

Towards practical quantum repeaters

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Overview

Quantum repeaters: motivation and principle

Repeaters with atomic ensembles

Multimode quantum memories

Repeaters with trapped ions

Outlook

Long-distance quantum communication

Fundamental motivation (how far can one stretch entanglement?), but also important for quantum cryptography, quantum networks.

Big problem: transmission losses

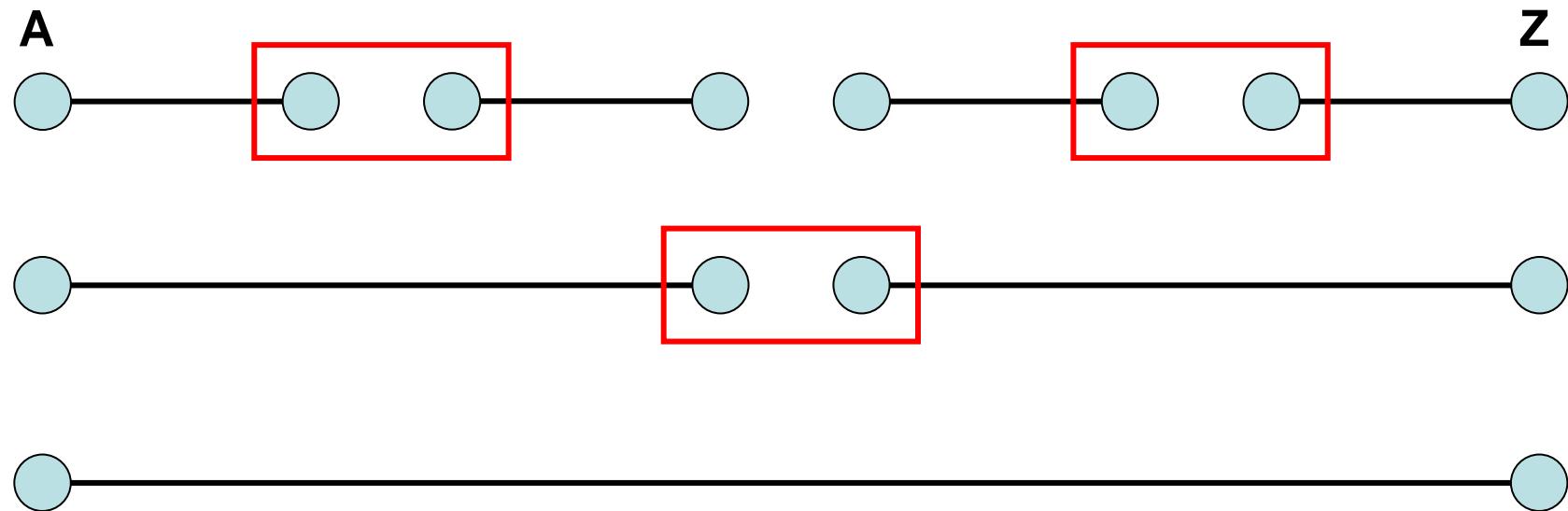
1000 km of fiber at optimal wavelength – transmission **10^{-17}** .

3 years to distribute one entangled pair with 1 GHz source!

Straightforward amplification impossible (**no-cloning theorem**).

Potential solution: quantum repeaters.

Quantum Repeater - Principle



Create entanglement **independently** for each link. Extend by swapping.

n links with transmission t each

Direct transmission $T \sim \frac{1}{t^n}$

H.-J. Briegel et al.,
PRL 81, 5932 (1998)

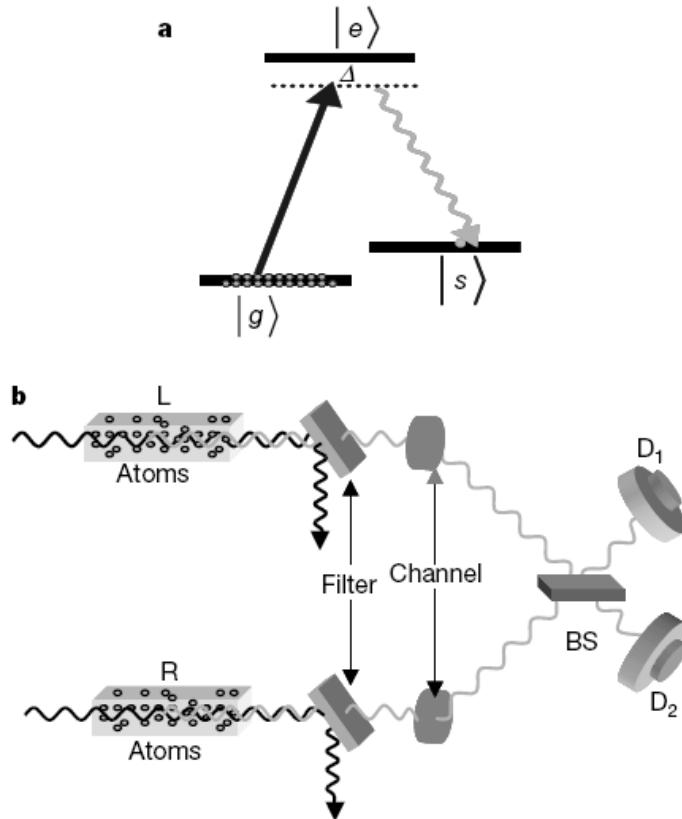
Repeater $T \sim \frac{1}{t}$

Requires heralded creation, storage and swapping of entanglement.

The DLCZ scheme: atomic ensembles and linear optics

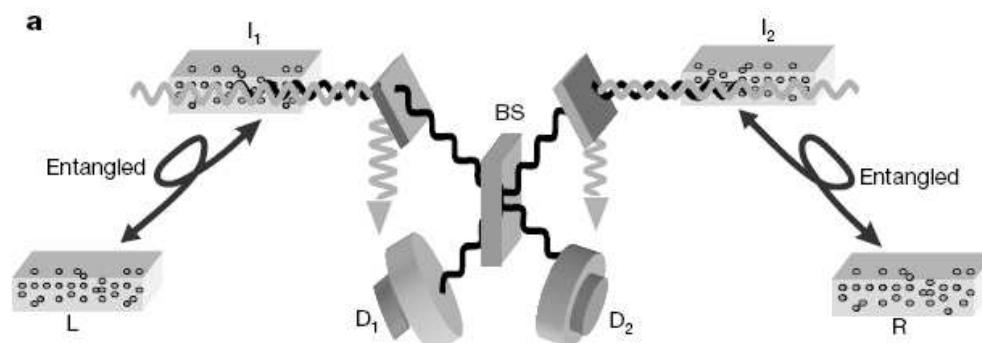
NATURE | VOL 414 | 22 NOVEMBER 2001 | www.nature.com

DLCZ = Duan, Lukin, Cirac, Zoller



Entanglement creation through single photon detection.

Entanglement swapping through efficient reconversion of memory excitation into photon



Improved repeaters with ensembles and linear optics

Entanglement swapping via two-photon detections

Jiang, Taylor, Lukin, PRA 76, 012301 (2007)

Entanglement generation via two-photon detections

Zhao et al, PRL 98, 240502 (2007); Chen et al, PRA 76, 022329 (2007)

Spatial multiplexing

Collins et al, PRL 98, 060502 (2007).

Photon pair sources and temporal multimode memories

Simon et al, PRL 98, 190503 (2007).

Single-photon source based protocol

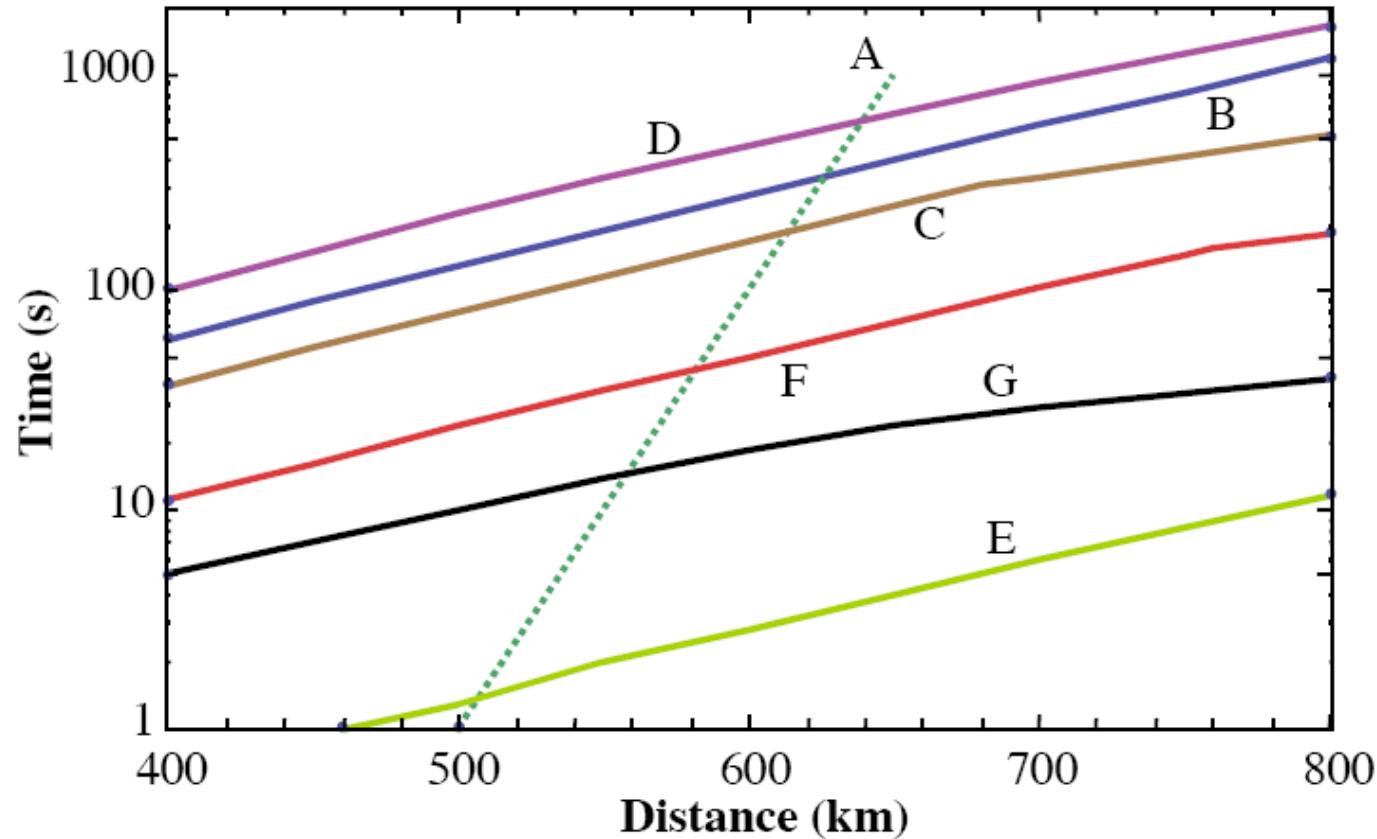
Sangouard et al, PRA 76, 050301(R) (2007)

Local generation of entangled pairs plus two-photon detections

Sangouard et al, PRA 77, 062301 (2008).

Review: N. Sangouard, C. Simon, H. de Riedmatten, N. Gisin, arXiv:0906.2699

Comparison of repeaters with ensembles and linear optics

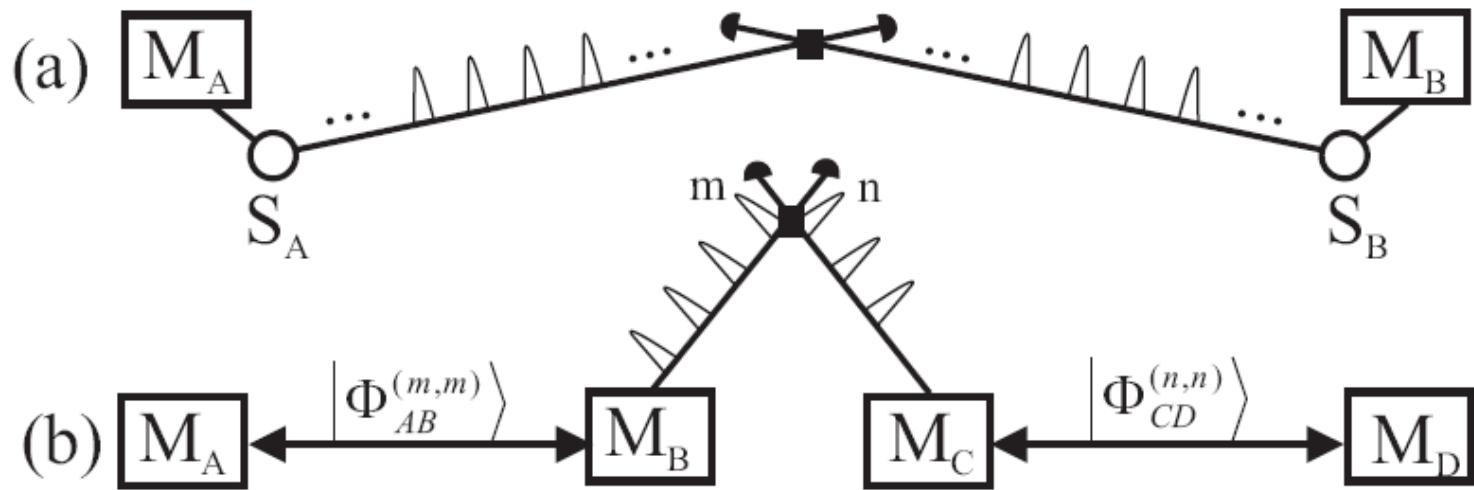


N. Sangouard,
C. Simon,
H. de
Riedmatten,
N. Gisin,
arXiv:0906.2699

Assuming 90% memory and detection efficiency.

Multiplexing is very attractive.

Repeaters with photon pair sources and multi-mode memories



Memories that are able to store and recall trains of N pulses.

N entanglement creation attempts per waiting time interval $L0/c$.

Speedup by factor of N

C. Simon et al, PRL 98, 190503 (2007).

Temporal multi-mode memories

Standard Photon Echo: thousands of modes, but not a quantum memory!

J. Ruggiero, J.L. Le Gouet, C. Simon, T. Chaneliere, PRA 79, 053851 (2009)

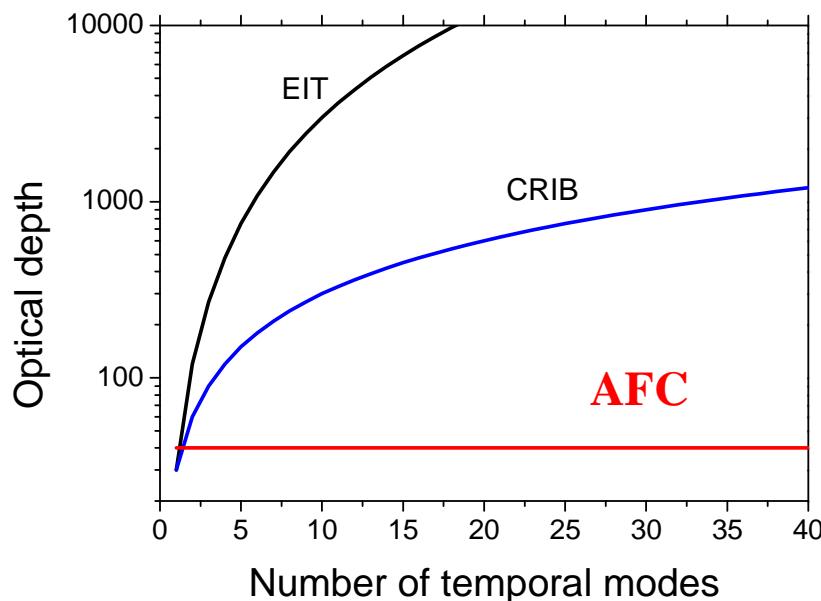
Stopped light (EIT): M.D. Lukin, RMP 75, 457 (2003) $N \propto \sqrt{d}$

Controlled Reversible Inhomogeneous Broadening (CRIB):

B. Kraus et al., PRA 73, 020302 (2006); C. Simon et al, PRL 98, 190503 (2007) $N=d/30$

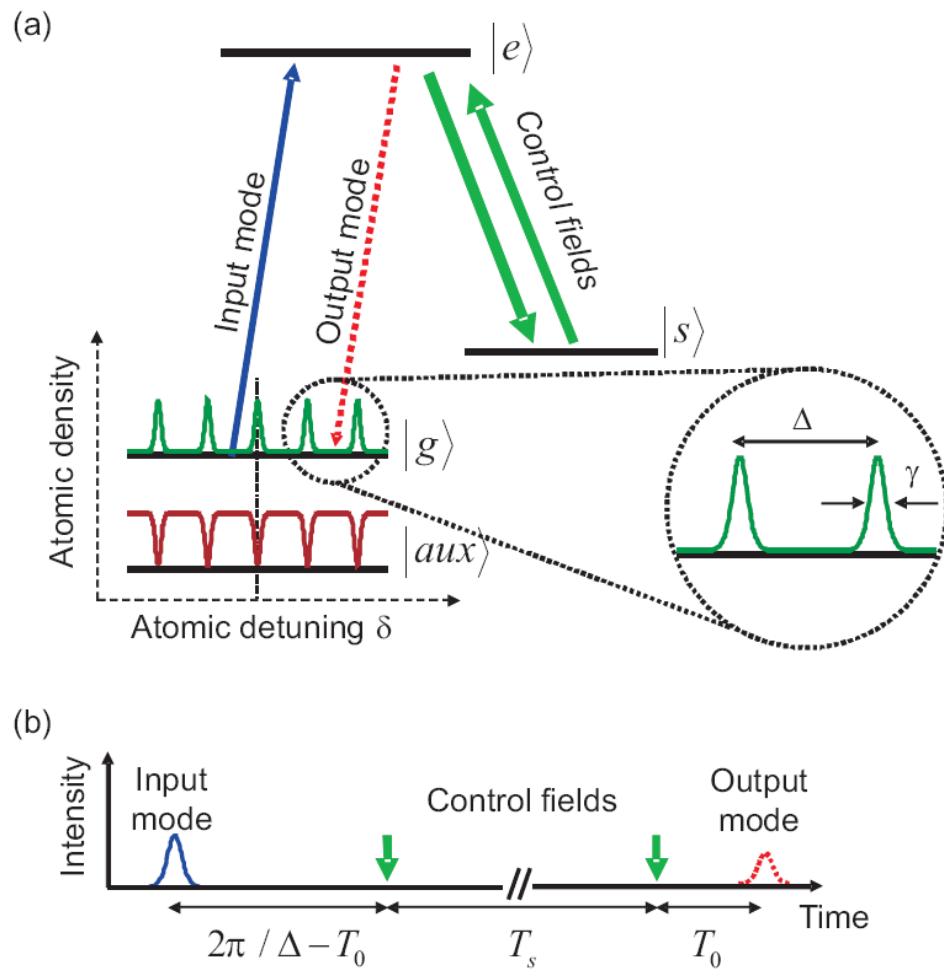
Atomic frequency comb protocol: N independent of d .

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



cf. J. Nunn et al.,
PRL 101, 260502
(2008).

Atomic Frequency Comb Quantum Memory



Designed for rare-earth ion doped crystals with **static inhomogeneous broadening**.
(e.g. Eu:Y₂SiO₅)

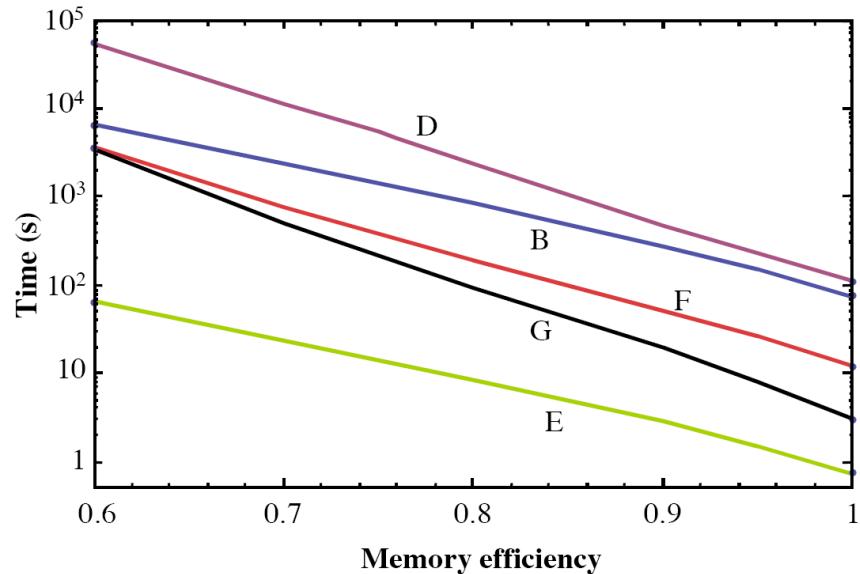
Sellars (ANU): EIT over 1 s, CRIB over 60 % efficiency with RE doped crystals

AFC promises efficient storage of **hundreds of temporal modes on seconds timescale**.

Nicolas Gisin on Thursday!

M. Afzelius, C. Simon, H. de Riedmatten, N. Gisin, PRA 79, 052329 (2009).
H. De Riedmatten et al., Nature 456, 773 (2008); M. Afzelius et al, arXiv:0908.2309.

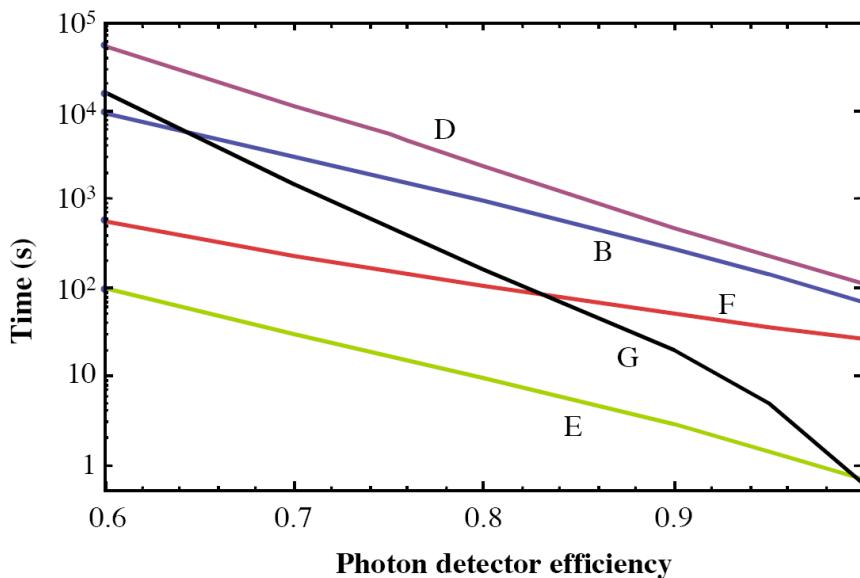
How good do memories and detectors have to be for repeaters?



1 percent drop in efficiency costs
7-19 percent in repeater rate

Status quo:

Memory efficiencies up to **50%**
for DLCZ (q) and EIT (cl) in atomic
gases, **60%** for CRIB (cl) in RE
doped solid.

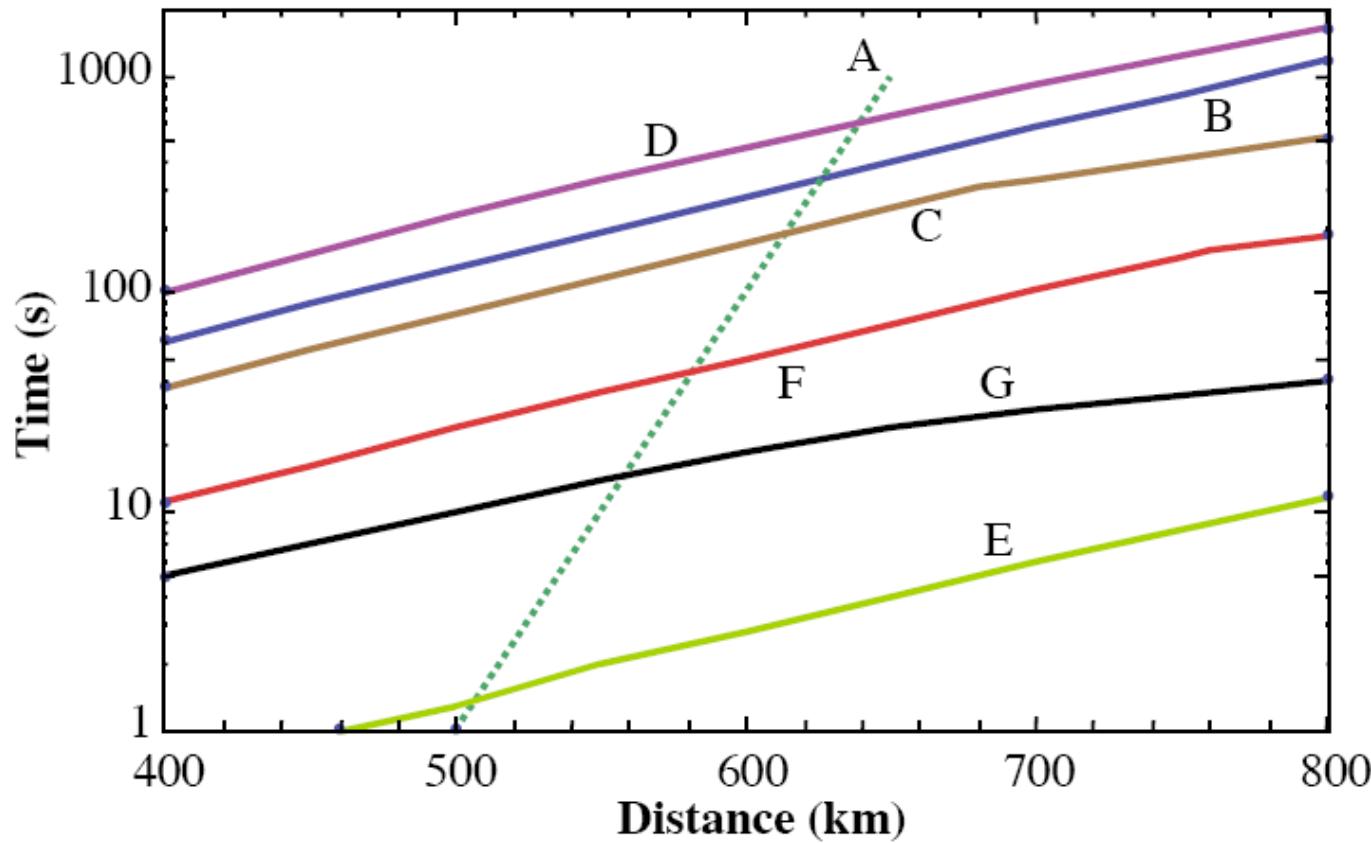


Overall detection efficiency 95%
(transition edge sensors)
A.E. Lita, A.J. Miller, S.W. Nam,
Opt. Exp. 16, 3032 (2008)

Reducing coupling losses
is essential!

N. Sangouard, C. Simon, H. de
Riedmatten, N. Gisin, arXiv:0906.2699

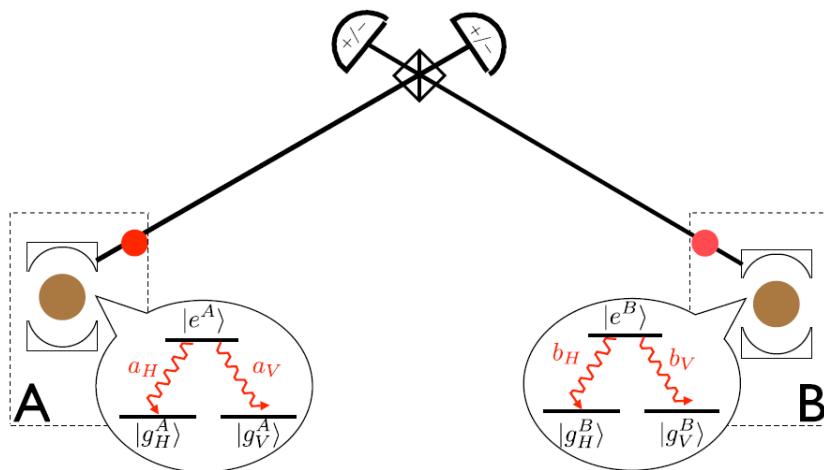
What about intercontinental entanglement?



Geneva – Calgary still seems out of reach.

Can we do better than multi-mode memories plus linear optics?

Repeaters with deterministic entanglement swapping



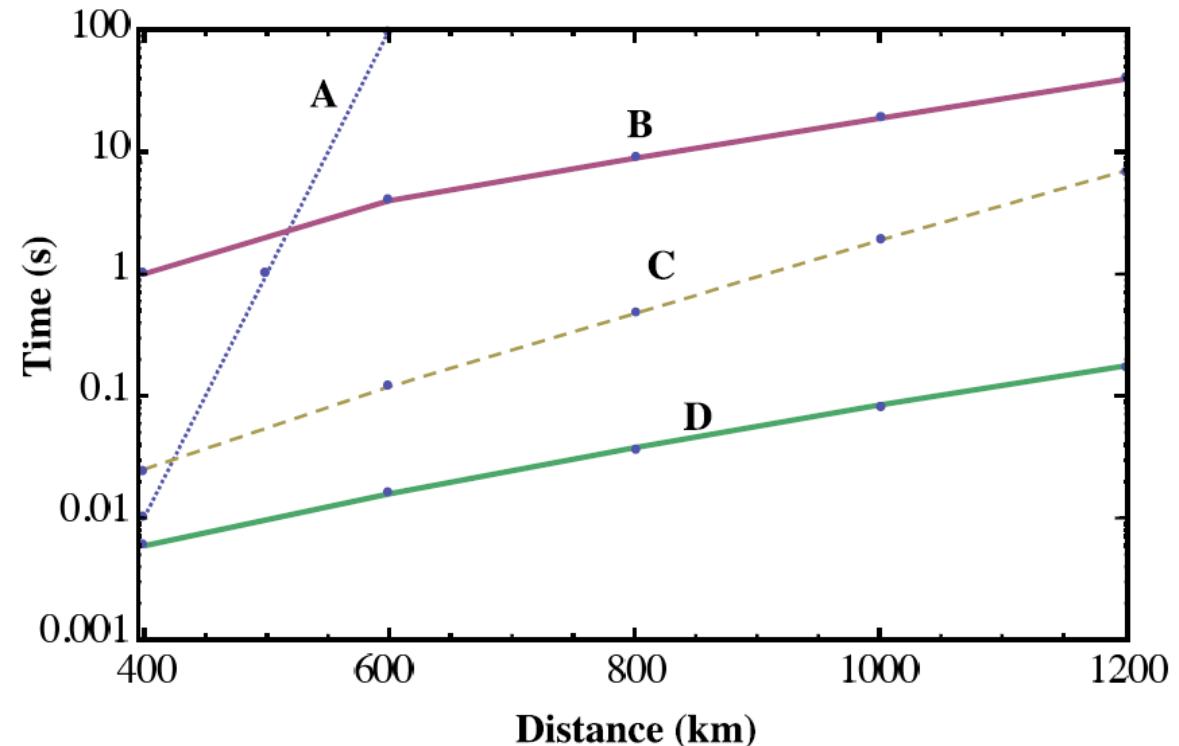
Repeaters with trapped ions.
N. Sangouard, R. Dubessy,
C. Simon, PRA 79, 042340 (2009)

Great gain in performance!

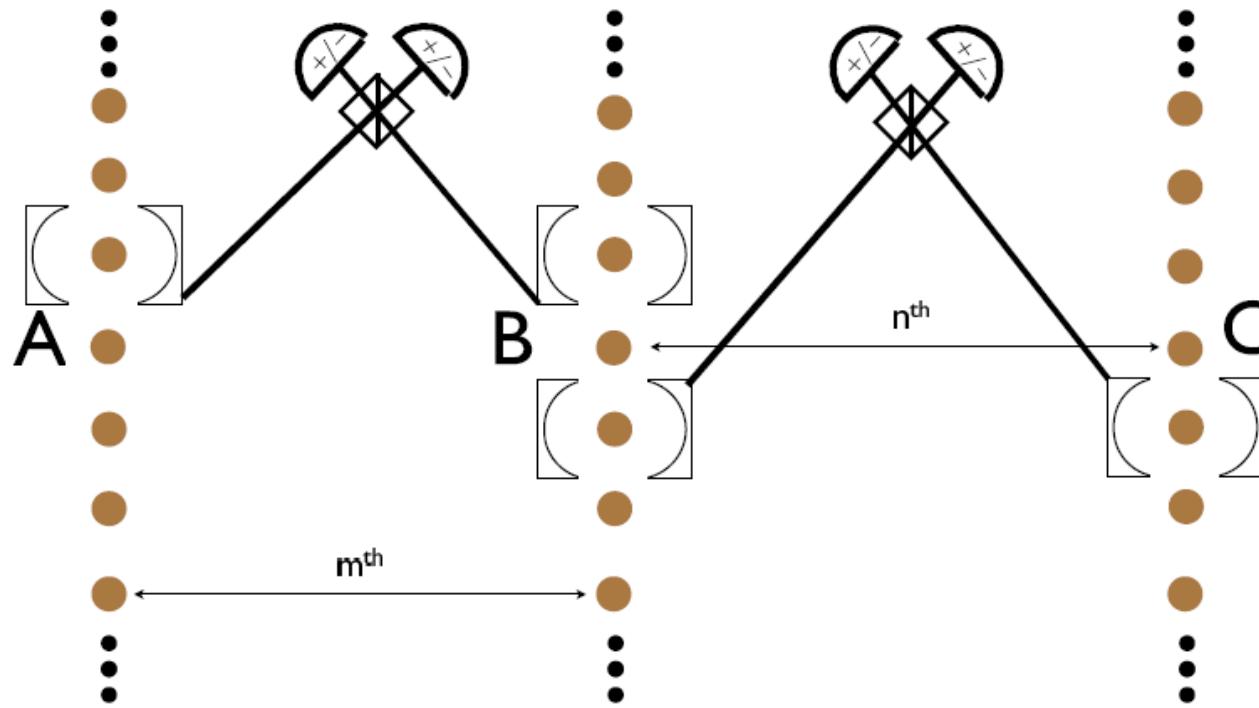
Quantum gates
with over 99% fidelity
(R. Blatt)

Ion-ion entanglement
(C. Monroe)

Efficient coupling to
cavity (R. Blatt)



Multiplexing based on ion chain transport



Straight-line transport is well developed for quantum computing applications.

N. Sangouard, R. Dubessy, C. Simon, PRA 79, 042340 (2009)

Outlook

Expect great progress on **multi-mode memories** with solid-state atomic ensembles (efficiency, number of modes). See also N. Gisin's talk!

Basic repeater demonstrations with such memories.

In-solid linear optical quantum information processing in these systems?

Deterministic entanglement swapping for **ensemble**-based memories?
(e.g. Rydberg states, continuous variables, ...)

Graduate student applications welcome!

Thanks to

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Hugo Zbinden

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Jean-Louis Le Gouet
Nicolas Sangouard

