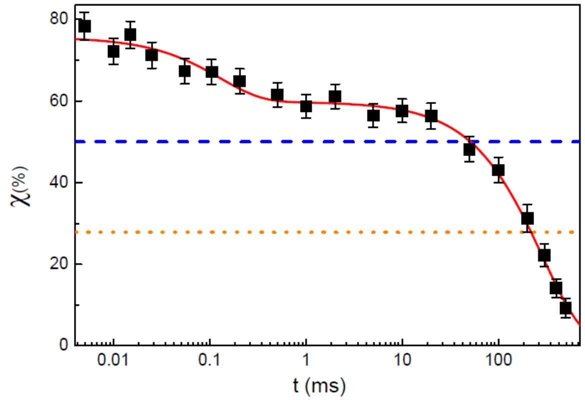
"Spin-wave"

(Quantum superposition of single collective spin excitation)

Photon pair with embedded memory

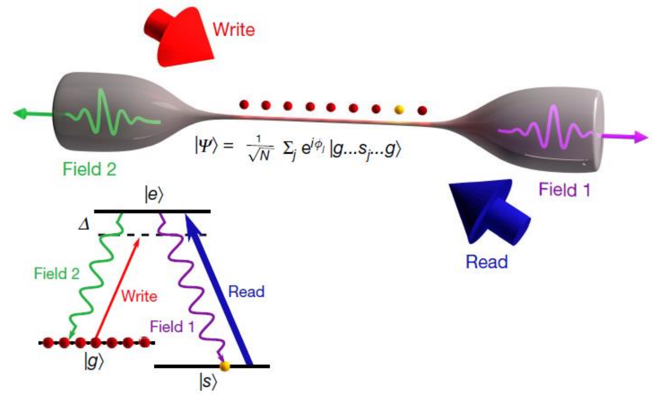
The DLCZ quantum memory

High-efficiency and long storage time



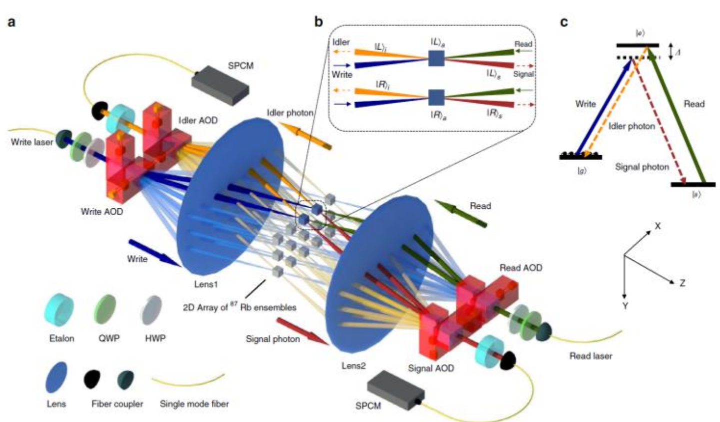
Yang et al, Nature Photon. (2016), Pan group
Radnaev et al, Nature Phys (2010), Kuzmich group

Atoms trapped around a nanofiber



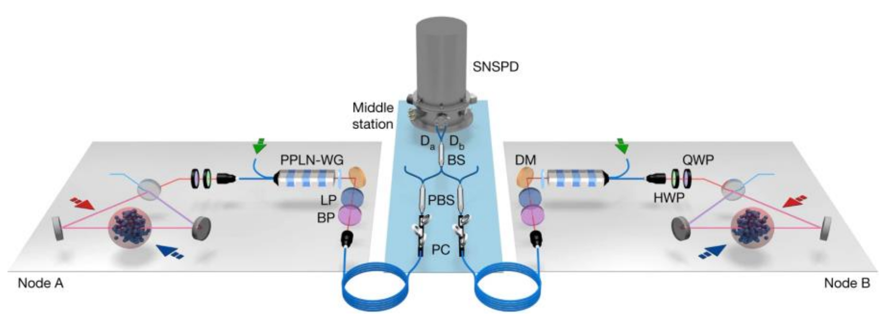
Corzo et al, Nature 566, 369 (2019), Laurat group

Spatial multiplexing



Pu et al, Nature Commun. (2017), Duan group

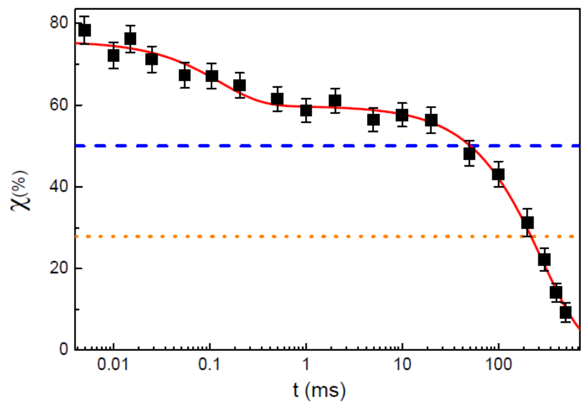
Entanglement between DLCZ memories



Chou et al, Nature (2005), Kimble group
Yu et al, Nature (2020), Pan group

The DLCZ quantum memory

High-efficiency and long storage time



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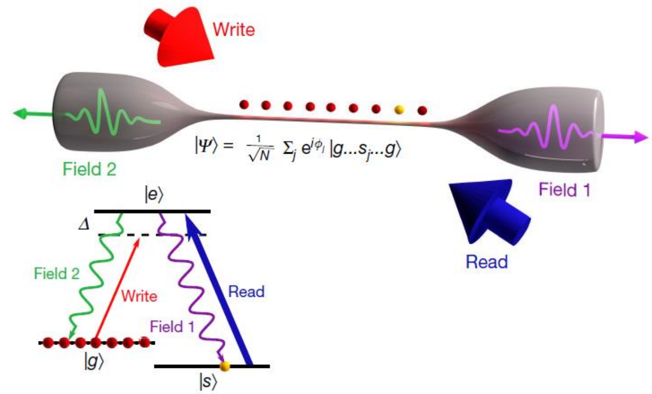
Radnaev et al, Nature Phys ... 0)

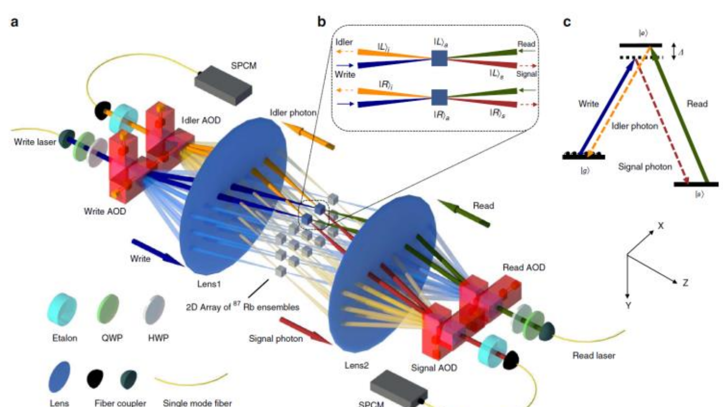
Atoms trapped around a nanofiber



Corzo et al, Nature 566, 369 (2019), Laurat group

Not natively temporally multi mode

Spatial multiplexing



Pu et al, Nature Commun. (2017), Duan group

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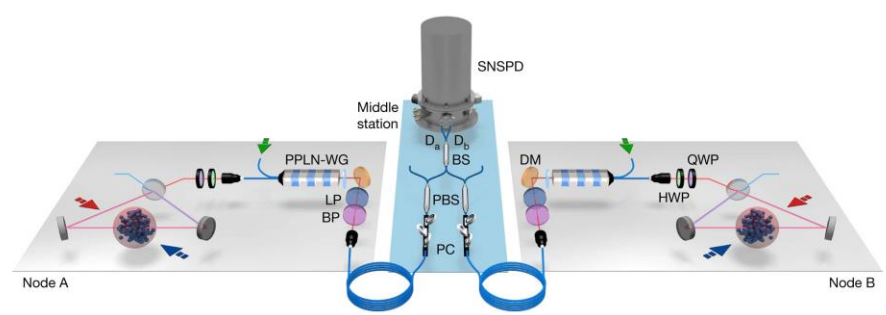


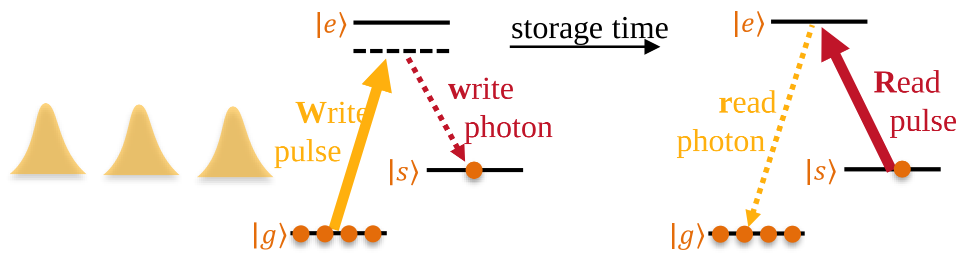
Chou et al, Nature (2005), Kimble group

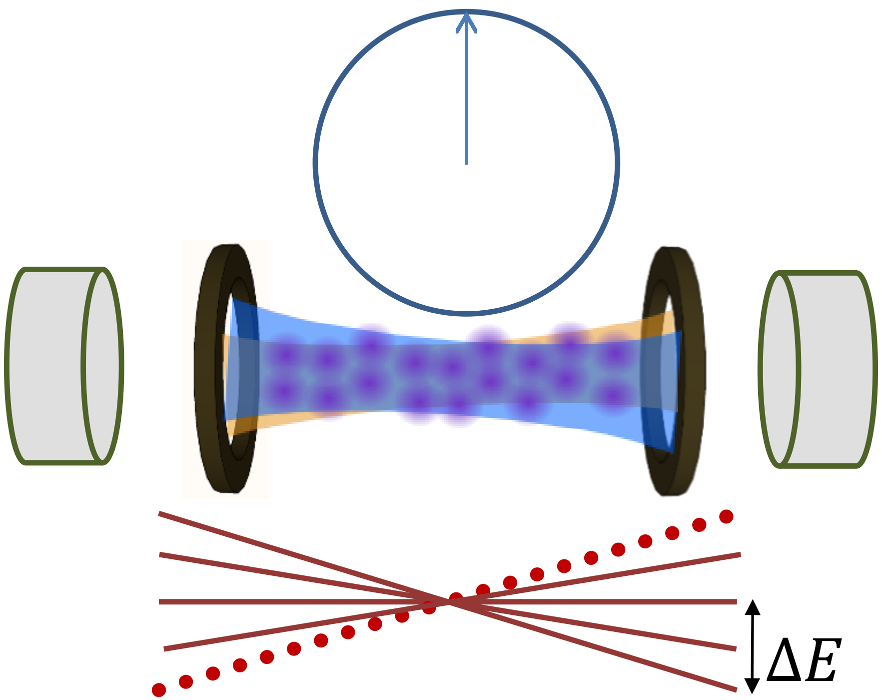
Yu et al, Nature (2020), Pan group

Temporally Multiplexed DLCZ Quantum Memory

Create distinguishable spin waves

- Controlled and reversible inhomogeneous broadening (CRIB) of the spin transition
- allows the creation of spin waves in multiple temporal modes in a single ensemble





Suppress multi-mode noise

Additional noise due to dephased spin waves suppressed by low finesse cavity

$$\alpha = \frac{2F}{\pi}$$

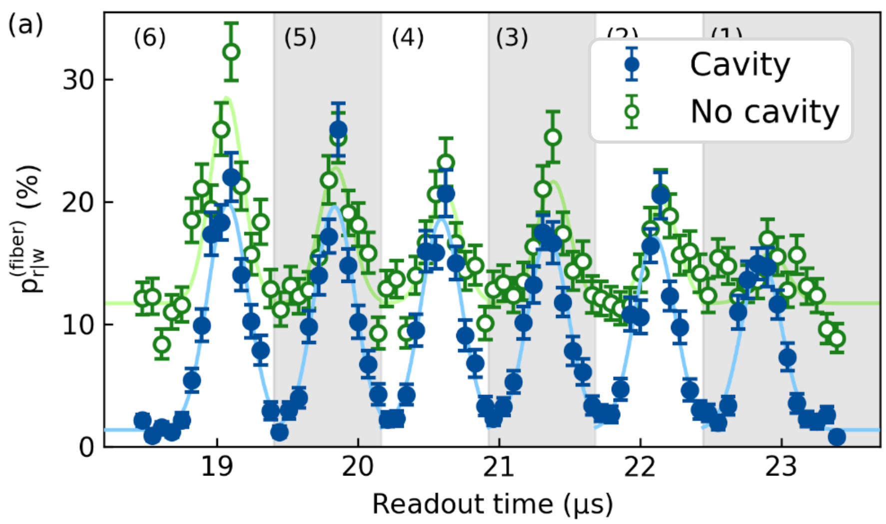
Noise suppression of order of Finesse

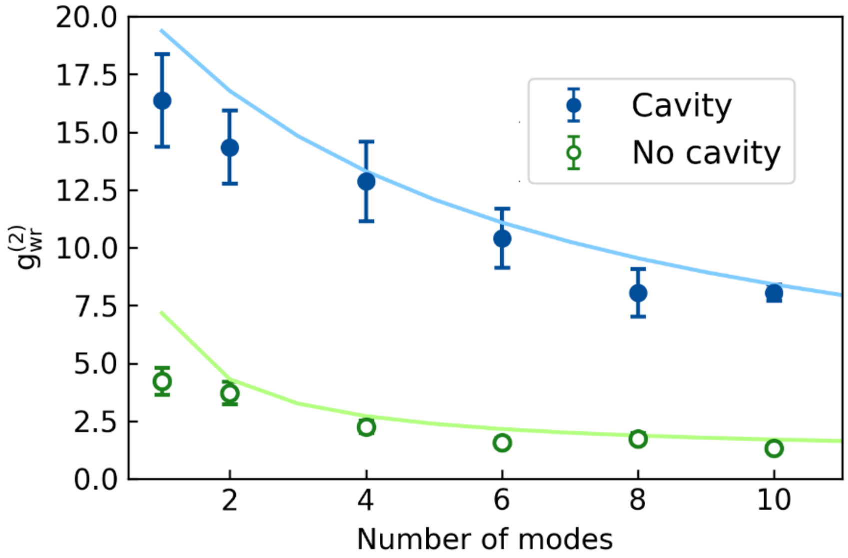
C.Simon, H. de Riedmatten and M.Afzelius, Phys.Rev.A **82**, 010304 (R) (2011)

A cold atom temporally multimode quantum memory

$$g^{(2)}_{w,r} = \frac{p_{w,r}}{p_w p_r}$$

Retrieval with feedforward readout

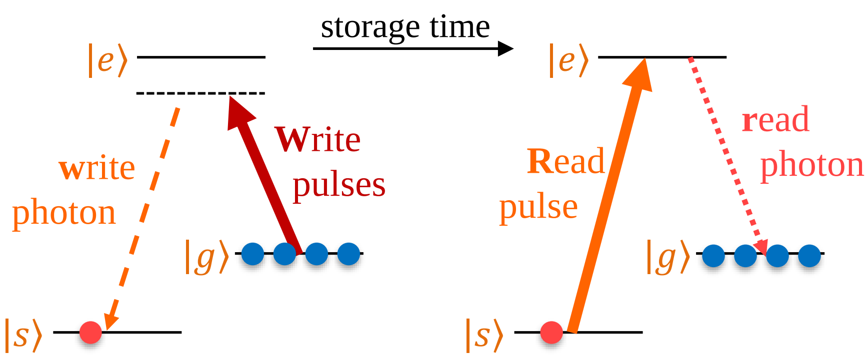


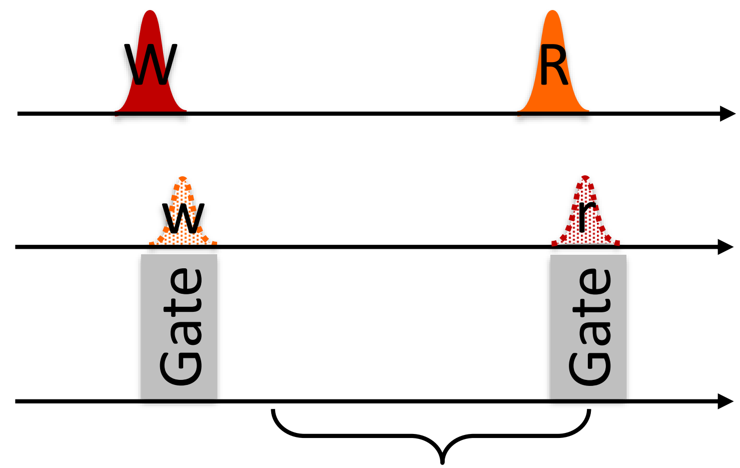


Number of modes limited by the cavity finesse, and storage time: >> 100 possible

L. Heller, P. Farrera, G. Heinze & H. de Riedmatten, Phys. Rev. Lett. 124, 210504 (2020)

Syncronizable single photons with highly tunable waveshape from Rb atoms





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

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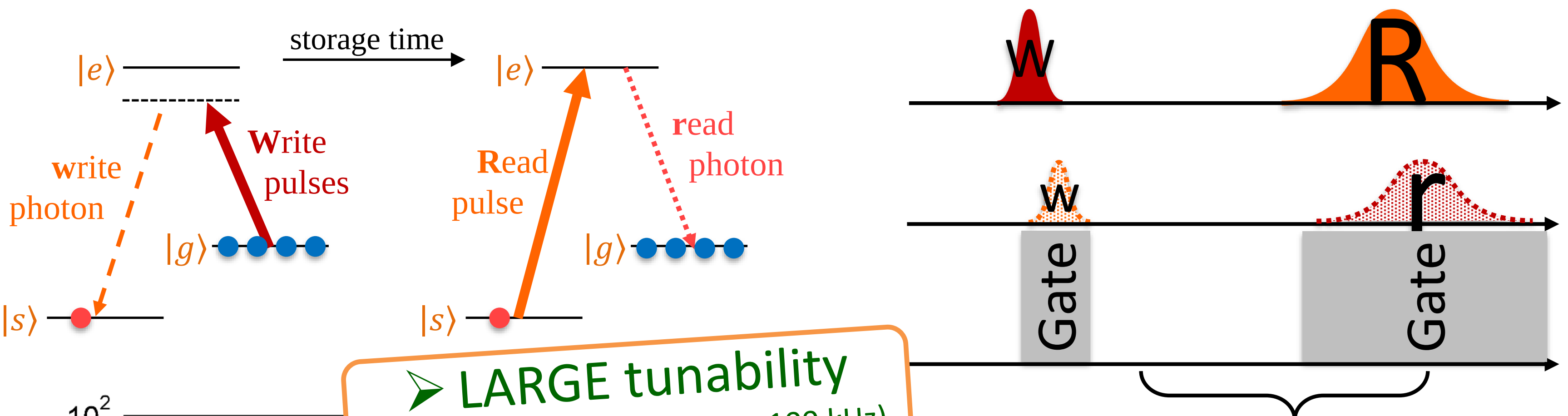
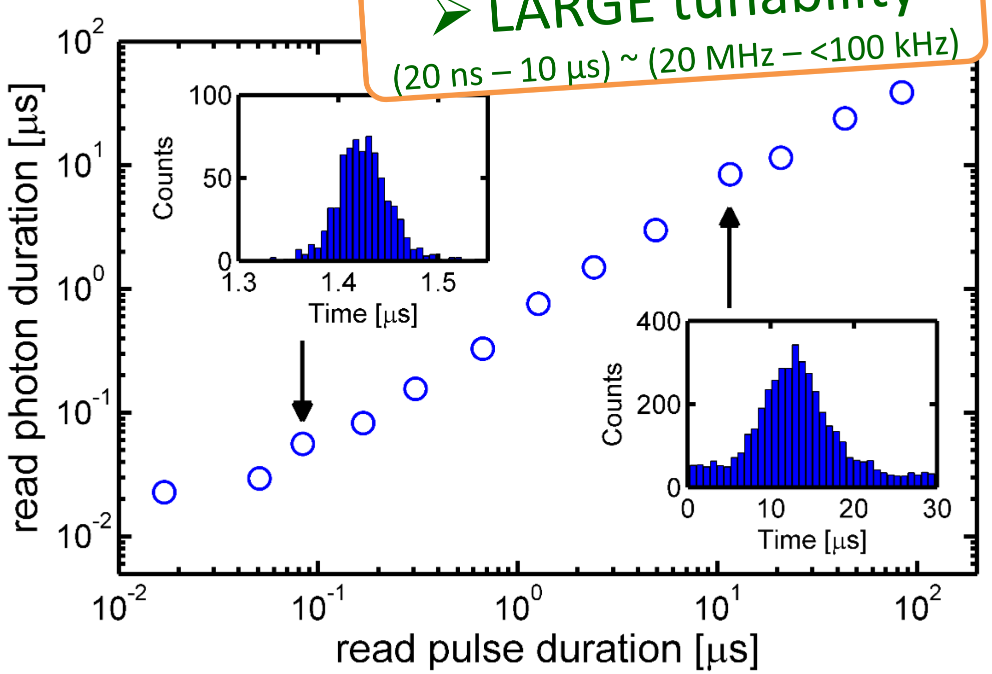


➢ LARGE tunability
(20 ns – 10 μs) ~ (20 MHz – <100 kHz)



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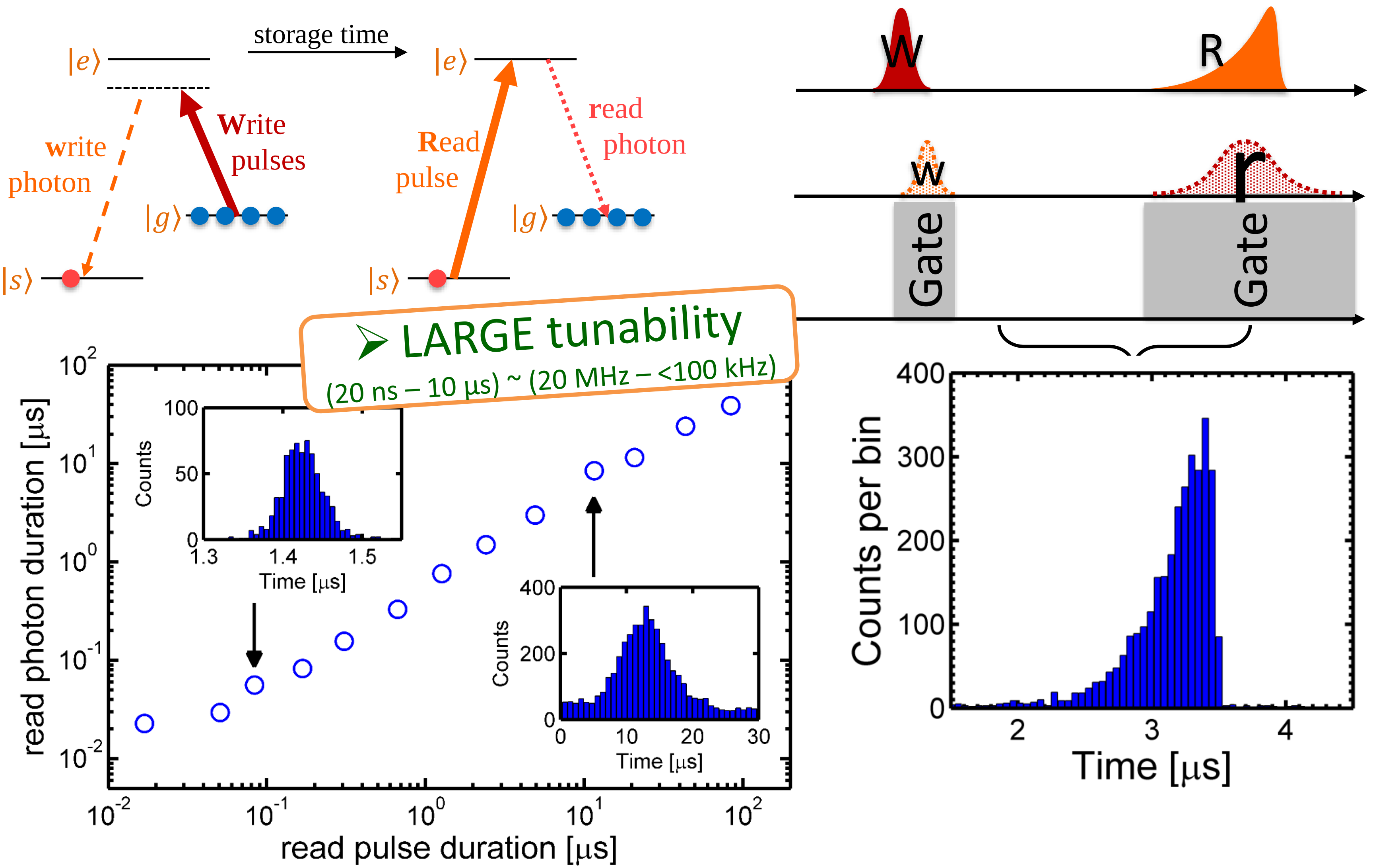

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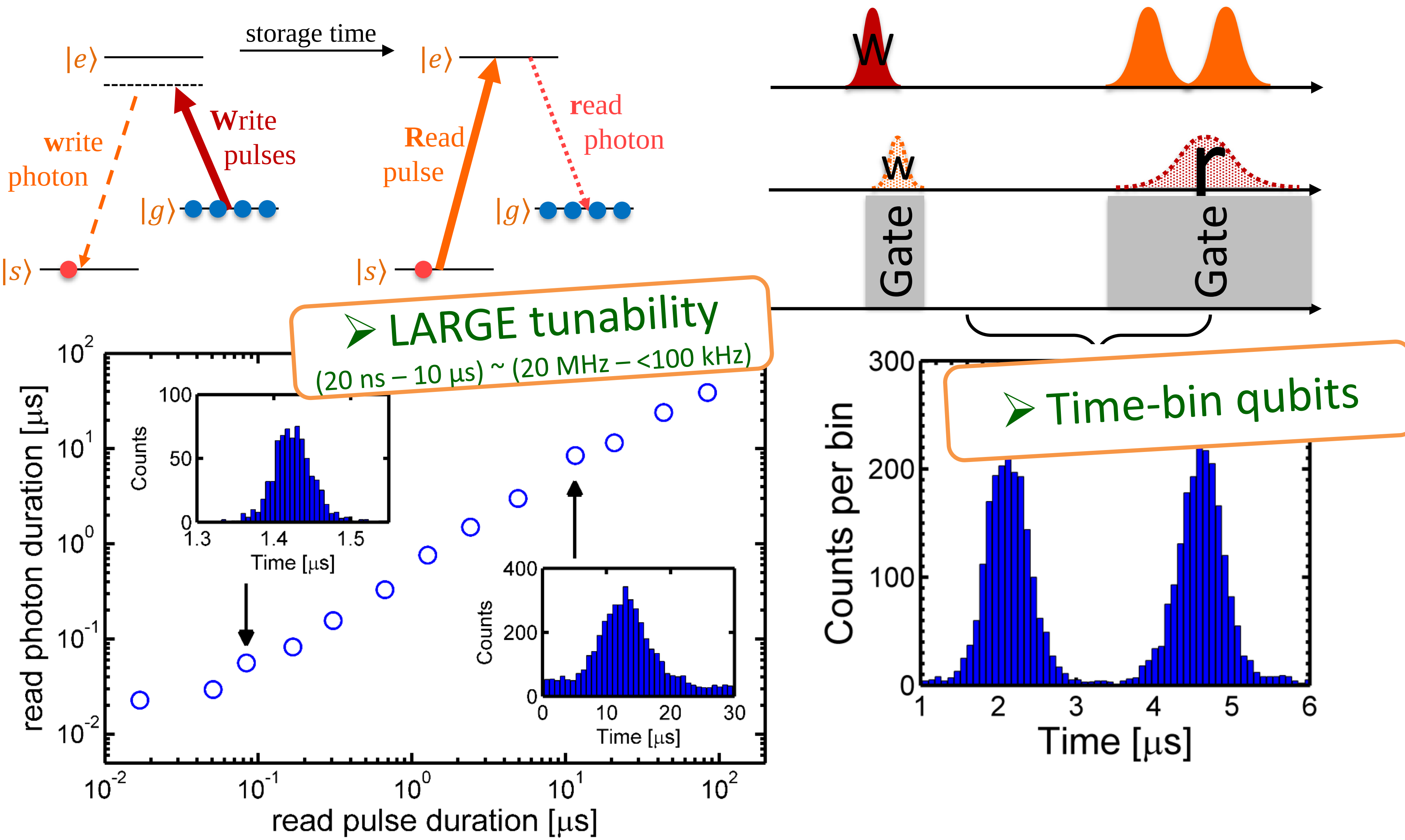

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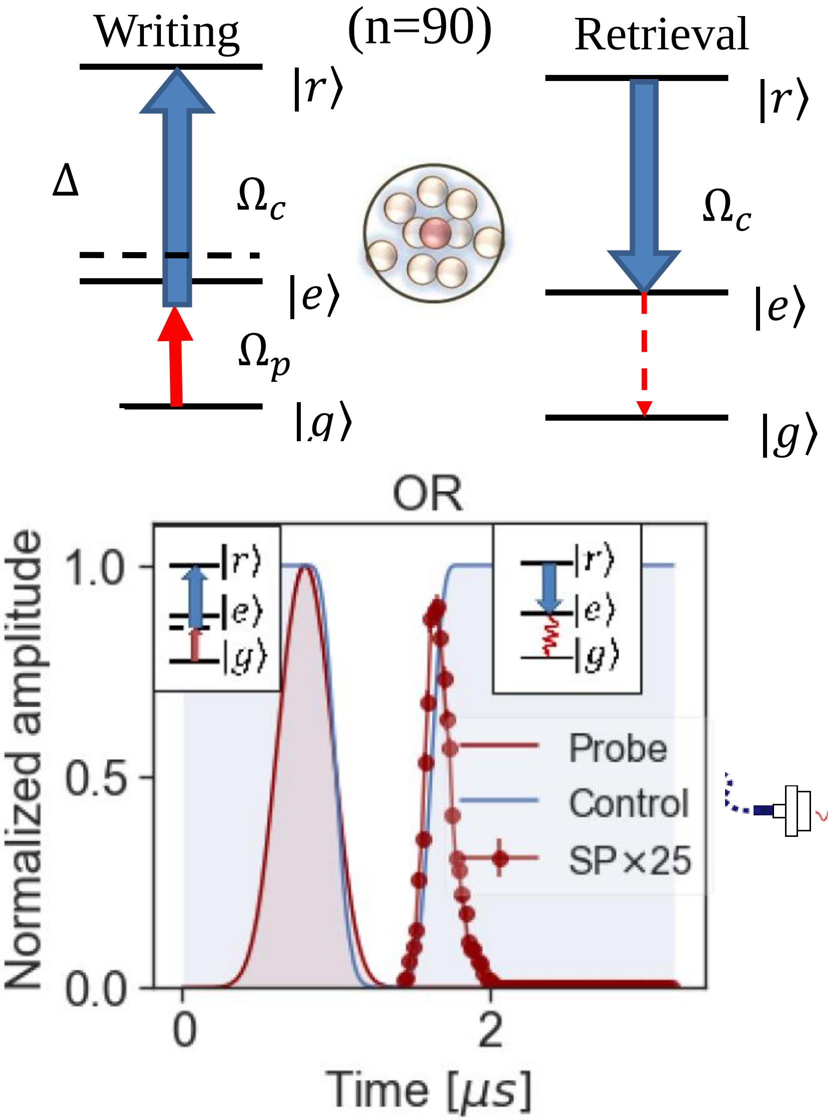
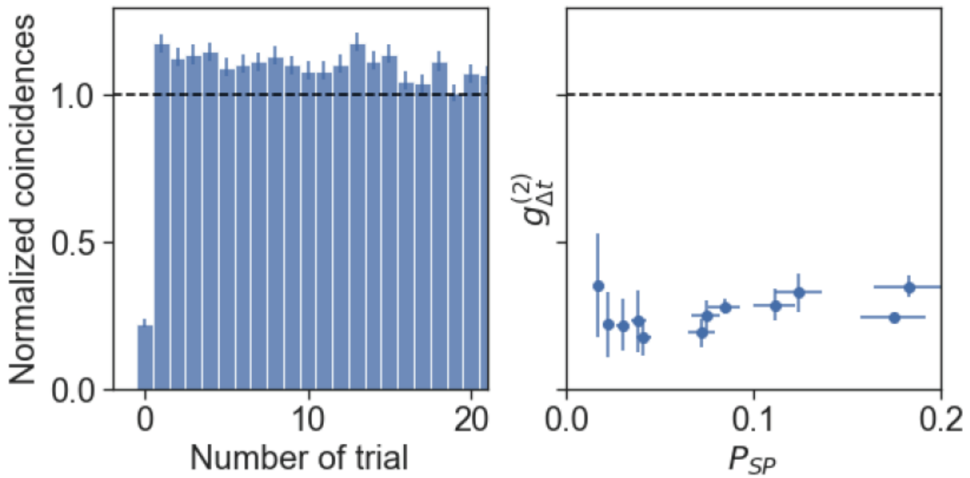
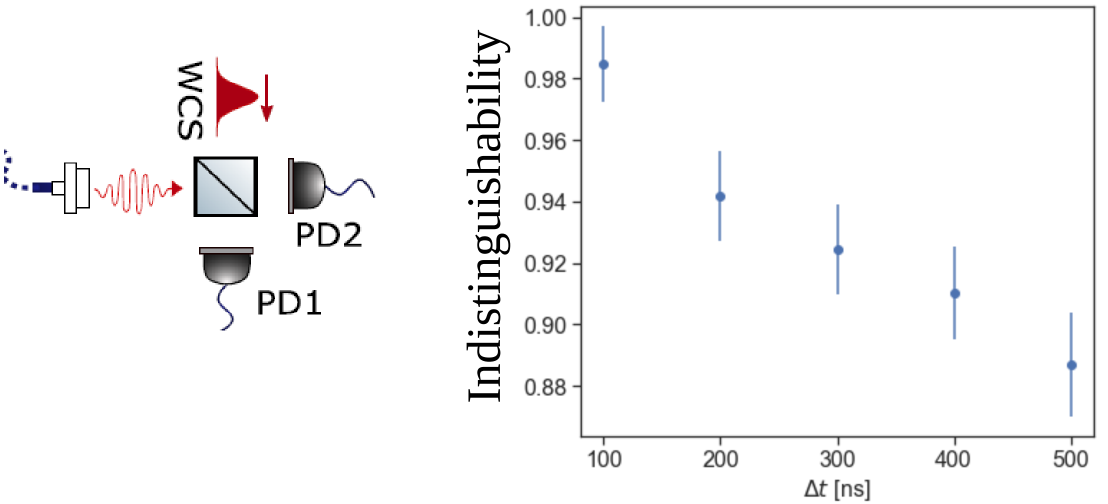
Quasi deterministic generation of single photon using off resonance Rydberg excitation





Generation of indistinguishable photons



See experiments by Vuletic/Lukin, Kuzmich, Adams, Dür/Rempe, Hofferberth, Pan, Rolston/Porto

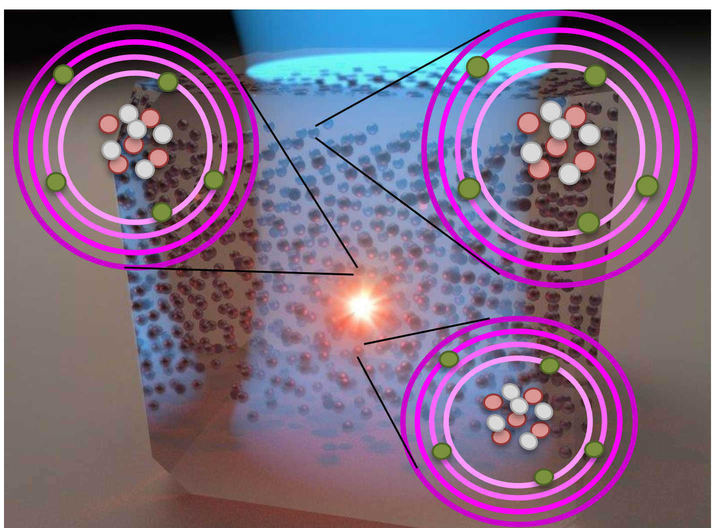
A. Padrón-Brito, J. Lowinsky, P. Farrera,, K. Theophilo, and H. de Riedmatten arXiv:2011.06901 (2020)

Entanglement between Solid-State Quantum Memories

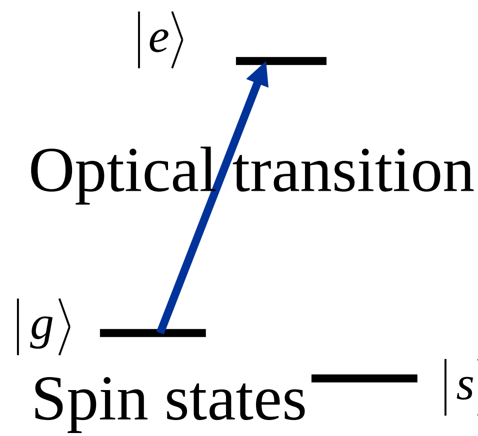
Quantum memory based on Rare-earth doped crystals

lanthanum	cerium	praseodymium	neodymium	promethium	samarium	europium	gadolinium	terbium	dysprosium	holmium	erbium	thulium	ytterbium
57	58	59	60	61	62	63	64	65	66	67	68	69	70
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
138.91	140.12	140.91	144.24	[145]	150.36	151.96	157.25	158.93	162.50	164.93	167.26	168.93	173.04
λ (nm) =		606	880			580					1550	790	980

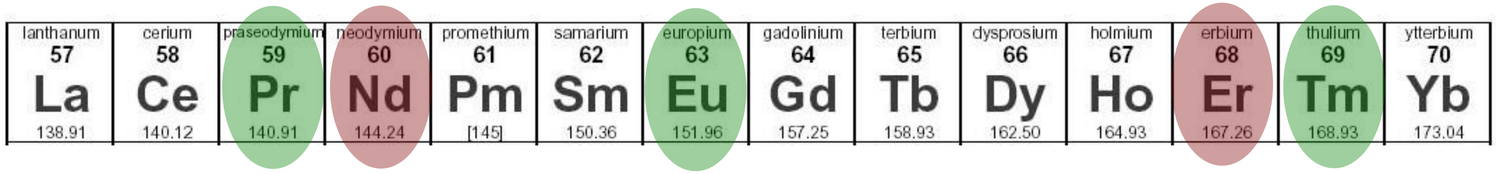
- Large number of stationary atoms with optical and spin transitions.
- Excellent coherent properties (T<4K)



Picture from MPL



Quantum memory based on Rare-earth doped crystals

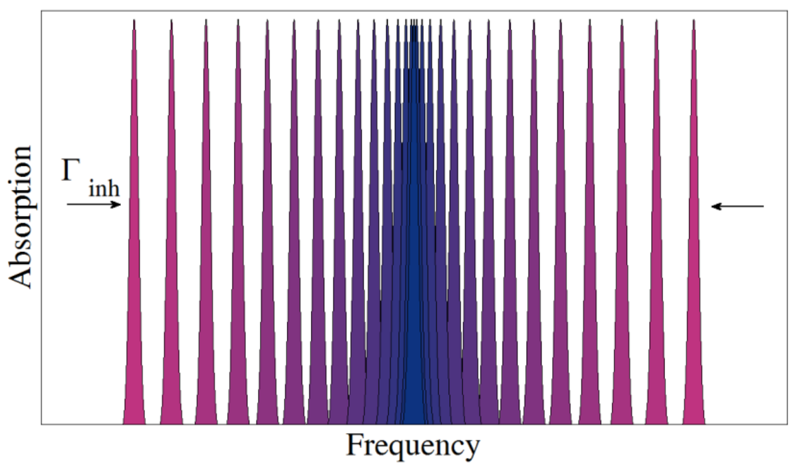


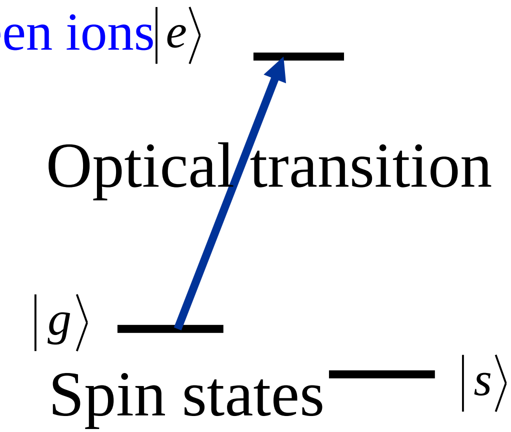
λ (nm) = 606 880 580 1550 790

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

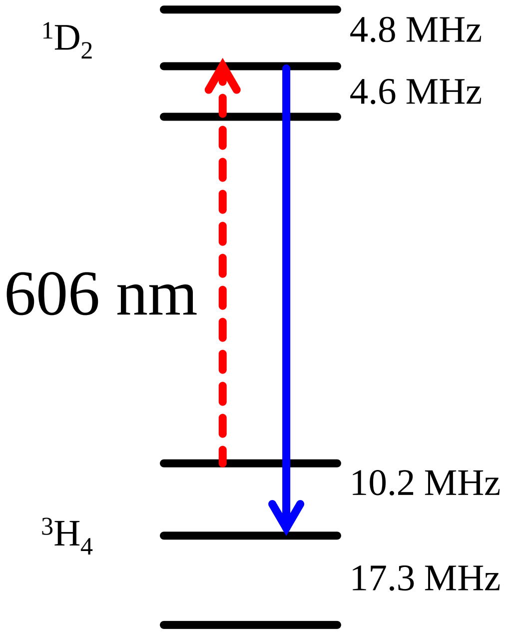
  A resource for multiplexing in time and frequency

- Compatible with integrated design
- Permanent dipole moments: dipolar interaction between ions





Praseodymium ion doped crystals ($Pr^{3+}:Y_2SiO_5$)



Spin T_2	~1s
Optical T_2	152 μs

Level structure suitable for spin-wave storage

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, C. Hubrich and T. Halfmann, PRL **111**, 033601 (2013)

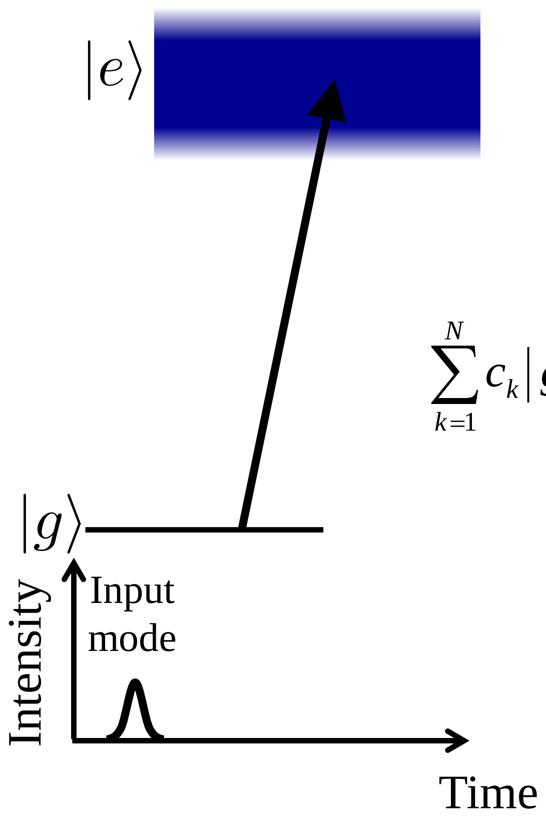
Quantum storage with 69% storage and retrieval efficiency

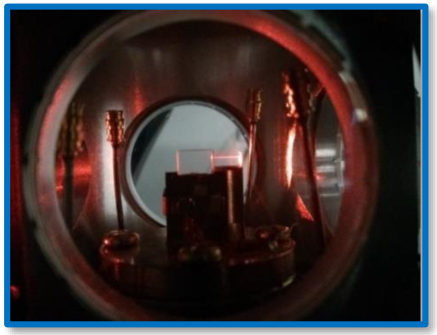
M.P. Hedges, et. al., Nature, **465** 1052, (2010)

Bandwidth 4MHz, Resonant wavelength 606 nm

Storage of quantum states of light challenging
- ✓ ultra-narrowband single photon source
- ✓ narrowband spectral filtering of noise

Atomic Frequency Comb

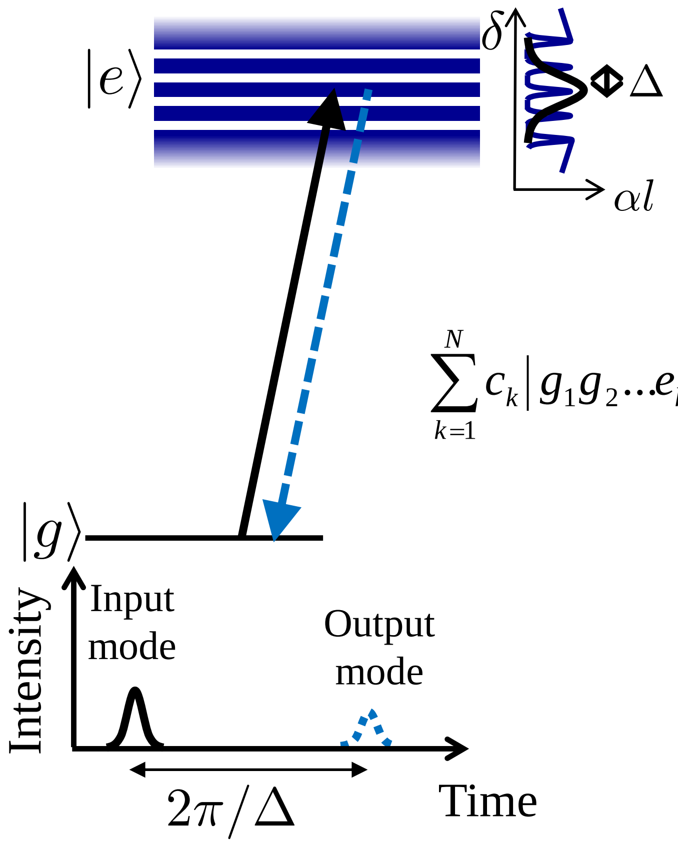


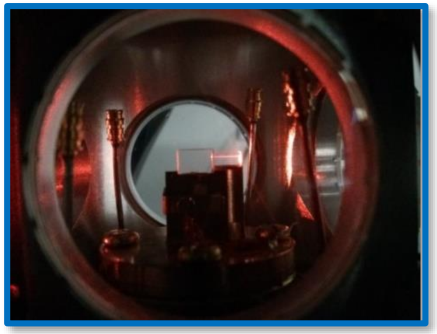


$$\sum_{k=1}^{N} c_k \left| g_1 g_2 \ldots e_k \ldots g_N \right\rangle \Rightarrow \sum_{k=1}^{N} c_k e^{-i\delta_k t} \left| g_1 g_2 \ldots e_k \ldots g_N \right\rangle$$

M. Afzelius, C. Simon, H. de Riedmatten, N. Gisin, *PRA* **79**, 052329 (2009)

Atomic Frequency Comb





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

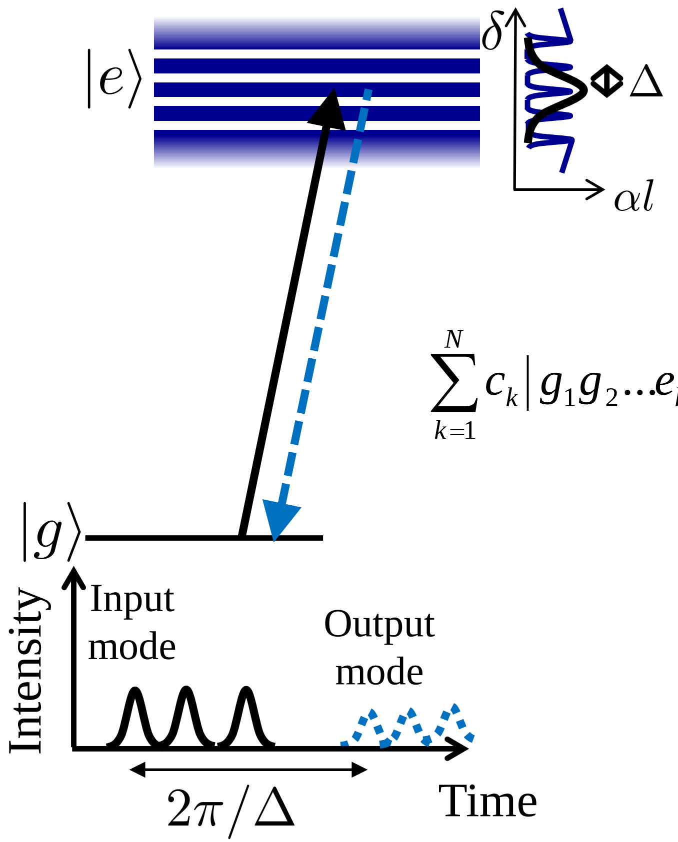
$$\delta_k = m_k \Delta \rightarrow e^{-i(m_k \Delta)t}$$

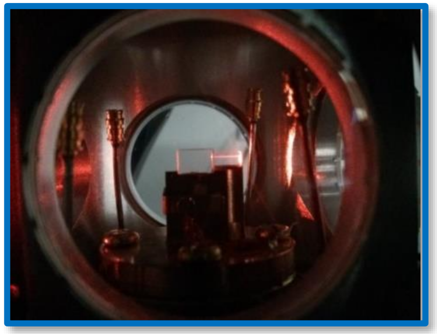
Rephasing after a time $t_e = \frac{2\pi}{\Delta}$

Collective, coherent emission in the forward mode

M. Afzelius, C. Simon, H. de Riedmatten, N. Gisin, *PRA* **79**, 052329 (2009)

Atomic Frequency Comb





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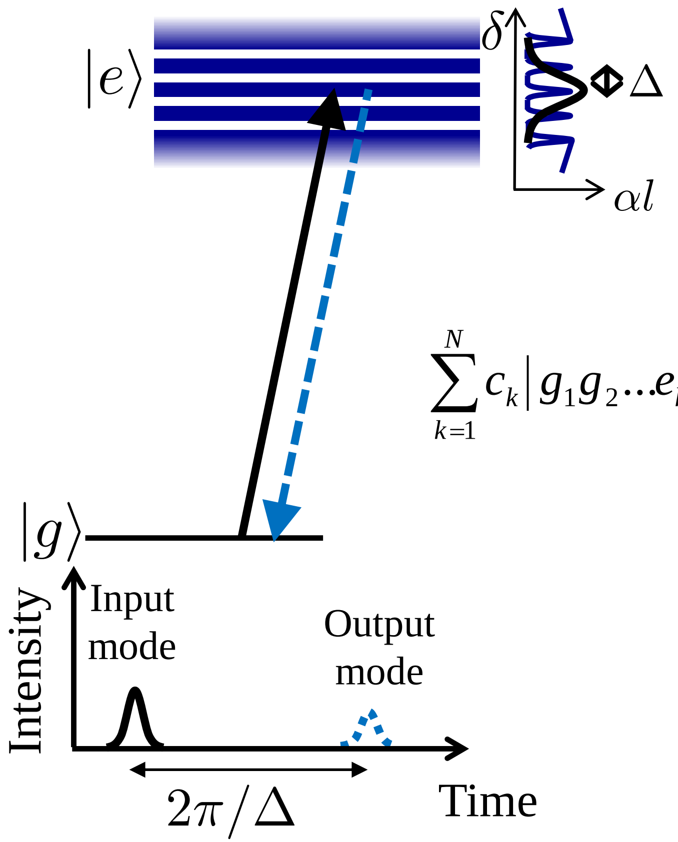
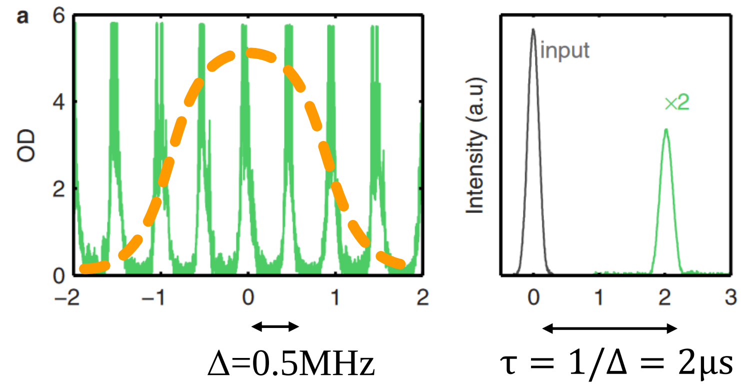
Temporally multimode

M. Afzelius, C. Simon, H. de Riedmatten, N. Gisin, *PRA* **79**, 052329 (2009)

Atomic Frequency Comb





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

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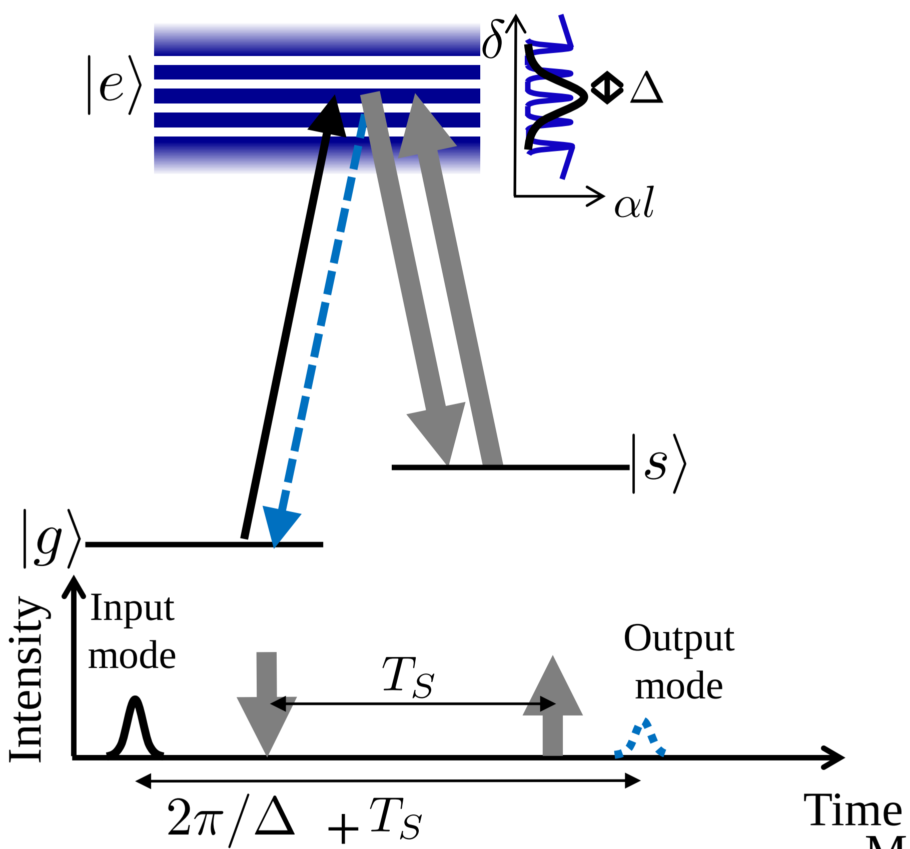
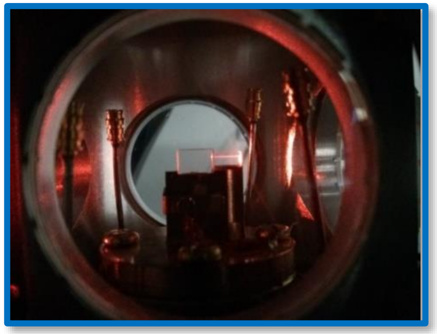
M. Afzelius, C. Simon, H. de Riedmatten, N. Gisin, *PRA* **79**, 052329 (2009)

Atomic Frequency Comb: spin-wave storage





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

$$\sum_{k=1}^{N} c_k |g_1 g_2 \ldots s_k \ldots g_N\rangle$$

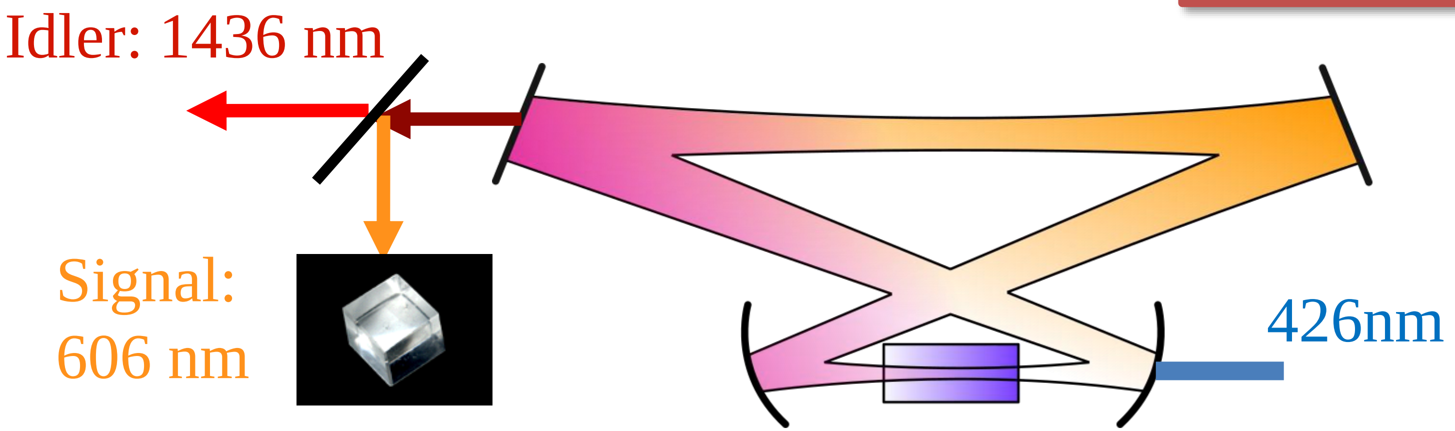
- On-demand read-out
- Longer storage times

Measurements at single photon level
Gündogan et al, PRL 2015 (ICFO)
Jobez et al, PRL 2015 (Geneva)

M. Afzelius, C. Simon, H. de Riedmatten, N. Gisin, *PRA* **79**, 052329 (2009)   M. Afzelius et al, *PRL* **104**, 040503 (2010)

Single Photons for Pr doped quantum memories with telecom heralding

Spontaneous Parametric Down Conversion (SPDC)
- Cavity enhanced
- Ultra narrow-band (< 2 MHz)
- Widely non-degenerate (606 nm and 1436 nm)



Parameters: Finesse = 150
FSR = 260 MHz

Pair creation probability (within cavity mode)

$$p_c \propto p_0 F^2$$

D.Lago,
S.Grandi

J. Fekete, D. Rieländer, M Cristiani, and H. de Riedmatten, Phys. Rev. Lett. 110, 220502 (2013)

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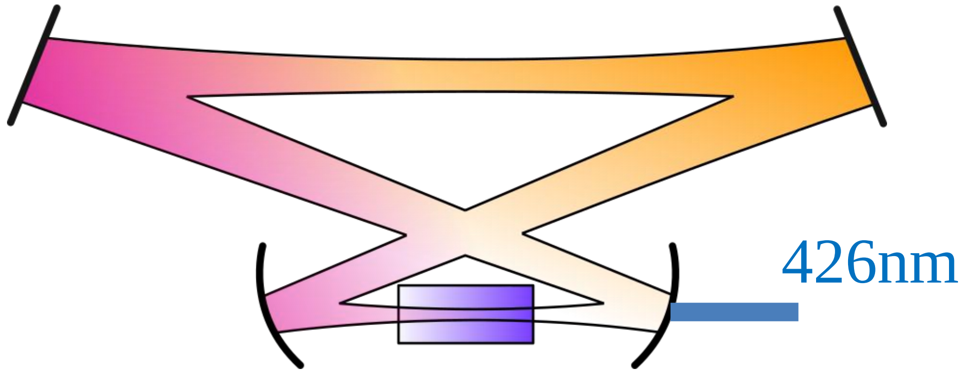

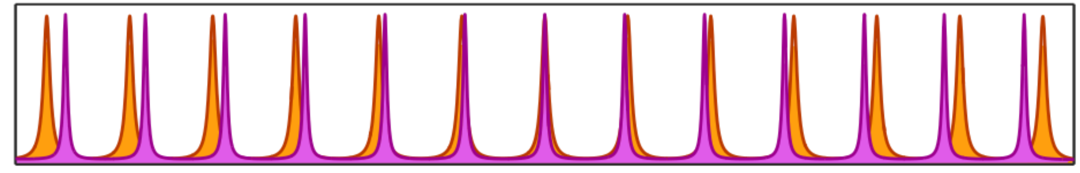

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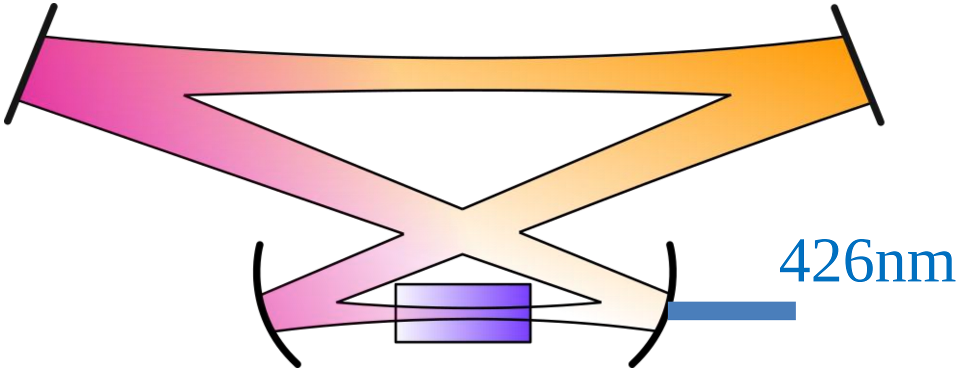
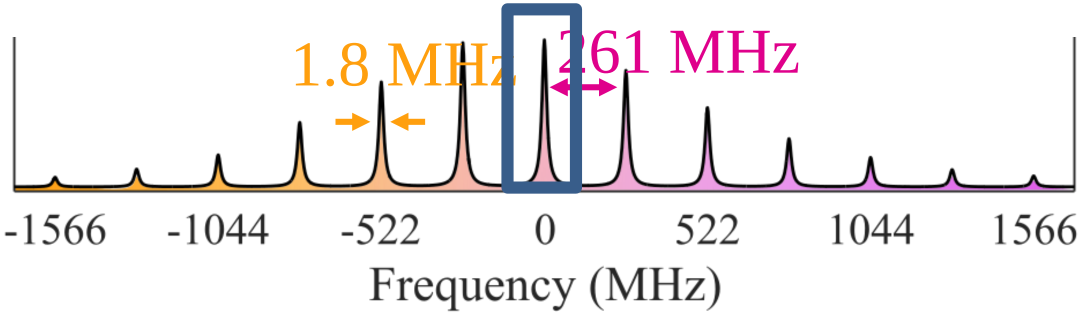
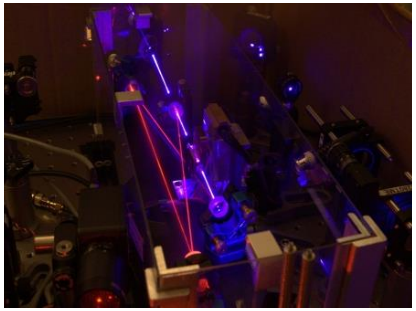


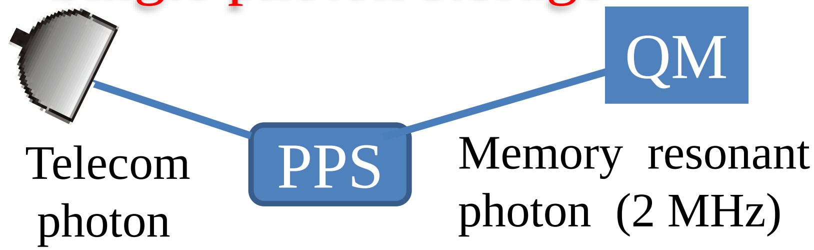


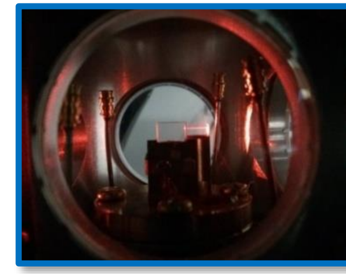
J. Fekete, D. Rieländer, M Cristiani, and H. de Riedmatten, Phys. Rev. Lett. 110, 220502 (2013)

Solid-state spin-wave quantum memories (long-lived)

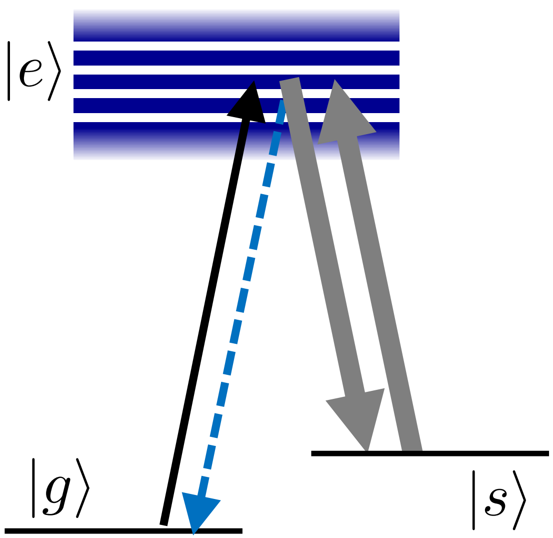


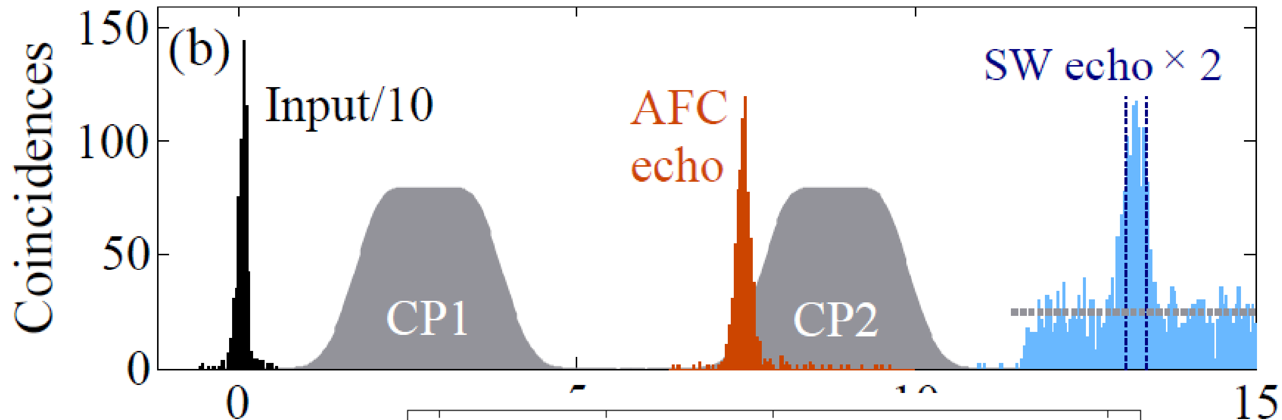
Single photon storage

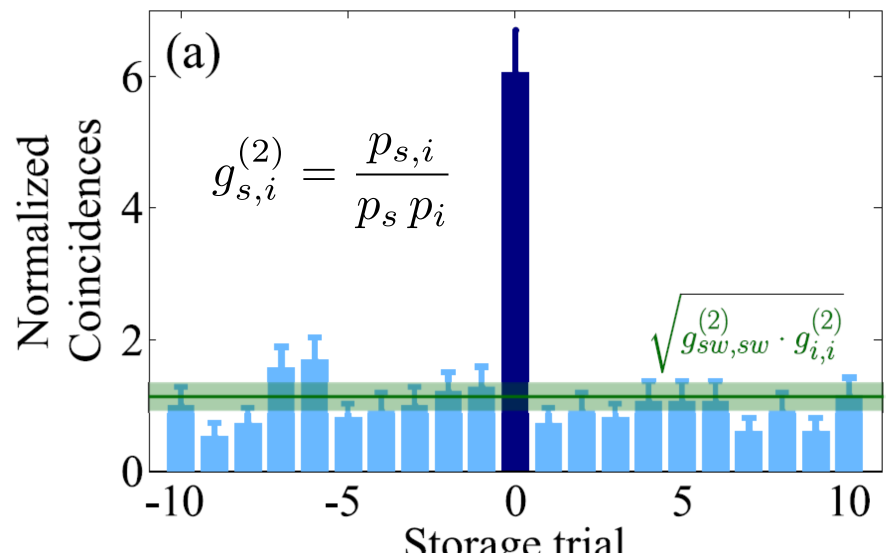




$Pr^{3+}:Y_2SiO_5$







A. Seri, A. Lenhard, D. Rieländer, M.Gündogan, P.M. Ledingham, M. Mazzera, H. de Riedmatten, PRX 7, 021028 (2017)

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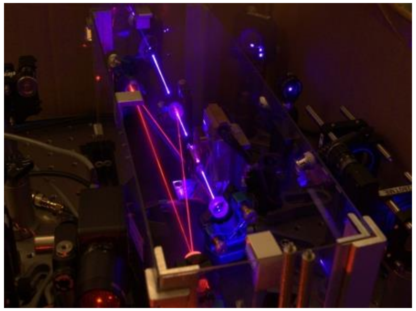
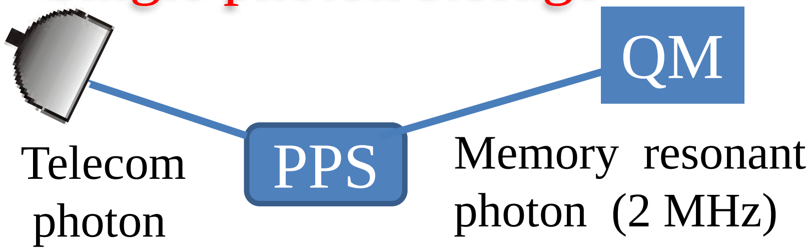
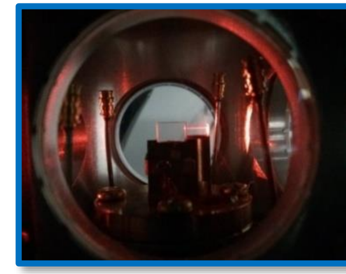
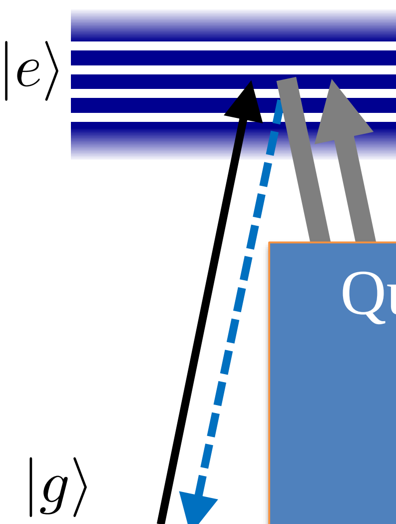


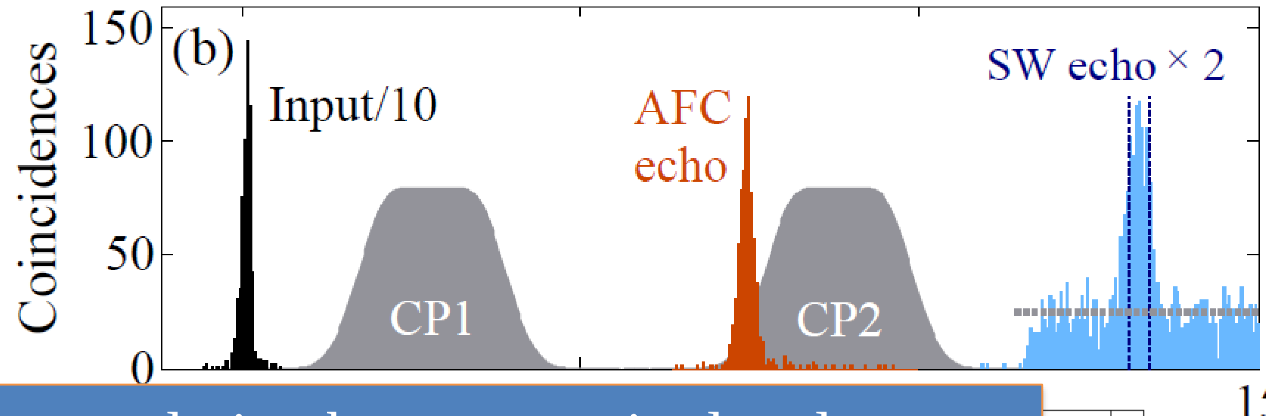
Single photon storage





$Pr^{3+}:Y_2SiO_5$

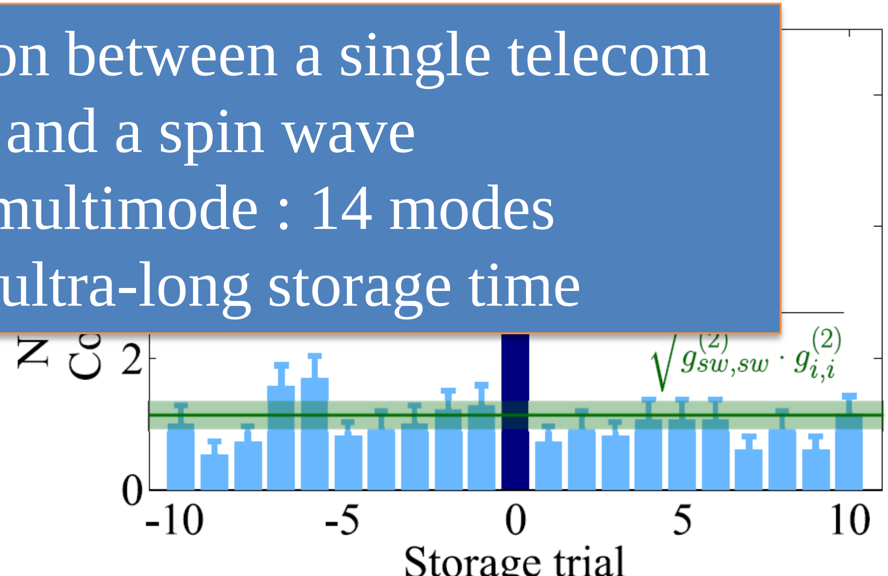




Quantum correlation between a single telecom photon and a spin wave

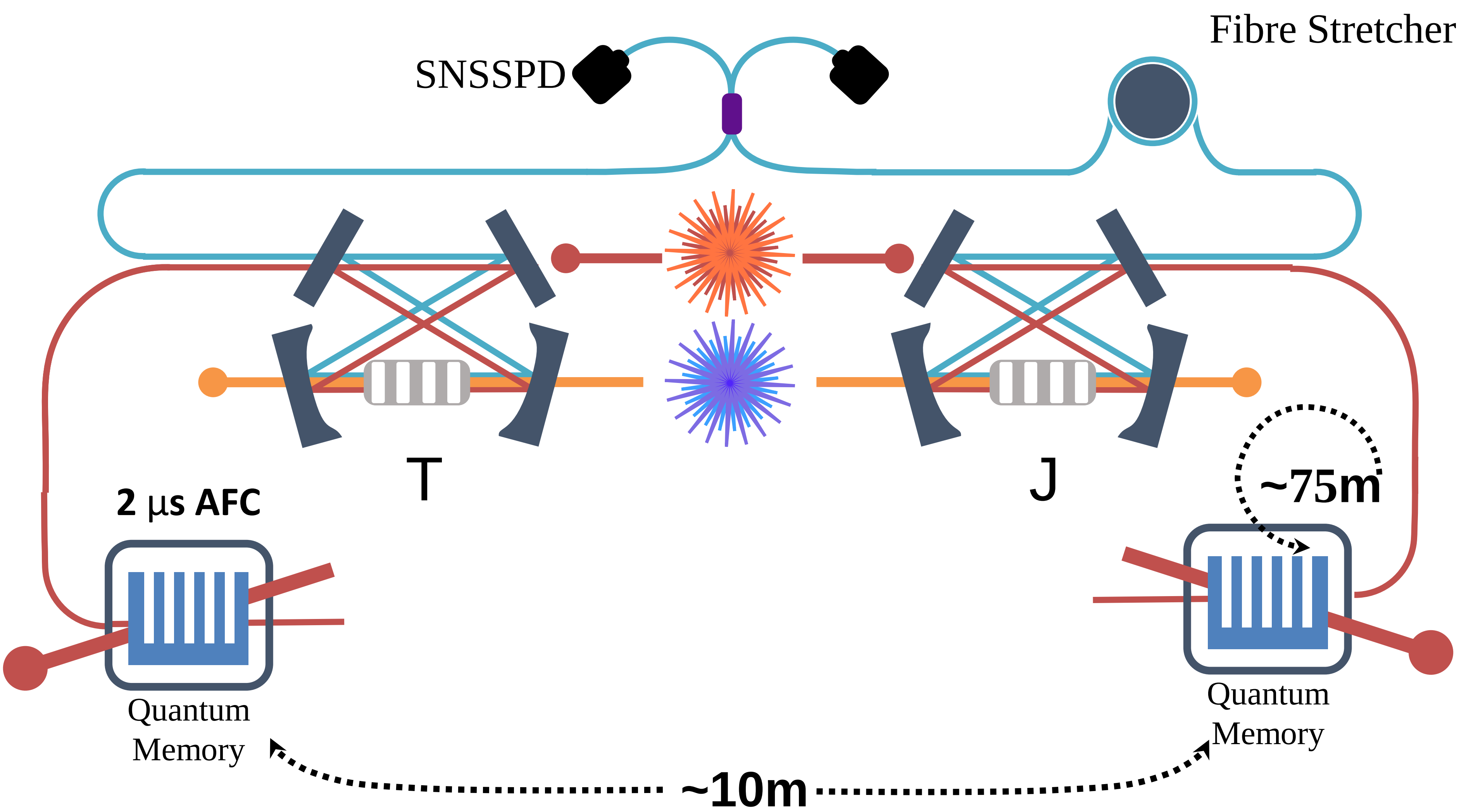
Temporally multimode : 14 modes

Prospects for ultra-long storage time



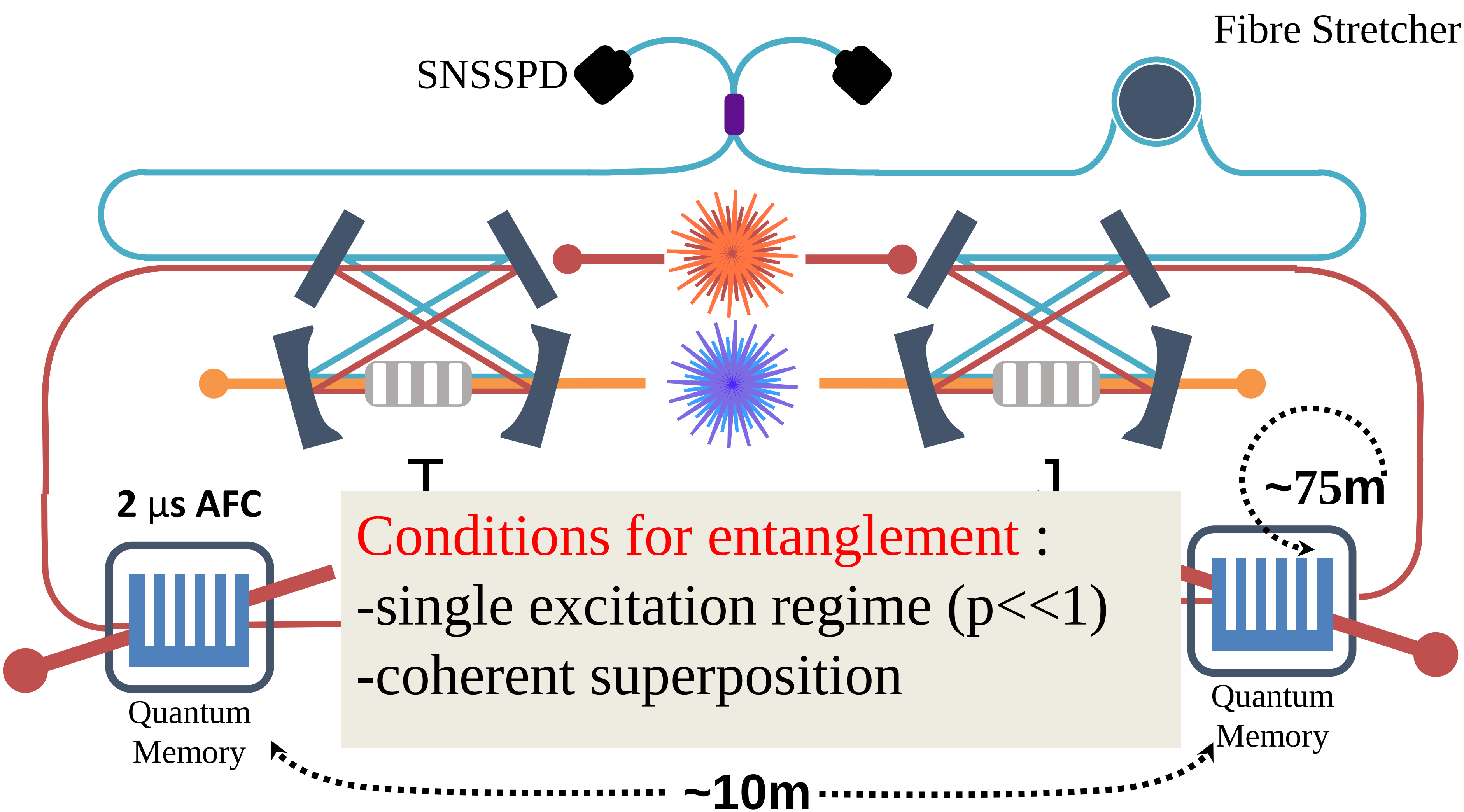
A. Seri, A. Lenhard, D. Rieländer, M.Gündogan, P.M. Ledingham, M. Mazzera, H. de Riedmatten, PRX 7, 021028 (2017)

Heralded entanglement



$$|\Phi_{AB}\rangle = \frac{1}{\sqrt{2}}(|1\rangle_A|0\rangle_B + e^{i\phi_{AB}}|0\rangle_A|1\rangle_B)$$

Heralded entanglement

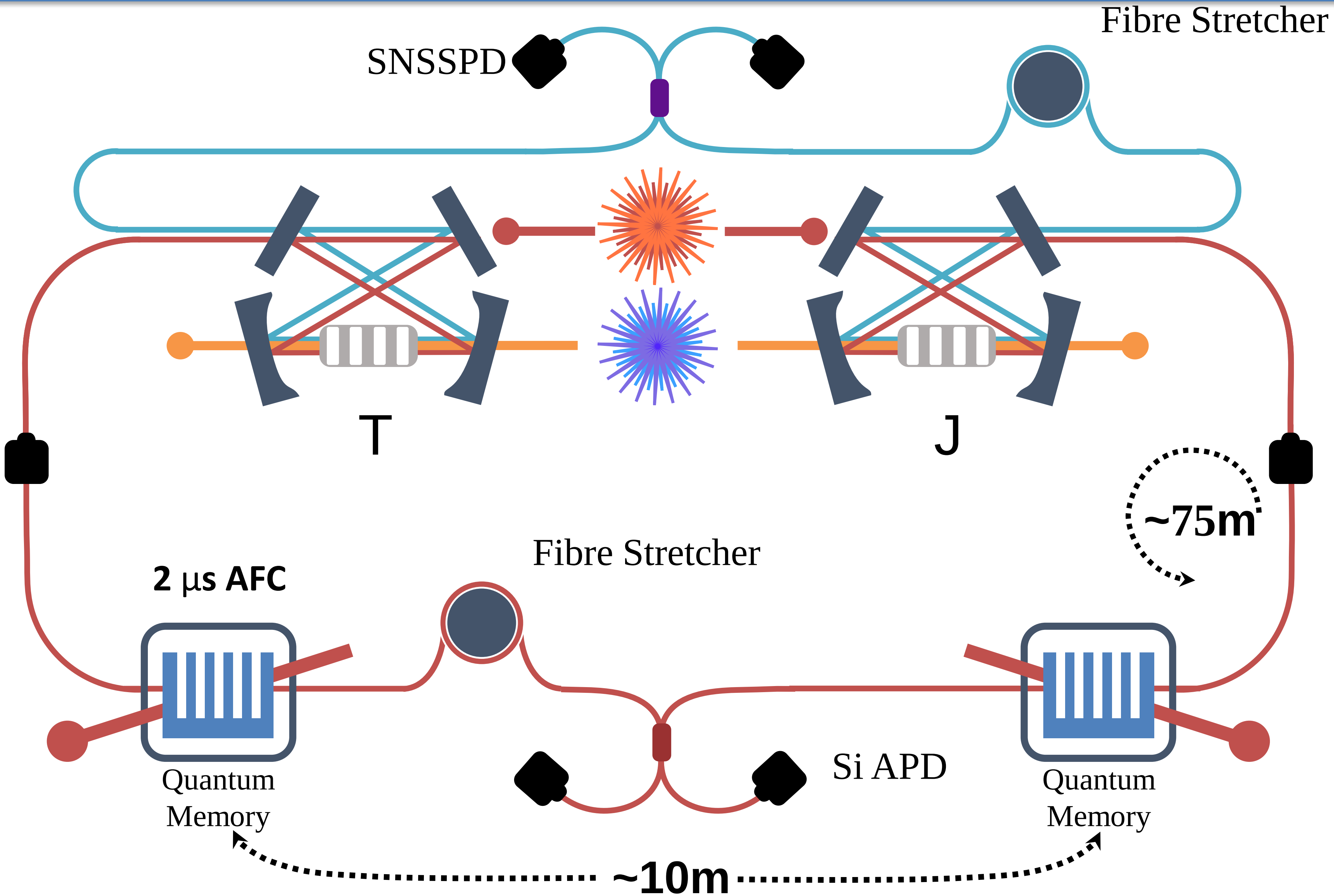


Conditions for entanglement :

- single excitation regime (p<<1)
- coherent superposition

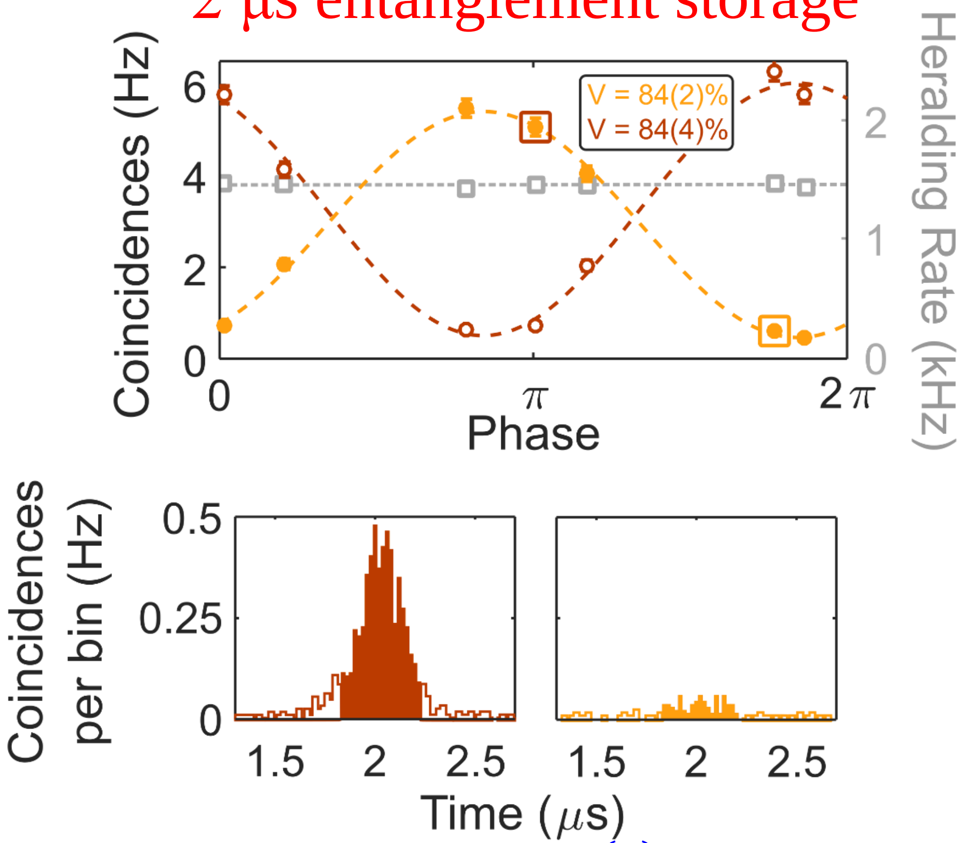
$$|\Phi_{AB}\rangle = \frac{1}{\sqrt{2}}(|1\rangle_A|0\rangle_B + e^{i\phi_{AB}}|0\rangle_A|1\rangle_B)$$

Heralded entanglement

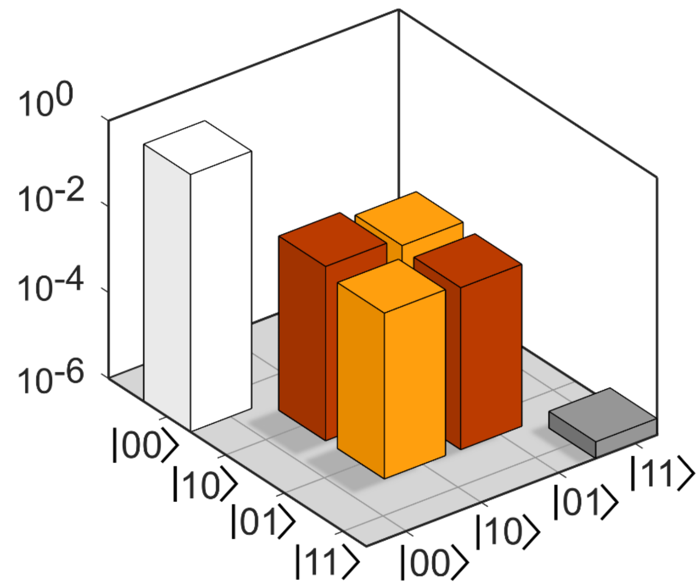


Heralded entanglement between solid-state QMs

2 µs entanglement storage



Quantum Tomography

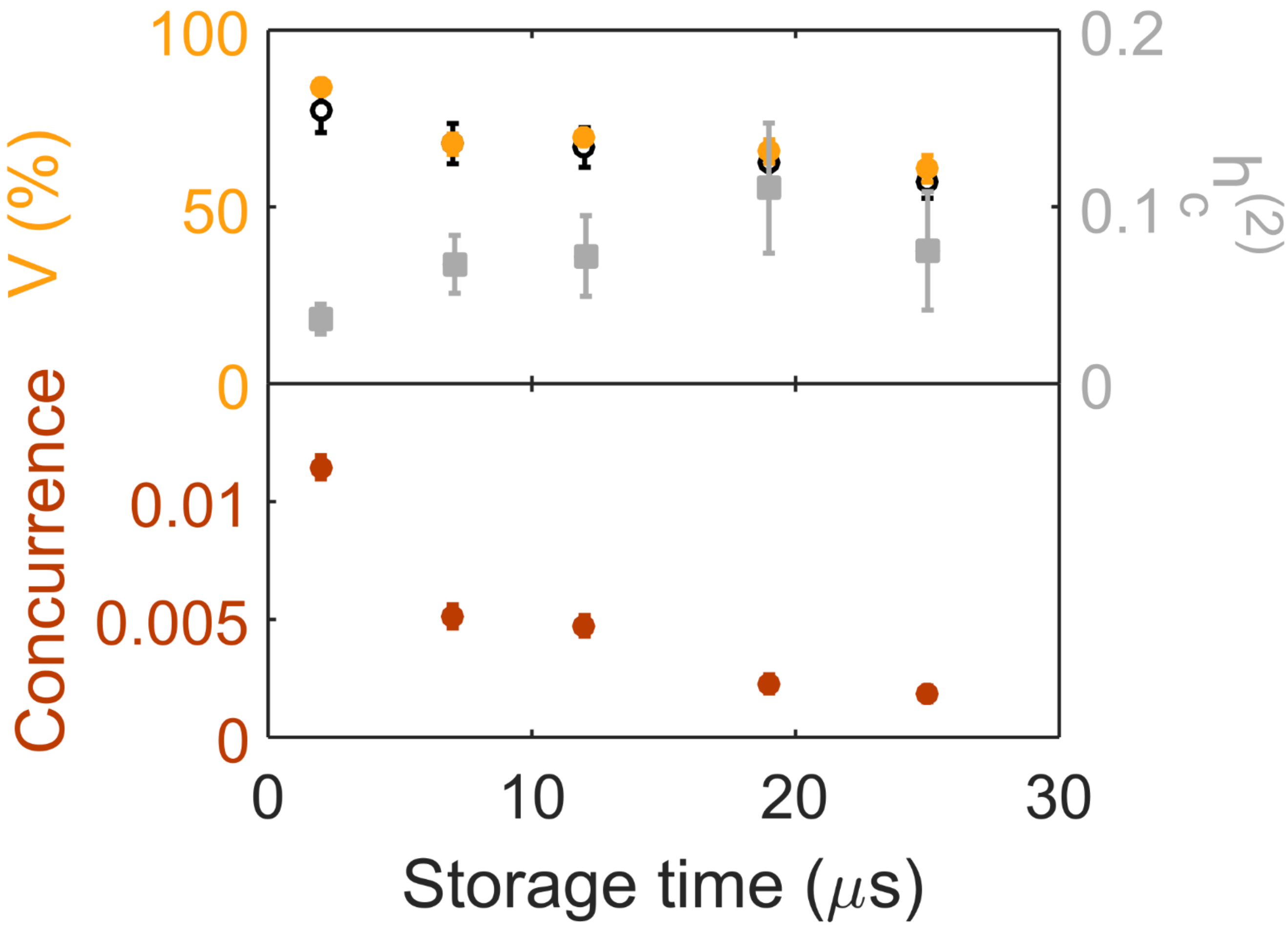


$$\rho = \begin{pmatrix} p_{00} & 0 & 0 & 0 \\ 0 & p_{01} & d & 0 \\ 0 & d^* & p_{10} & 0 \\ 0 & 0 & 0 & p_{11} \end{pmatrix}$$

- Single-photon purity: $h_c^{(2)} = \frac{p_{11}}{p_{10} \times p_{01}}$ = 0.036(8)
- Coherent superposition : V = 84 %
- Concurrence: $1.15(5) \cdot 10^{-2}$ (*$9.0(1) \cdot 10^{-2}$ in the crystal*)
- Heralding rate: 1.43 kHz (43% duty cycle)

D. Lago, S. Grandi, J.V. Rakonjac, A. Seri , H. de Riedmatten, arXiv:2101.05097 (2020)
See also Liu et al, arXiv:2101.04945 (2020) (Hefei)

Heralded entanglement : Longer storage times

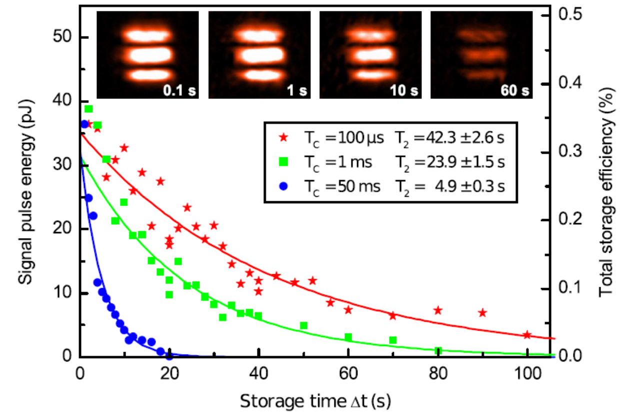


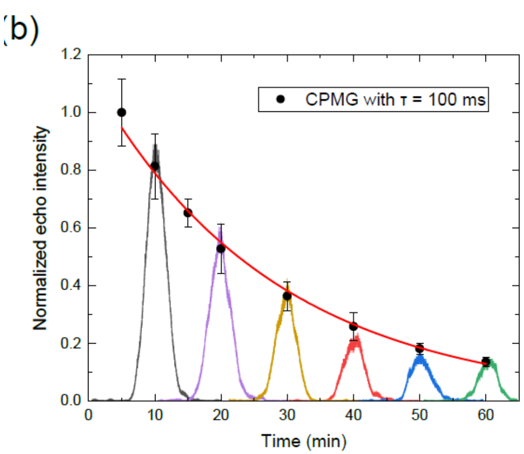
Storage allowing up to 5km of separation between nodes

Significantly longer storage times require spin-wave storage

Long-lived solid-state quantum memories ?

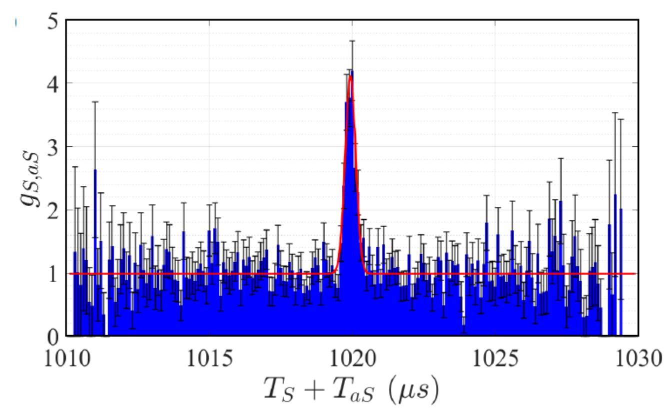
Coherent optical memory (classical pulses):
Storage time 1 minute
Pr:YSO crystal
Heinze *et al*, PRL 2013



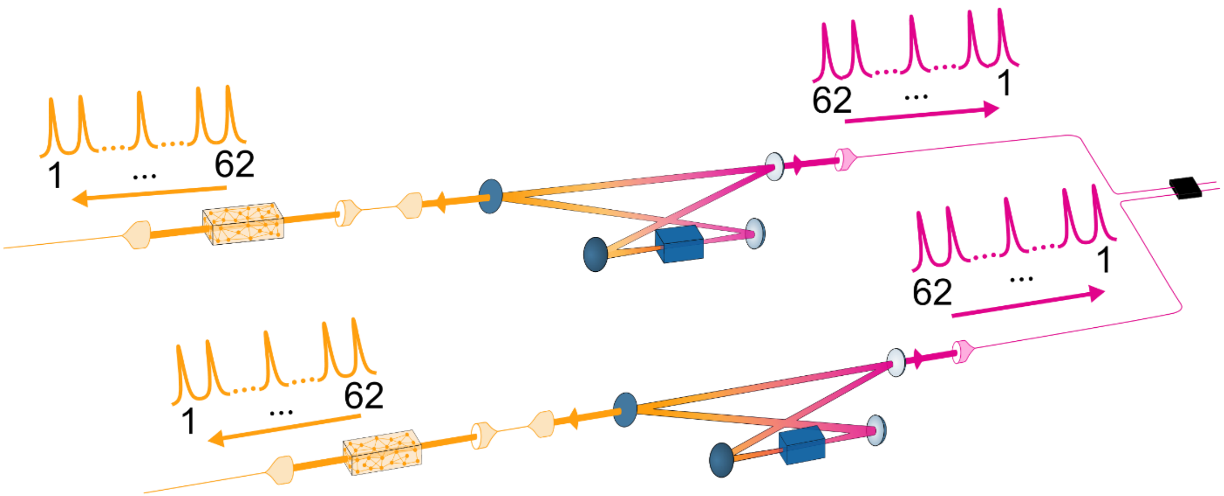


Spin coherence : 6 hours Eu:YSO crystal
Zhong et al, , Nature 2015
1 hour AFC light storage (Ma et al, arXiv:2012.14605)

Longest storage time so far with single photons
Storage time 1 ms
Eu:YSO crystal
Laplane *et al*, PRL 2017 (Geneva)

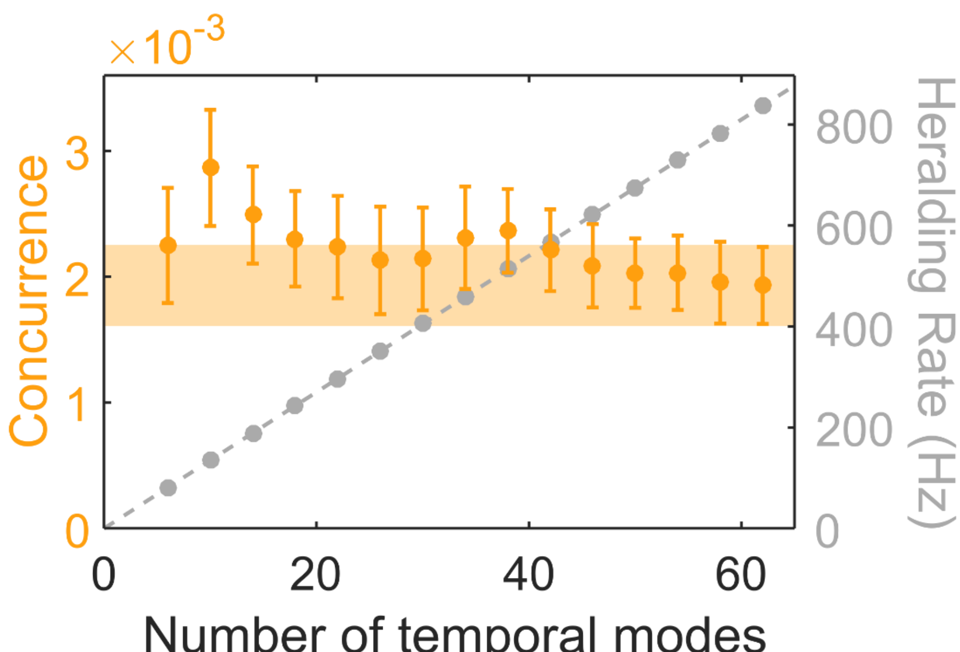


Heralded entanglement : Multimode operation

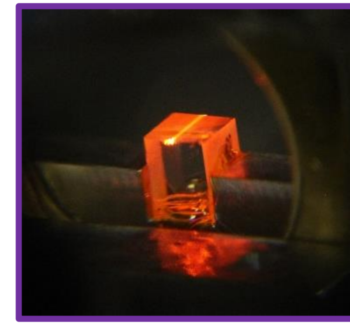


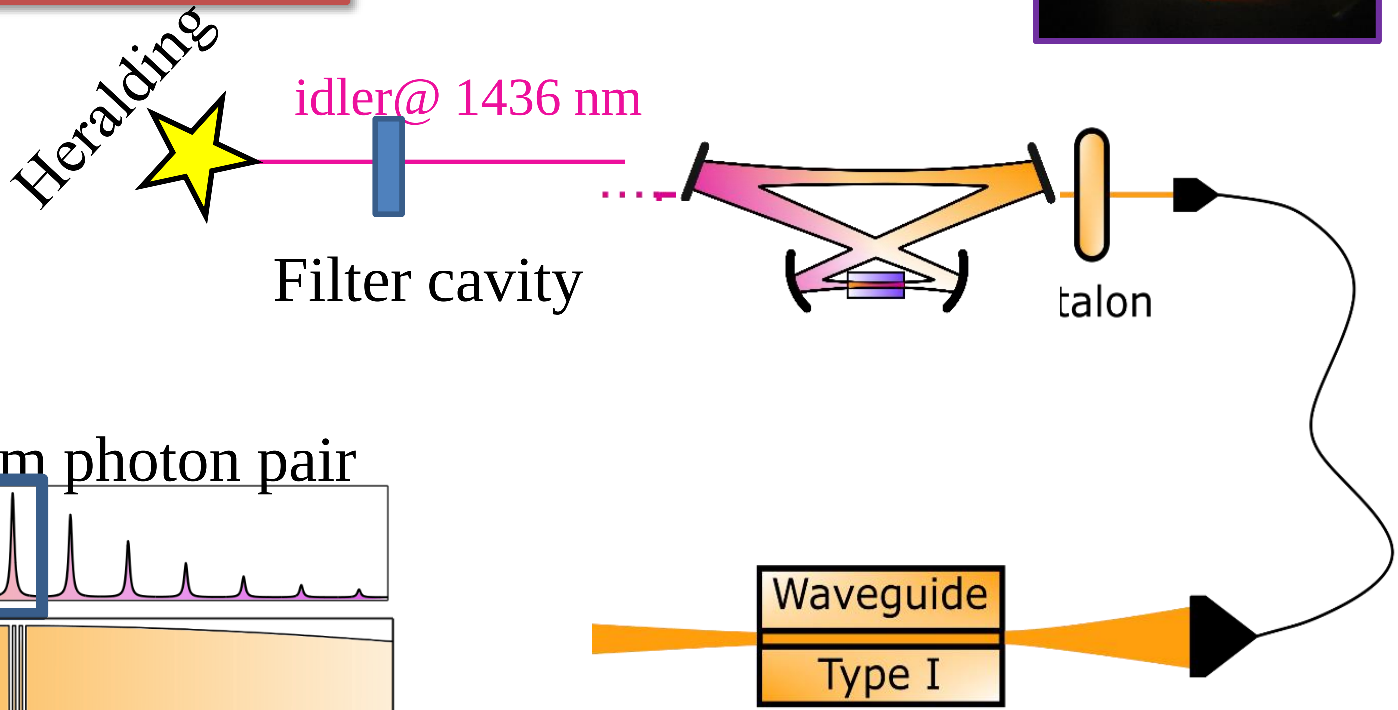
Simulate a communication time of 25 us (5 km of fibers)

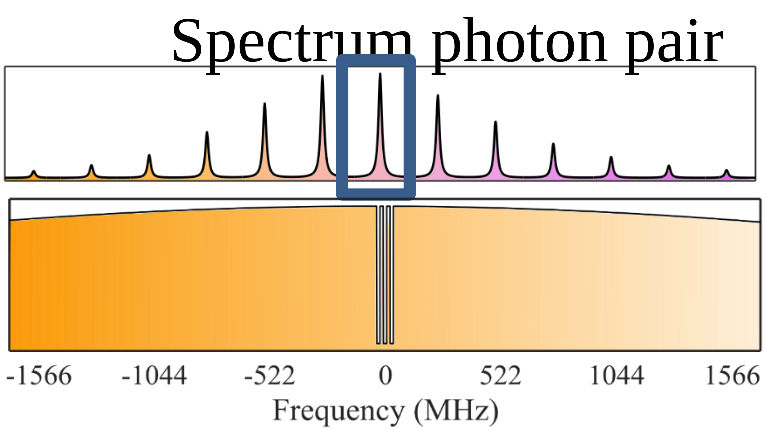
We can store up to **62 modes**, with constant concurrence, but increasing heralding rate



Frequency Multiplexed
Single Photons for Pr doped quantum memories

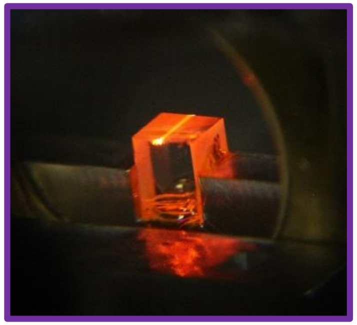


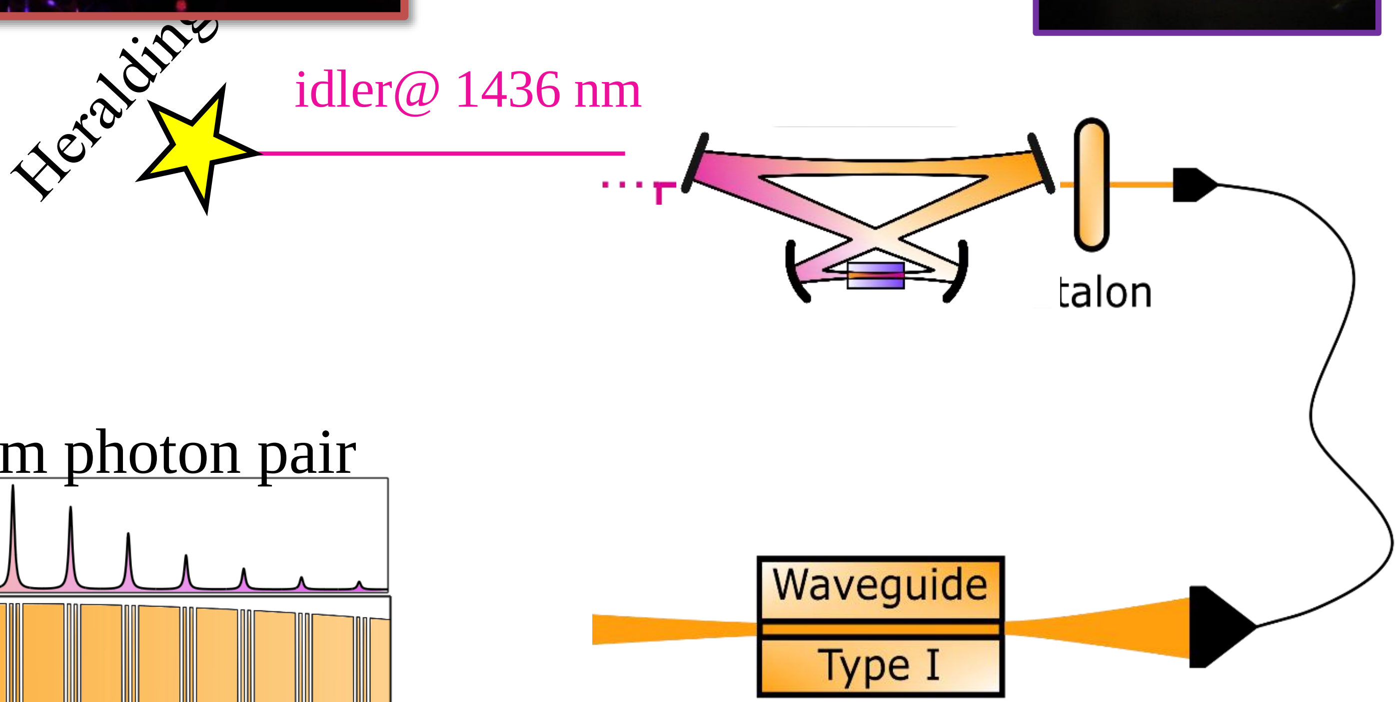




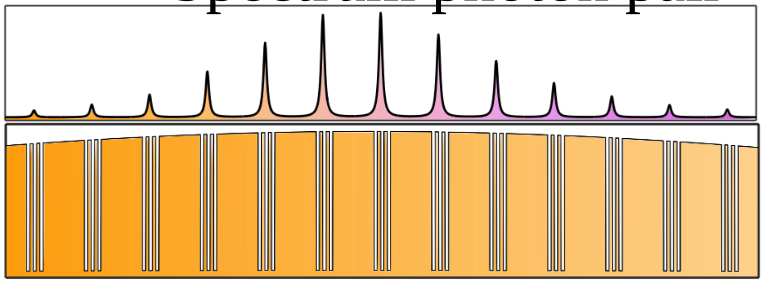
Seri, Lago, Lenhard, Corrielli, Osellame, Mazzera and de Riedmatten, Phys. Rev. Lett. 123, 080502 (2019)

Frequency Multiplexed Single Photons for Pr doped quantum memories



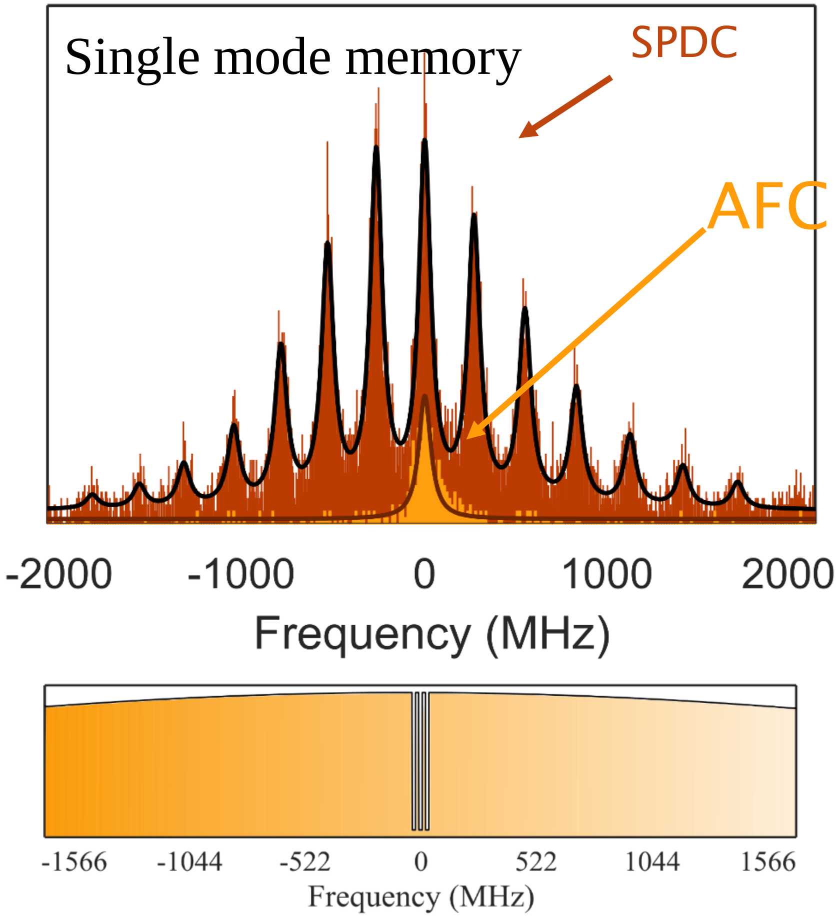


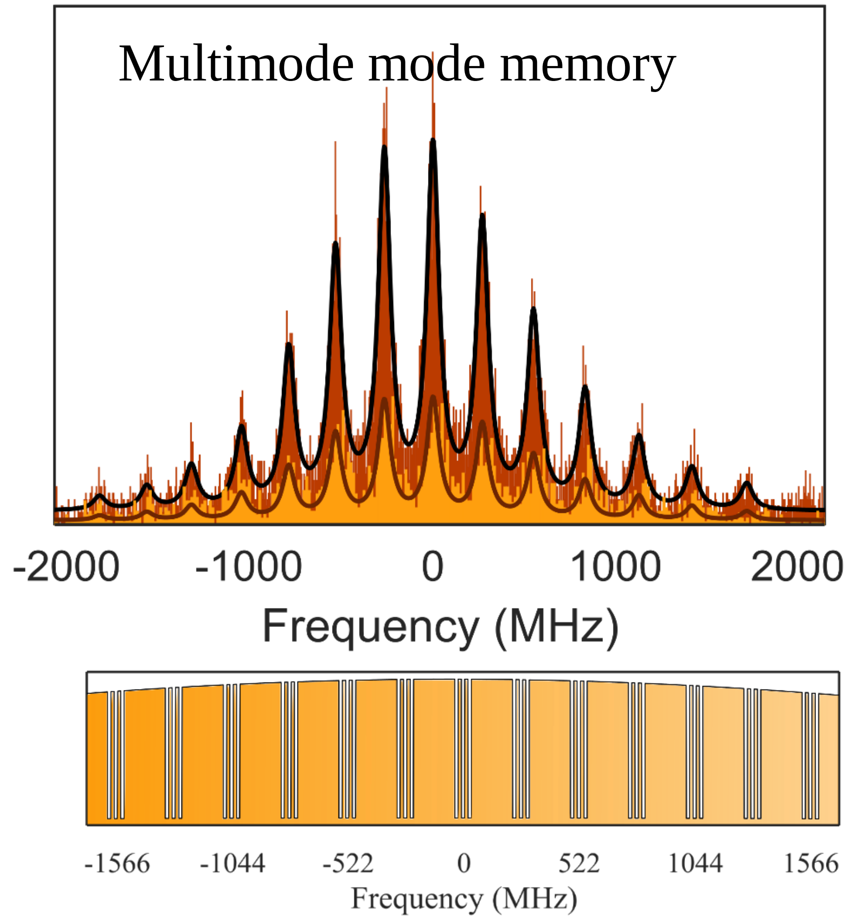
Spectrum photon pair



Seri, Lago, Lenhard, Corrielli, Osellame, Mazzera and de Riedmatten, Phys. Rev. Lett. 123, 080502 (2019)

A frequency multiplexed waveguide QM for Single Photons





Up to 15 frequency modes stored

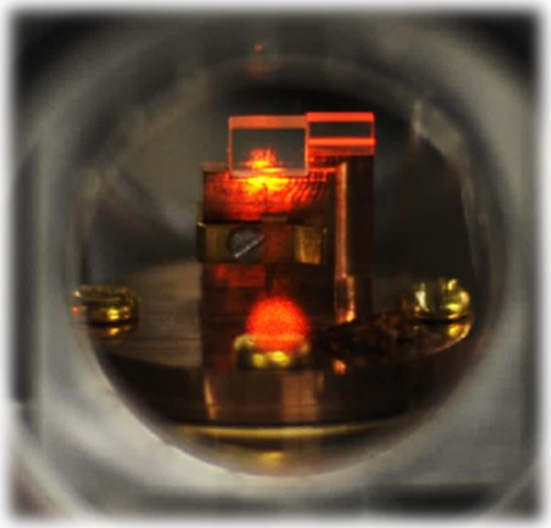
9 temporal modes

Total 135 modes

Can be used to store frequency entanglement

Seri, Lago, Lenhard, Corrielli, Osellame, Mazzera and de Riedmatten, Phys. Rev. Lett. 123, 080502 (2019)
See also Sinclair et al, Phys. Rev. Lett. 113, 053603 (2014) (weak coherent states)

The dream multimode quantum memory



20 temporal modes
20 frequency modes
100 spatial modes

Total : 40000 modes

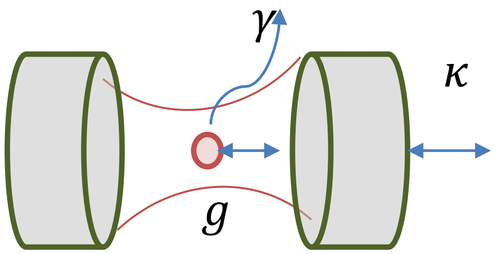
Towards Quantum nodes with single rare-earth ions

Ensemble based solid-state nodes are good for multiplexing, but have limited quantum processing capabilities

Single rare-earth ions:

- Long-Lived Spin-photon interface (possibly at telecom)
- Permanent dipole moments
- Quantum gates between two ions possible
- Coherence preserved in nanostructures

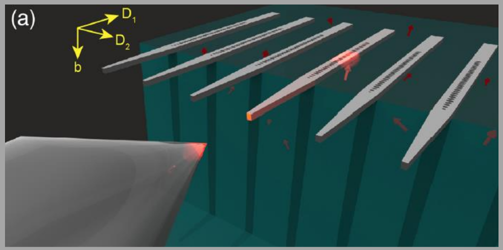
- Weak optical transitions: low single photon emission efficiency
- Need strong Purcell enhancement : nanoscale optical cavity



Purcell factor: $C = \frac{3\lambda^3}{4\pi^2}\zeta\frac{Q}{V}$

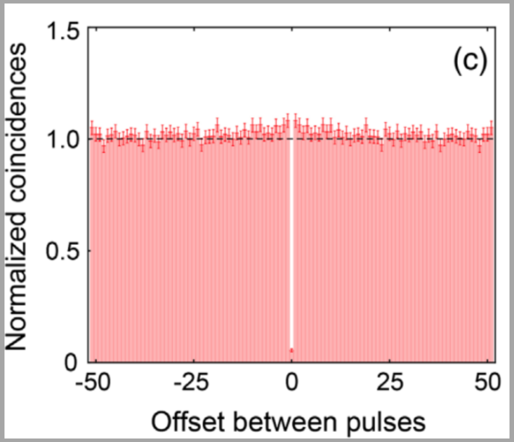
Collection efficiency: $\beta = \frac{C}{C+1}$

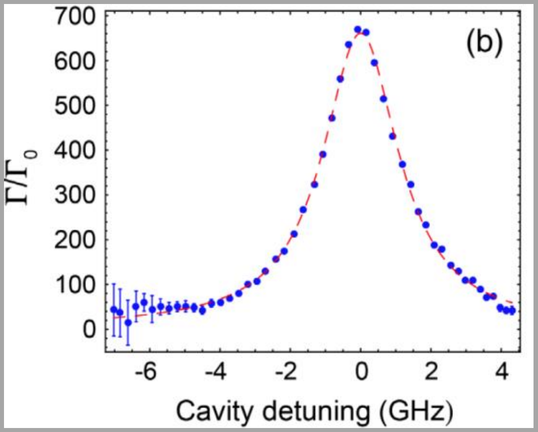
State of the Art : Cavity enhanced detection



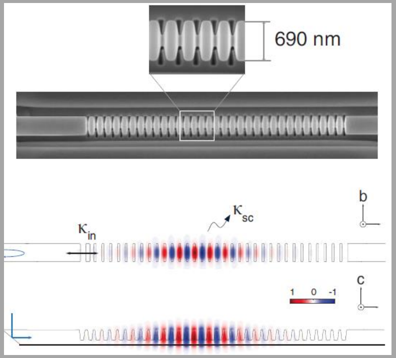
Si photonic crystal on $Er^{3+}:Y_2SiO_5$

Telecom wavelengths



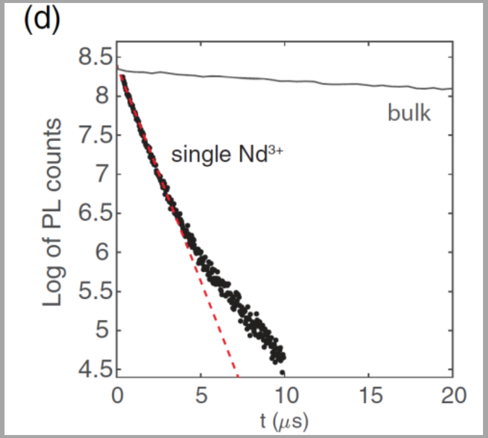


Dibos et al. PRL 2018, Thomson group, Princeton



Photonic Crystal cavity in Nd:YVO

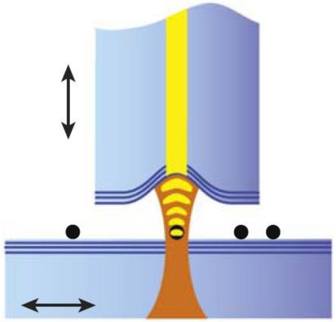
Zhong et al. PRL 2018, Faraon group



T1 cav = 2 us,
Purcell enhancement 45

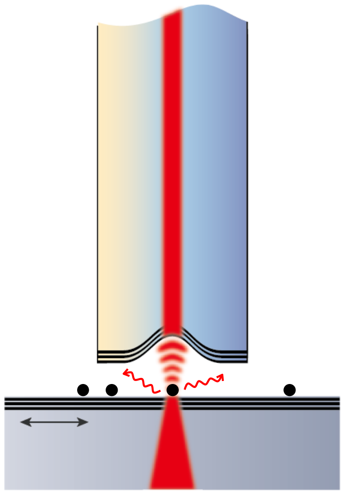
- Nano/micro structured cavity-emitter systems
- Not easily tuneable

Alternative approach: open cavity



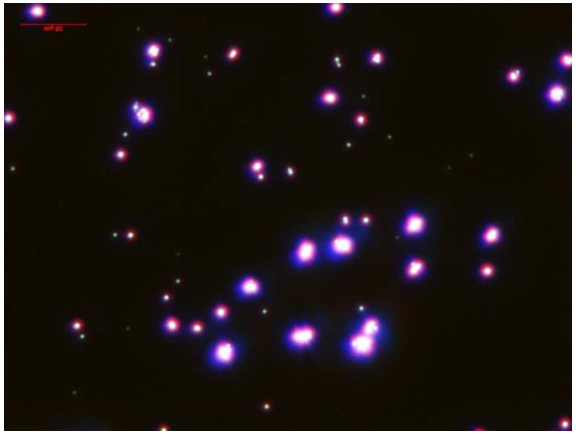
Casabone et al. NJP 2018

Towards quantum nodes with single Er Ions

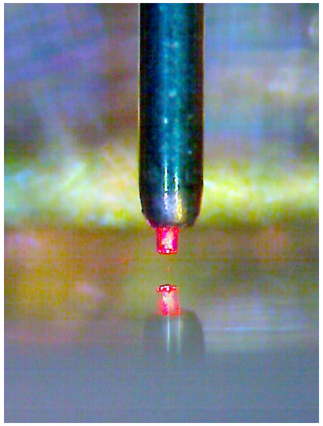


- Erbium doped Y_2O_3 nano-crystals coupled to fiber-based micro-cavities : emission at 1536 nm, T_1 = 15 ms
- Nano crystals spin coated on a mirror
- Cavity Q = 80,000 (F = 20,000) and V = 10 um^3
  → C = 200

Cavity locked in closed loop cryostat

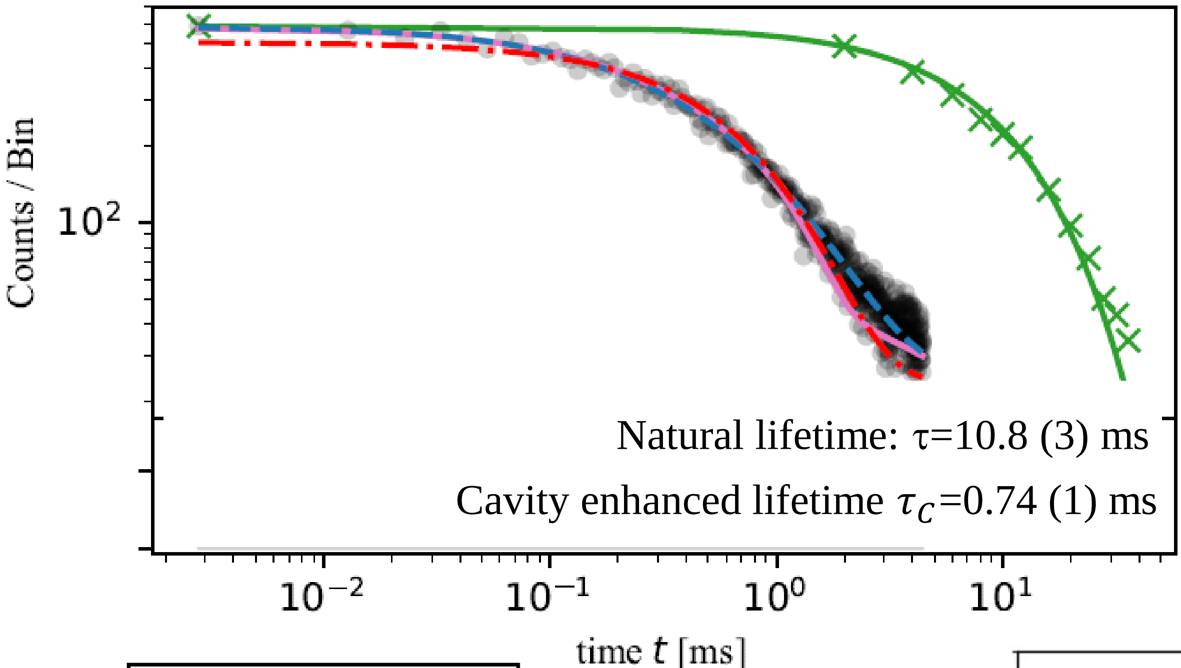


Nanocrystal fabrication : P. Goldner, Paris

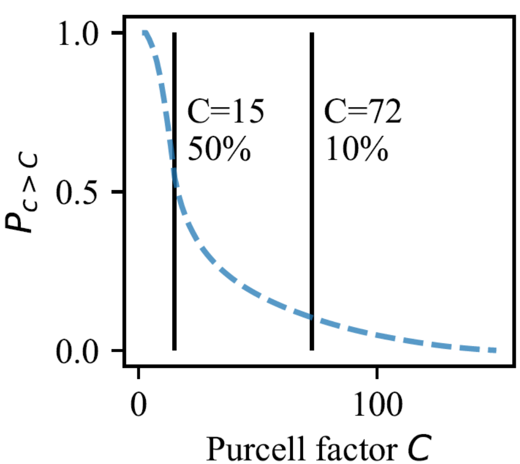


Fibers: D. Hunger, KIT

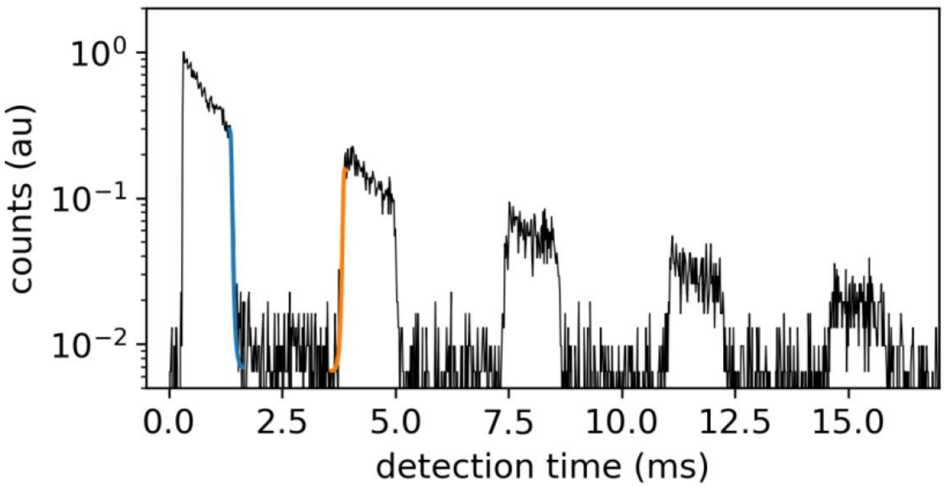
Tunable Purcell enhanced emission of a small ensemble of Erbium ions



Control cavity coupling and Purcell factor with rates 100 faster than spontaneous emission rate



10 % of ions
See C > 72

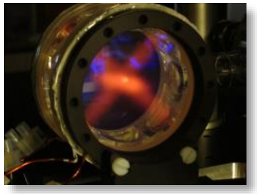


B. Casabone, C. Deshmukh et al, (2019), arXiv:2001.08532 (Collaboration ICFO-KIT-ParisTech)

Summary and outlook

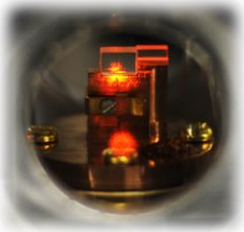
Atomic gases QMs:

- Excellent quantum memories
- Possibility for Q processing and deterministic operations using Rydberg excitations



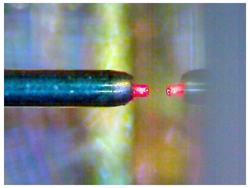
Solid-state RE based QMs :

- Well established, excellent multimode memory
- Demonstrated telecom heralded entanglement (extendable to long distances)
- Need to improve performances
- Demonstrate large scale elementary networks

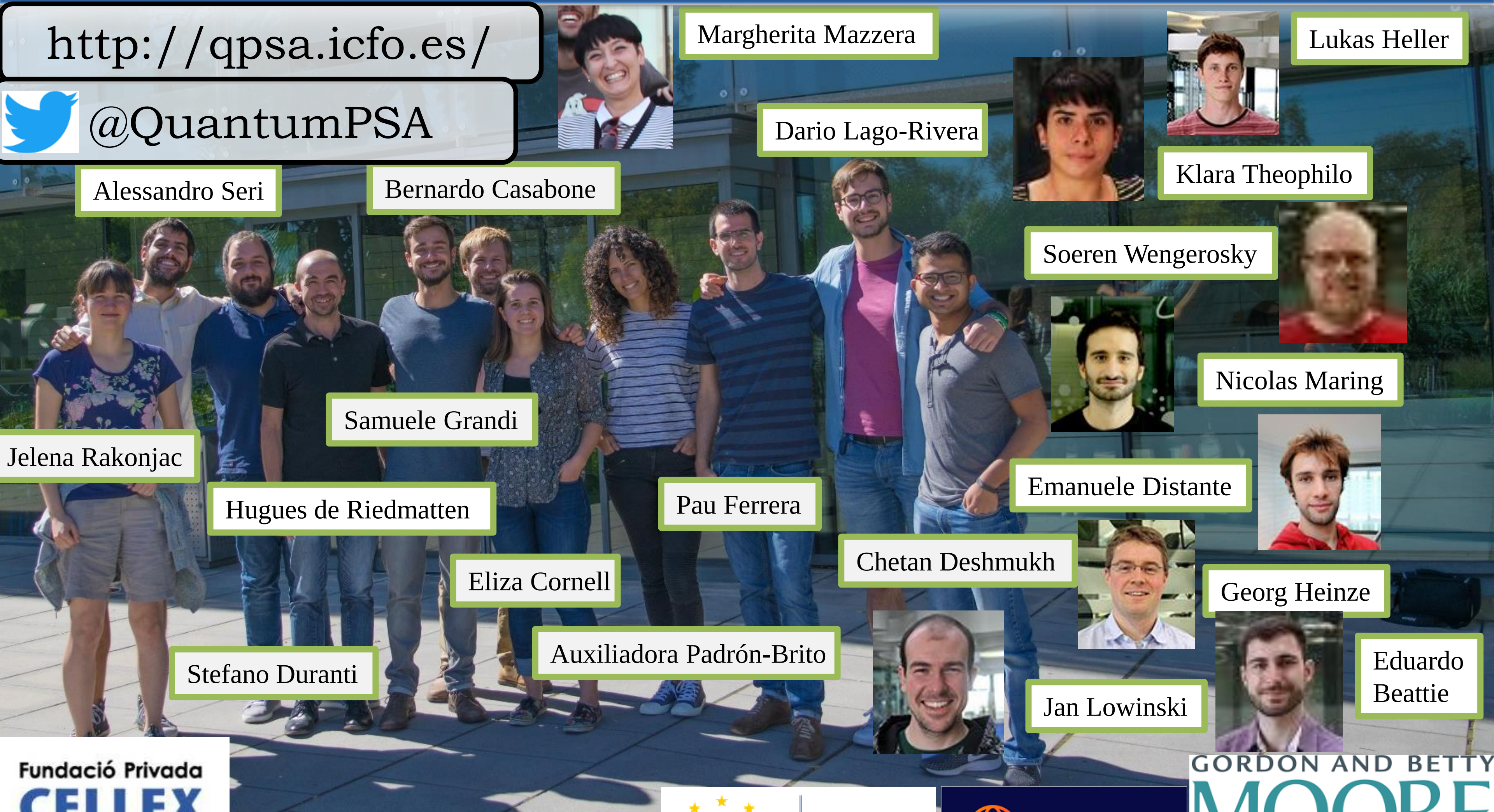


Single ions in solids:

- Efficient and coherent spin-photon interface (enabled by good coherence properties at nanoscale)
- Large number of optically adressable single ion qubits
- Possibility of quantum logic between qubits



Quantum Photonics group at ICFO



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SQUARE Scalable Rare Earth Ion QUAntum Computing Nodes

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