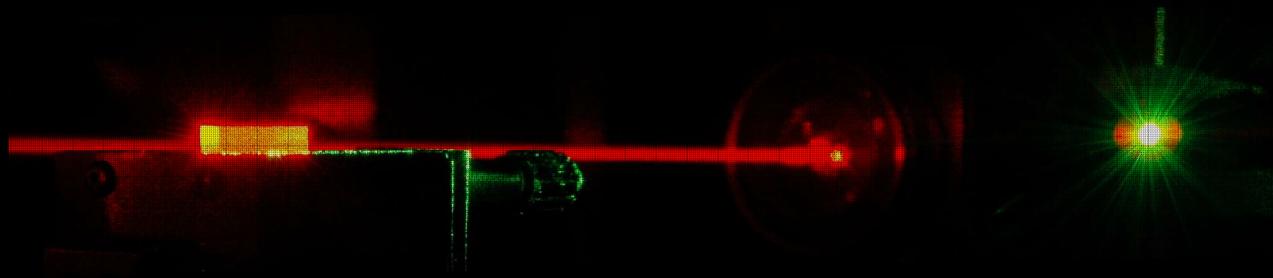


Solid-State Quantum Memories for Quantum Repeaters



Nicolas Gisin, Mikael Afzelius, Hugues de Riedmatten

H. Zbinden, Ch. Simon, D. Stucki , R. Thew, N. Sangouard
Ch. Clausen, J. Minar, B. Lauritzen, I. Usmani, N. Walenta

**Group of Applied Physics
Geneva university, Switzerland**



Main trends in QKD

- § Cheaper
- § Reliability

- § Higher bit rates
- § Longer distances

- § Simpler to analyse
- § Device independent
- § Quantum repeaters

Most relevant for
Applications

Today's main trend

Academic research





Higher bit rates & longer distances



bit rate at emission
goal: > 1 Gbit/s

channel
loss

« no » loss in
Bob's
optics

Efficient
detector

+ noise \Rightarrow real time secret bit rate
goal: > 1 Mbit/s

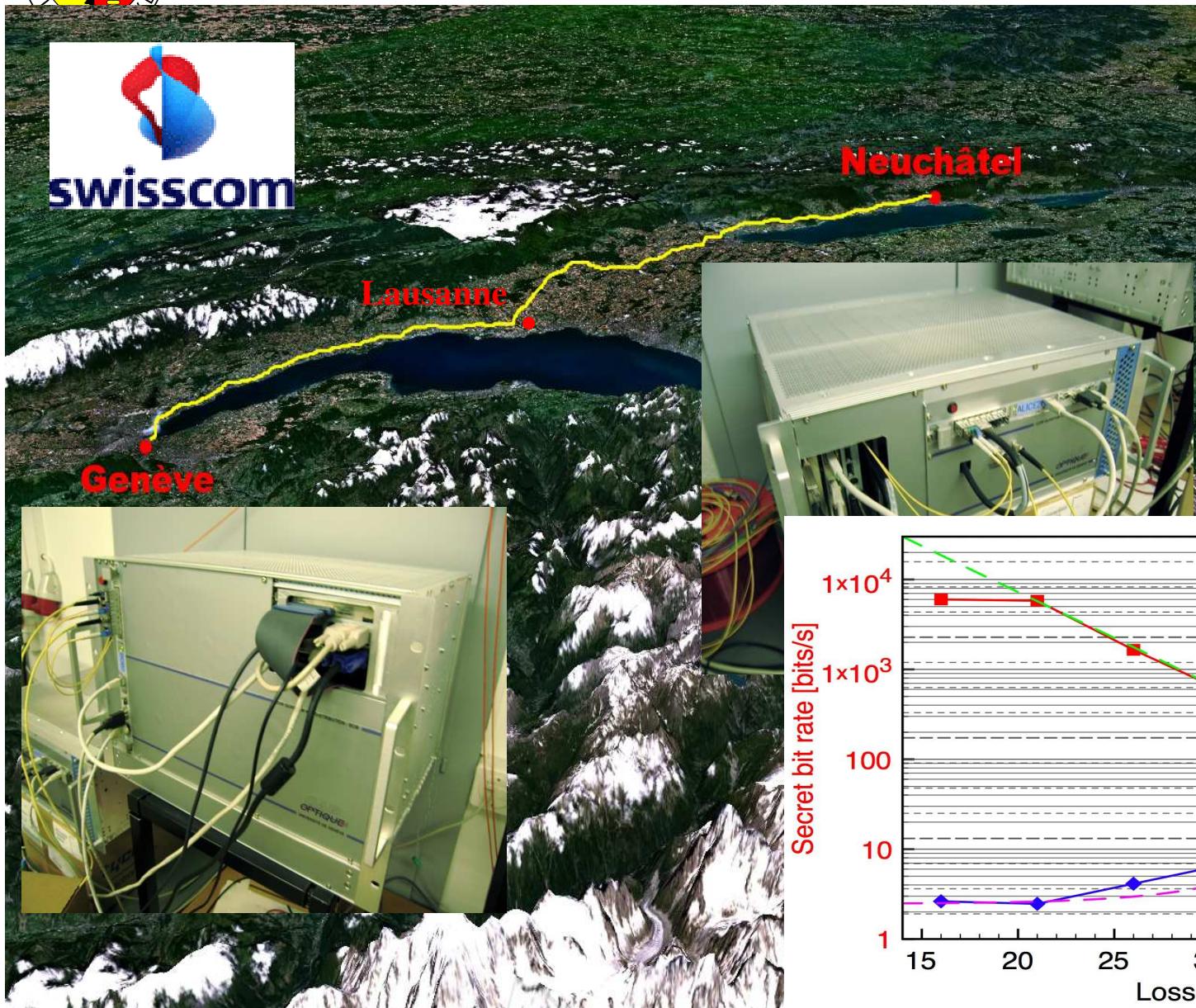
APL [87, 194105, 2005](#)
NJP [11, 075003 \(2009\)](#)
Optics Express [17, 13326 \(2009\)](#)



Coherent One Way QKD with SSPD

Optics Express 17, 13326 (2009)

Superconducting nano-wire



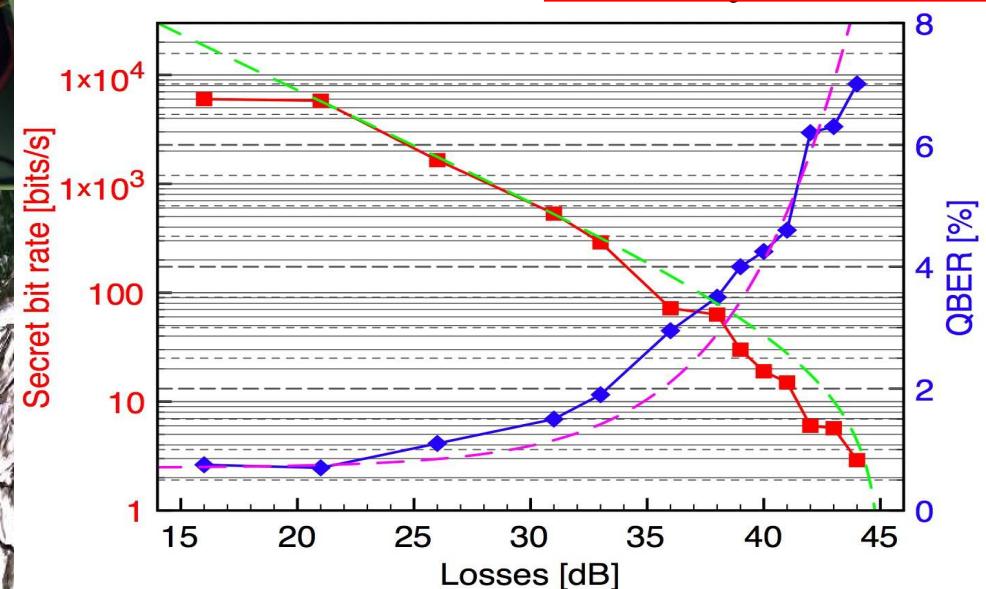
EU projects Secoqc
& Sinphonia

2 dark fibers
~150km

43 dB loss
(0.29dB/km)

660 MHz

Continuous real time
secret key distillation

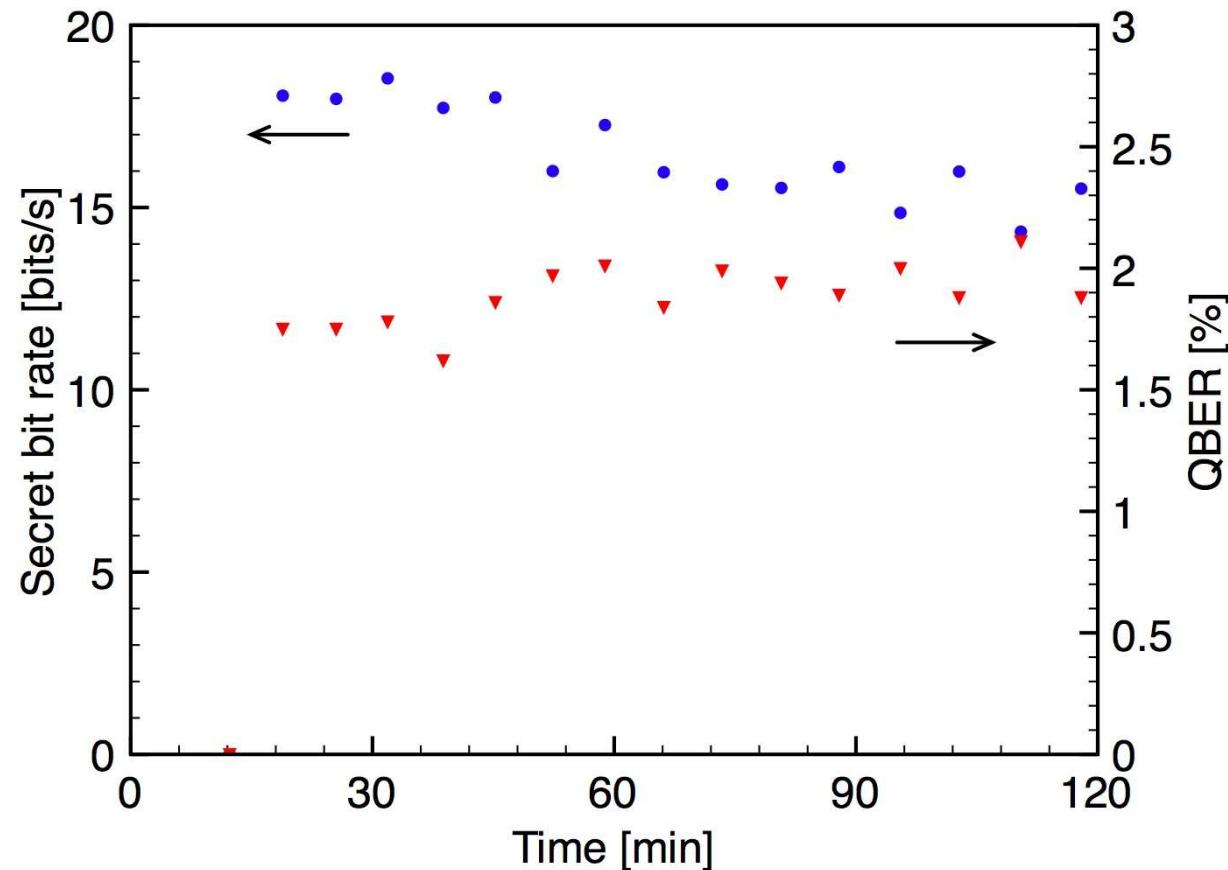




QKD over 250 km of Ultra-Low-Loss fibers from Corning Inc.

NJP 11, 075003 (2009)

Corning Inc. recently developed a commercially available ITU G.652 compliant low loss fiber with attenuation values at 1550nm of 0.165 dB/km

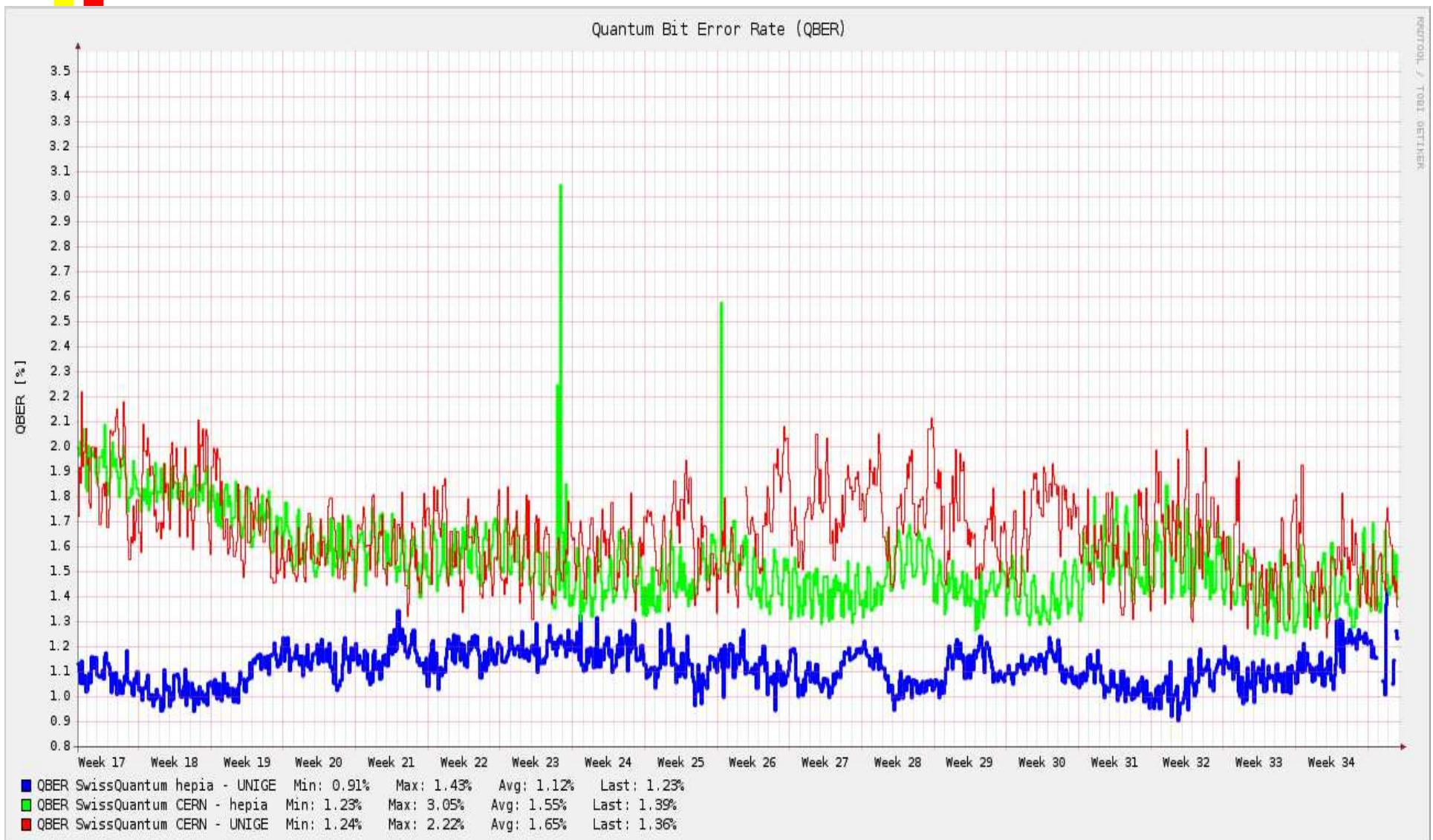




Reliability: Swiss Quantum Network

<http://www.swissquantum.com>

Runs continuously since March'09
Results presented October 8th during Telecom



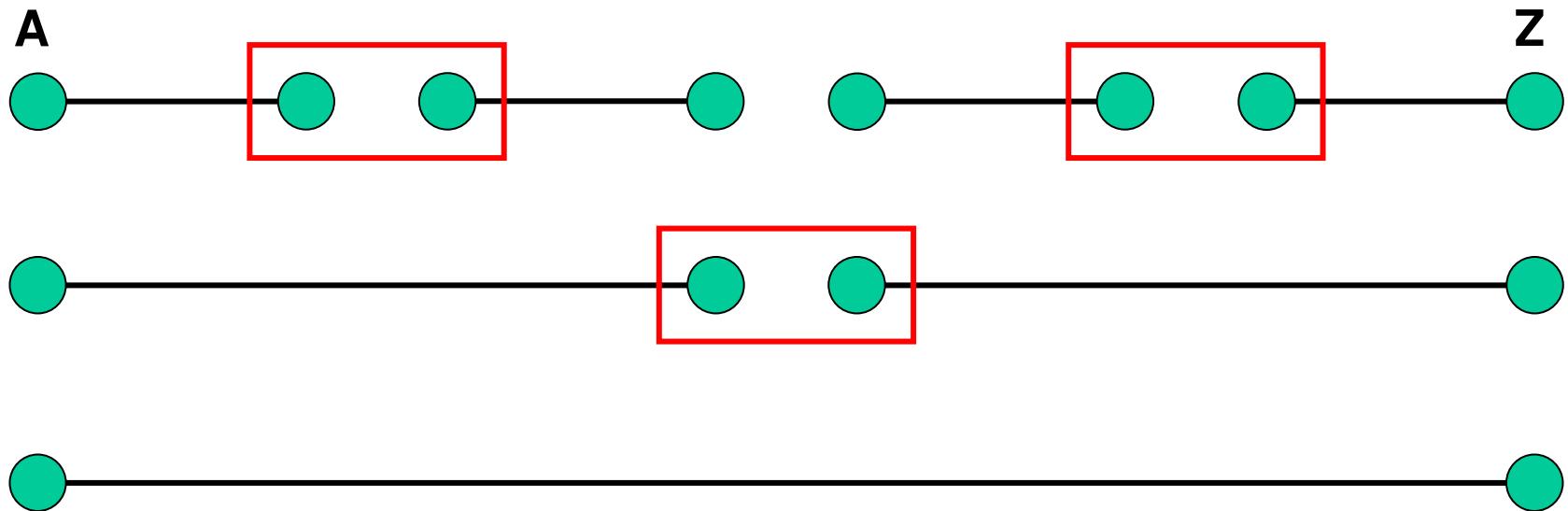


How far can one send a photon?

- § The quantum channel loss sets an exponential limit to the probability that a photon sent by Alice reaches Bob.
- § Let's say that a minimal "meaningful" rate is 1 bit/sec.
- § Engineering solution:
source 10^{10} Hz, decoy state protocol (hence rate proportional to transmission coeff. t)
 $\Rightarrow t = 10^{-10}$ is acceptable, ie 100 dB loss.
- § Fiber loss at $\lambda=1550\text{nm}$: 0.2 dB/km
 $\Rightarrow 500 \text{ km}$ is "only" an engineering problem.



Quantum Repeater - Requirements



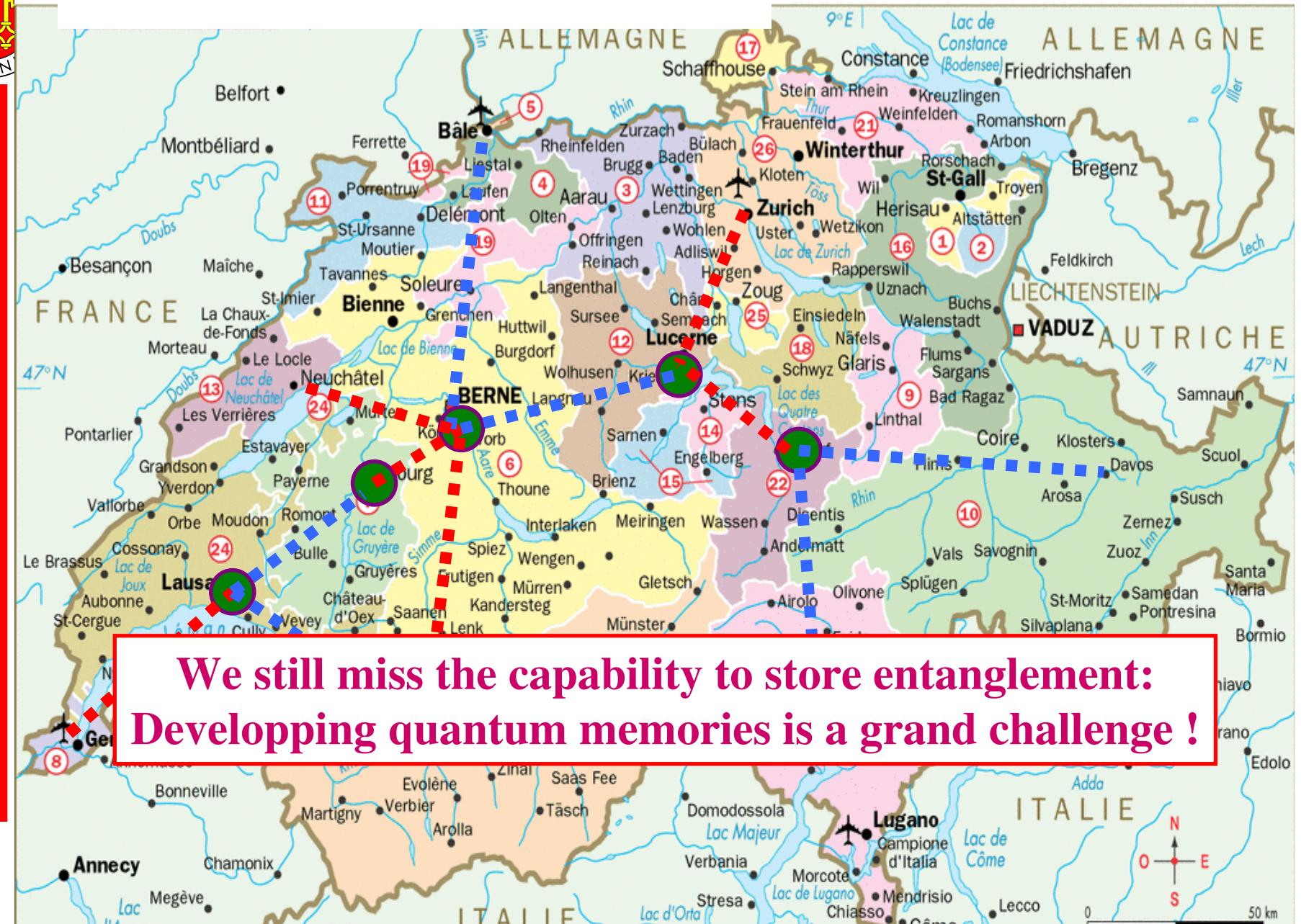
- § Distribution of entanglement over long distances
- § Multi-mode quantum memories
- § Entanglement swapping @ telecom λ

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



The long term vision:

Q repeaters





Solid state quantum memory at the single photon level

Goals : demonstrating the coherent and reversible mapping of (pseudo-) single photons onto a large ensemble of atoms frozen in a solid @ 3K.

In Geneva we follow two strategies:

1. CRIB: Controlled Reversible Inhomogeneous Broadening
2. AFC: Atomic Frequency Comb

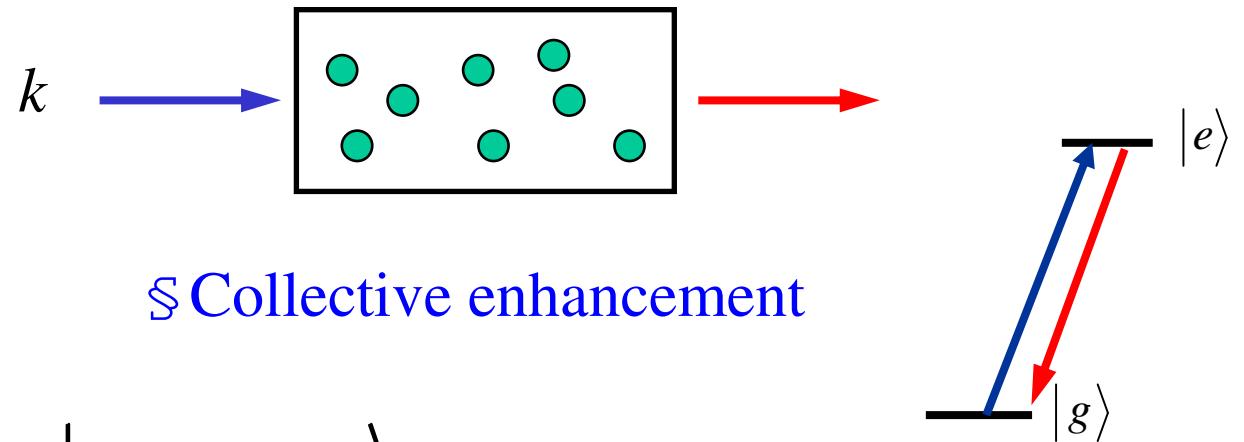
Both strategies are based on photon echo ideas, but avoid fluorescence that would spoil the single-photon signal.
See J. Ruggiero et al., PRA 79, 053851 (2009)



Atom-photon interface for Q networks

Atomic ensembles

§ Easy to absorb light



§ Collective enhancement

$$|g_1 \dots g_j \dots g_N\rangle$$

$$\rightarrow \frac{1}{\sqrt{N}} \sum_j e^{i\vec{k}\vec{r}_j} e^{i\Delta_j t} |\textcolor{yellow}{g_1 \dots g_N \dots g_N}\rangle$$

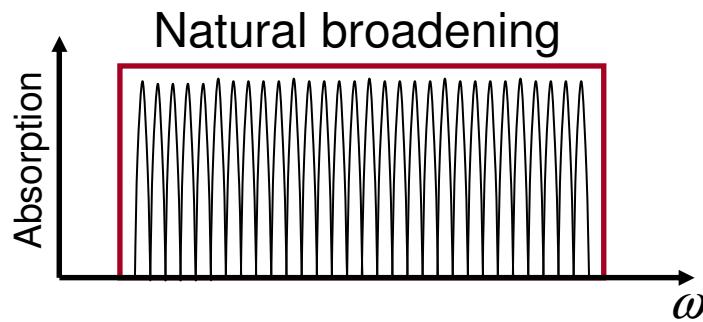
Inhomogeneous ensemble

Non-collective state \Rightarrow Low emission probability, N
Collective state \Rightarrow High emission probability, N^2



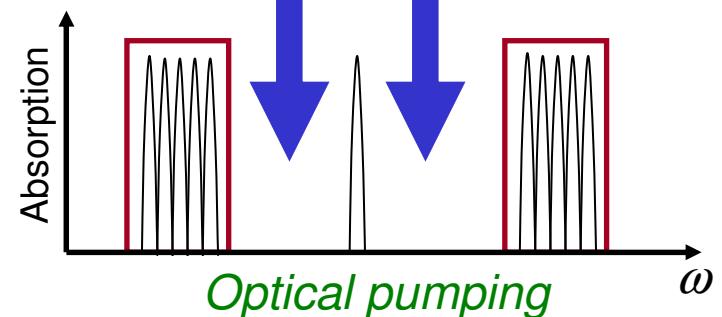
1. CRIB: Controlled Reversible Inhomogeneous Broadening in rare-earth doped solids

STEP 1

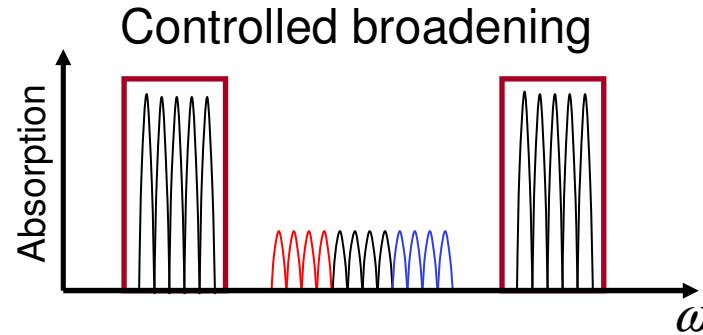


STEP 2

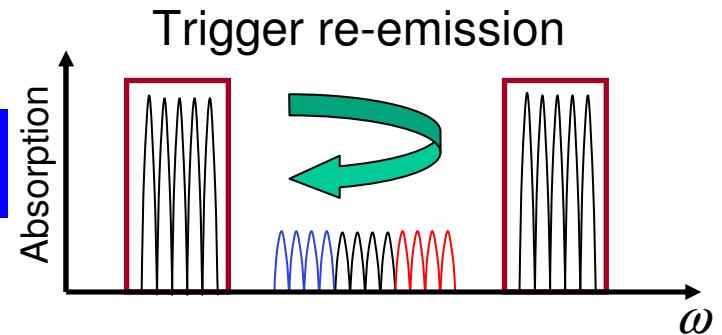
« Burn a hole »



STEP 3



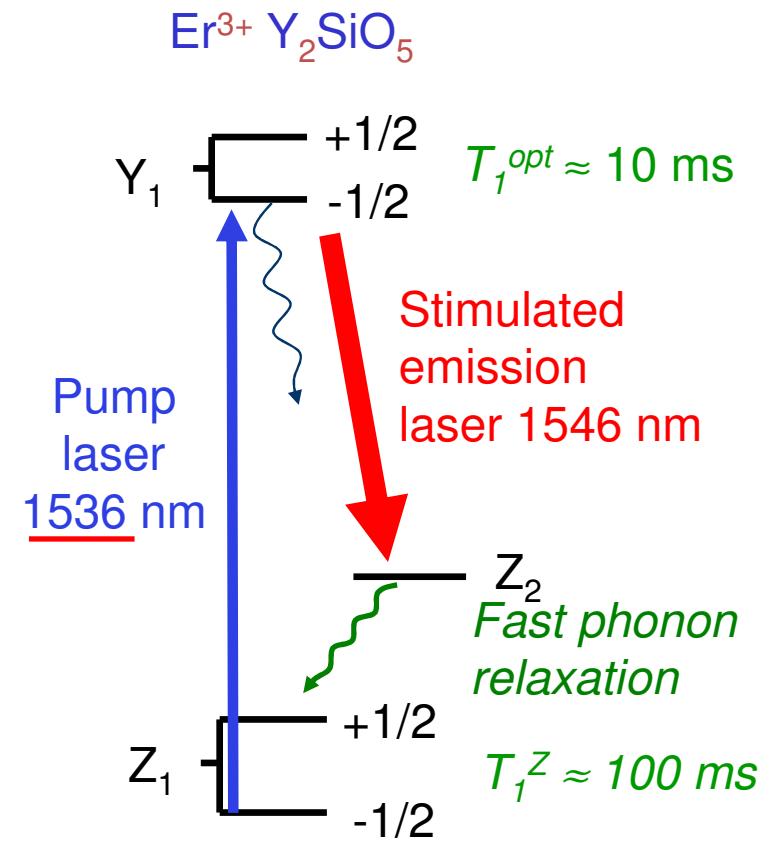
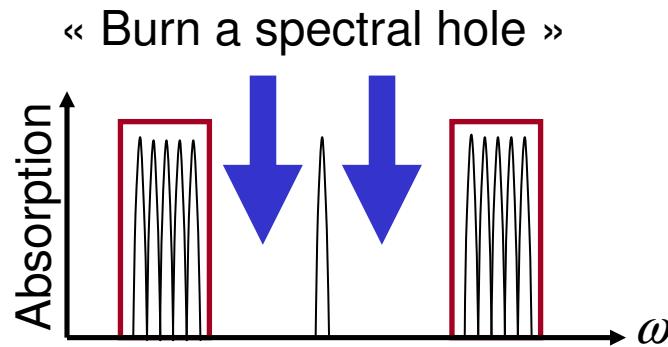
STEP 4



Can store and retrieve many temporal modes with high efficiency.



State preparation using optical pumping



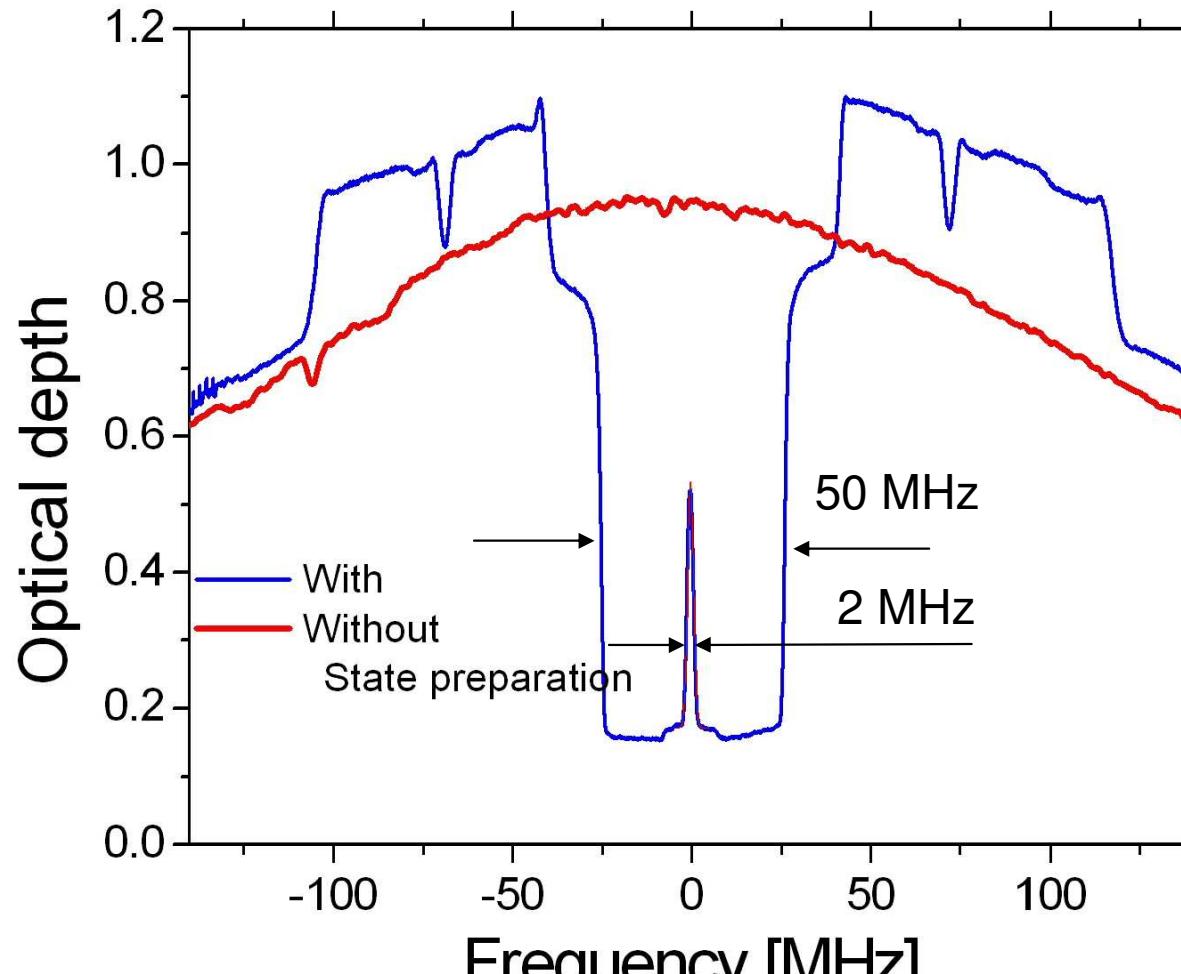
B. Lauritzen et al, PRA 78, 043402 (2008)

S. Hastings-Simon et al, PRB 78, 085410 (2008)



Results of spectral tailoring in $\text{Er}^{3+} \text{Y}_2\text{SiO}_5$

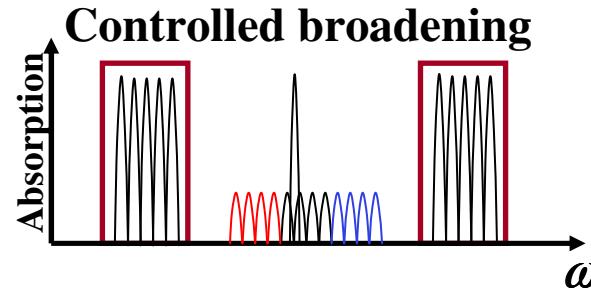
$\lambda = 1536 \text{ nm}$



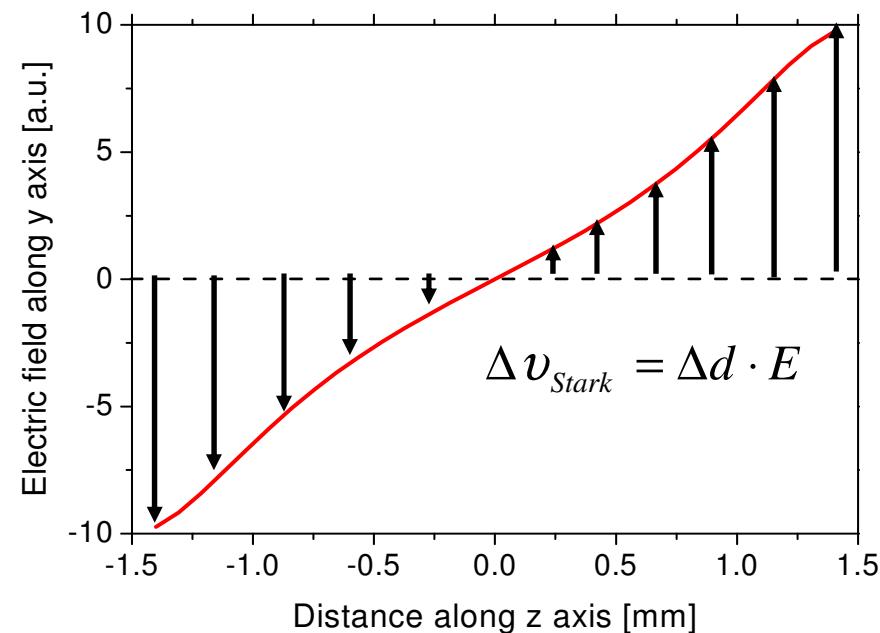
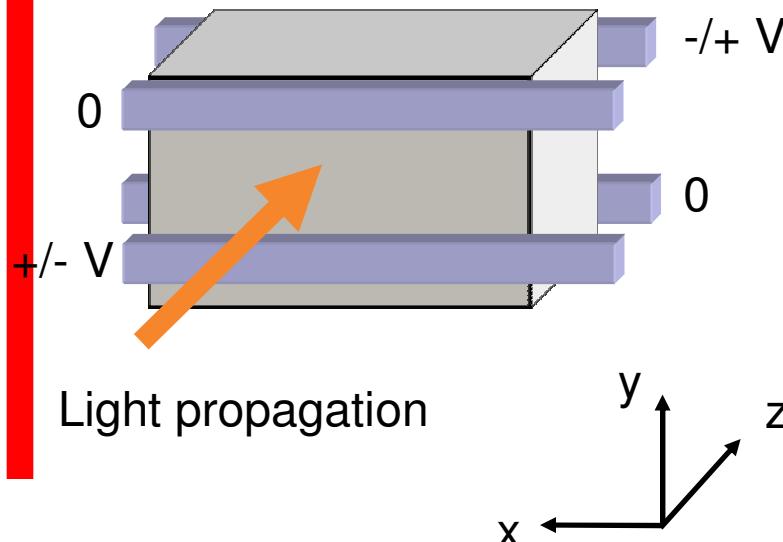


Controlling atomic evolution with linear Stark effect

GAP Optique Geneva University

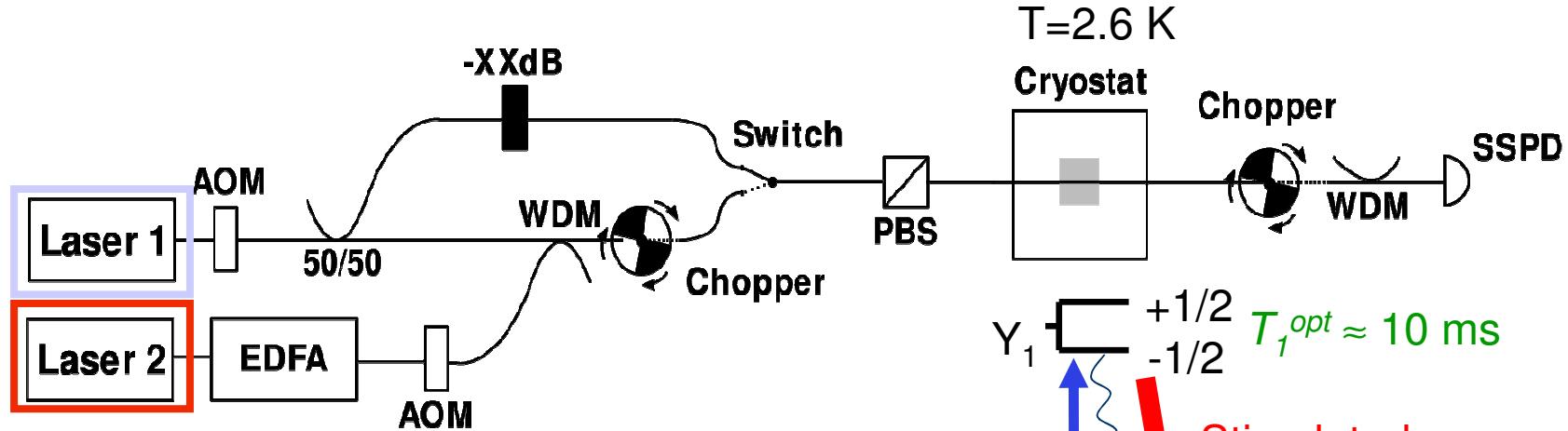


Linear Stark shifts by external field gradient

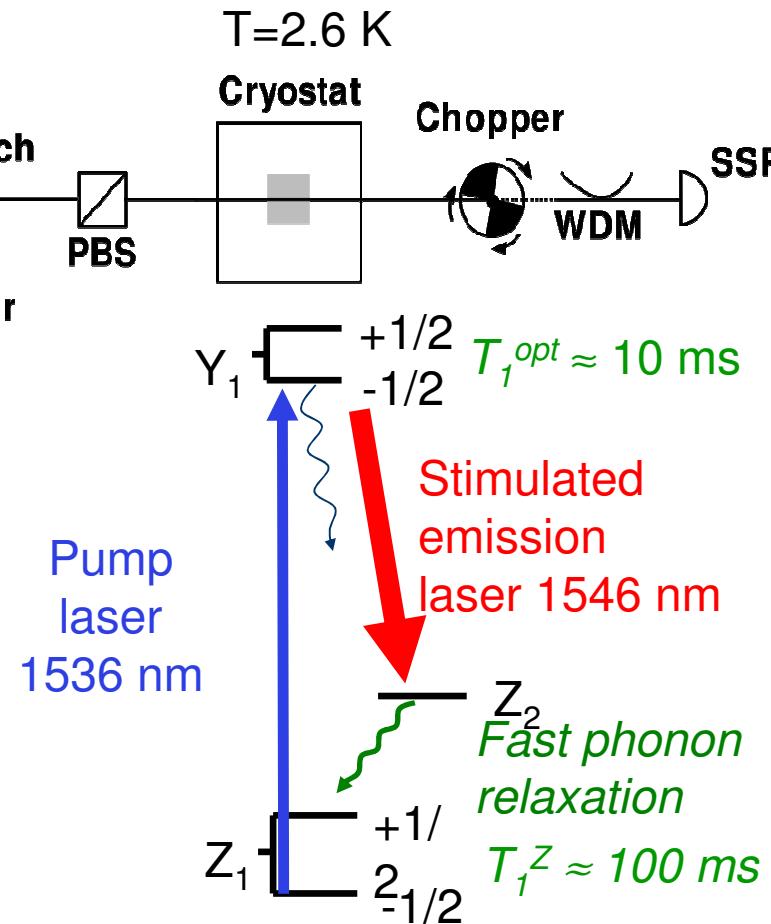




CRIB at telecom wavelength – weak pulse storage

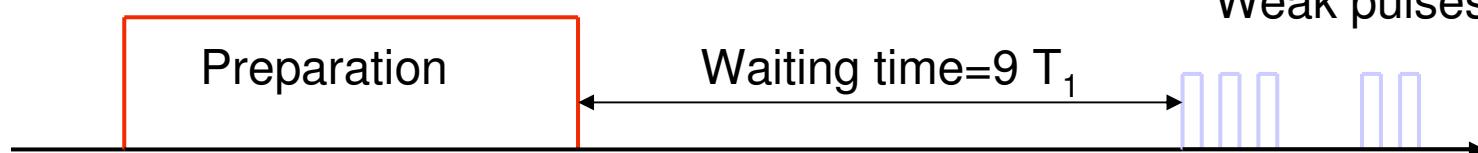


Detection with
Superconducting
single photon detectors
Efficiency: 0.07
Dark counts: 10 Hz



Avoid Fluorescence noise

8000 storage trials
Weak pulses

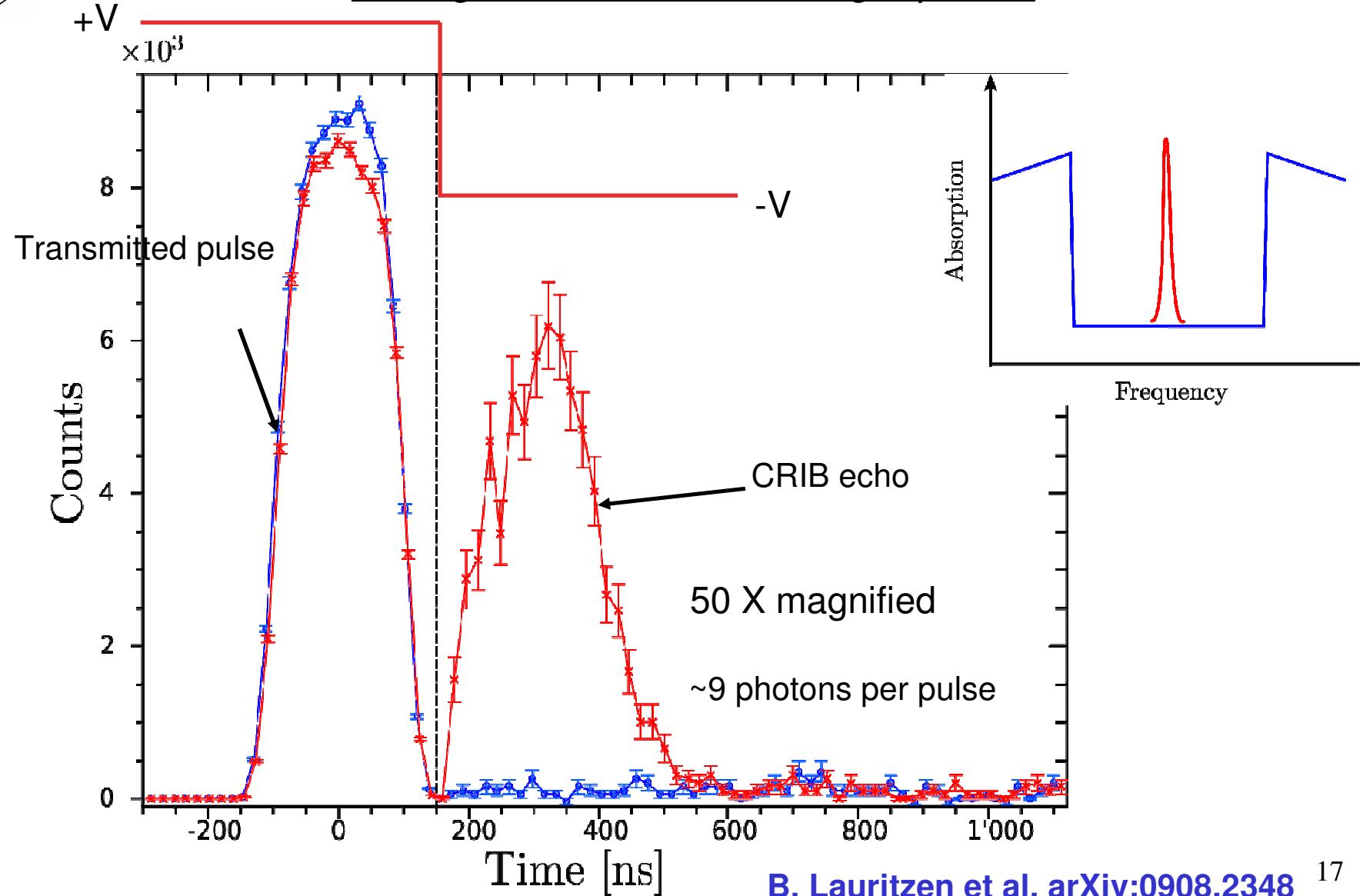




GAP Optique Geneva University

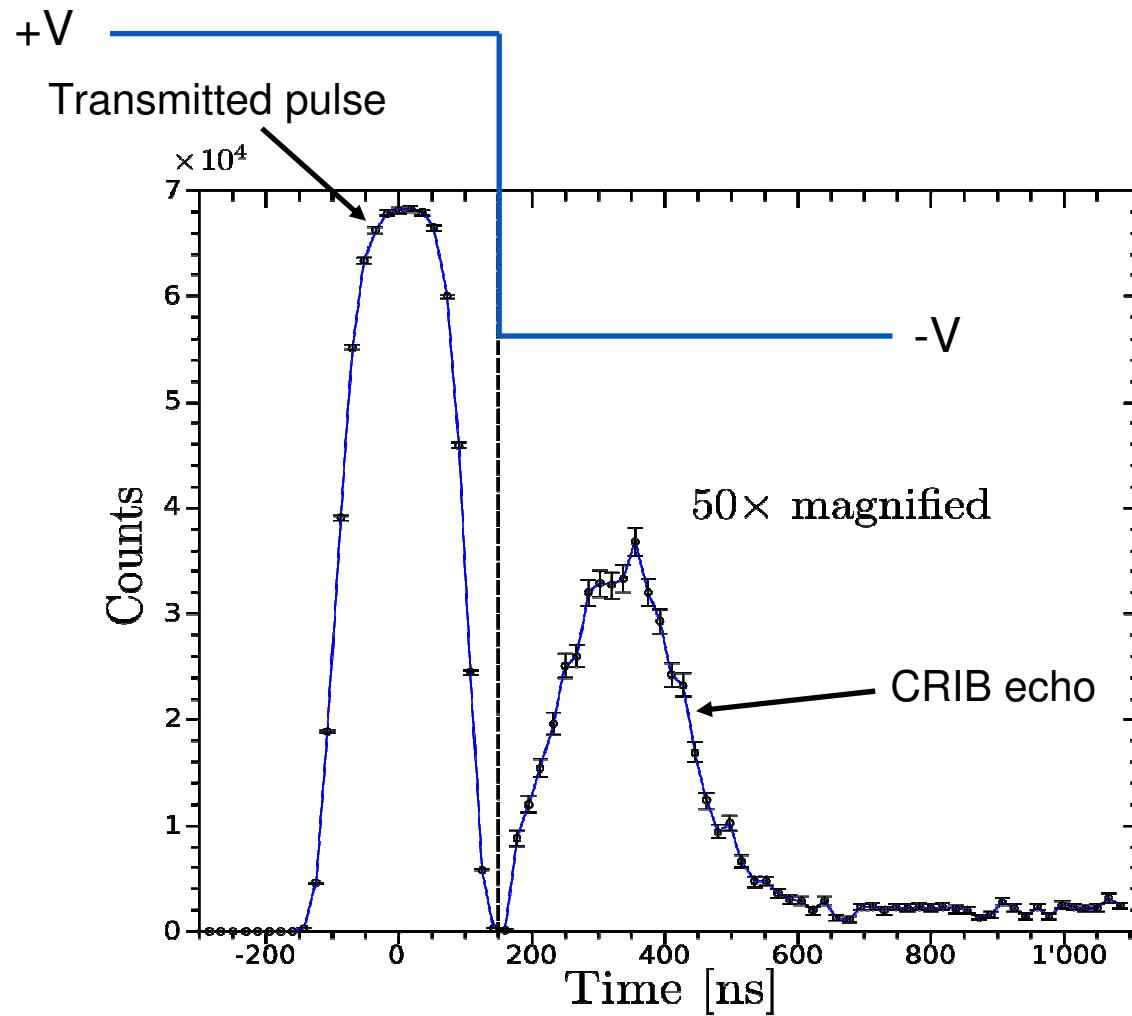
CRIB at telecom wavelength – single photon storage

Storage of weak coherent light pulses





CRIB at telecom wavelength – weak pulse storage at the Single photon level



~0.6 photons
per pulse

Efficiency $\approx 0.5\%$

B. Lauritzen et al, arXiv:0908.2348

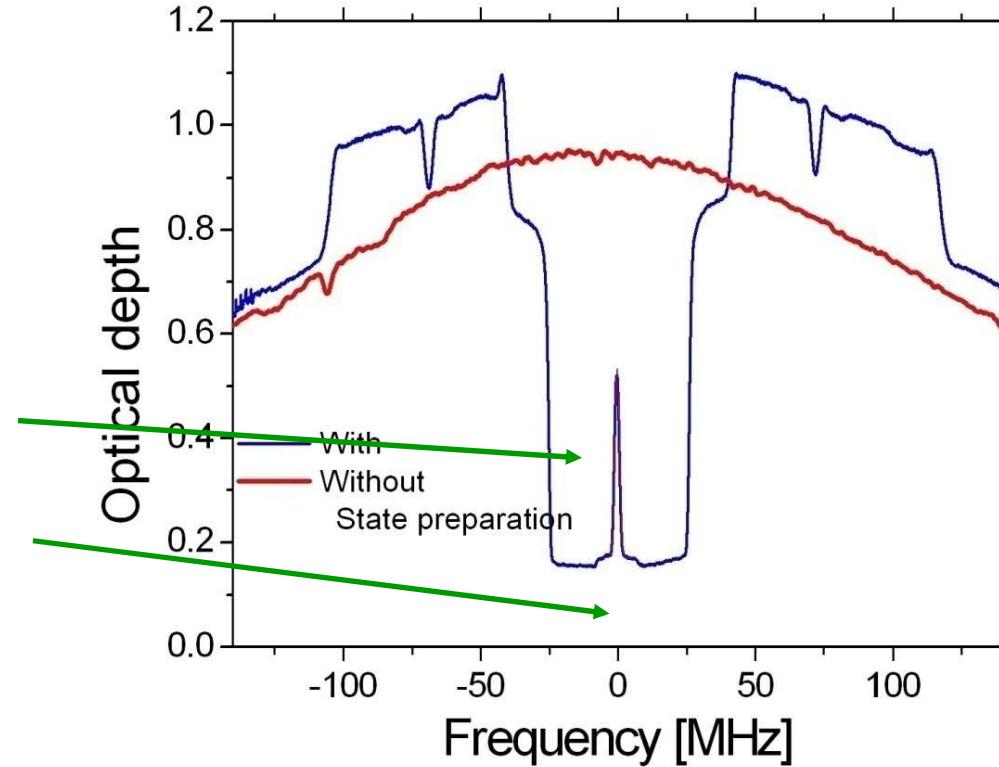


CRIB at telecom wavelength

Why is the efficiency low ?

Low efficiency due to:

- Low optical depth
- Poor optical pumping



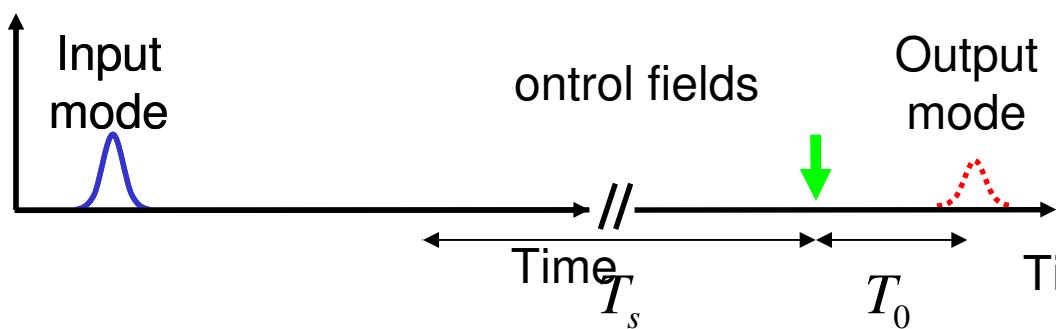
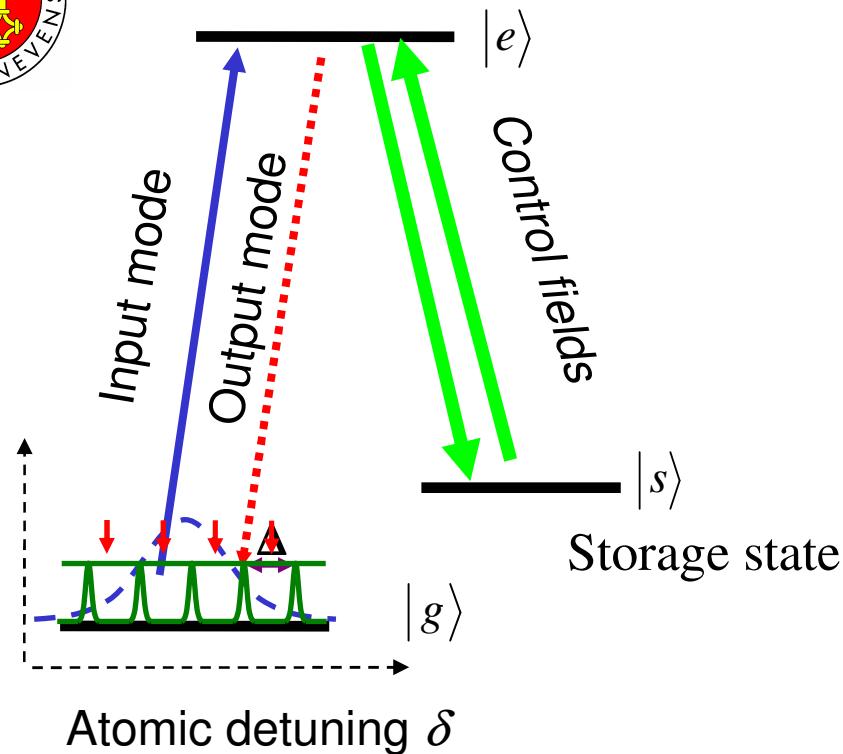
Increase optical pumping efficiency

Higher B, other crystals, Hyperfine states ?



2. Atomic Frequency Comb (AFC) Quantum Memory

Ensemble of inhomogeneously broadened atoms



State after absorption
(superradiant Dicke state)

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

Dephasing

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

$$\delta_k = m_k \Delta$$

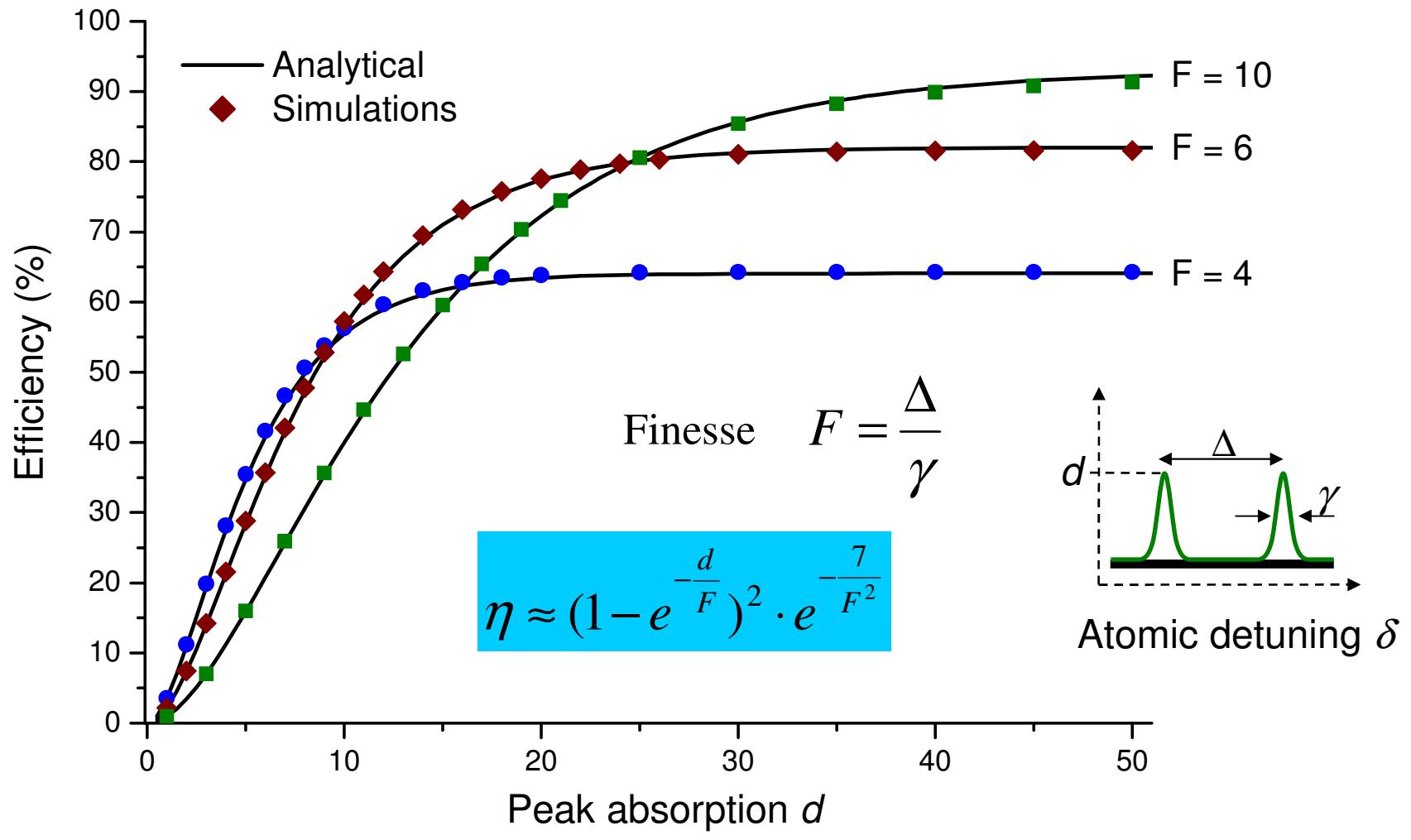
Periodic structure =>
Rephasing after a time

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

Collective emission in the
BACKWARD Photon echo
like emission



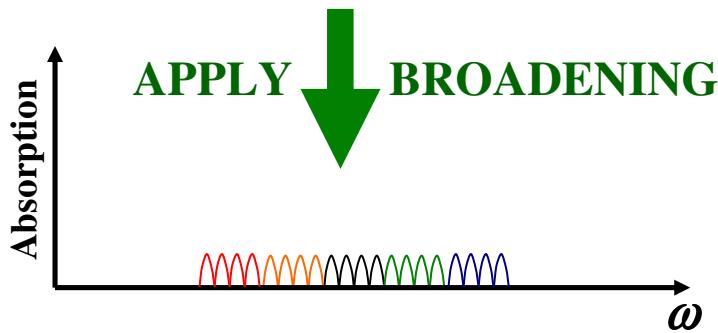
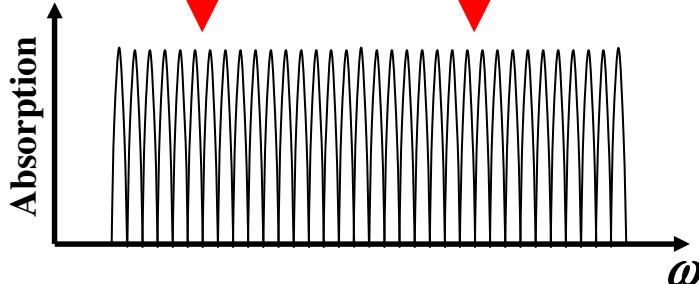
Efficiency vs optical depth (theory)





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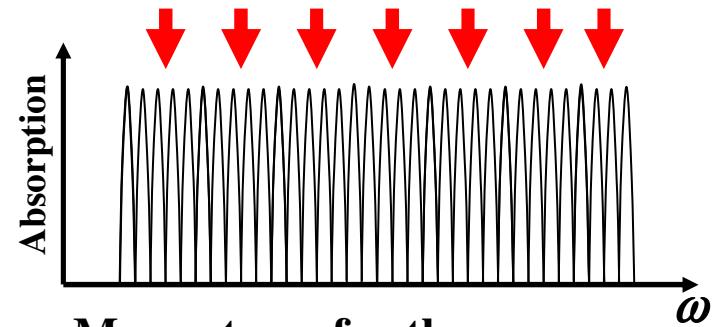
CRIB



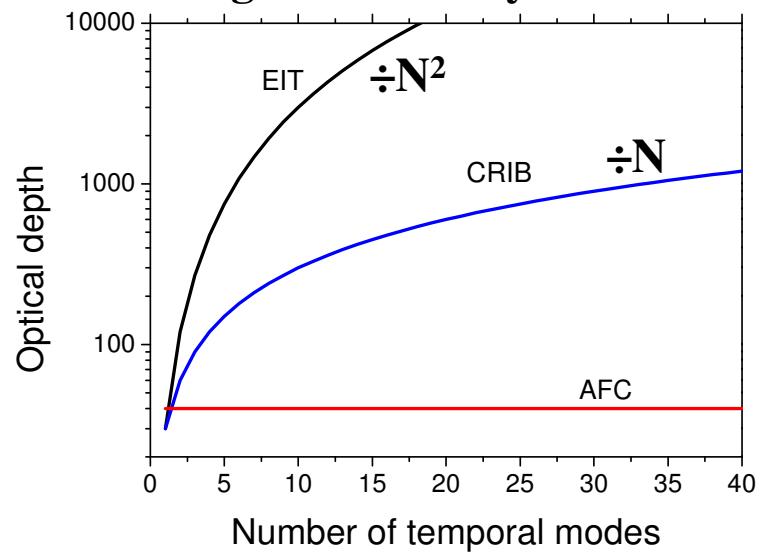
Many atoms are lost in the preparation step
⇒ Low efficiency!

CRIB vs AFC

AFC

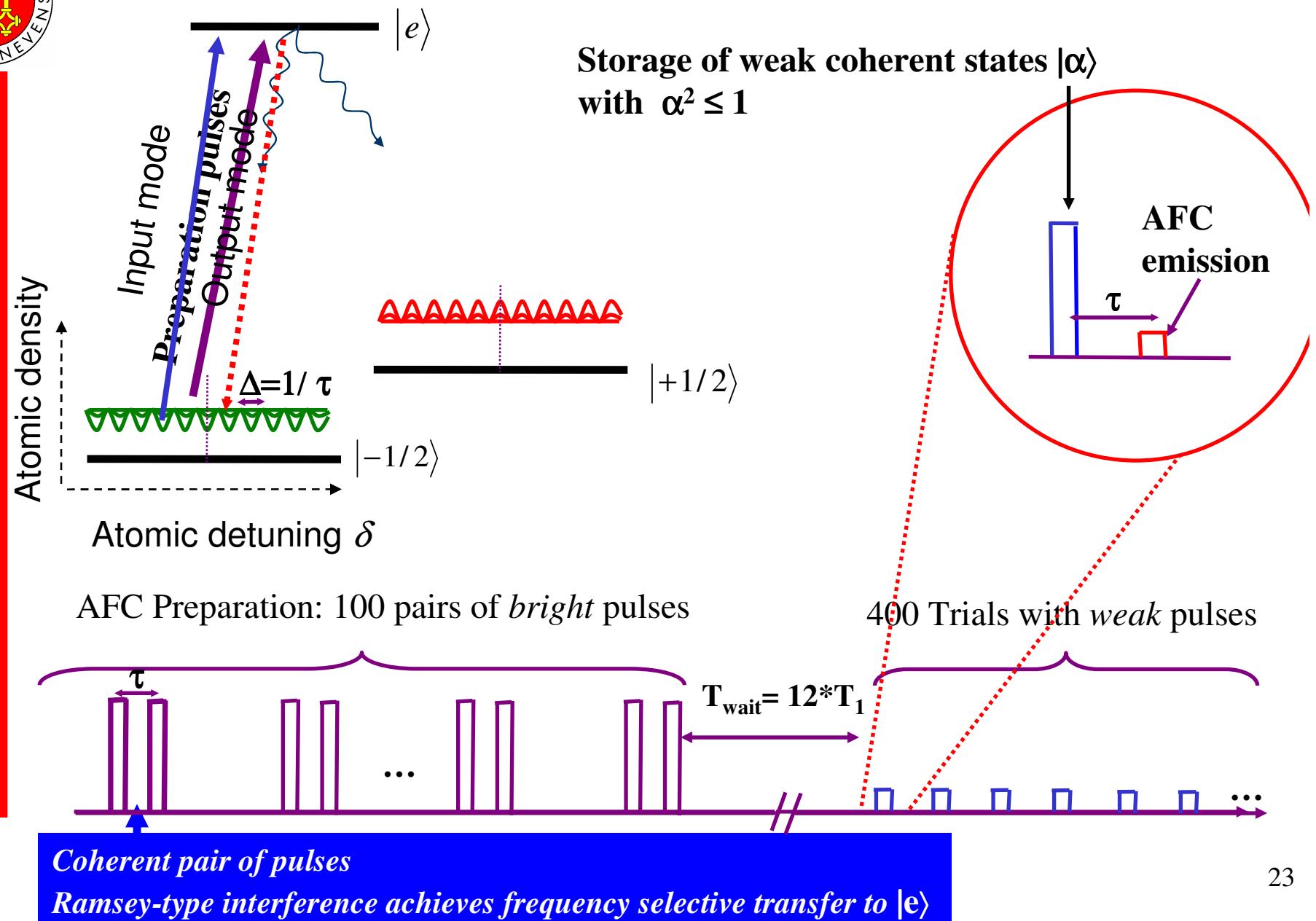


More atoms for the same bandwidth using an AFC
⇒ Higher efficiency!





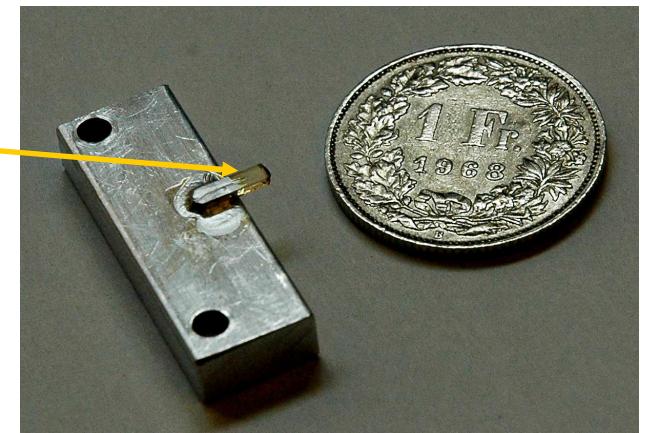
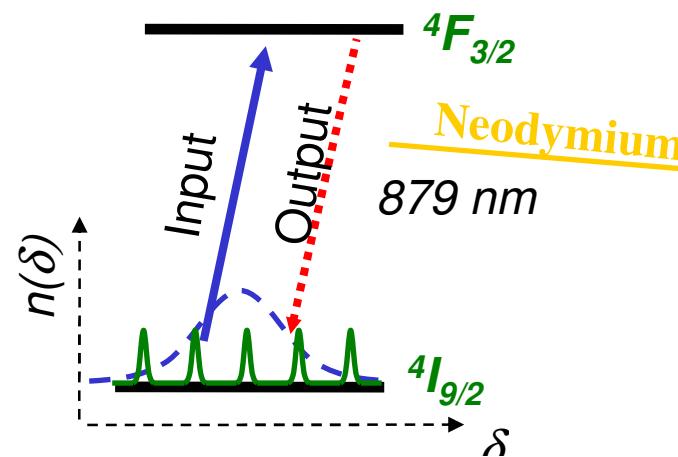
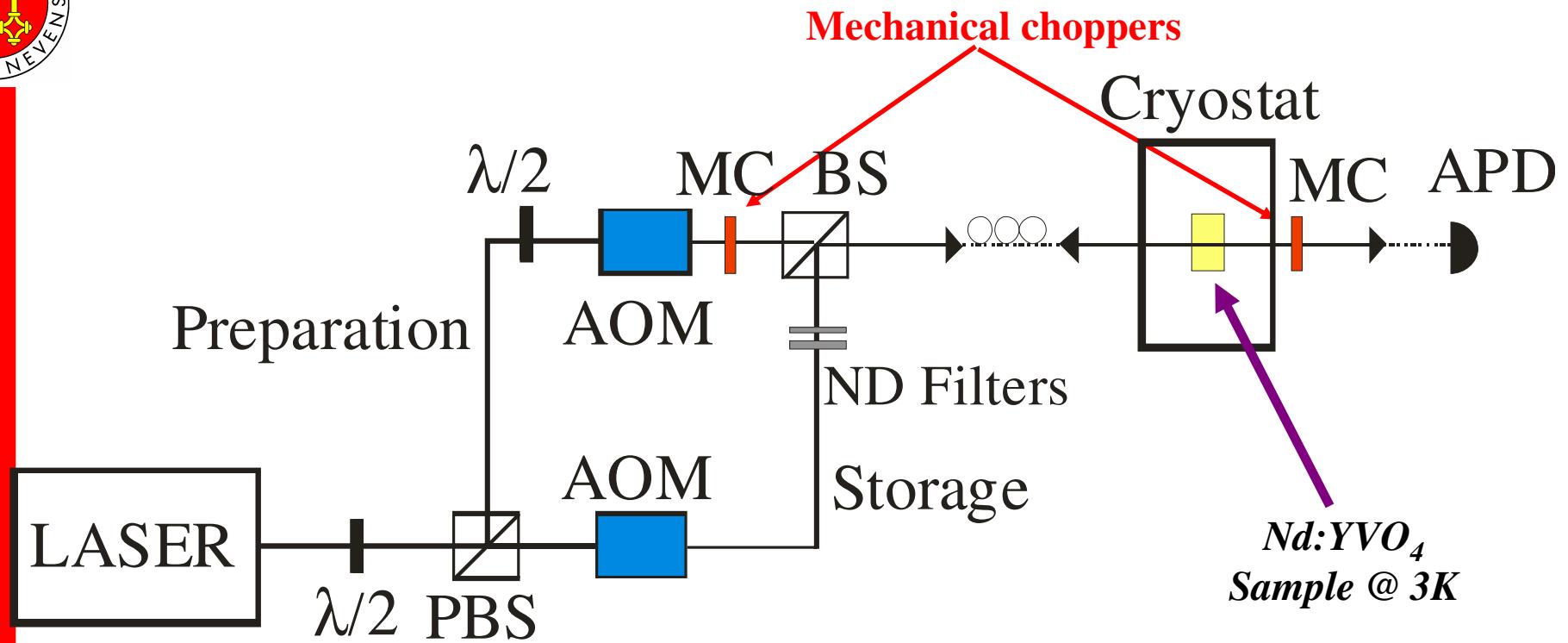
Atomic frequency grating preparation





GAP Optique Geneva University

The experimental set-up

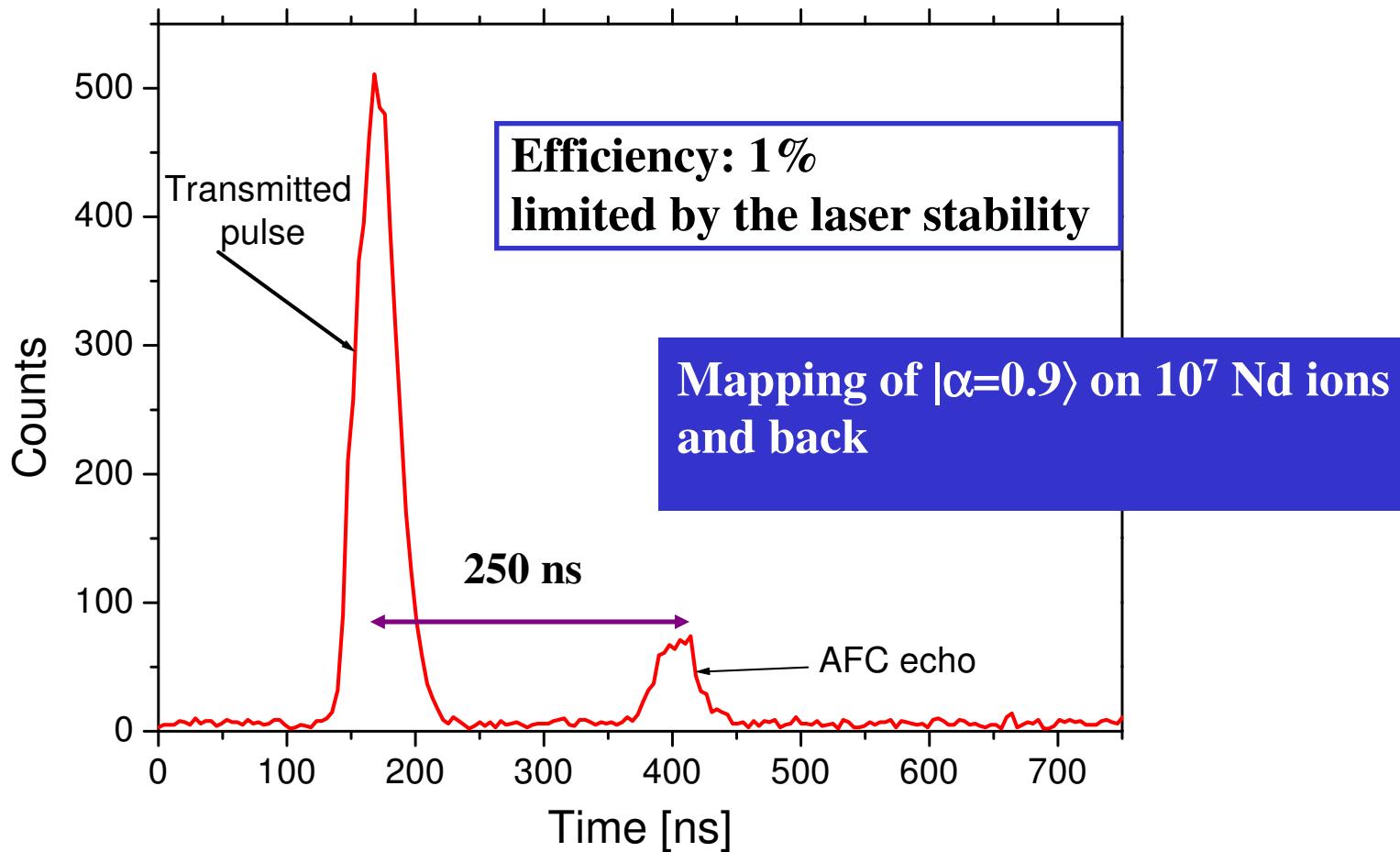




Light-matter quantum interface at the single photon level

Incident pulse: $\alpha^2 = 0.8$ photons per pulse in average
Spectral grating prepared for storage time 250 ns

Collaborations:
Prof. S. Kroll, Lund
Prof. W. Tittel, Calgary
Dr N. Sangouard, Paris

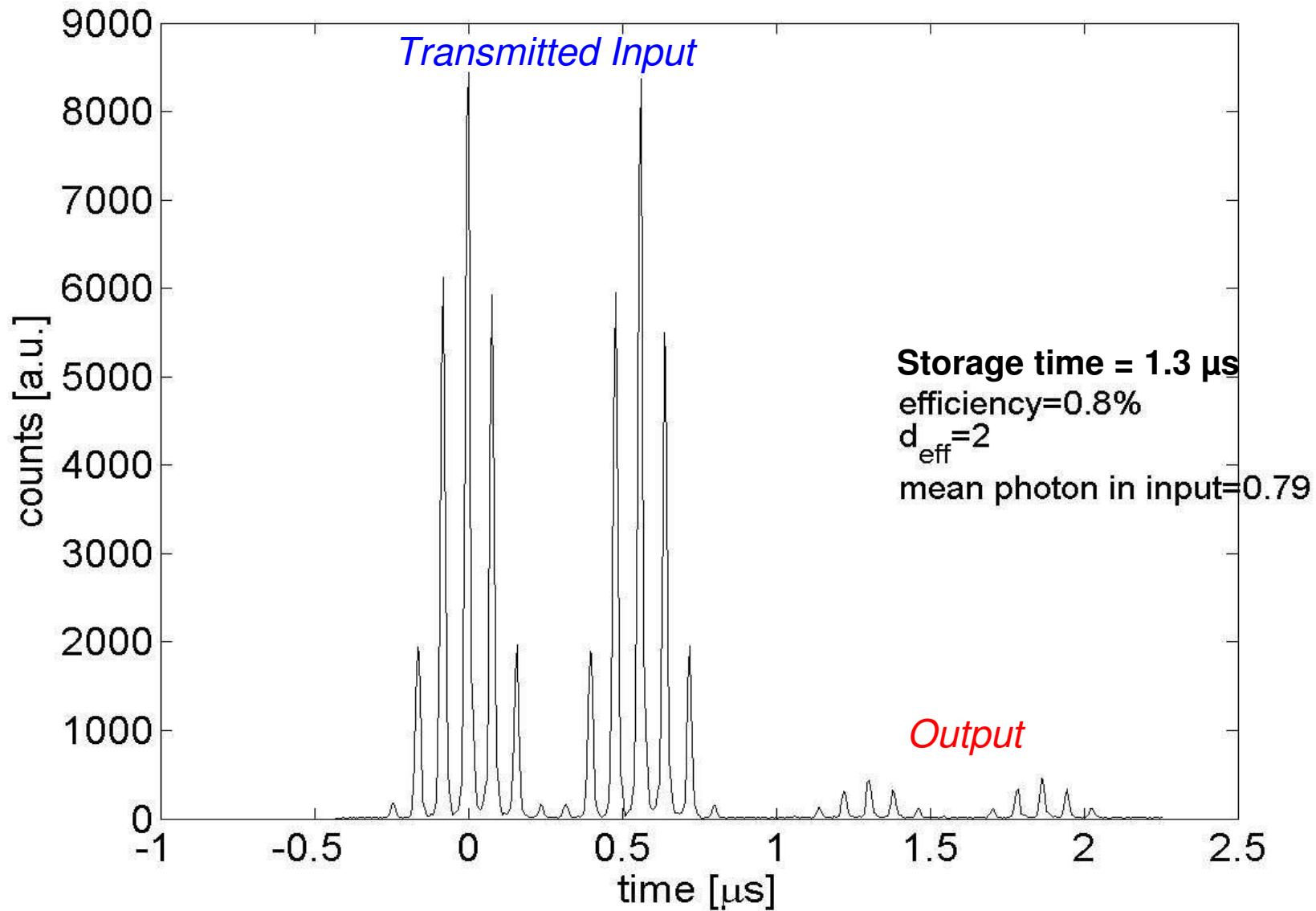


H. De Riedmatten, M. Afzelius et al, Nature 456, 773, 2008



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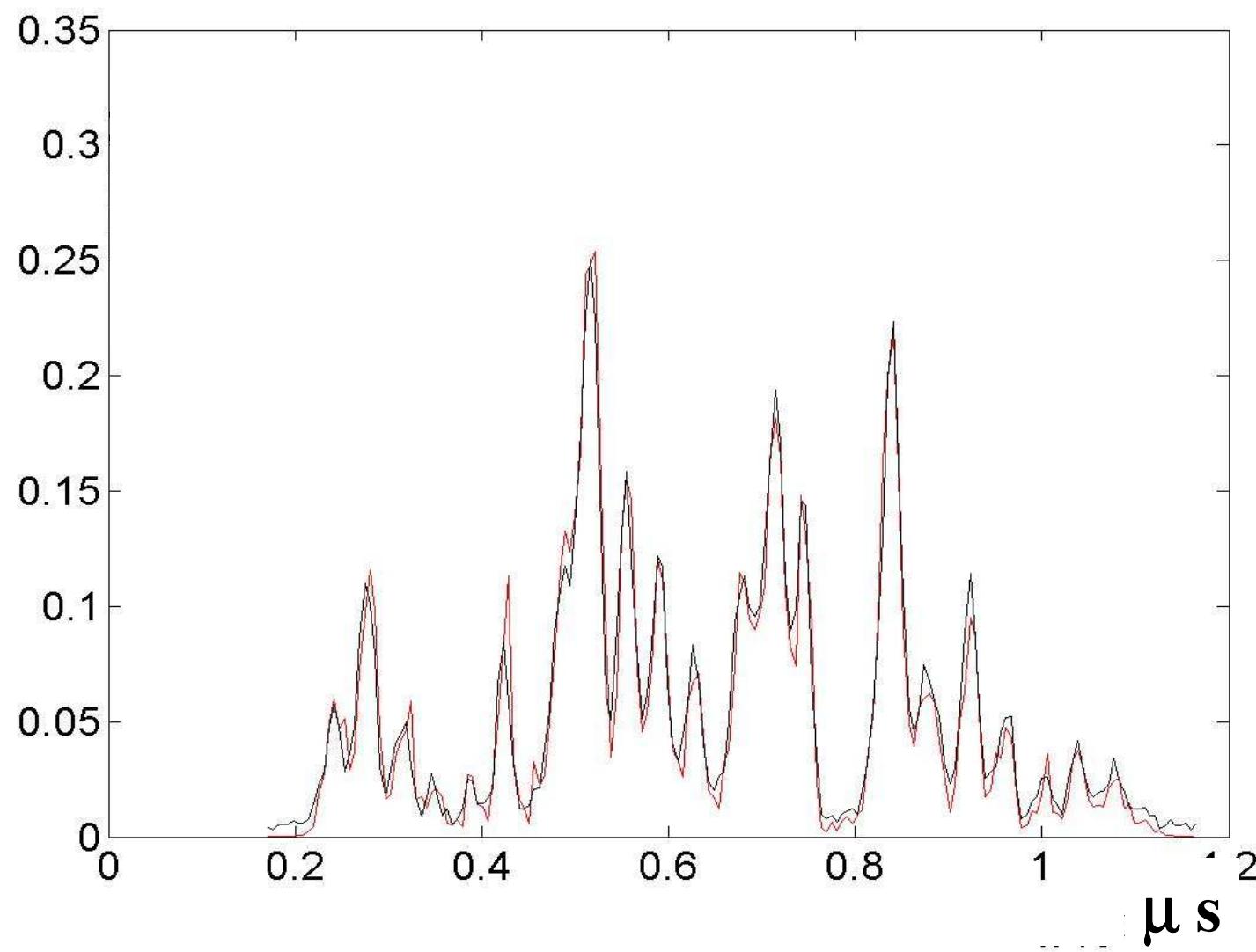
Multimode Storage (Nd:YSO)





Storage of arbitrary waveform (Nd:YSO)

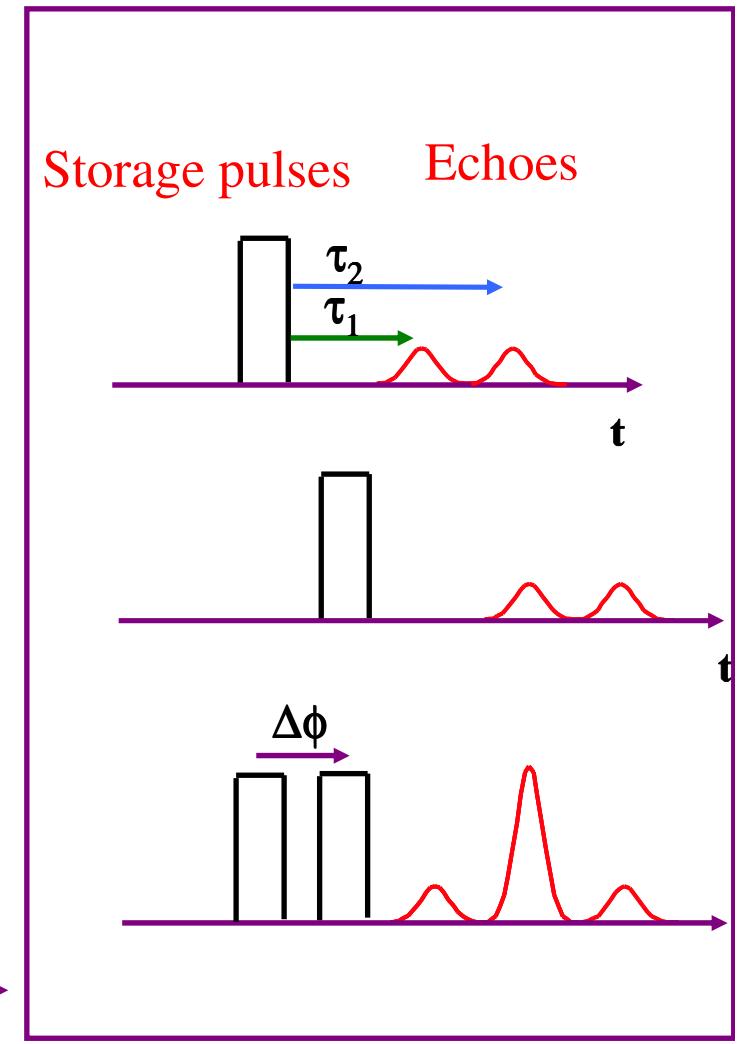
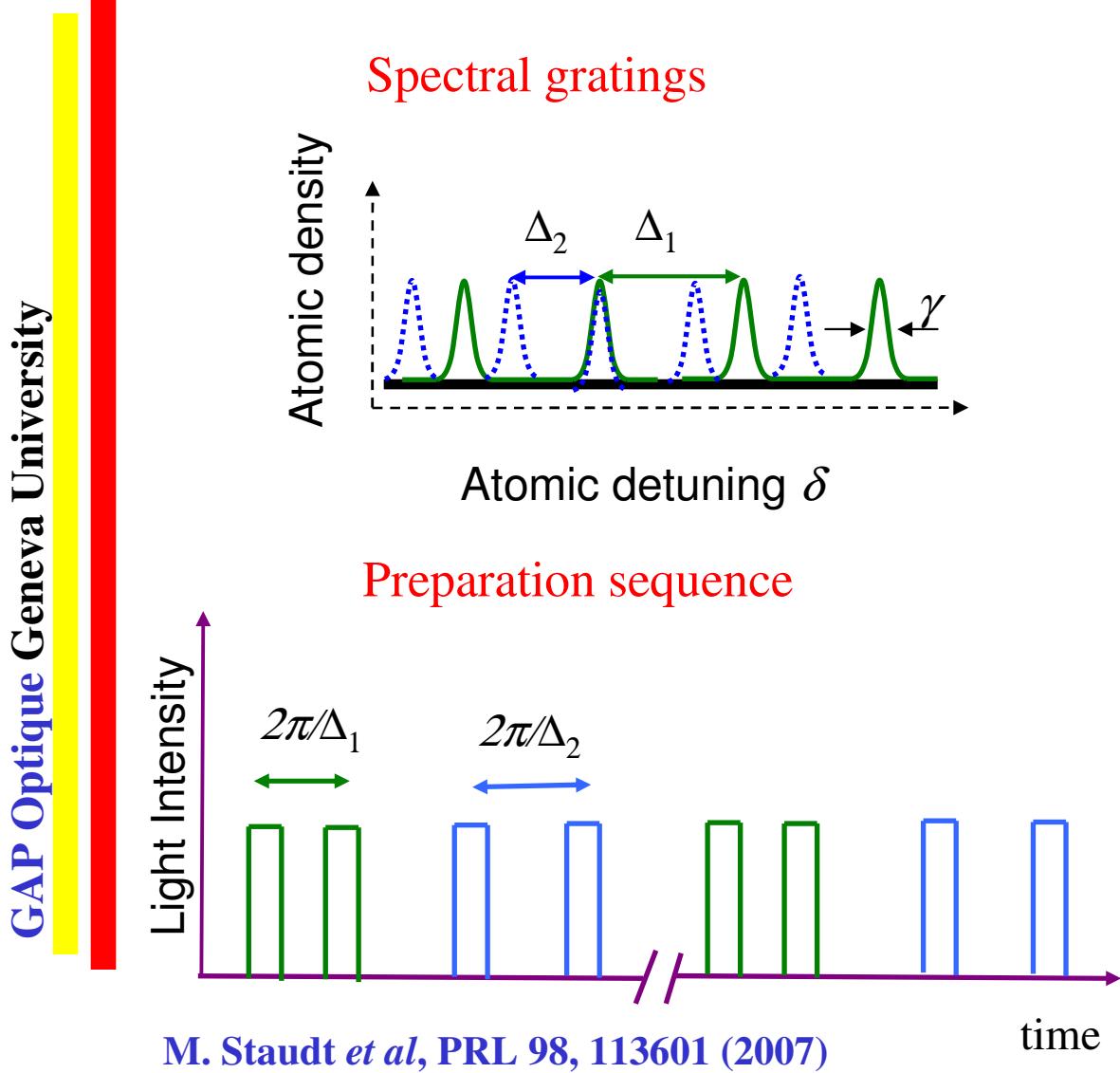
Overlap between input and output





Probing the coherence of the storage

By preparing two gratings, it is possible to read out twice:

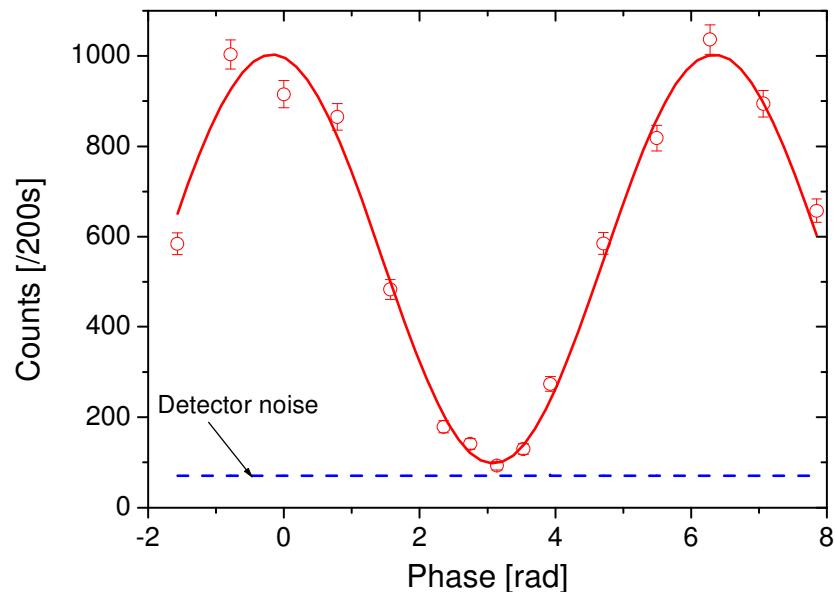
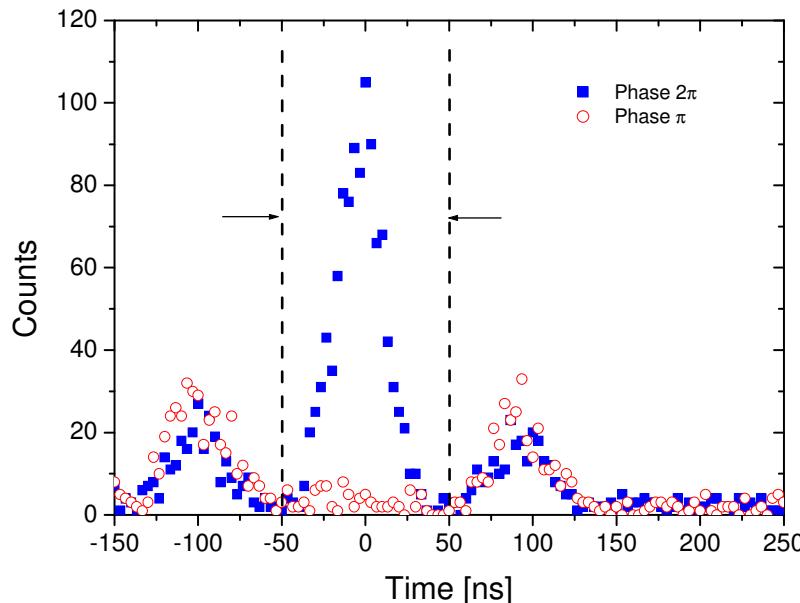


M. Staudt *et al*, PRL 98, 113601 (2007)



Probing the coherence of the storage

Incident pulses: 0.8 photon per pulse on average



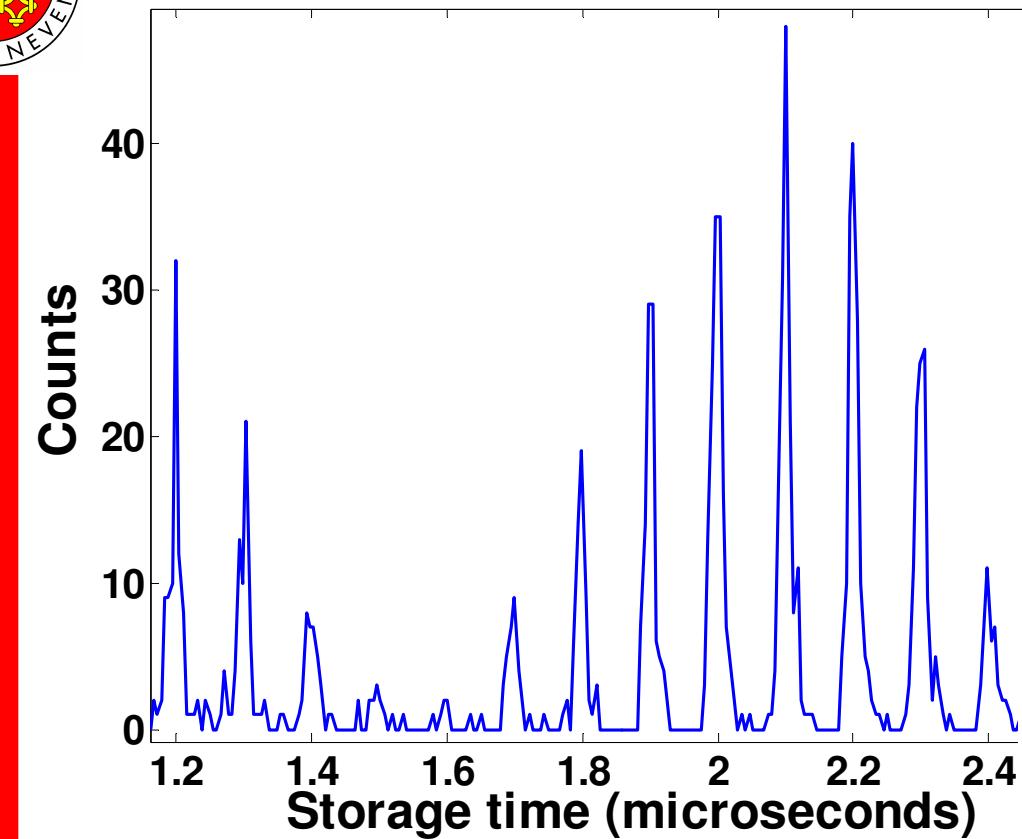
Storage times: 200 ns and 300 ns

Visibility : $95 \pm 3 \%$



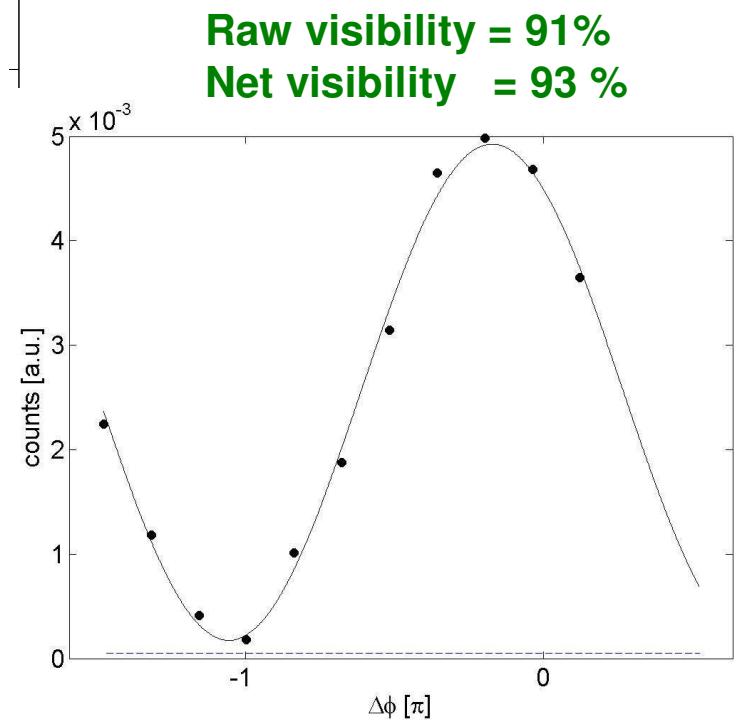
Interferences of multiple modes (Nd:YSO)

GAP Optique Geneva University



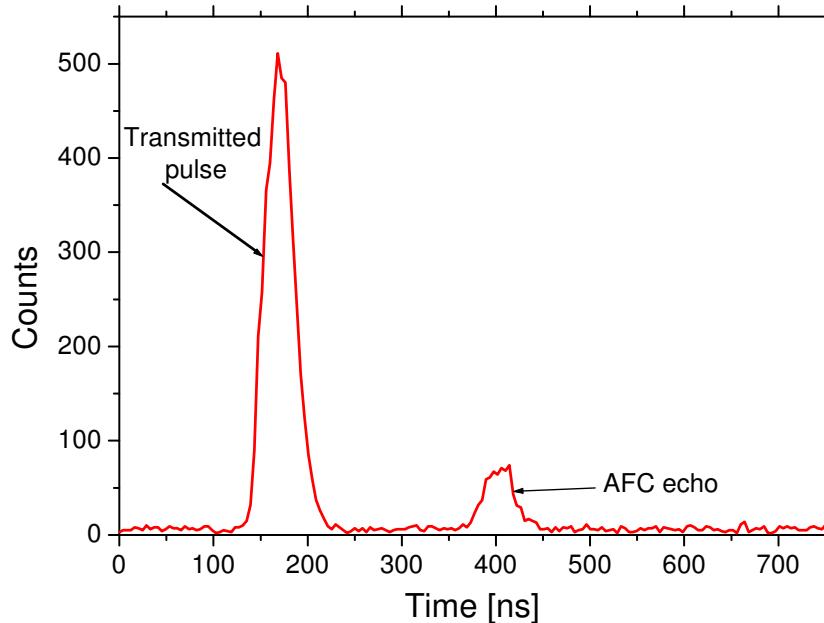
Two AFC gratings for double-readout:
1.2 and 1.3 μ s

12 input modes, spaced by 100 ns

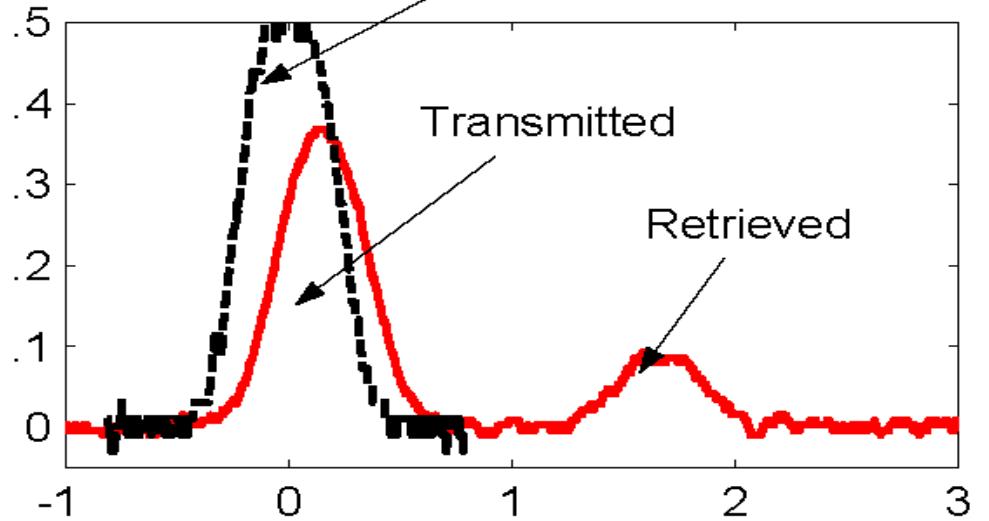


AFC in various places, ions and crystals

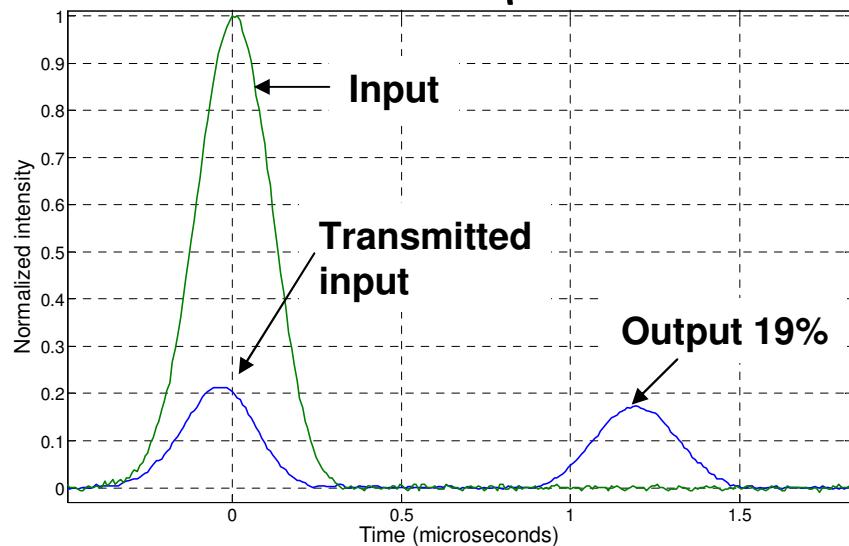
Nd:YVO in Geneva: $\eta=1\%$



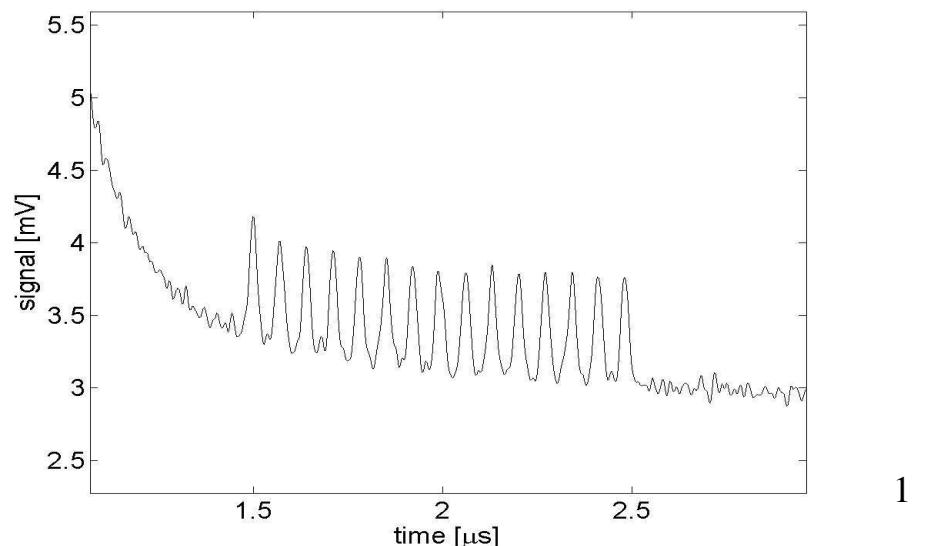
Tu:YAG in Orsay/Paris: $\eta=9\%$
Incoming $\times 0.5$



Pr:YSO in Lund: $\eta=19\%$



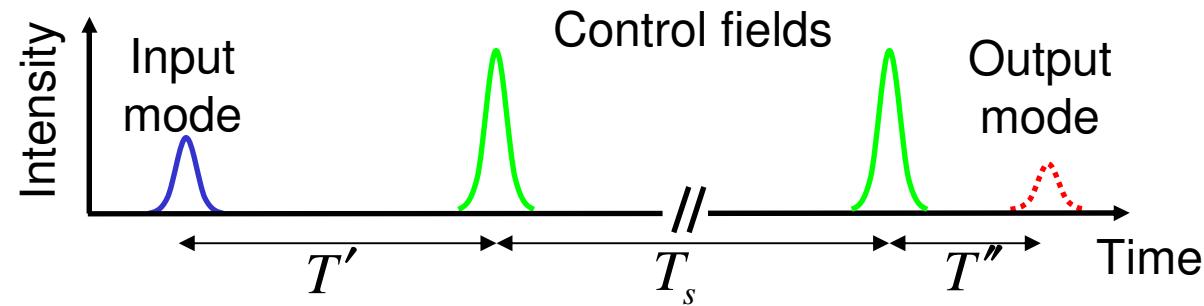
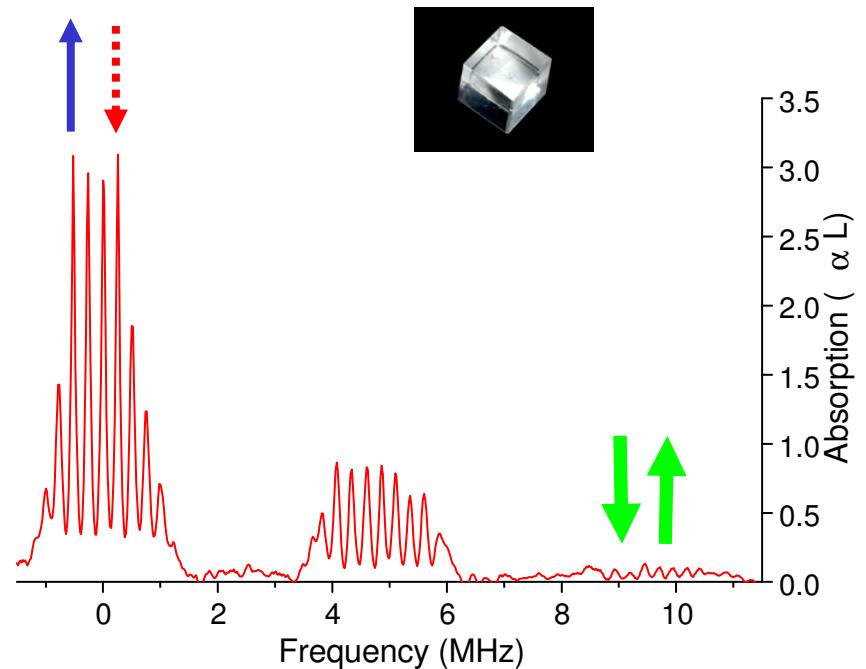
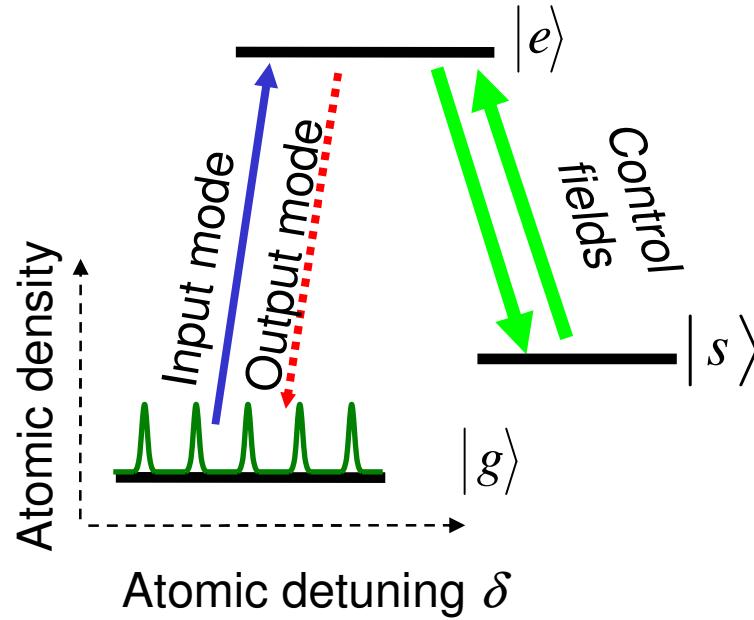
Nd:YSO in Geneva: $\eta=5\%$





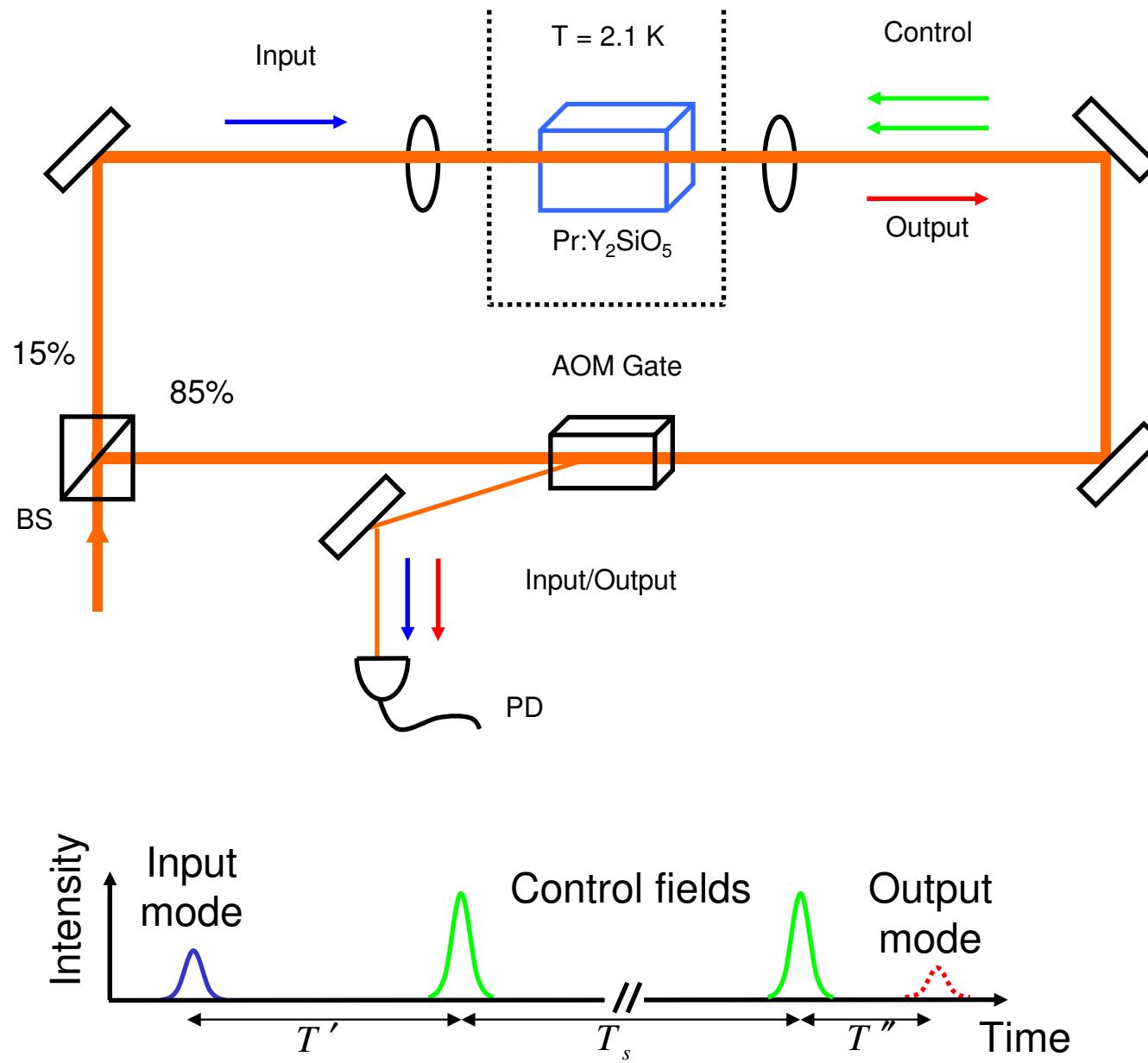
2b. AFC storage experiment in $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$

Geneva-Lund collaboration





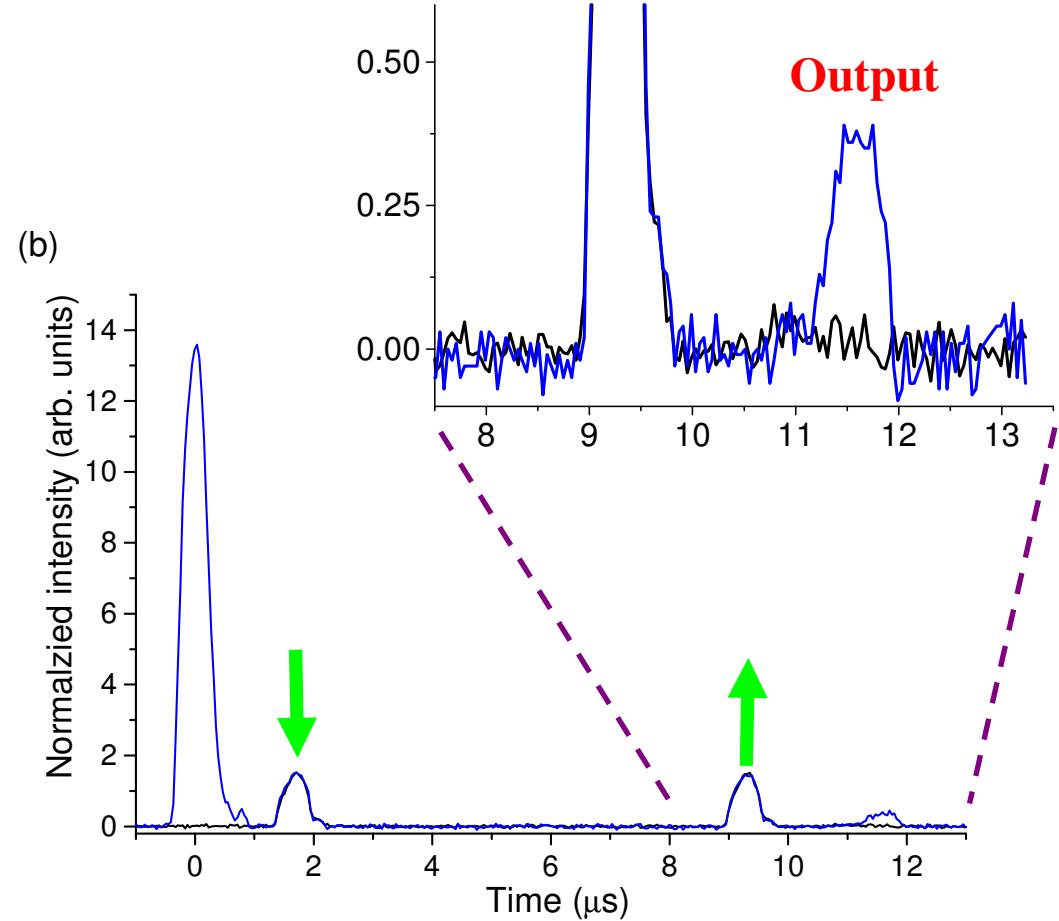
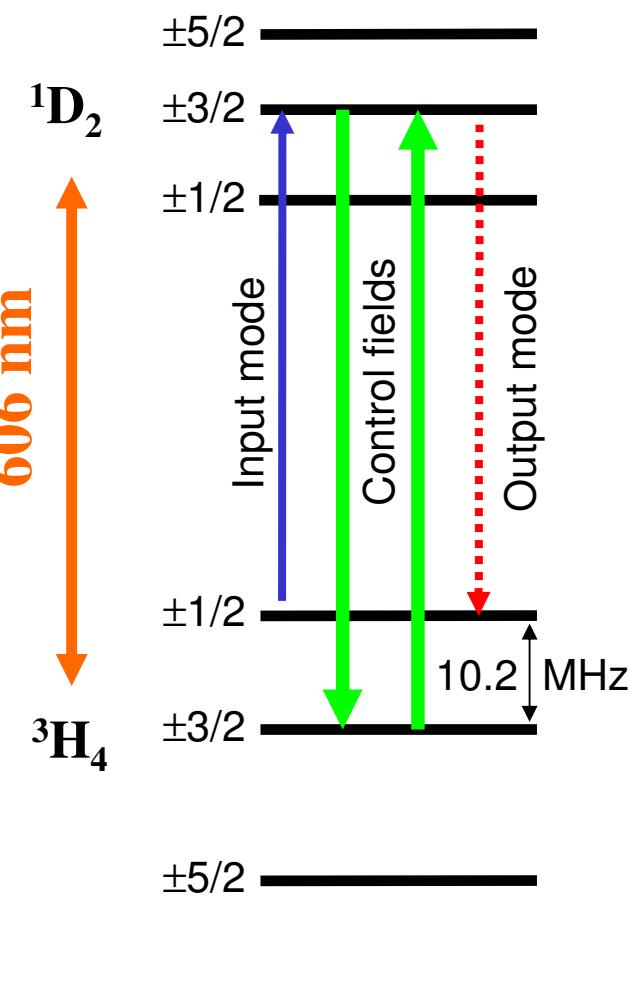
AFC storage exp. in Lund in $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$



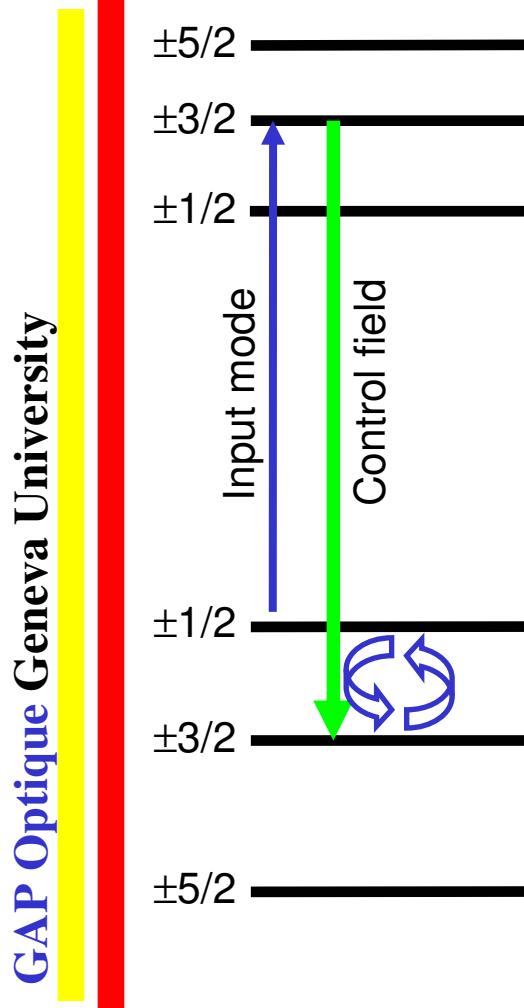


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AFC storage experiment in $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$

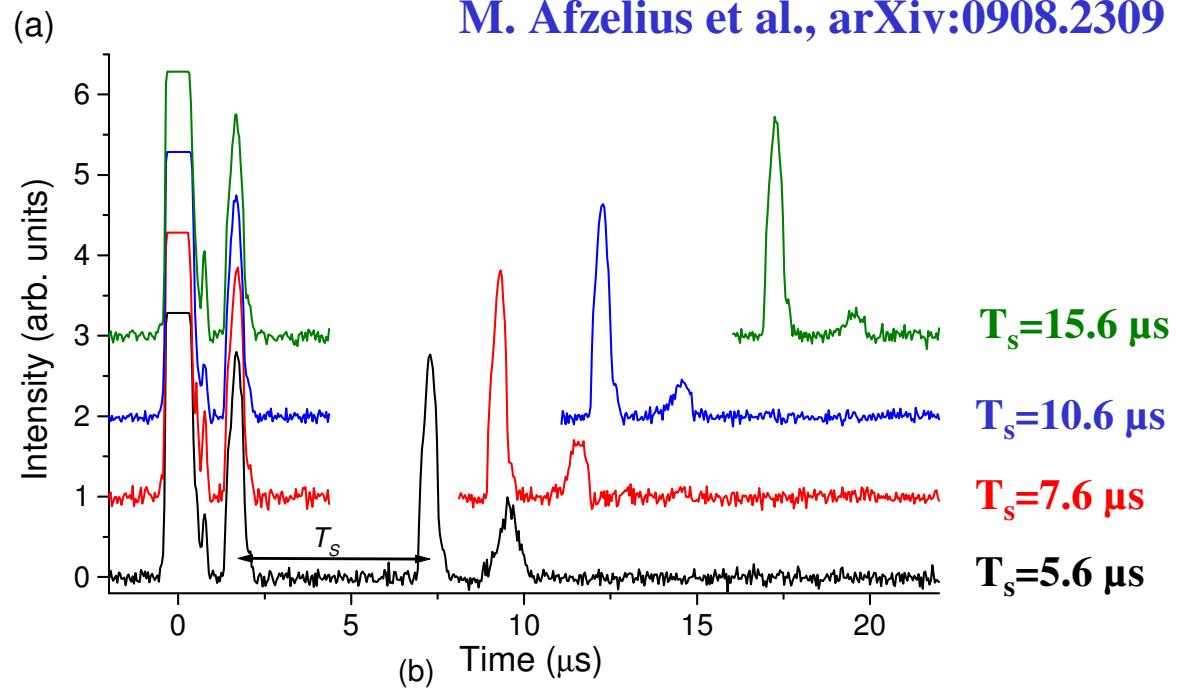


M. Afzelius et al., arXiv:0908.2309



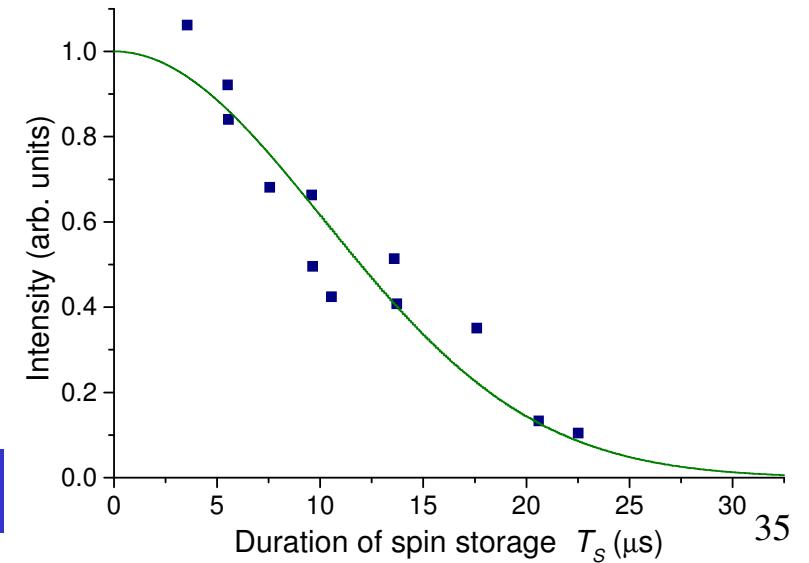
AFC storage experiment in $\text{Pr}^{3+}:\text{Y}_2\text{SiO}_5$

M. Afzelius et al., arXiv:0908.2309



*Decay of coherence
due to inhomogeneous
spin dephasing.*

*Fitted spin distribution
Gaussian FWHM: 26 kHz*



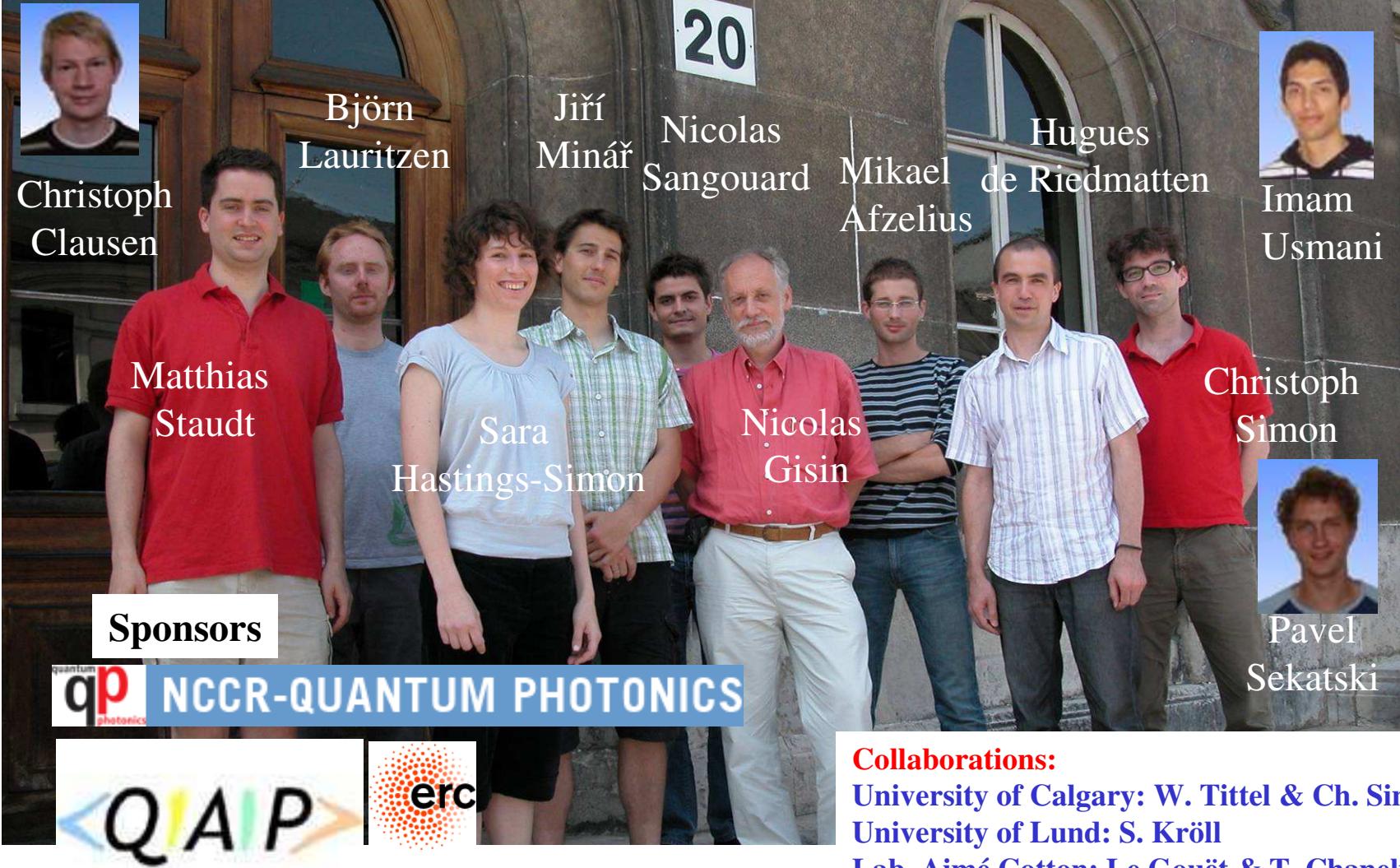
Solution: Spin echo \Rightarrow 1 s spin coherence !



GAP Optique Geneva University

The Quantum Memory Group

Group of Applied Physics, Geneva University



Collaborations:

University of Calgary: W. Tittel & Ch. Simon
University of Lund: S. Kröll
Lab. Aimé Cotton: Le Gouët & T. Chanelière
ENSCP: P. Goldner
University of Verona: M. Bettinelli

Cerberis – the best of two worlds

High-Speed Classical Encryption



High-speed link encryptor

Quantum Key Distribution



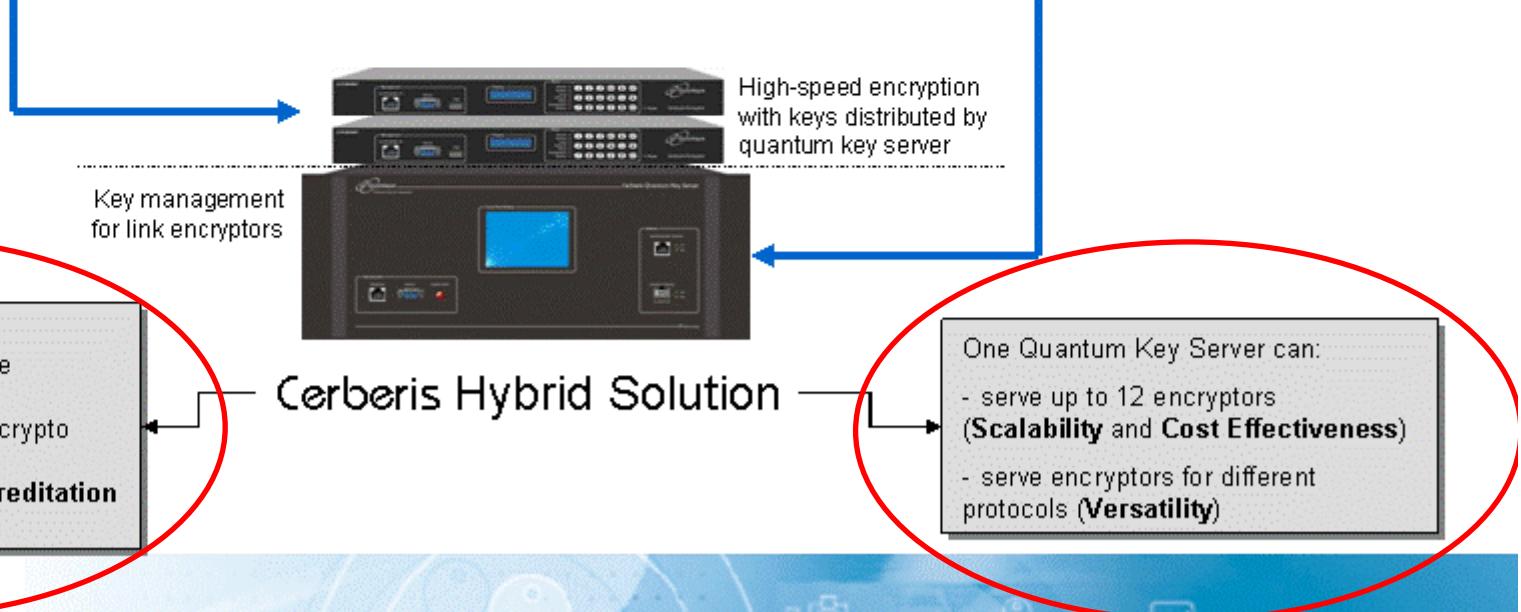
Quantum key server

➤ Transparent Layer 2 Encryption

- Up to 10 Gbps
- Multiprotocol (Ethernet, SONET, Fibre Channel, ATM)
- Accredited (FIPS, Common Criteria)

➤ Provably secure key distribution

- Distilled key distribution rate: 1000 bps over 25km/6dB
- Standard range: 50km (100km upon request)





Announcement:

2nd Winter School on Practical Quantum Cryptography

February 2010 / Swiss Alps

- Goal:** ► This Winter School introduce, the exciting topic of Quantum Cryptography in a relaxed and stimulating atmosphere. Special emphasis will be put on practical quantum cryptography system design.
- Dates:** ► Monday February 8 to Thursday February 11, 2010
(Arrival on Sunday afternoon and departure on Friday morning.)
- Location:** ► Les Diablerets in the Swiss Alps
- Price:** ► EURO 2'900.- per participant
(This amount includes board and accommodation, course participation, teaching materials, and recreational activities. It does not include travel to and from Les Diablerets.)
- More:** ► www.idquantique.com/products/academy.htm

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www.idquantique.com