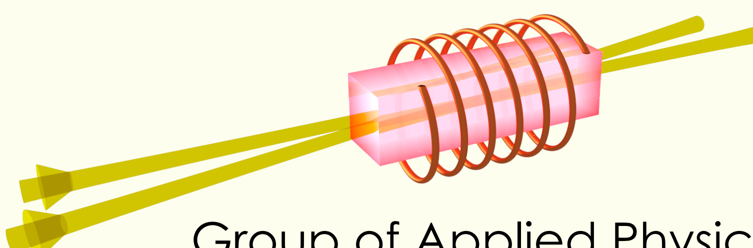
# Generation of temporally multiplexed pairs of photons with controllable delay in a crystal

Cyril Laplane, Jean Etesse, Pierre Jobez,
Nicolas Gisin, Mikael Afzelius



Group of Applied Physics

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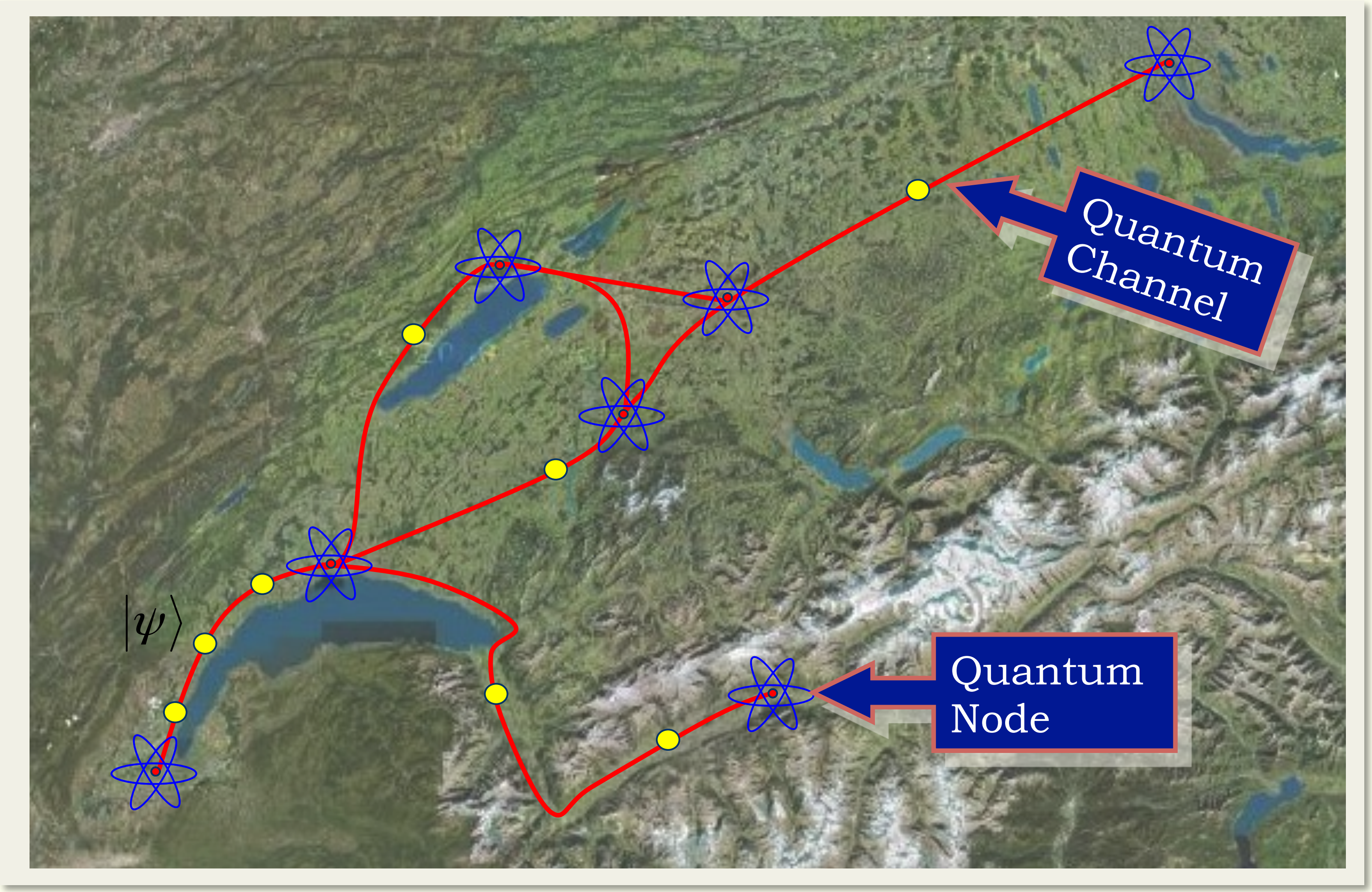
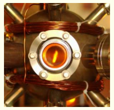
# The quantum internet

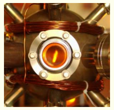


# DLCZ-like elementary repeater link

How to distribute entanglement between two distant nodes ?

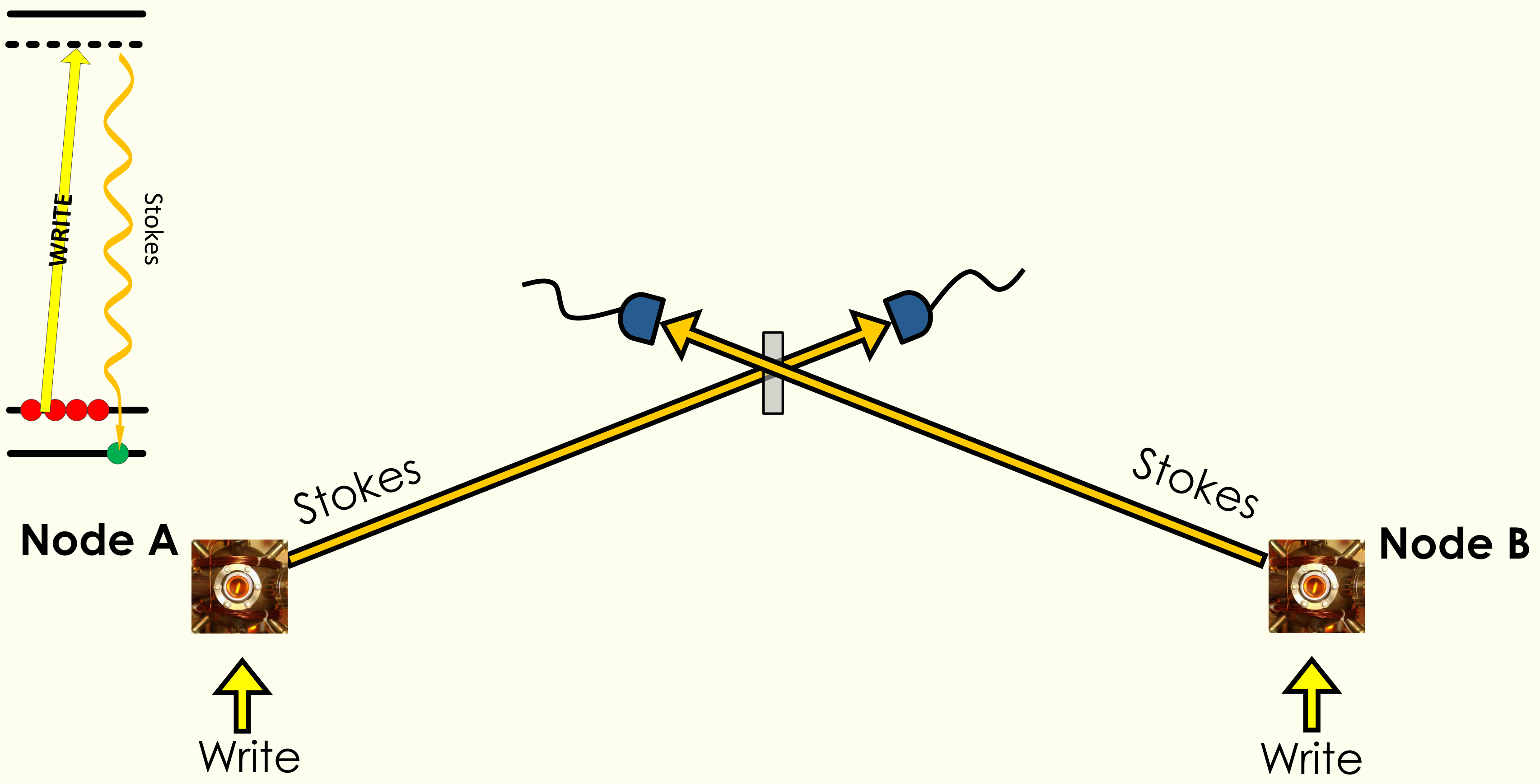
**Node A**



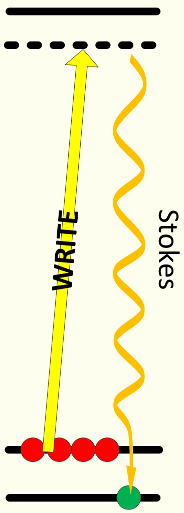


**Node B**

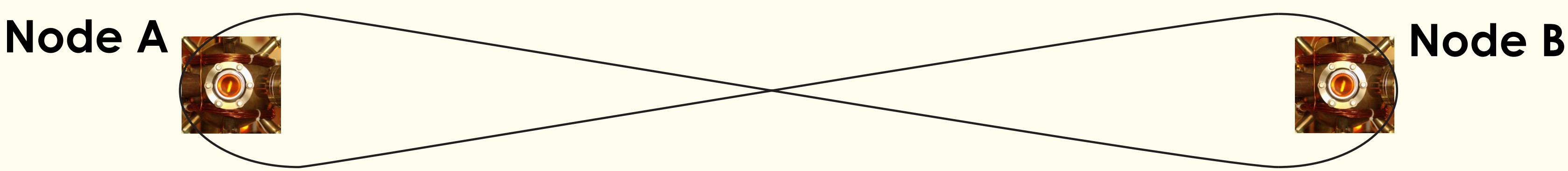
# DLCZ-like elementary repeater link



# DLCZ-like elementary repeater link




$$|\psi\rangle_{\mathrm{AB}} = \frac{1}{\sqrt{2}}\left(|1\rangle_A|0\rangle_B + |0\rangle_A|1\rangle_B\right)$$



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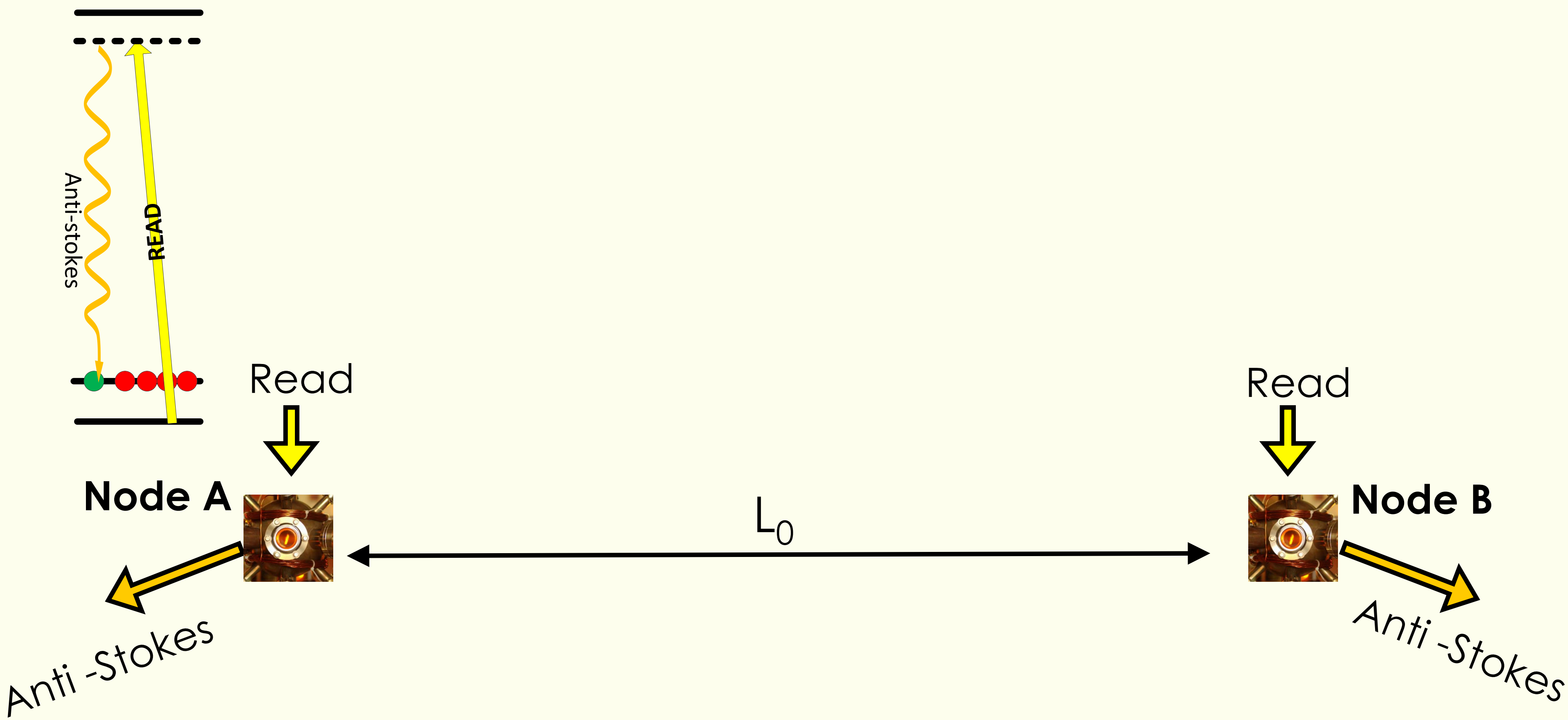
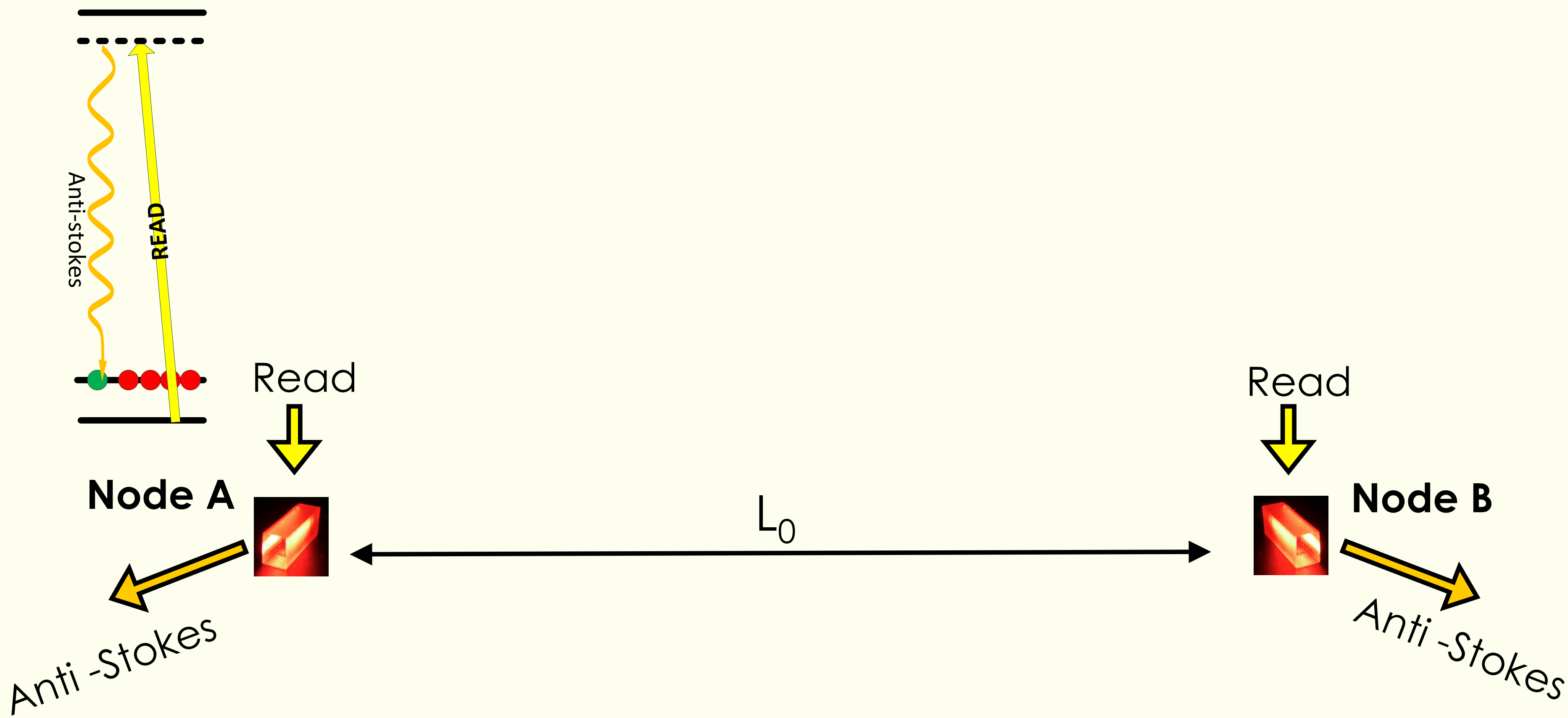



Single-mode storage: rate limited by $c/L_0$
N-mode storage: rate limited by $N.c/L_0$

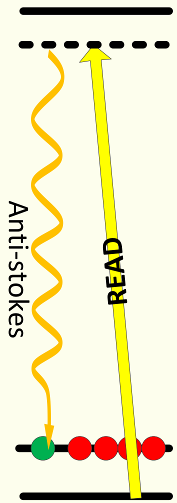
'Multimode DLCZ' scheme necessary for "fast" repeaters

# DLCZ-like elementary repeater link




Our goal:
Solid state repeater link with REID crystals

# DLCZ-like elementary repeater link

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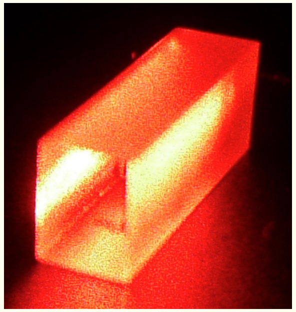
Challenge:



Large inhomogeneous broadening

⟶ off-resonant fields for high cooperativity

But low electric dipole for REIDC ...

C. Ottaviani *et al*, Phys. Rev. A **79**, 063828 (2009)

# Outline

I – REID crystals as a quantum interface

II – The DLCZ protocol on REID crystals

III – Experimental results

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# Rare-earth ion 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 |
| $\lambda$ (nm) = | | | 606 | 880 | | | 580 | | | | | 1530 | | 980 |

## Properties of rare earths:

- Weak interaction with crystal enviroment
  - "atom" like energy structure for 4f-4f transitions
  - "frozen gas" of ions, no motional decoherence
- High number of stationary ions ($10^7$-$10^{12}$)
  strong light-matter coupling
- Long optical coherence times (T < 4K), $T_2^{opt}$ = 1 µs – 10 ms
- Long spin coherence times (T < 4K), $T_2^{hyp}$ = 1 ms – 6 h*
- Large optical inhomogeneous broadenings 100 MHz – 10 GHz

*M. Zhong *et al.*, Nature **517**, 7533 177-180 (2015)

# Rare-earth ion doped crystals

| | lanthanum 57 | cerium 58 | praseodymium 59 | neodymium 60 | promethium 61 | samarium 62 | europium 63 | gadolinium 64 | terbium 65 | dysprosium 66 | holmium 67 | erbium 68 | thulium 69 | ytterbium 70 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
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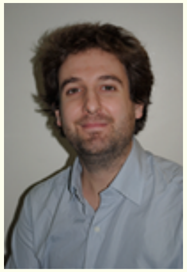
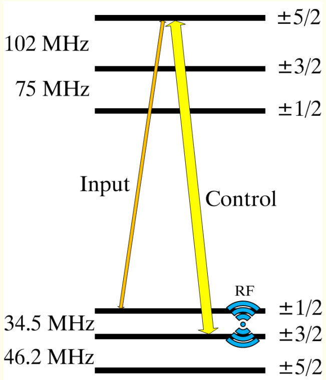
P. Goldner



A. Ferrier

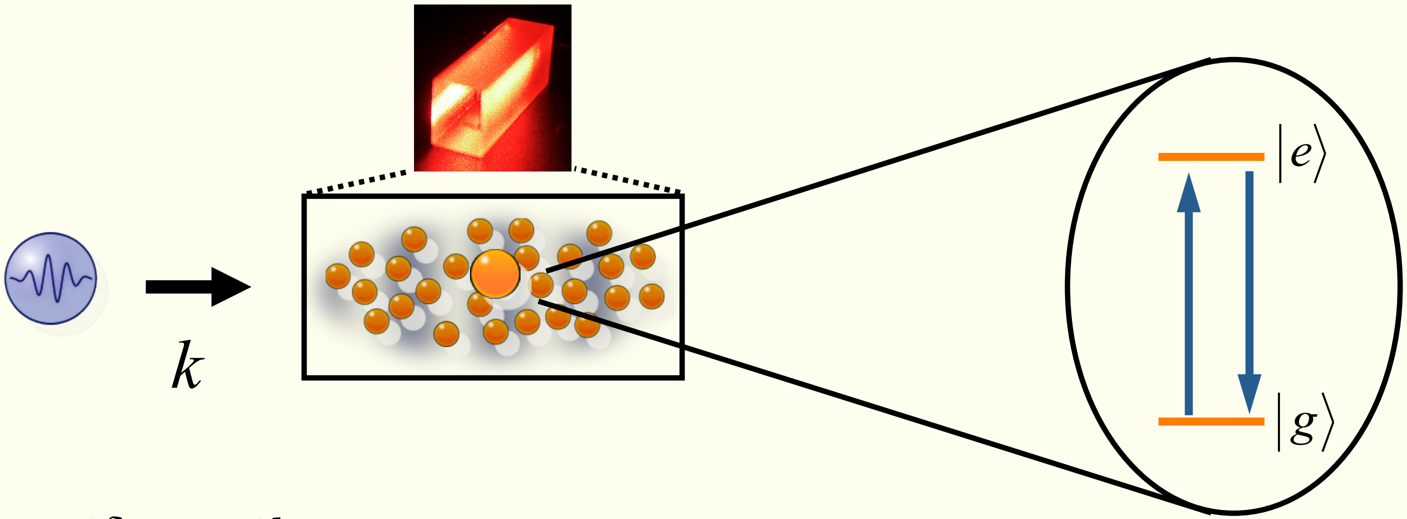
0.1% $^{151}Eu^{3+}:Y_2SiO_5$




*M. Zhong et al., Nature **517**, 7533 177-180 (2015)

# Inhomogeneity in REID crystals

Absorption of an input photon by the ensemble creates a coherence...




$$|\psi\rangle \propto \sum_{i=1}^{N} c_i e^{i\delta_i t} e^{-ikz_i} |g_1 ... e_i .. g_N\rangle$$

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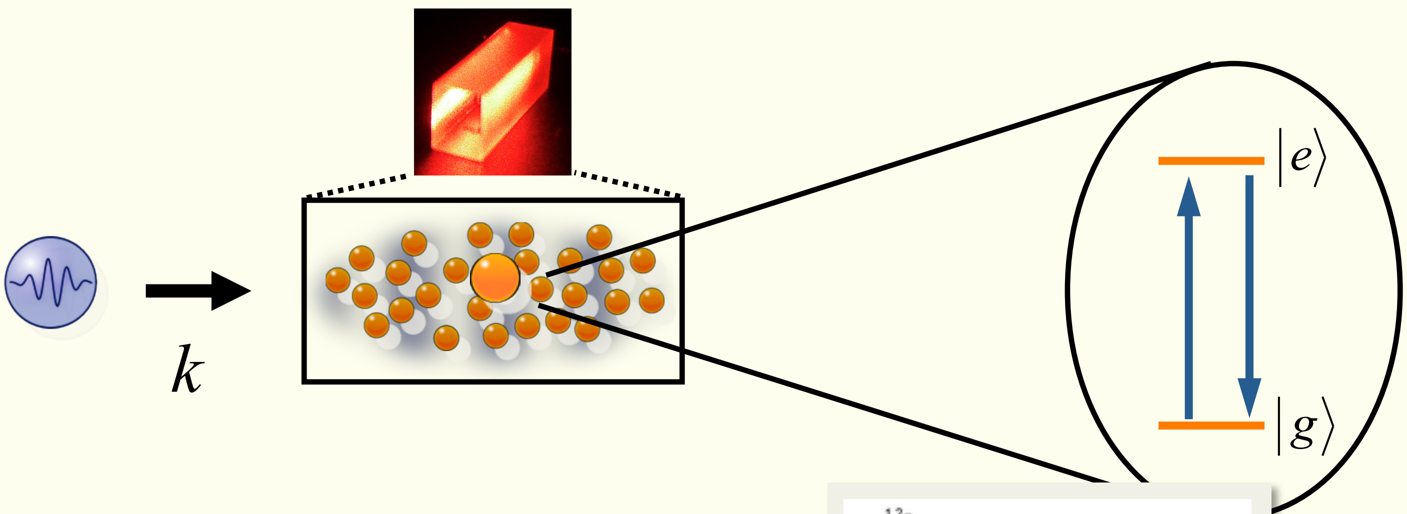
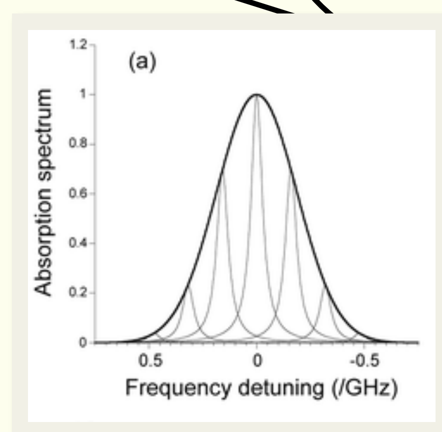



$$|\psi\rangle \propto \sum_{i=1}^{N} c_i e^{i\delta_i t} e^{-ikz_i} |g_1 \ldots e_i \ldots g_N\rangle$$

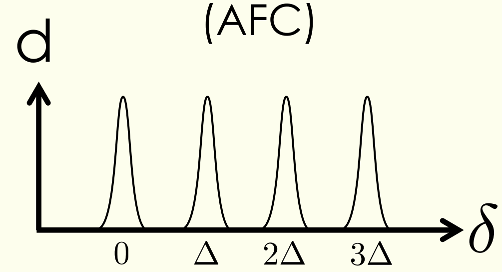
...which dephases quickly

# The AFC Protocol

The idea: only keep the atoms whose detuning is equal to

$$\delta_i = m_i \Delta$$

Atomic Frequency Comb (AFC)



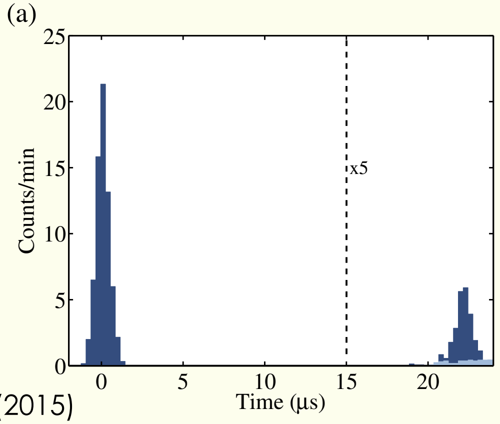

M. Afzelius *et al.*, Phys. Rev. A **79**, 052329 (2009)

Such that the new state that evolves is

$$|\psi\rangle \propto \sum_{i=1}^{N'} c_i e^{i m_i \Delta t} e^{-ikz_i} |g_1 \ldots e_i .. g_N\rangle$$

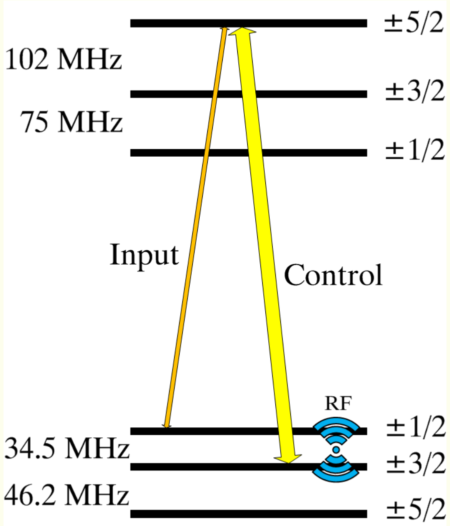
At time $t = \frac{2\pi}{\Delta}$ , the selected atoms are back in phase !

Two level AFC photon echo




P. Jobez *et al.*, Phys. Rev. Lett. **114**, 230502 (2015)

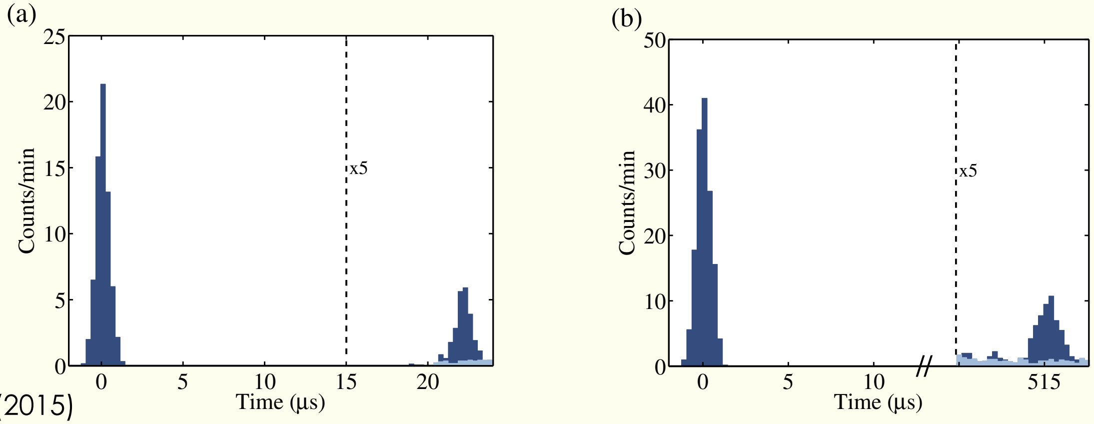
# The AFC Protocol




By adding a third level, the optical coherence can be transferred to a nuclear spin coherence

On-demand storage and retrieval of optical excitations

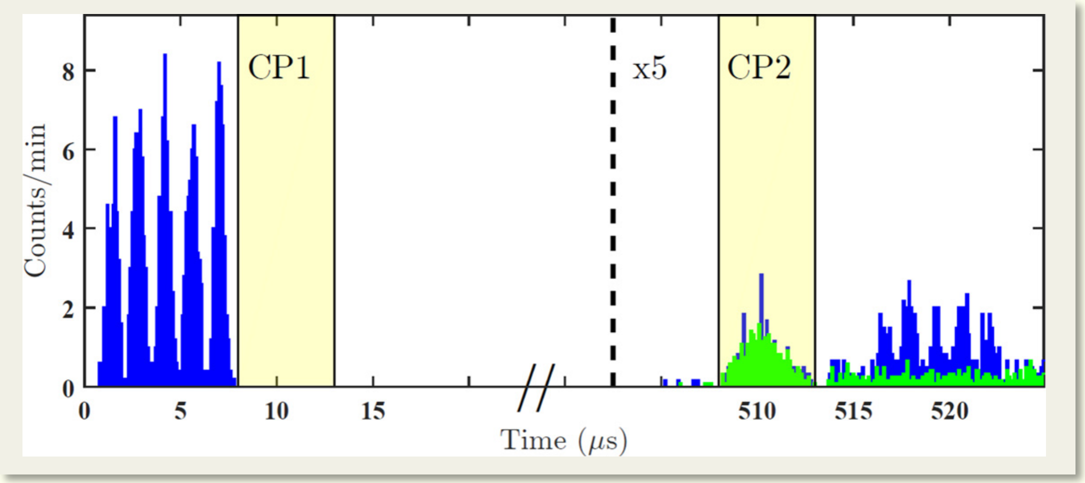
Three level AFC photon echo




P. Jobez *et al.*, Phys. Rev. Lett. **114**, 230502 (2015)

# The AFC Protocol

Force of the protocol: multimode capacity




Storage of five polarisation qubit modes

C. Laplane *et al.*, New J. Phys. **18**, 0130062 (2016)

# Outline

I – REID crystals as a quantum interface

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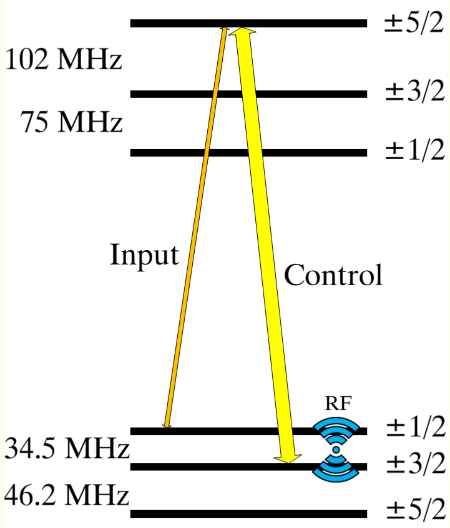
# A homogeneous-like system

Thanks to the AFC rephasing effect, the system behaves like an homogeneous system at a precise instant, the instant of re-emission.

⇒ Fields can be applied on resonance



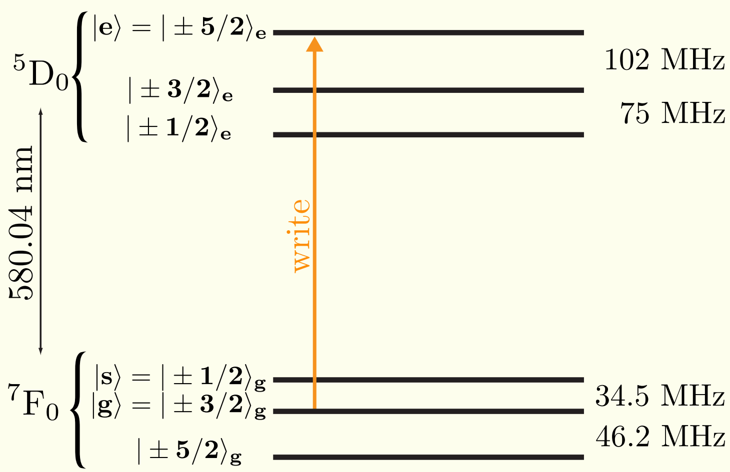

Idea of the protocol: the control field is replaced by a spontaneous decay

P. Sekatski *et al.*, Phys. Rev. A **83**, 053840 (2011)

# The AFC-DLCZ protocol

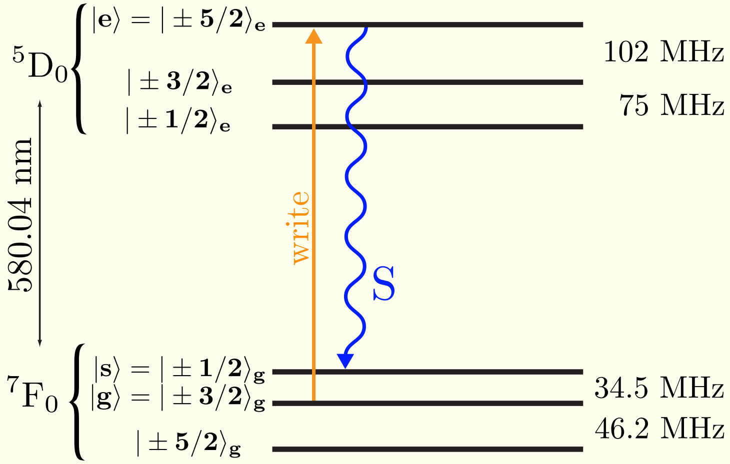
A weak 'write' pulse is sent on the **AFC** transition

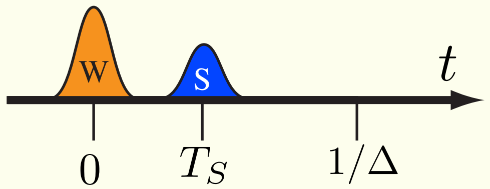
0.1% $^{151}Eu^{3+}:Y_2SiO_5$




# The AFC-DLCZ protocol

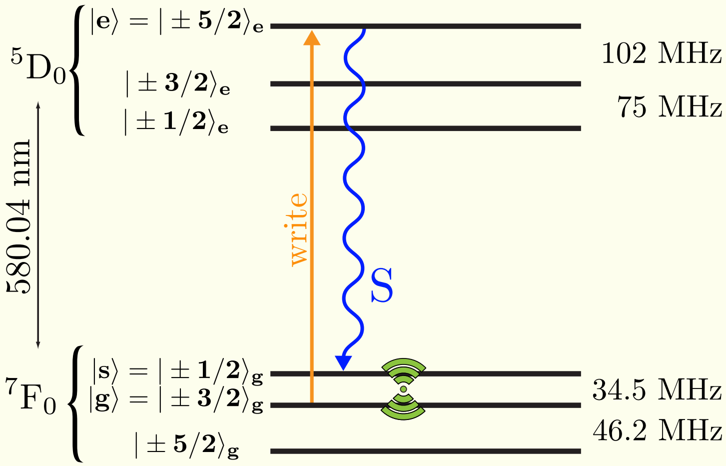
Stokes photons are spontaneously emitted on the strongest transition, before the AFC echo of the write pulse

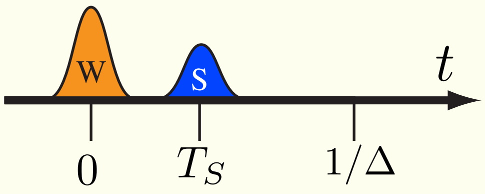


# The AFC-DLCZ protocol

A radio-frequency pulse is sent to invert the populations on the $|s\rangle$ and $|g\rangle$ states...

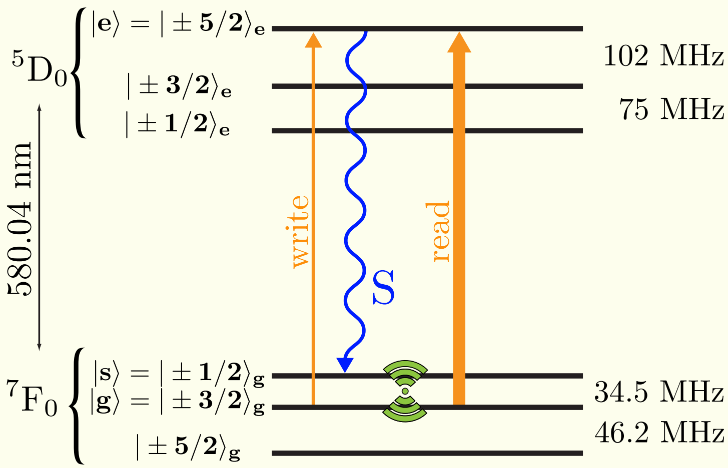


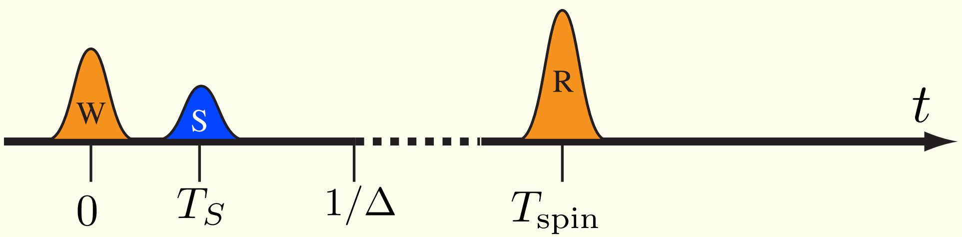



# The AFC-DLCZ protocol

A radio-frequency pulse is sent to invert the populations on the $|s\rangle$ and $|g\rangle$ states...

... so that read and write pulses have the same frequency...



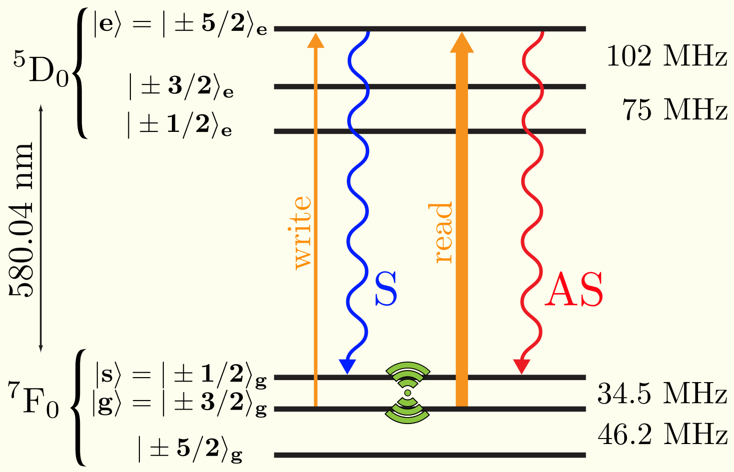



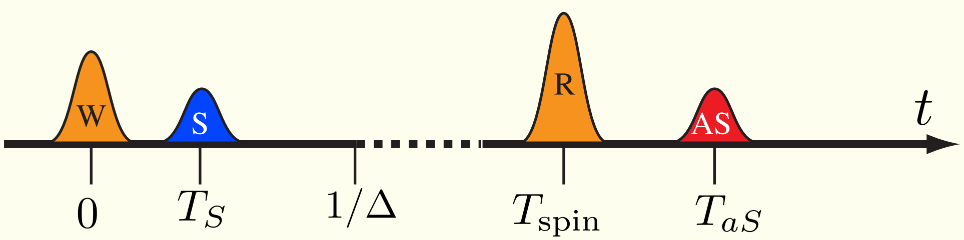
# The AFC-DLCZ protocol

A radio-frequency pulse is sent to invert the populations on the $|s\rangle$ and $|g\rangle$ states...

... so that read and write pulses have the same frequency...

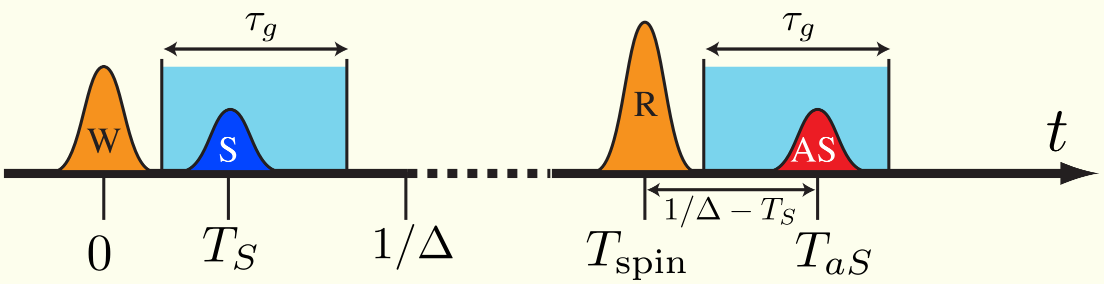
... and Stokes and anti-Stokes as well.



# The AFC-DLCZ protocol

The rephasing of the Stokes field occurs thanks to the AFC, leading to the emission of its echo: the anti-Stokes




Both are correlated in time: **temporal multiplexing capacity !**

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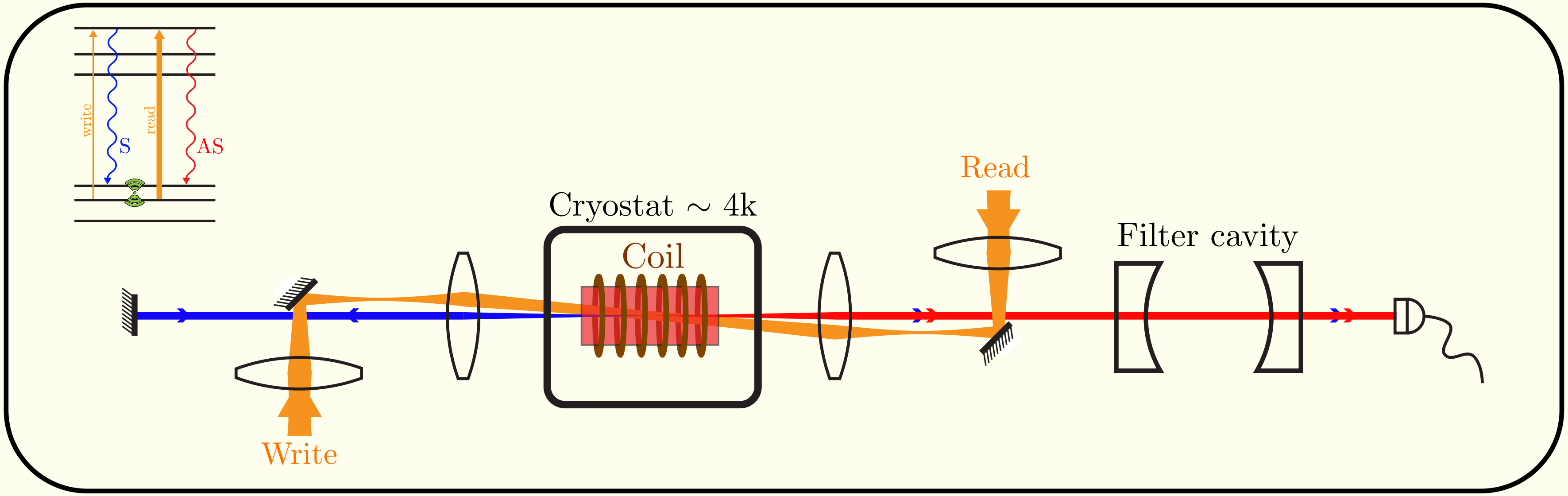
# Experimental apparatus

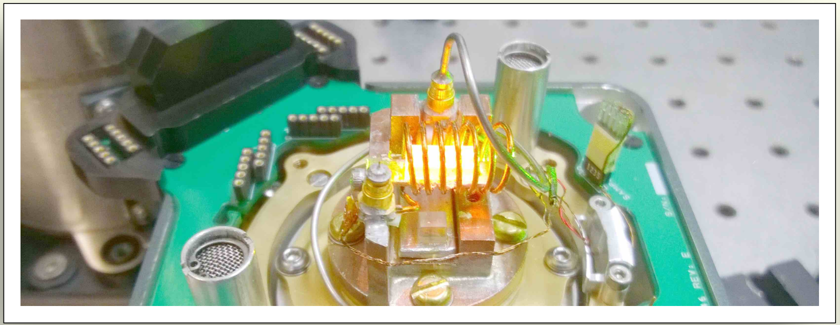
Need for a high-quality filtering:

- spatial angle between write/read and Stokes/aStokes
- Fabry-Perot cavity to detect only Stokes and aStokes

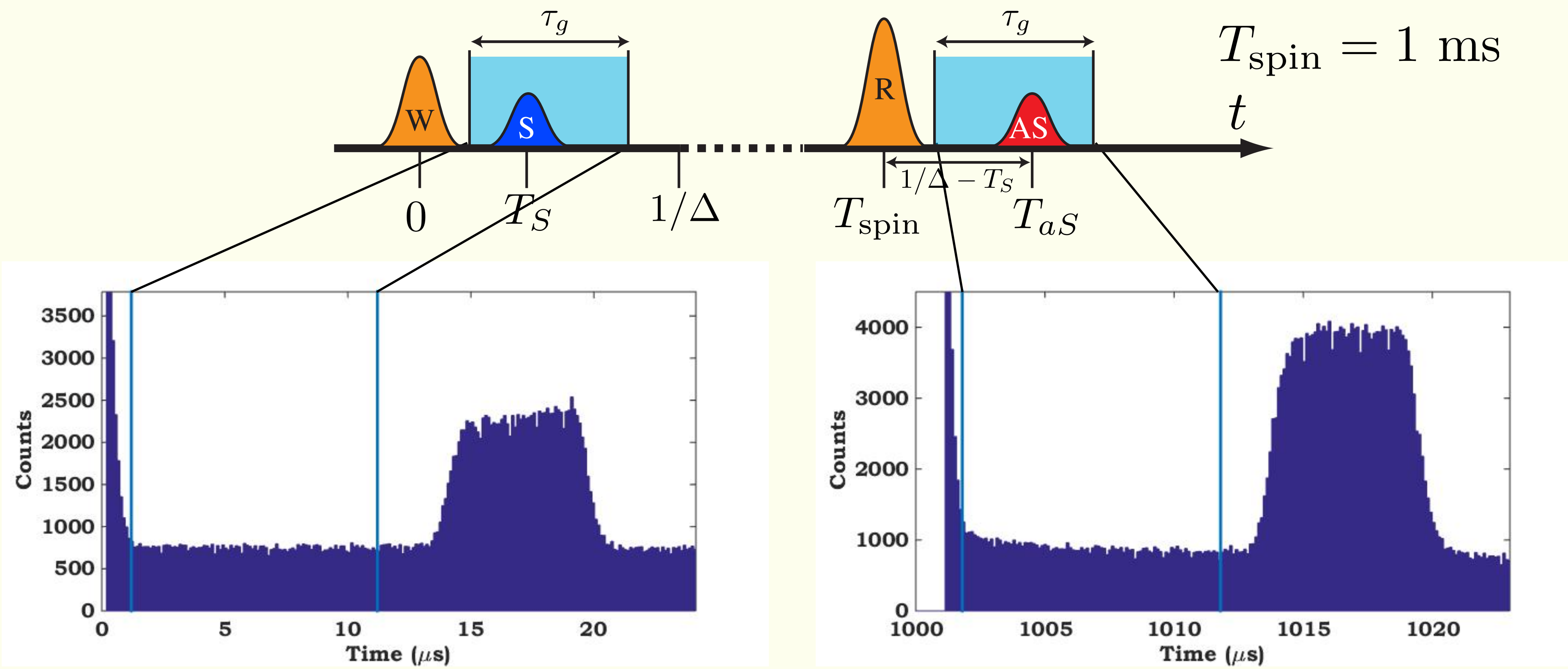



Double-pass configuration to double *d* and use only one cavity

# Experimental apparatus




# Results

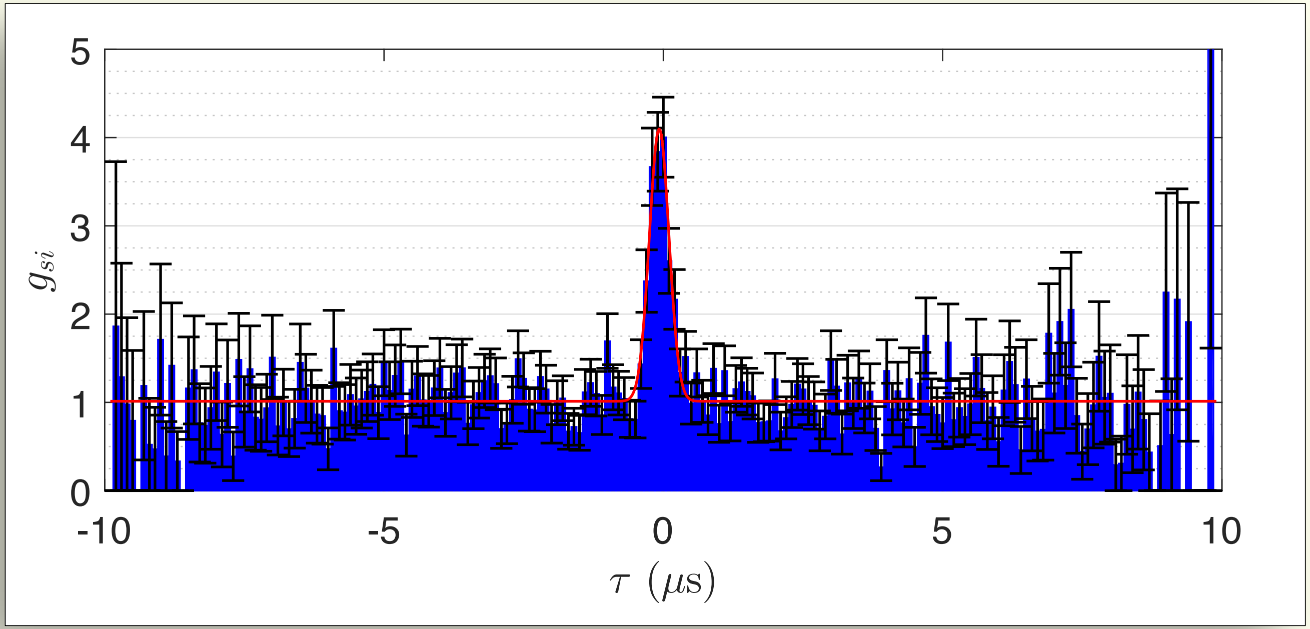



Integration time: 52.1069 h,
2 626 190 experimental runs
2 268 coincidences

# Results

If we plot the cross-correlation function $g_{si}$ as a function of

$$\tau = T_S + T_{aS} - T_{\text{spin}} - 1/\Delta$$

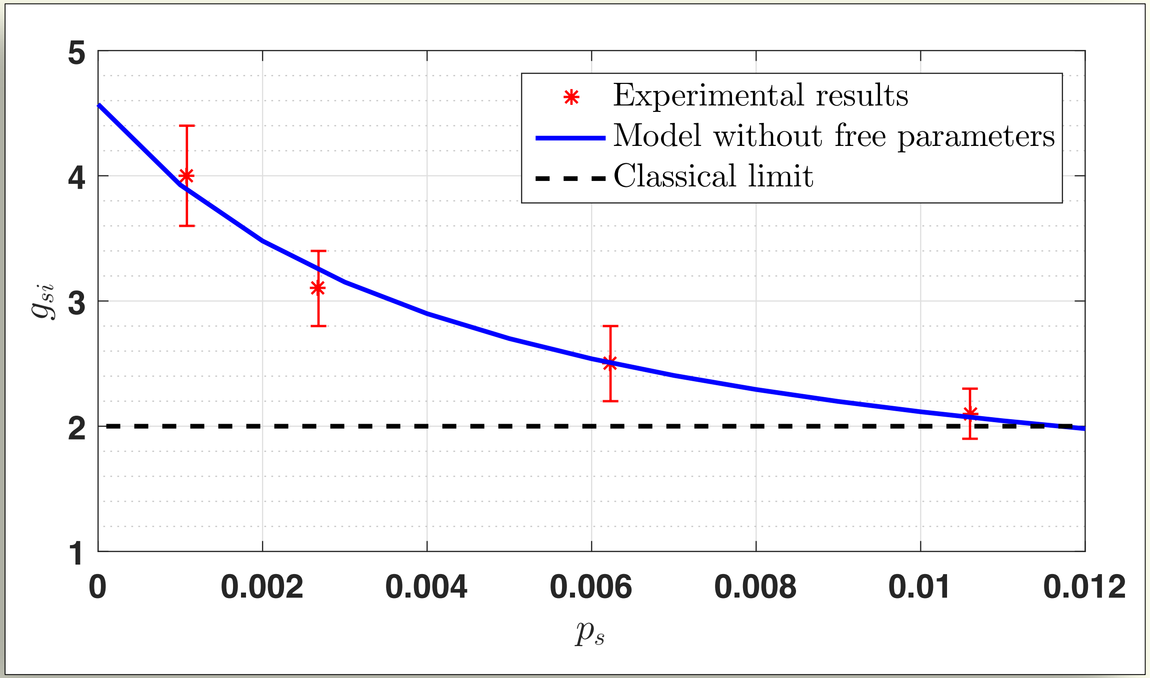



Fitted peak width: 414 ns FWHM

⟶ capacity of at least 10 modes in 10 μs gates

# Results

Peak $g_{si}$ as a function of the Stokes probability (100 ns bin)




Model : $g_{\mathrm{si}} = 1 + \dfrac{\eta}{(\eta + \beta)p_S + p_n}$

Measured efficiency: $\eta = 0.5\%$

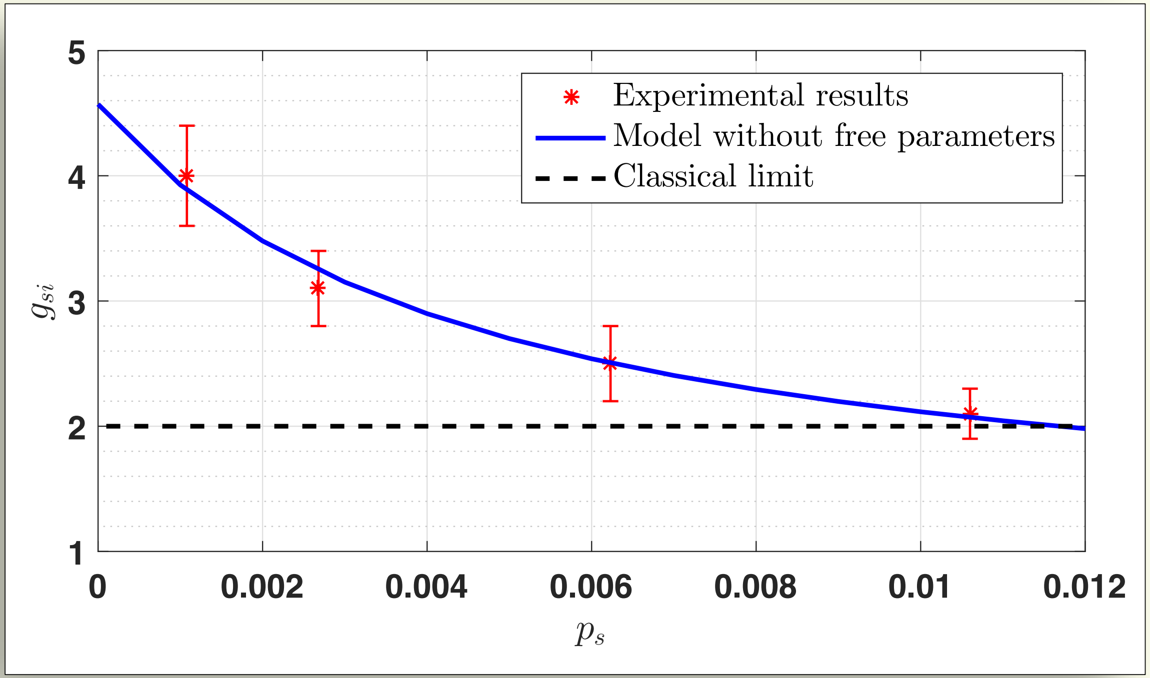
Intrinsic noise: $p_n = 0.14\%$

Noise dependant on $p_S$:

$\beta = 0.3$

# Results

Peak $g_{si}$ as a function of the Stokes probability (100 ns bin)



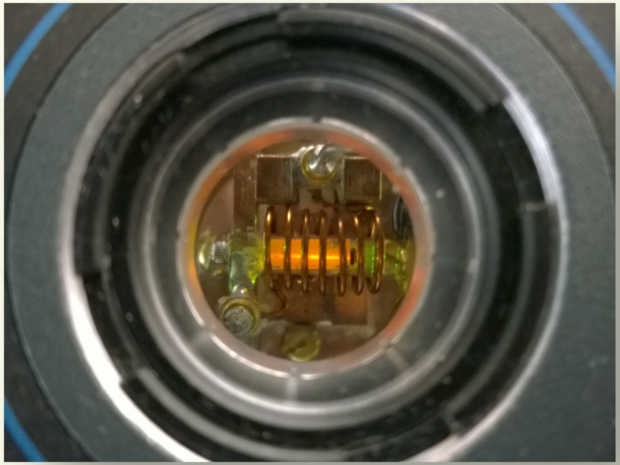

**Non-classical correlation** up to $p_S$=10% (in 1 μs)

# Conclusion

- An inhomogeneously broadened medium can be excited on resonance and still lead to a coherent emission

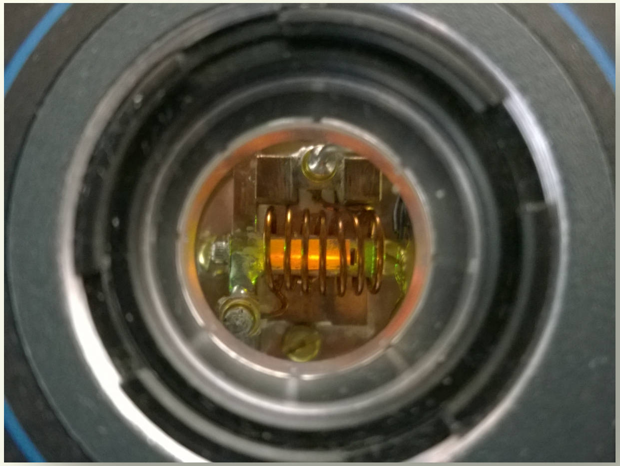
- Non-classical correlation between two single photons separated by 1 ms were demonstrated

- Temporal multiplexing up to 10 modes



# Perspectives

- Measure the autocorrelation of Stokes and aStokes photons to prove the non-classical correlation un-ambiguously
- Explore new configurations to explain the low efficiency
- Prove the generation of delayed energy-time entanglement



# Quantum memory group

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