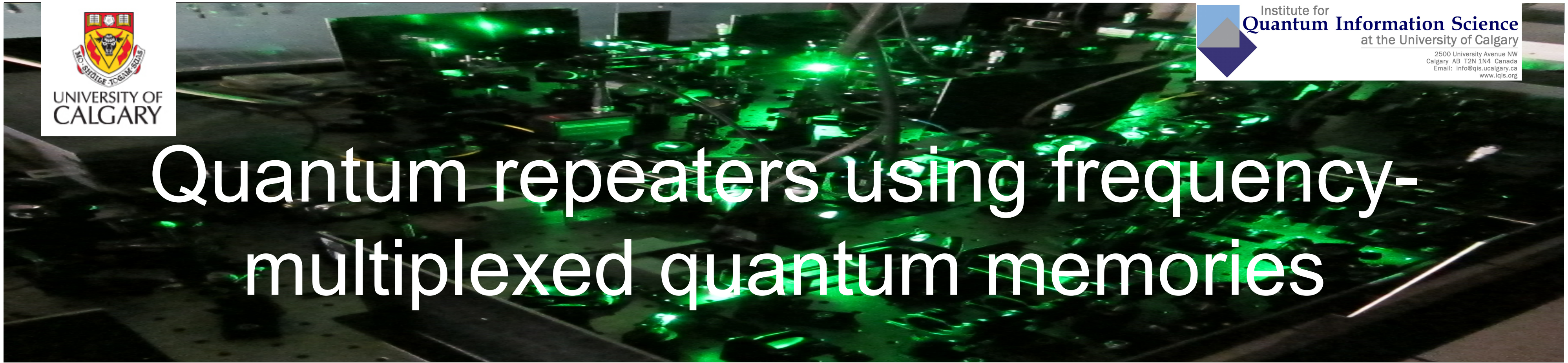

Quantum repeaters using frequency-multiplexed quantum memories

E. Saglamyurek[1], N. Sinclair[1], H. Mallahzadeh[1], J. Jin[1], J. Slater[1], D. Oblak[1], F. Bussières[1*], M. George[2], R. Ricken[2], W. Sohler[2], and W. Tittel[1]

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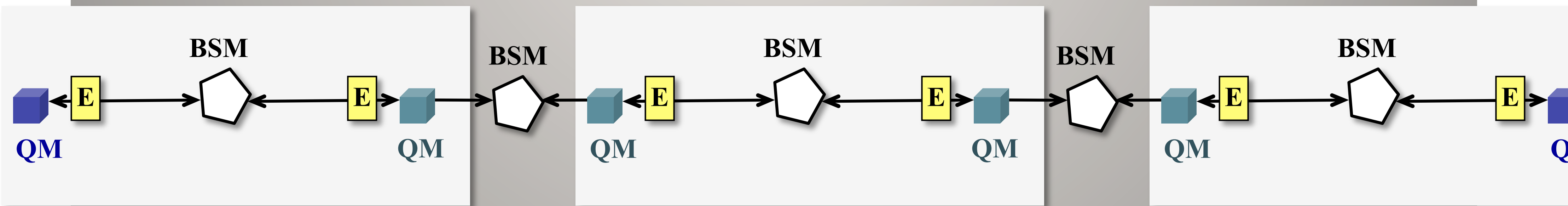

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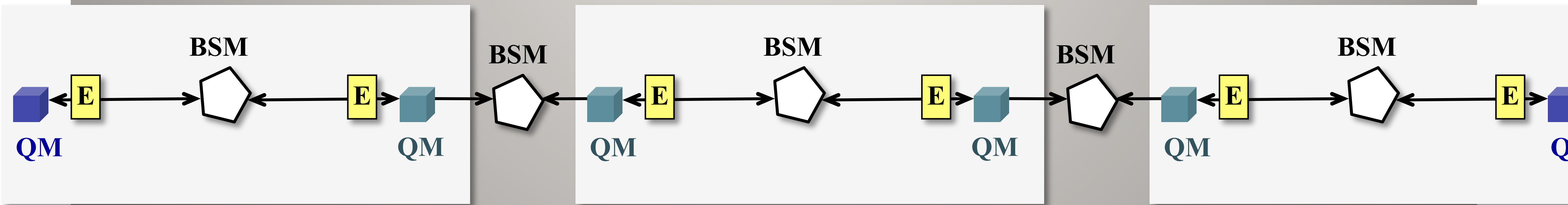
Quantum repeaters using frequency-multiplexed quantum memories

- Photon-echo quantum memory (AFC) in RE crystals
- Broadband waveguide quantum memory for entangled photon
- Multi-mode storage and read-out on demand in frequency space
- Conclusion



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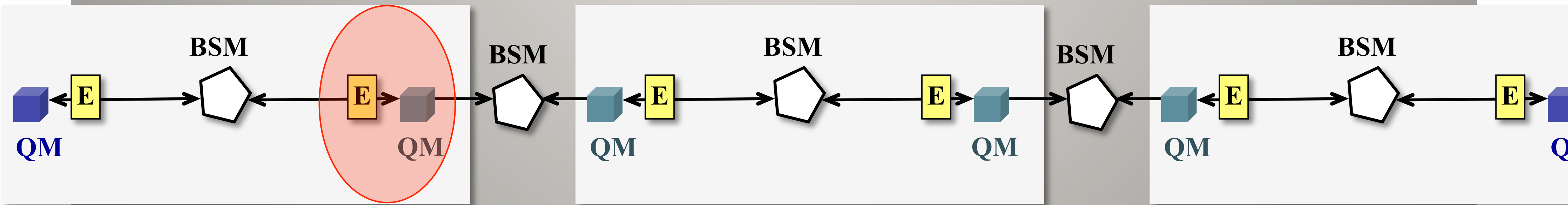

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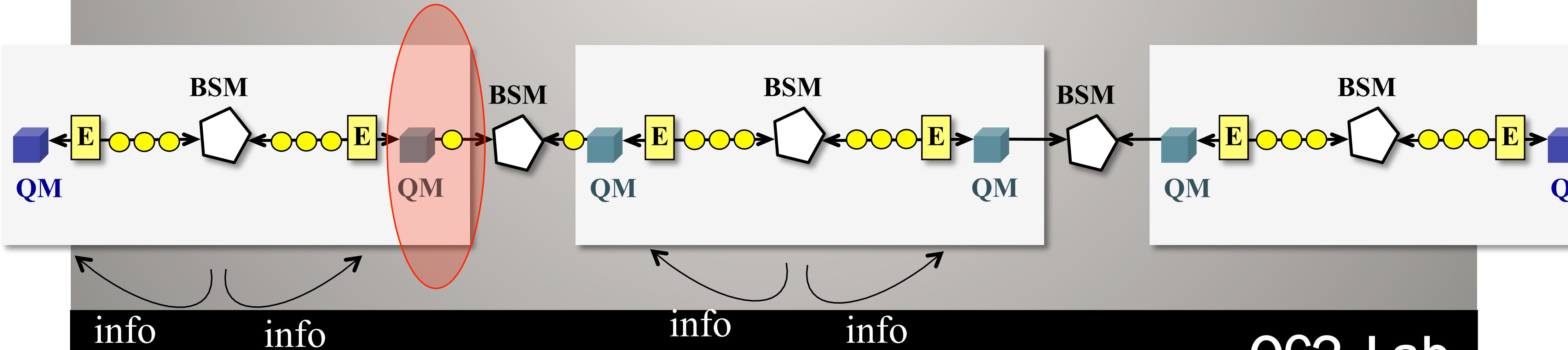
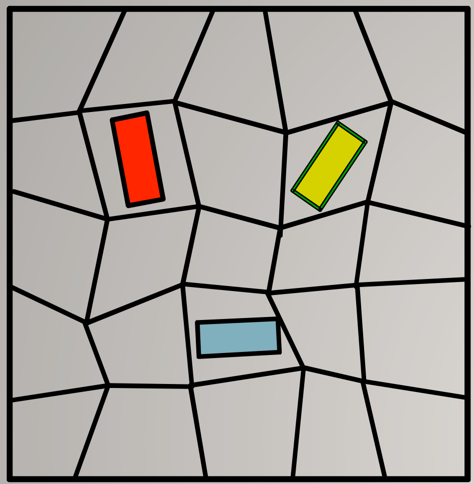
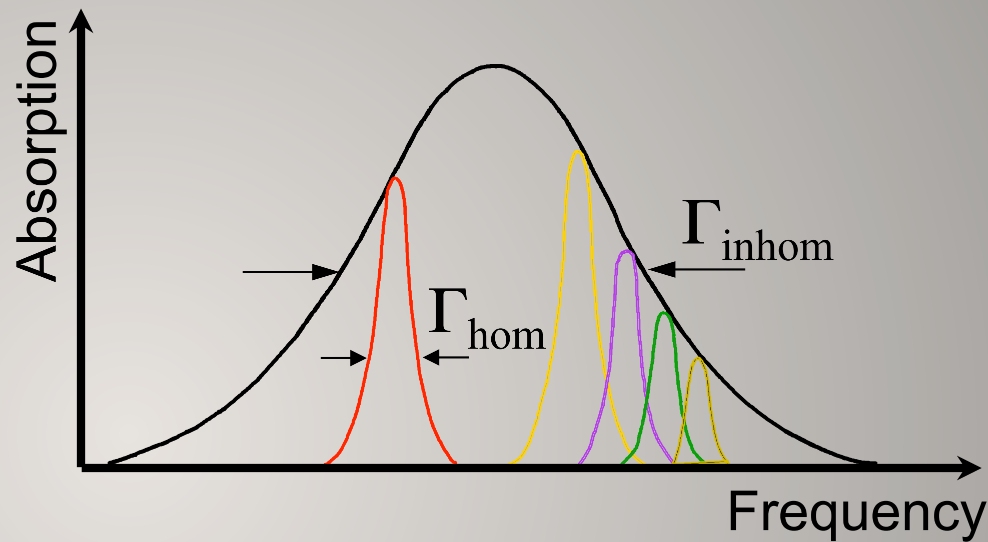


Rare-earth-ion doped crystals





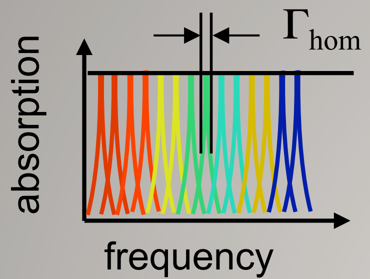
Stress and defects → Inhomogeneous broadening

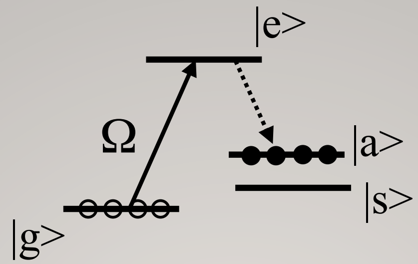
- naturally trapped emitters with free atom - like spectra
- transitions in the visible and at telecom wavelength
- at 4 K: $\Gamma_{hom} \approx$ 50 Hz – 100 kHz, T_2 up to 4 ms
- ground state coherence up to 30 s
- $\Gamma_{inhom} \approx$ 500 MHz – 500 GHz

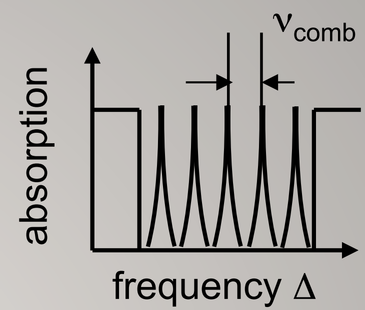
-> capacity for long-term storage over large spectral width

Photon-echo quantum memory (AFC)

1. Preparation of an atomic frequency comb







2. Absorption of a photon -> fast dephasing

$$\left|\psi\right\rangle = \frac{1}{\sqrt{N}} \sum_{j=1}^{N} c_j e^{-i2\pi\Delta_j t} e^{ikz_j} \left| g_1 \dots e_j \dots g_N \right\rangle$$

3. Phase matching $\phi(z) = -2kz$ enables backwards recall

4. Rephasing at $t_R = 1/\nu_{comb}$ with $2\pi\Delta_j t_R = m\, 2\pi$

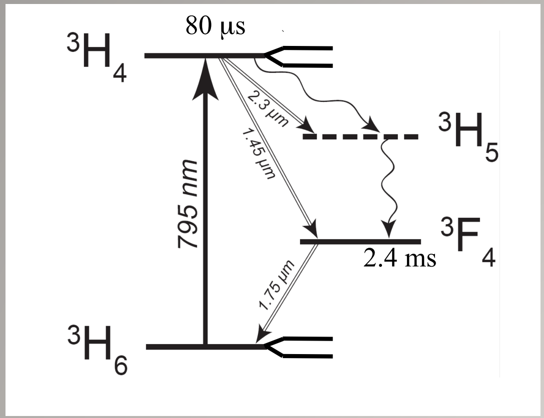
5. Reversible mapping of optical coherence onto spin coherence allows recall on demand

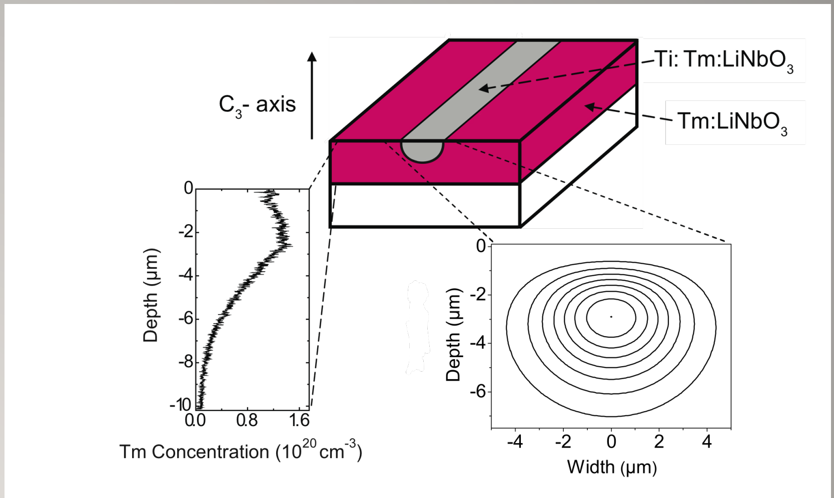
Experiments: Geneva, Lund, Paris, Calgary, Barcelona, Hefei

-> Reemission of light with unity efficiency and fidelity, very good broadband and multi-mode storage capacity

Hesselink *et al.*, PRL (1979); Afzelius *et al.*, PRA (2009); De Riedmatten *et al.*, Nature. (2008); Afzelius *et al.*, PRL (2010), Bonarota *et al.*, New J. Phys 2011.

Ti:Tm:LiNbO$_3$ waveguides





<u>Thulium</u>

- 795 nm zero-phonon absorption line, Γ_{hom} ~200 kHz @3K
- large, polarization and wavelength dependent optical depth (α~2.2/cm @ 3K & 795.5 nm)
- $T_1(^3H_4)$=80 μs
- optical pumping into magnetic ground-state sublevels (T_1~sec @ B=150G & T=3K)

<u>LiNbO$_3$</u>:

- (no inversion symmetry -> Stark shifting of resonance lines (for CRIB quantum memory))
- “telecommunication” material, waveguide fabrication well mastered

<u>Waveguide</u>

- large Rabi frequencies
- (fast switching of large electric fields using closely spaced electrodes (for CRIB quantum memory))
- simplified integration with fibre optic components and into networks

N. Sinclair, WT *et al.*, J. Lumin. (2010), C. Thiel *et al.*, J. Lumin. (2010)

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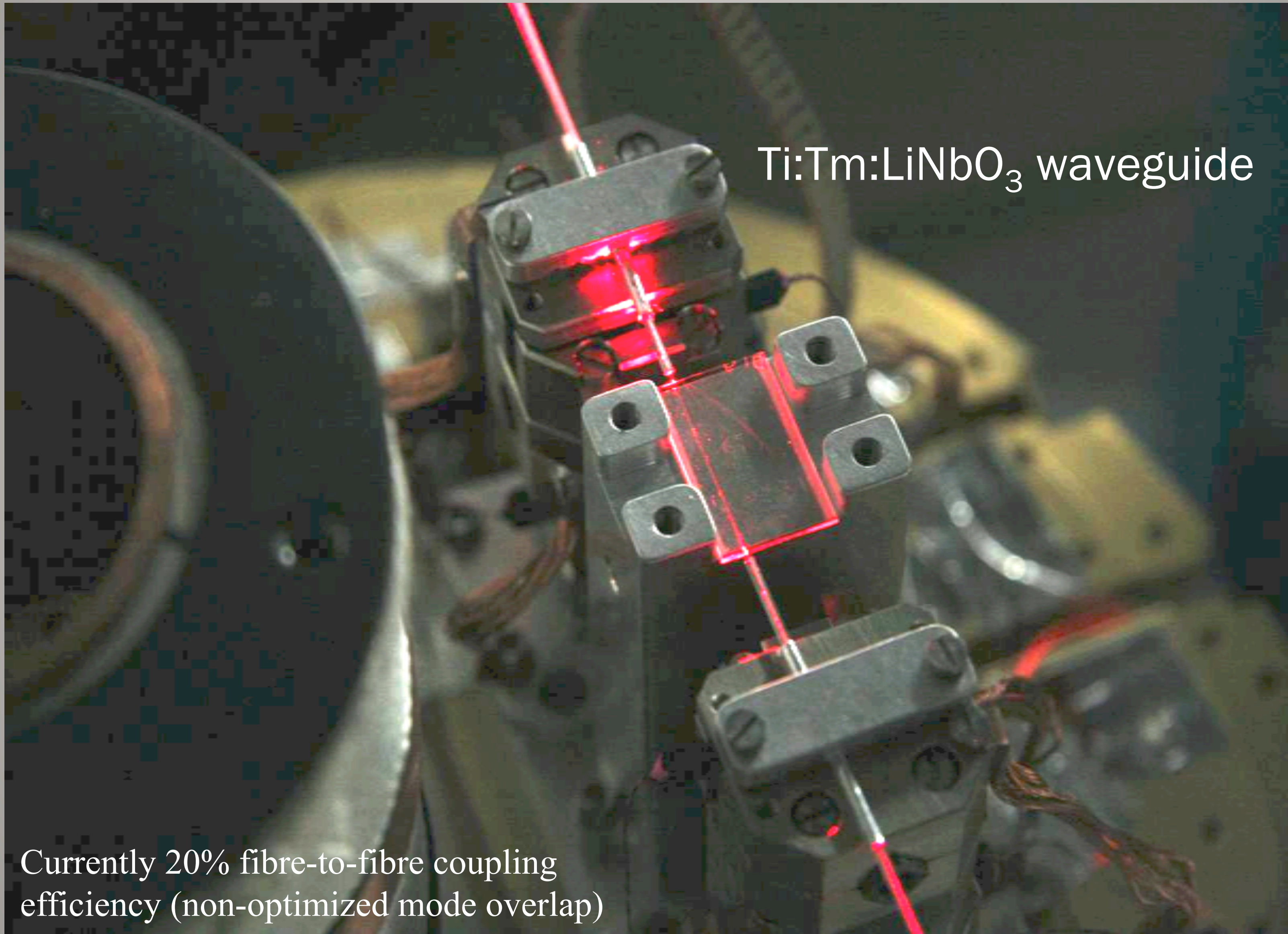
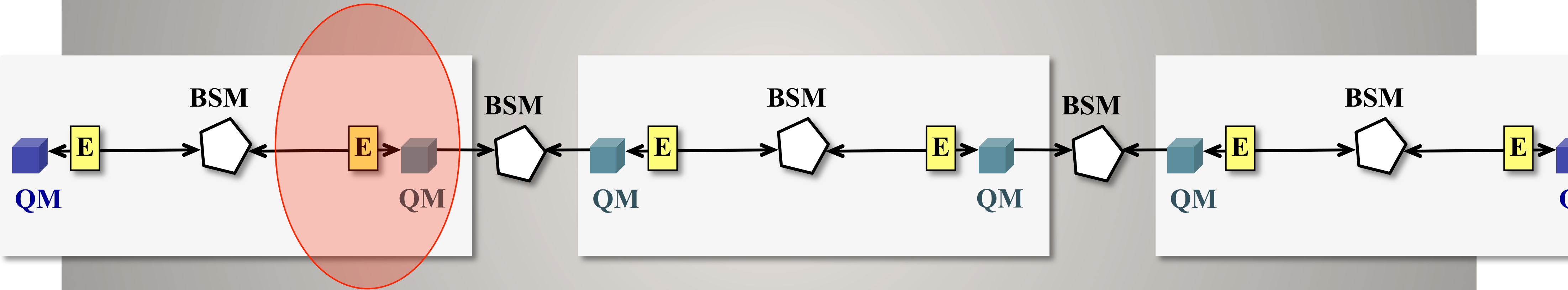
Waveguide quantum memory



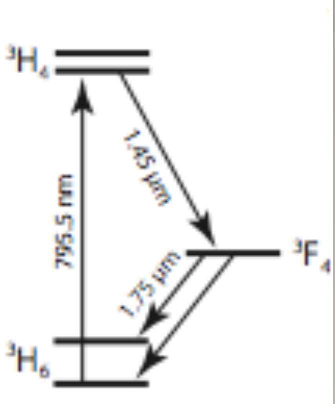
Broadband waveguide quantum memory for entangled photons

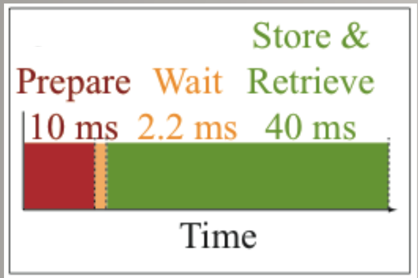


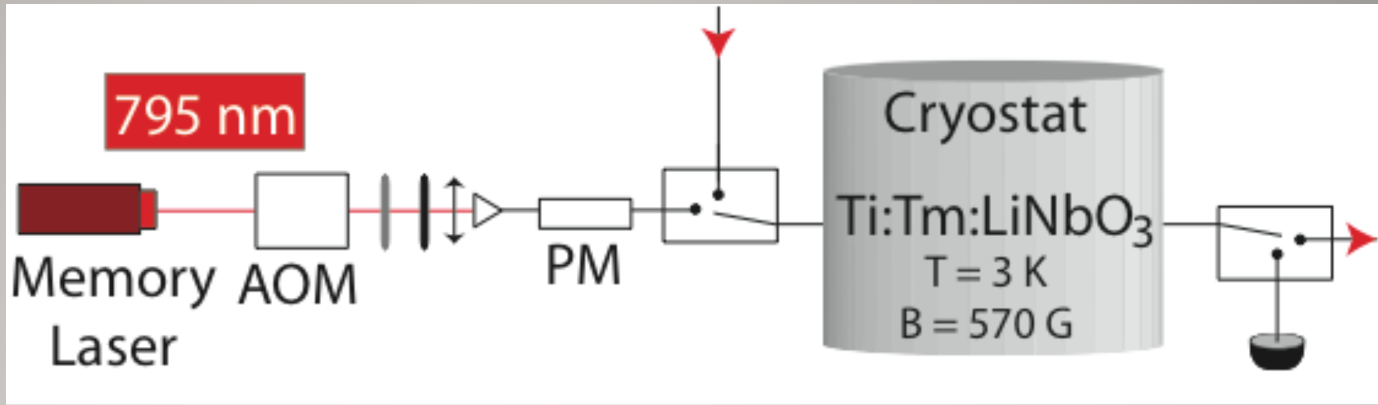
challenge: match bandwidth of entangled photons with memory

Briegel *et al*., Phys. Rev. Lett (1998); Hammerer *et al.*, Rev. Mod. Phys (2010); Simon *et al*. Rev. Mod. Phys. (2011)

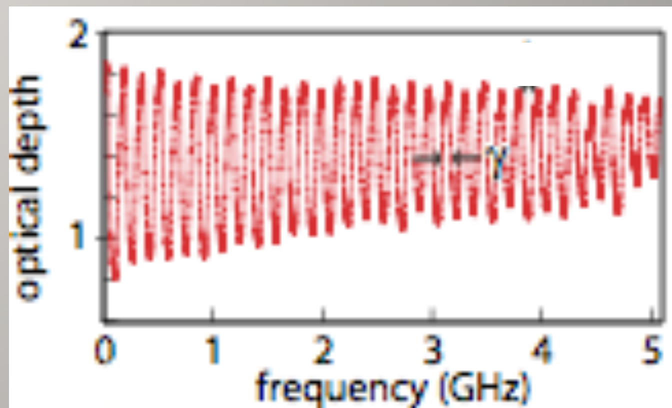
The memory setup







$$\eta = e^{-d_1/F}\left(\frac{d_1}{F}\right)^2 e^{-7/F^2} e^{-d_0}$$

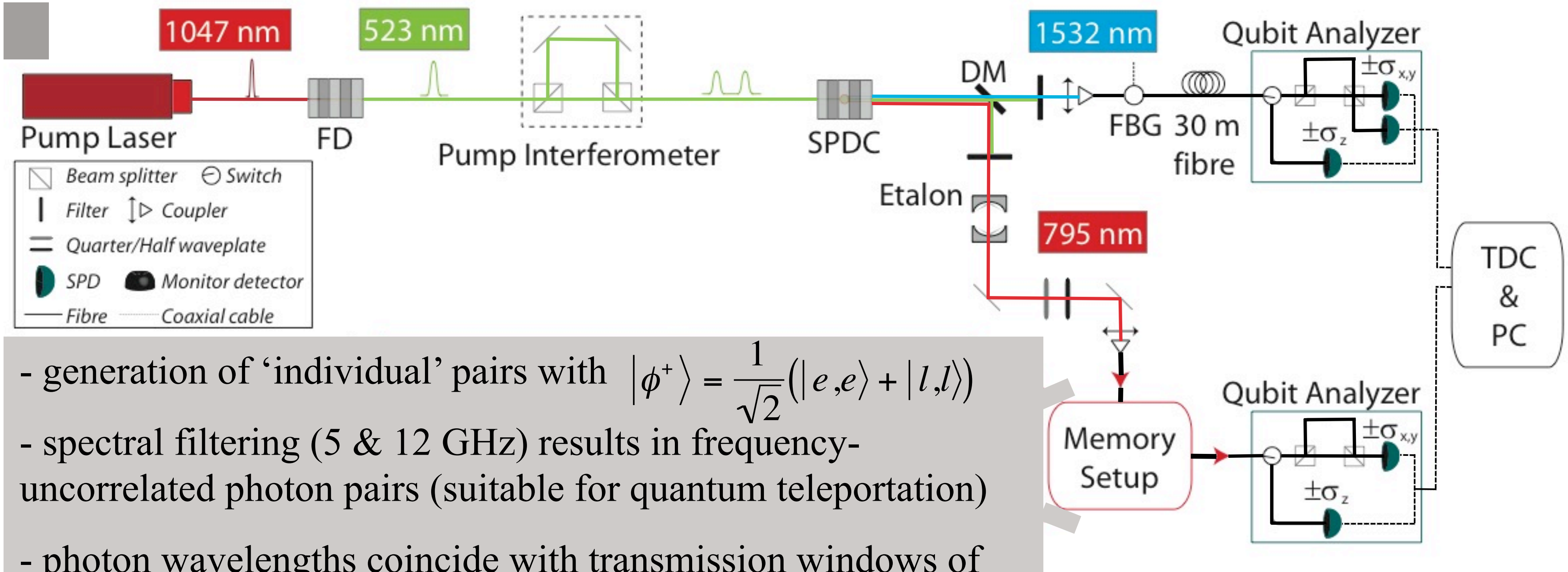


-5 GHz broad grating, generated via laser sideband chirping

-146 MHz tooth separation -> 7 ns storage time

- total system efficiency 0.2% (coupling loss, Finesse of two, sinusoidal AFC, non-uniform AFC, etc.)

Broadband waveguide quantum memory for entangled photons: schematics



- generation of 'individual' pairs with $|\phi^{+}\rangle = \frac{1}{\sqrt{2}}(|e,e\rangle + |l,l\rangle)$

- spectral filtering (5 & 12 GHz) results in frequency-uncorrelated photon pairs (suitable for quantum teleportation)

- photon wavelengths coincide with transmission windows of free-space and telecom fibres

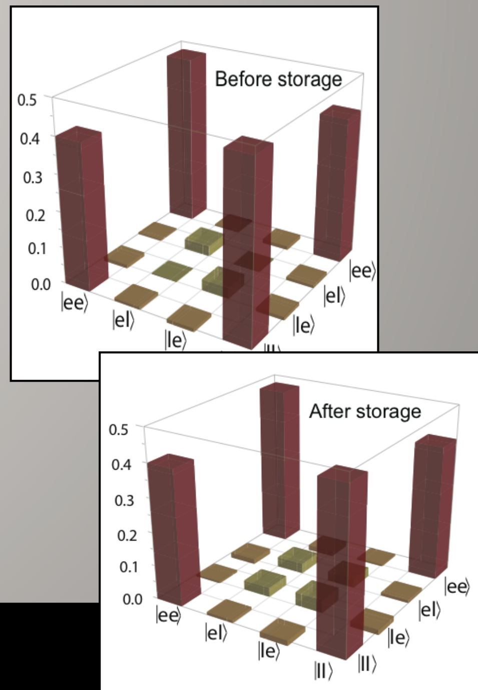
- qubit analyzers allow projections onto superpositions of |e> and |l>

- measurement without and with memory -> ρ_{in}, ρ_{out}

Storing one out of two entangled photons

	Entanglement of formation	Input-Output Fidelity	Purity	Fidelity with $\lvert\phi^{+}\rangle$	CHSH-Bell parameter S
ρ_{in}	0.644±0.042	0.954±0.029	0.757±0.024	0.862±0.015	2.379±0.034
ρ_{out}	0.65±0.11		0.763±0.059	0.866±0.039	2.25±0.06

- no measurable degradation of (post-selected) entanglement during storage
- a small unitary transformation
- initial (and recalled) state have limited purity and fidelity with target
- experimental violation of CHSH Bell inequality ($S_{LHV} \leq 2$)



E. Saglamyurek, WT *et al.*, Nature (2011). Clausen *et al.*, Nature (2011)

Storing one out of two entangled photons

	Entanglement of formation	Input-Output Fidelity	Purity	Fidelity with $\lvert\phi^{+}\rangle$	CHSH-Bell parameter S
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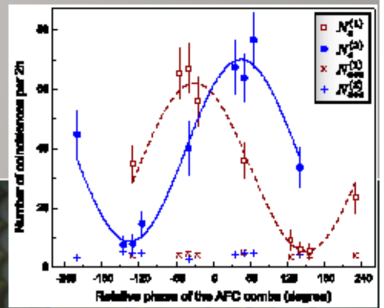
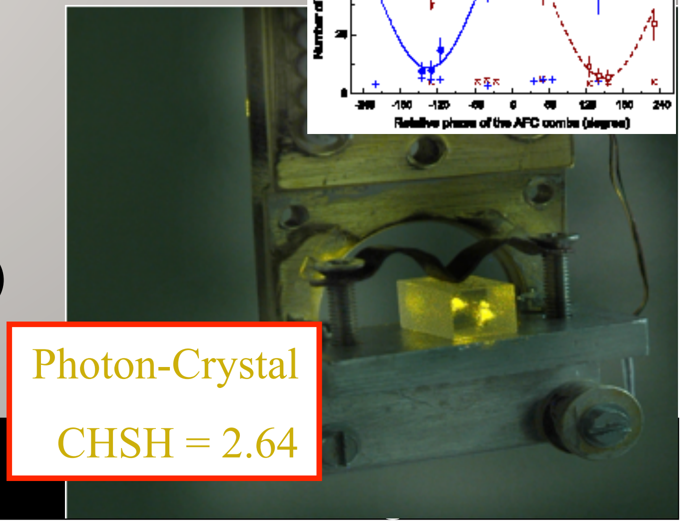
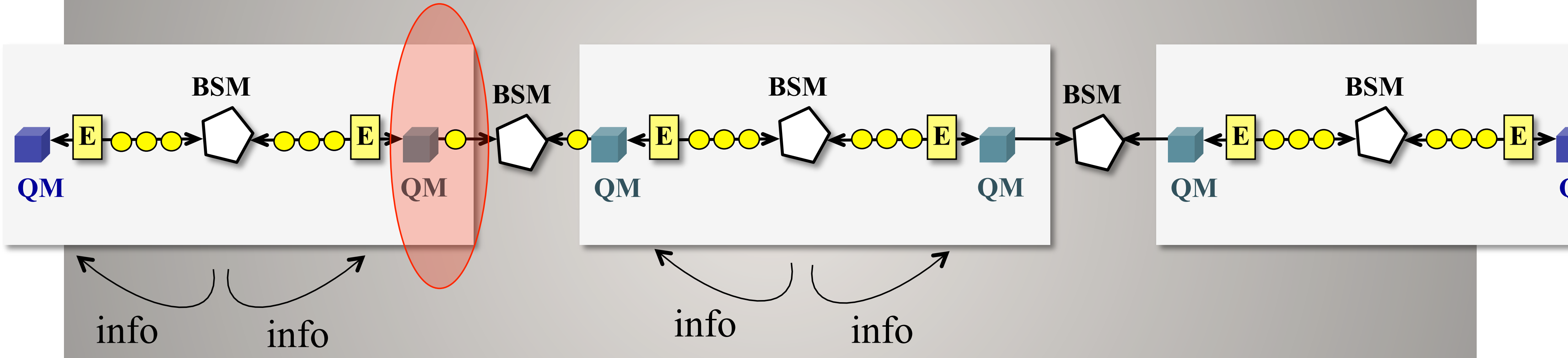
- a small unitary transformation
- initial (and recalled) state have limited purity and fidelity with target
- experimental violation of CHSH Bell inequality ($S_{LHV} \leq 2$)
- similar results in the Gisin group



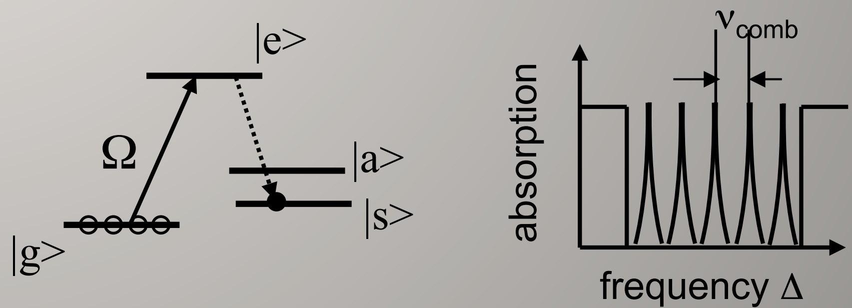


E. Saglamyurek, WT *et al.*, Nature (2011). Clausen *et al.*, Nature (2011)

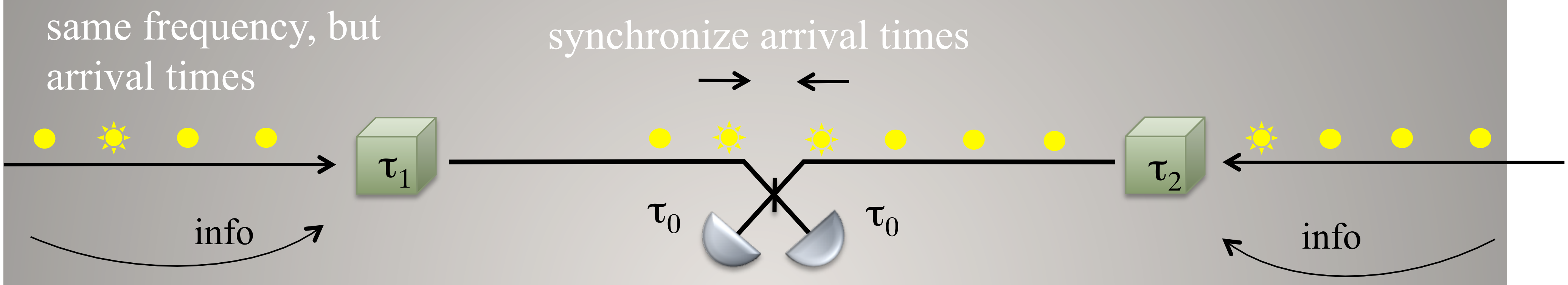
Multi-mode storage and read-out on demand



- AFC QM allows read-out on demand in the temporal domain via coherence transfer
- additional benefit: long storage times
- feasible, but challenging



Multi-mode quantum repeater: temporal versus frequency modes



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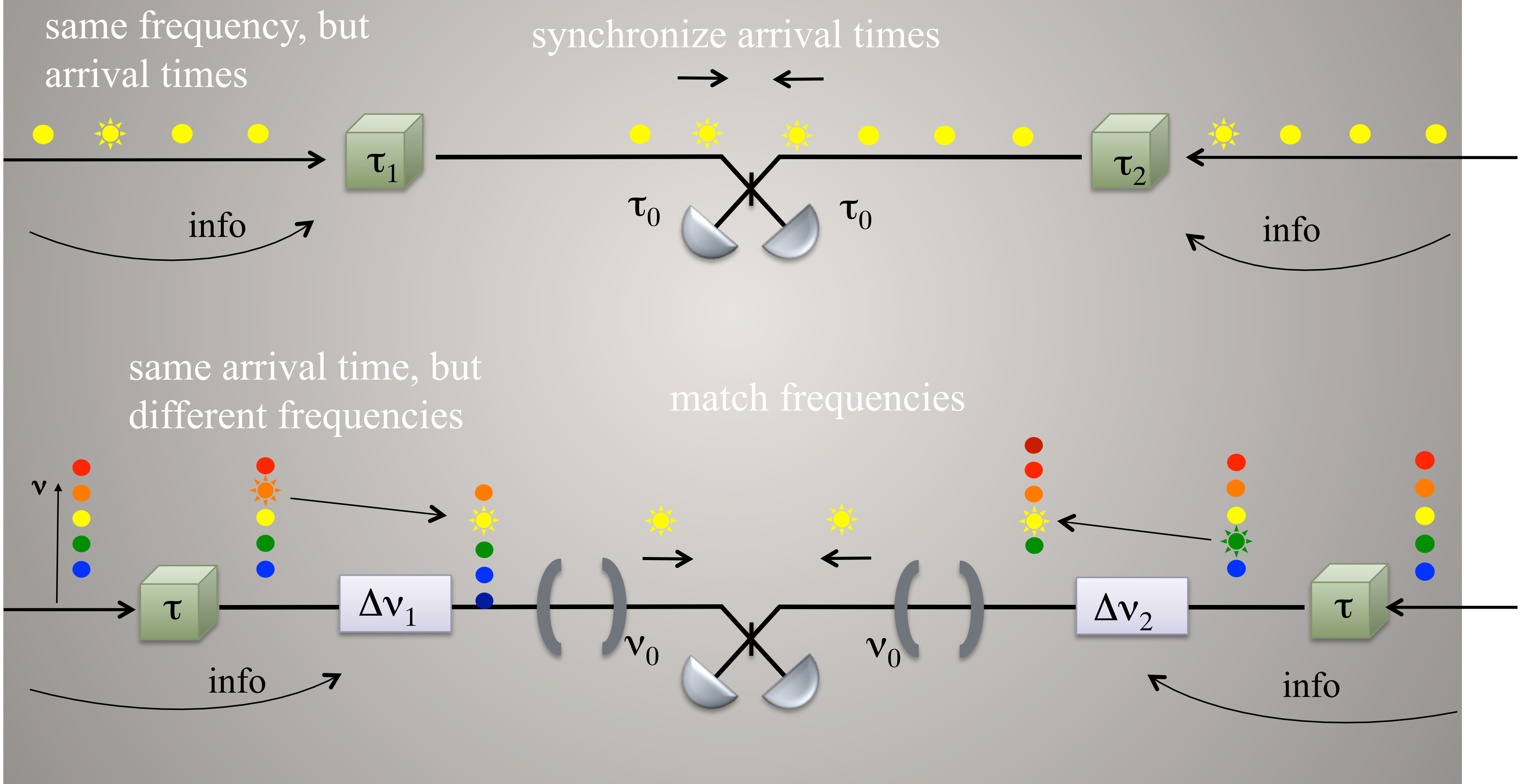
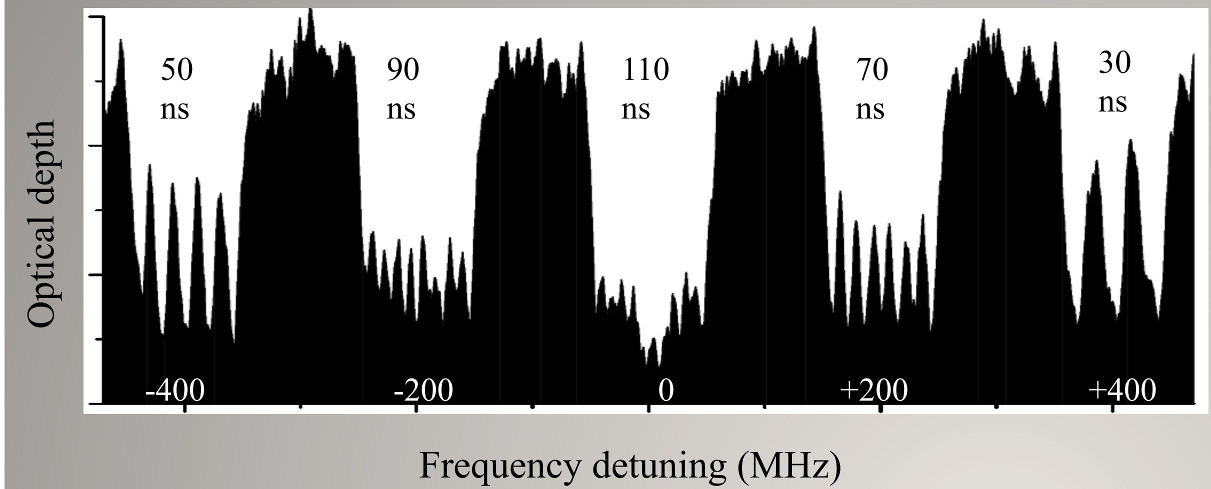
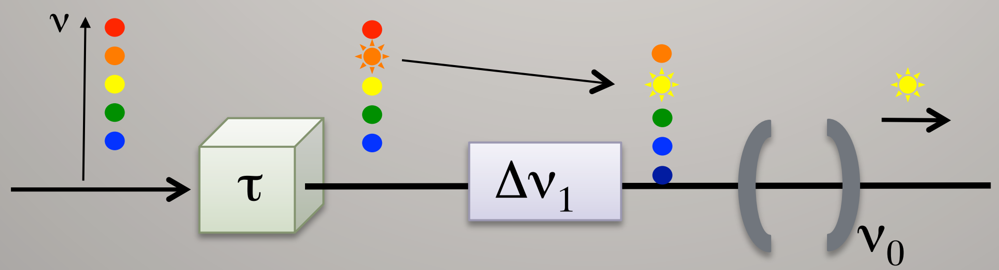


Multi-mode storage in 100 MHz wide frequency bins



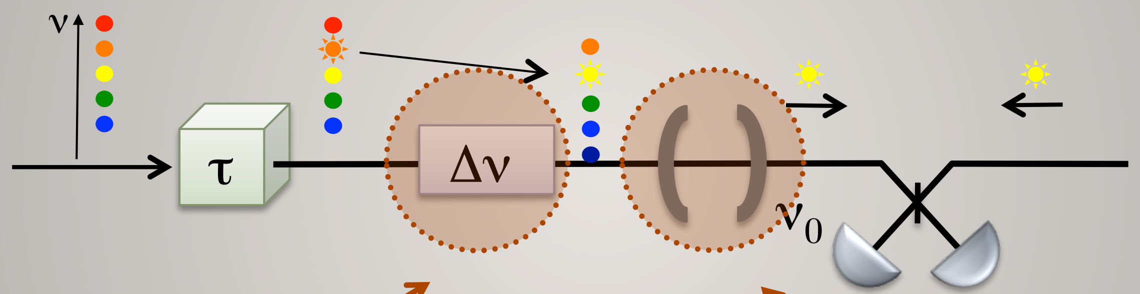
(coupling of frequency to different storage times for simplified characterization)

- AFC quantum memory in $Tm{:}LiNbO_3$ is perfectly suited for frequency multiplexing (Γ_{inh}=300 GHz)
- generation of ten, 100 MHz wide frequency bins and simultaneous storage of 10 ns long attenuated laser pulses at respective frequencies
- recall followed by frequency shifting and filtering at reference frequency ν_0



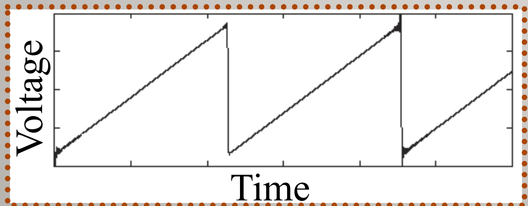
Multi-mode storage and read-out on demand in frequency space

Quantum memory is supplemented with phase modulator and cavity for on-demand frequency selective read-out



$\Delta\nu$ = 84 MHz
FSR = 23 GHz

+

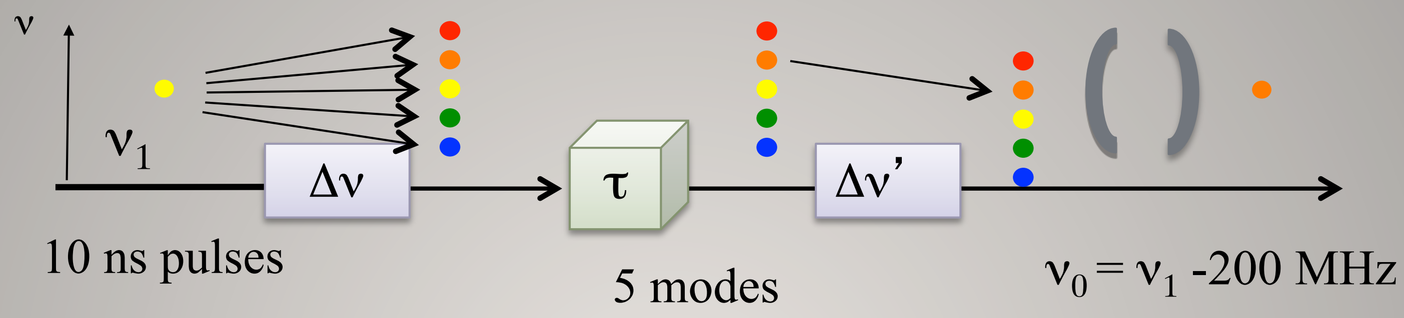


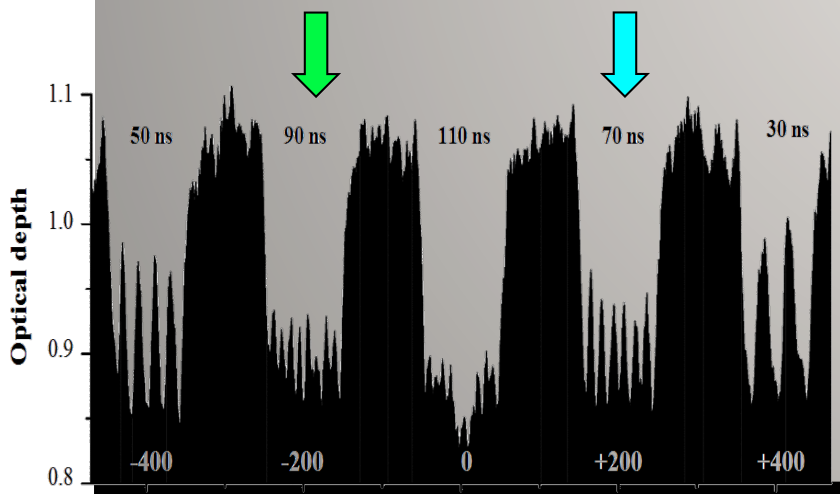
Efficient serrodyne frequency shifting

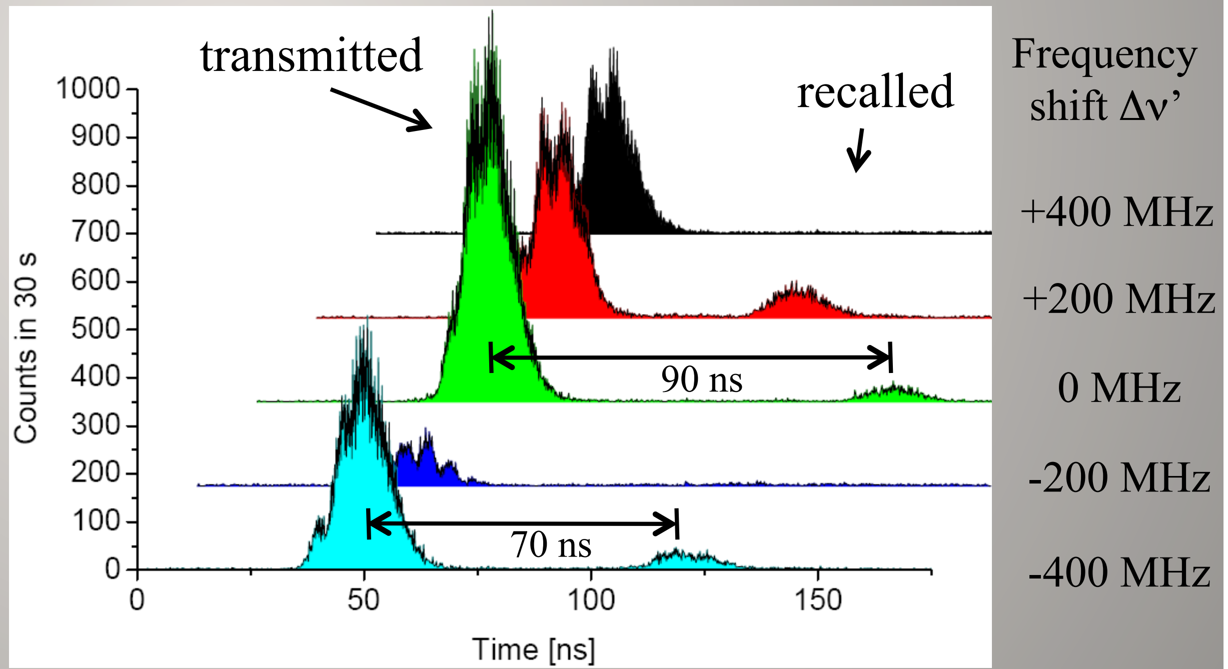
We use a stable monolithic cavity for frequency filtering

Johnson et al., Opt. Lett (2009); Palittapongarnpim et al., Rev. Sci. Instrum. (2012).

Multi-mode storage and on-demand frequency selective recall







-> (almost) only desired mode is recalled

N. Sinclair, WT et al. (manuscript in preparation).

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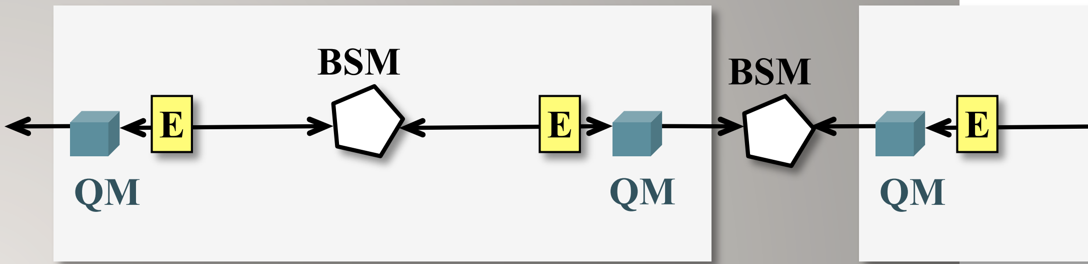
Conclusion

- **AFC quantum memory** stands out through its **large bandwidth and MM capacity**
- Demonstration of
  - **entanglement storage**
  - **MM storage & recall on demand**
  - **real-world Bell-state measurement (talk by J. Slater on MDI-QKD)**



- Provided storage efficiency can be increased (using impendence matched cavity), this allows memory-enhanced linear optics QIP
- For quantum repeater, storage times in excess of 100 μsec will be required (coherence-transfer to long-lived ground states)


PhD and PDF positions available (email to wtittel@ucalgary.ca)
Thank you
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Prof. W. Sohler
Canada Foundation for Innovation
Fondation canadienne pour l'innovation
NSERC
CRSNG
Les Fiducies
Killam
Trusts
Alberta
Advanced Education and Technology
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