29 Dec 2016

Memory-Assisted Quantum Key Distribution

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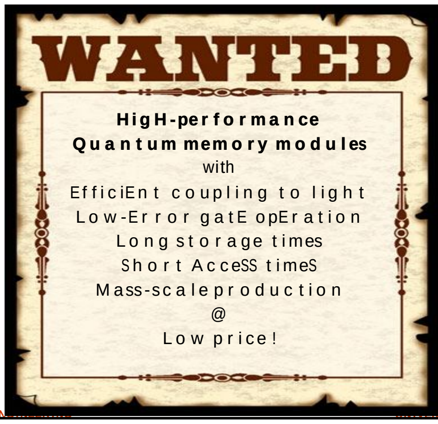
Quantum Memories Wanted!



Quantum Memories in Action!

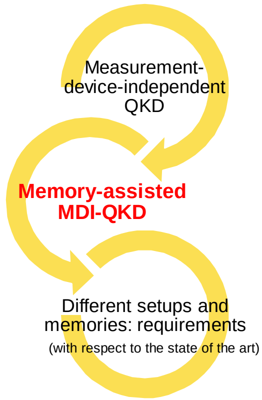
But, do we have such a memory?

How about existing (imperfect) memories? Can we use them in some useful way?

Benchmark: to beat an existing no-memory quantum system by adding quantum memory modules

Let's find some examples!

Story line



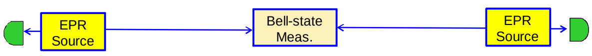
Measurement-Device-Independent QKD (MDI-QKD)

- EPR Protocol

Measurement-Device-Independent QKD (MDI-QKD)

- EPR Protocol

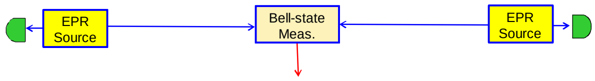
- Entanglement Swapping Protocol



Measurement-Device-Independent QKD (MDI-QKD)

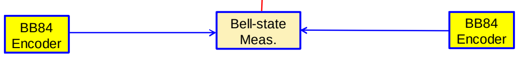
- EPR Protocol

- Entanglement Swapping Protocol



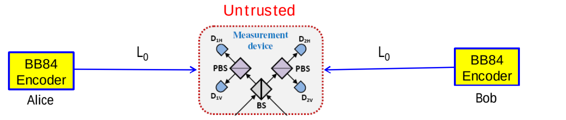
Untrusted → Meas-Device Independent

- Reverse EPR protocol



[Biham, Huttner & Mor, PRA **54,** 2651 (1996)]
[Lo, Curty & Qi, PRL **108,** 130503 (2012); Braunstein & Pirandola, PRL **108,** 130502 (2012)]

Measurement-Device-Independent QKD (MDI-QKD)



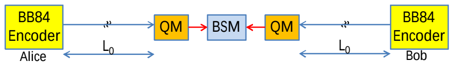
[Lo, Curty, & Qi, PRL **108,** 130503 (2012)]

- Resilient to detector attacks
- Suitable for access networks; End users only require the source/encoder
- BSM with linear optics and photodetectors

$$\text{Key rate} \propto \underbrace{\exp(-\alpha L_0)}_{\eta} \times \exp(-\alpha L_0)$$

Memory-Assisted MDI-QKD

- Let's combine MDI-QKD with the repeater idea: SETUP A



QM: Quantum Memory
BSM: Bell-state Measurement

[PRA **89**, 012301 (2014)]
[NJP **16**, 043005 (2014)]

- Memory-assisted protocol:
  - Send encoded photons toward memories
  - Attempt to store them into memories; whenever successful, stop and wait for the other side → a heralding mechanism needed
  - Do the BSM whenever both memories are loaded

Memory-Assisted MDI-QKD

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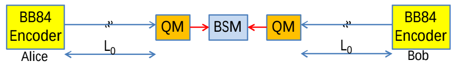
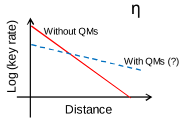


QM: Quantum Memory
BSM: Bell-state Measurement

[PRA **89**, 012301 (2014)]
[NJP **16**, 043005 (2014)]

- Expected benefit: better rate-vs-distance behaviour

$$\text{Key rate} \propto \underbrace{\exp(-\alpha L_0)}_{\eta}$$



Memory-Assisted MDI-QKD

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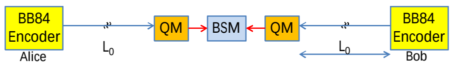
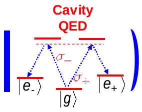


QM: Quantum Memory
BSM: Bell-state Measurement

- But, how about memory errors? Wouldn't the memory decohere?



T_2 : dephasing time constant in $|e_+\rangle - |e_-\rangle$ space
T_1 : amplitude decay time from $|e_+\rangle$ or $|e_-\rangle$ to $|g\rangle$

Memory-Assisted MDI-QKD

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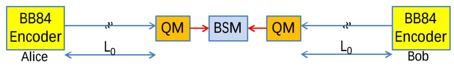
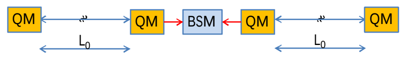


QM: Quantum Memory
BSM: Bell-state Measurement

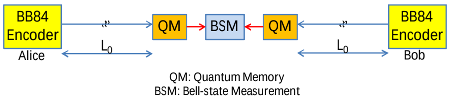
- What is the advantage over quantum repeaters? Simpler @ the user end &



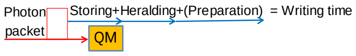
	attempt period	Coherence time
Qu. repeater	L_0 /c	$\propto L_0$ /c
MA MDI-QKD		

Writing time

- Let's combine MDI-QKD with the repeater idea:



- Writing time: The time it takes for a single photon at the memory input to be stored into the QM, and we get to know about it



- For SETUP A, the repetition period >= writing time

Memory-Assisted MDI-QKD

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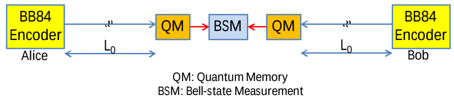

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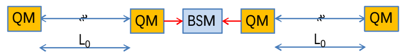
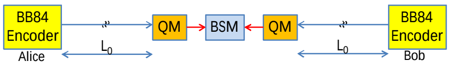


	attempt period	Coherence time
Qu. repeater	L_0 /c	$\propto L_0$ /c
MA MDI-QKD	Writing time	$\propto$ Writing time

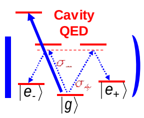
For fast memories, milder requirements on coherence time

Memory-Assisted MDI-QKD: Heralding Schemes

- In SETUP A, QMs need to be heralding:



- Direct heralding is typically slow (~ms). Can we avoid it?



Memory-Assisted MDI-QKD: Heralding Schemes

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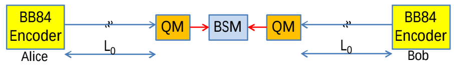

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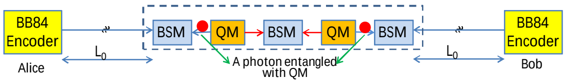

SETUP B:

- Entangle a photon with the QM

- Use this photon to teleport the incoming state to the QM

Memory-Assisted MDI-QKD: Heralding Schemes

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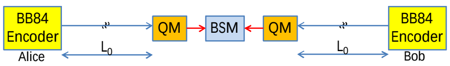

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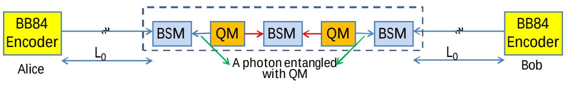
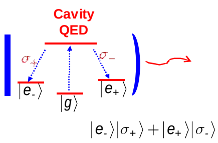
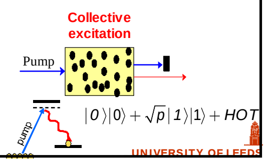
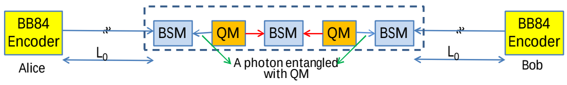






Memory-Assisted MDI-QKD: Key Rate Analysis

- Let's see how our SETUP B performs in a realistic setup once we include various sources of nonideality including memory dephasing and decay, dark count and background noise, various inefficiencies (writing, reading, detectors, loss) and *timing issues*



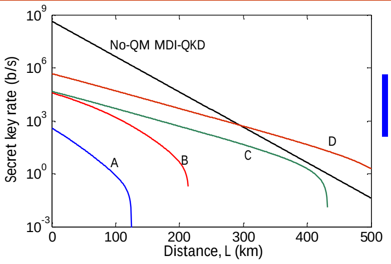
- We find the achievable key rate under the normal mode of operation, where there are no eavesdroppers. More details at

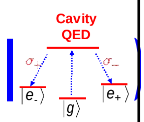
[NJP **16**, 043005 (2014)]

[arXiv:1407.8016; IEEE JSTQE (2015)]

[arXiv:1603.03623]

MDI-QKD with Single Atoms in SETUP B





Curve A:
coherence time, T_2 = 100 μs
Reading time = 1 μs; Writing time = 21 μs
Entangling efficiency = 0.4
Retrieval efficiency at no decay = 1

Curve B:
→ 1 μs

Curve C:
T_2 = 1s

Curve D:
T_2 = 1s
0.1 μs

Improvements needed

All curves: QE = 0.93; Dark count = 1/s; Repetition rate for no-QM: 1 GHz
Parameters taken from [Nature **484**, 195 (2012)]

How About Ensemble-Based Memories?

Towards high-speed optical quantum memories

[Nat. Photon. **4,** 218 (2010)]

K. F. Reim[1], J. Nunn[1], V. O. Lorenz[1,2], B. J. Sussman[1,3], K. C. Lee[1], N. K. Langford[1], D. Jaksch[1] & I. A. Walmsley[1]

Quantum memories, capable of controllably storing and releasing a photon, are a crucial component for quantum computers[1] and quantum communications[2]. To date, quantum memories[3, 4, 5, 6] have operated with bandwidths that limit data rates to megahertz. Here we report the coherent storage and retrieval of sub-nanosecond low-intensity light pulses with spectral bandwidths exceeding 1 GHz in caesium vapour. The novel memory interaction takes place through a far off-resonant

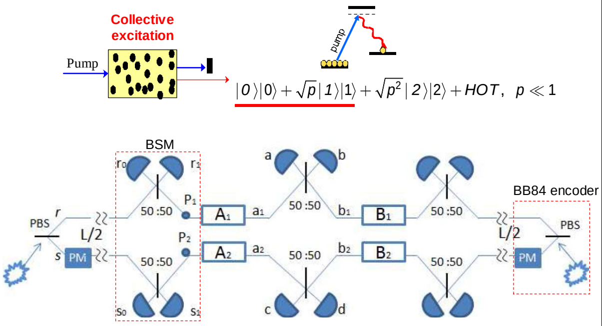
Broadband waveguide quantum memory for entangled photons

[Nature **469**, 512 (2010)]

Erhan Saglamyurek, Neil Sinclair, Jeongwan Jin, Joshua A. Slater, Daniel Oblak, Félix Bussières, Mathew George, Raimund Ricken, Wolfgang Sohler & Wolfgang Tittel

The reversible transfer of quantum states of light into and out of matter constitutes an important building block for future applications of quantum communication: it will allow the synchronization of quantum information[1], and the construction of quantum repeaters[2] and quantum networks[3]. Much effort has been devoted to the development of such quantum memories[1], the key property of which is the preservation of entanglement during storage. Here we report the reversible transfer of photon–photon entanglement into entanglement between a photon and a collective atomic excitation in a solid-state device. Towards this end, we employ a thulium-doped lithium niobate waveguide in conjunction with a photon-echo quantum memory protocol[4], and increase the spectral acceptance from the current maximum[5] of 100 megahertz to 5 gigahertz. We

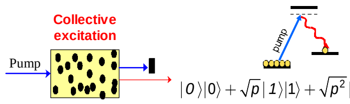
MDI-QKD with Atomic Ensembles in SETUP B



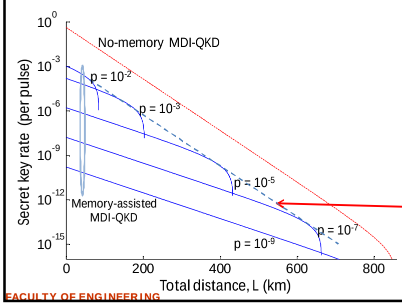
$$|0\rangle|0\rangle + \sqrt{p}\,|1\rangle|1\rangle + \sqrt{p^2}\,|2\rangle|2\rangle + HOT, \quad p \ll 1$$

With prob p^2, we get two overall excitations in Alice/Bob's memories
→ will cause error in the middle BSM

MDI-QKD with Atomic Ensembles



$$|0\rangle|0\rangle + \sqrt{p}\,|1\rangle|1\rangle + \sqrt{p^2}\,|2\rangle|2\rangle + HOT$$



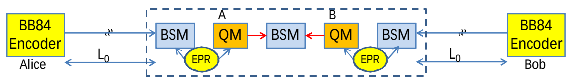
[IEEE JSTQE (2015)]

What to do next?

- Our first attempt failed!
- Possible Solutions:
  - Change the entangling procedure
  - Find another suitable memory candidate
- Here we consider some of these options
  - What can be done with a good EPR source?
  - What can be done with a good single-photon source?
  - How about NV centres in Diamond?

Memory-Assisted MDI-QKD: SETUP C

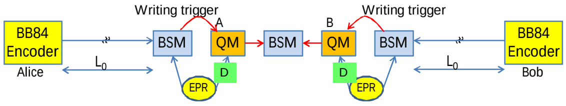
- An alternative (indirectly) heralding scheme: SETUP C



- Not fully heralding, but with efficient writing schemes, is almost there.
- We cannot use EPR sources based on parametric down-conversion (the same multi-photon statistics as atomic ensembles)
- EPR sources based on quantum dots, however, have potentially lower double-pair emission rates ($g^{(2)} < 0.004$, [Nat. Photon. 8, 224 (2014)]) as compared to their single-pair generation rate (0.1-0.9); high repetition rates (→ 1GHz)

Memory-Assisted MDI-QKD: SETUP C (modified)

- An alternative (indirectly) heralding scheme



- One great possibility: delayed writing!

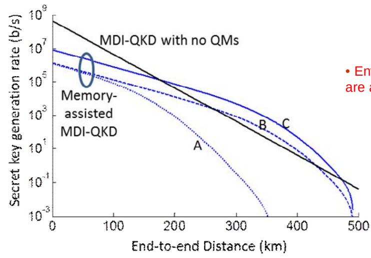
Only write to the memory if the side-BSM is successful
We need to delay one of the EPR photons for a short time

→ Overhead time for cooling/preparing the QMs is almost irrelevant

→ Clock rate ~independent of the writing time

- Qdot-based EPR sources may need more time to mature, but that's no longer a memory problem! ☺

How would it perform?



- Entangled states are assumed ideal

Curve A:	Curve B:	Curve C:
coherence time = 1.5 μs	150 μs	150 μs
Writing/reading time = 300 ps		
Entangling efficiency = 0.12		
Retrieval efficiency at no decay = 30%		73%

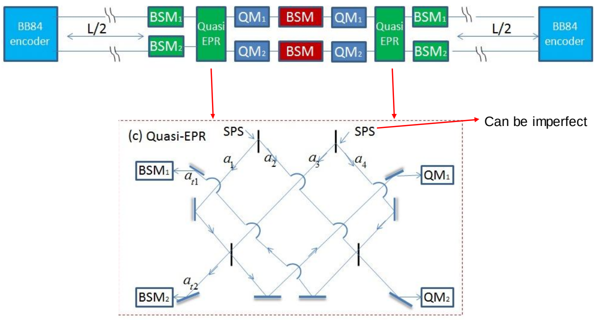
- available today!

All curves: QE = 93%; Dark count = 1/s; Repetition rate: 1 GHz; writing eff = 1

Parameters from [PRL **107,** 053603 (2011); Nature **466,** 217 (2010); Nat. Phys. **8,** 517 (2012)]

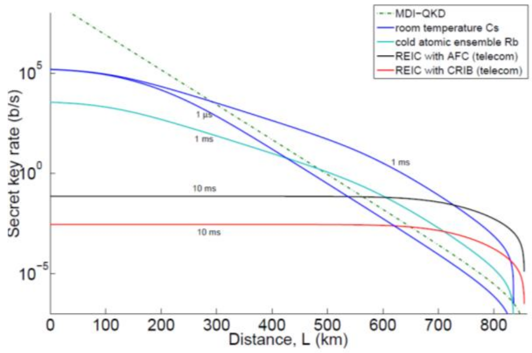
How about Using Single Photon Sources?

- SETUP D



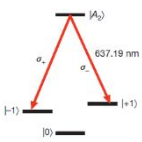
[presented at CLEO:2016]

Performance of Ensemble-Based Memories



MDI-QKD with NV Centers in Diamond

- To avoid multiple excitation effects, we can use single-atom like memories
- Negatively charged NV centres in diamond look like a plausible option
  - They can be entangled with photons
  - They are rather fast; 10 ns for writing
  - Long coherence times up to 0.6 s



[Nature 466, 730 (2010)]

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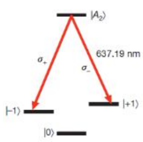
  - They can be entangled with photons
  - They are rather fast; 10 ns for writing
  - Long coherence times up to 0.6 s
  - Cavity-enhanced NV centres



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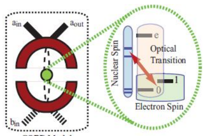
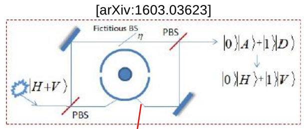


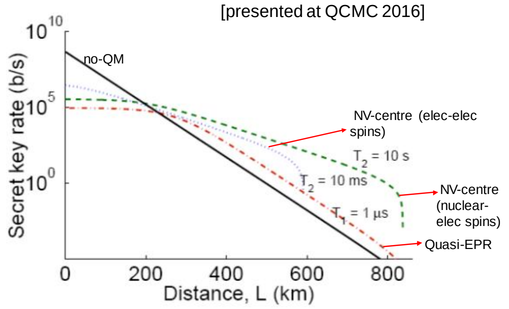
[PRX 4, 031022 (2014)]

[arXiv:1603.03623]



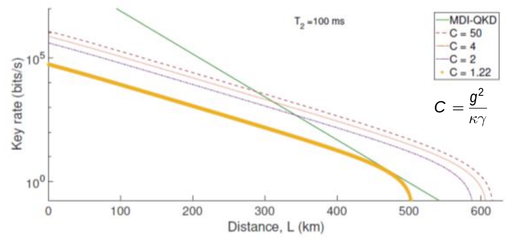
state dependent phase

Key Rate Comparison



- Up to three orders of magnitude over a *single* no-QM system

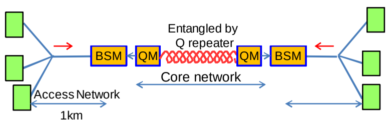
Moderate requirements on cavity coupling

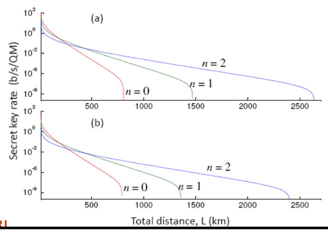


$$C = \frac{g^2}{\kappa\gamma}$$

Scalability: Long-distance Trust-free QKD

- Memory-assisted MDI-QKD is not scalable like quantum repeaters
- Eventually, one should think of MDI-QKD + Repeater setups:

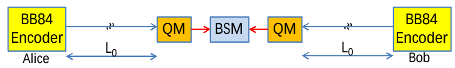




[Lo Piparo & Razavi, IEEE JSTQE 2015; arXiv:1407.8025]

Summary

SETUP A: offers better rate-vs-distance behavior; requires heralding memories, with short access times and large storage-BW products



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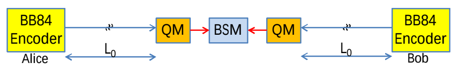
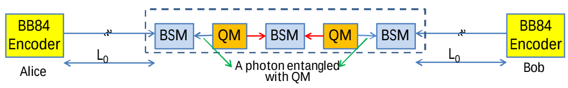
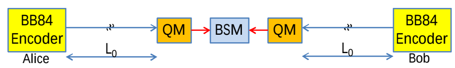


SETUP B: Relaxes the heralding requirement; cannot work with ensemble-based memories

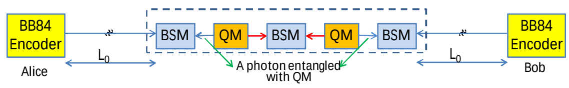


Summary

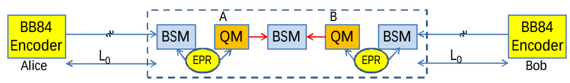
SETUP A: offers better rate-vs-distance behavior; requires heralding memories, with short access times and large storage-BW products



SETUP B: Relaxes the heralding requirement; cannot work with ensemble-based memories



SETUP C: Further relaxes constraints on the writing time; can work with ensemble-based memories; can use practical SPS



Summary

Take-home Message:

Even with imperfect quantum memories of about today's technology, we can devise memory-assisted QKD systems that outperform their no-memory counterparts. That is the first step toward building long-distance QKD systems.

PhD Positions in Europe!

QCALL is a European Innovative Training Network (ITN) that offers 15 extremely well-funded PhD positions on various topics related to quantum communications

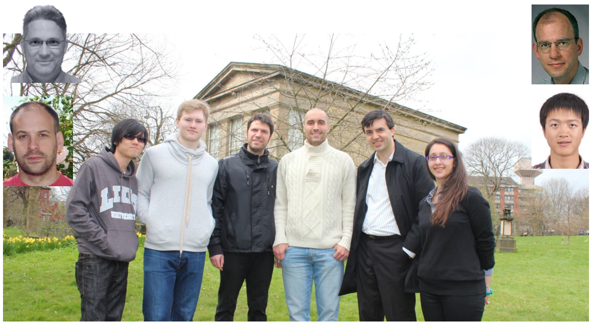
- 3 years of funded PhD research with annual salaries > €43k and research budget > €60k per student
- Dedicated schools on QKD and quantum networks + complementary-skill training + extensive internship/placement programmes
- Eligibility: meeting mobility criterion + being an early-stage researcher
- PhD start date: Early 2017 – Oct 2017; Deadline for application: **15 Jan 2017**

http://www.qcall-itn.eu

Partners:

- **ID Quantique:** 1 project on quantum hacking; contact *F Brussieres*
- **Telecom ParisTech:** 1 project on Hybrid CV QKD; *R Alleaume*
- **Toshiba Research Europe Ltd:** 2 projects on MDI-QKD and Integration; *A Shields*
- **University of Dusseldorf:** 2 projects on repeaters and multipartite entanglement; *D Bruss*
- **University of Geneva:** 2 projects on QKD and quantum memories; *H Zbinden*
- **University of Leeds:** 2 projects on MDI-QKD and repeaters; *M Razavi* (**Coordinator**)
- **University of Padova:** 2 projects on satellite QKD and QRNGs; *P Villoresi*
- **University of Pierre and Marie Curie:** 1 project on beyond-QKD protocols; *E Diamanti*
- **University of Vigo:** 2 projects on security of QKD and beyond-QKD protocols; *M Curty*
- Plus collaborative partners at **BBN**, **Heriot-Watt**, **Inria**, **IQC**, **Madrid**, **Max Planck** & **NTT**

Thank You



SEVENTH FRAMEWORK PROGRAMME

QUANTUM COMMUNICATIONS HUB

PEOPLE