Quantum Repeaters

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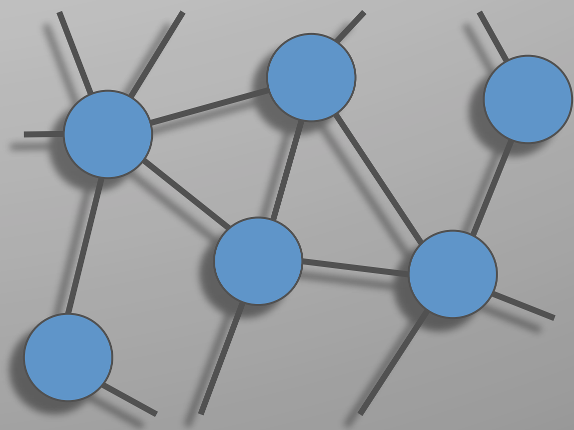
Outline

- Entanglement and quantum repeater - an introduction
- A quantum repeater based on spectral multiplexing
- Solid-state quantum memory (based on rare-earth crystals)
  - Properties of RE crystals
  - Protocols
  - (Entangling two different RE crystals)
  - ((Spectrally multiplexed storage))
- Conclusion



Entanglement – a fundamental property

Entanglement is a puzzling prediction of quantum theory

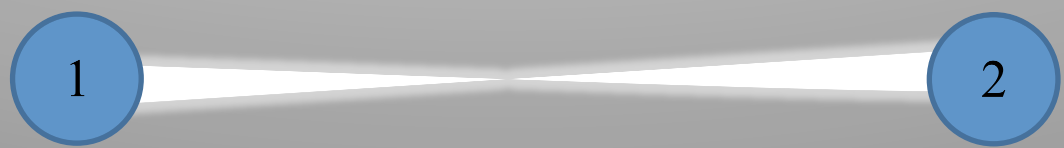
$$|\psi\rangle_{12} = \big(|0\rangle_1 \otimes |0\rangle_2 + |1\rangle_1 \otimes |1\rangle_2\big)/\sqrt{2}$$

For pure states: $|\psi\rangle_{12} \neq |\psi\rangle_1 \otimes |\psi\rangle_2$

-> ψ entangled

Outcomes of measurements (of sufficiently high entangled states)

violate Bell inequality: S=E(a,b)+E(a,b')+E(a',b)-E(a',b') ≤2



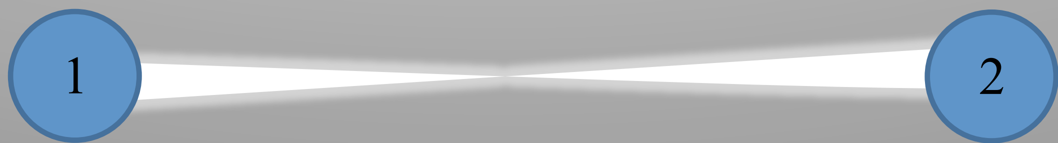
Entanglement – a resource

Entanglement between distant quantum systems (qubits) is at the heart of quantum communication

$$|\psi^+\rangle_{12} = \big(|01\rangle_{12} + |10\rangle_{12}\big)/\sqrt{2} \qquad |\psi^-\rangle_{12} = \big(|01\rangle_{12} - |10\rangle_{12}\big)/\sqrt{2}$$

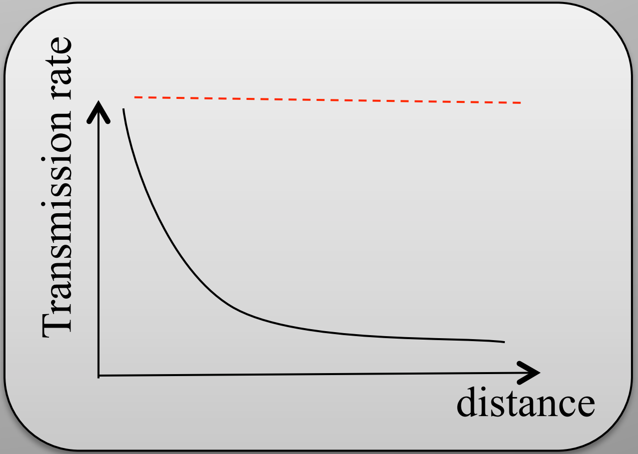
$$|\phi^+\rangle_{12} = \big(|00\rangle_{12} + |11\rangle_{12}\big)/\sqrt{2} \qquad |\phi^-\rangle_{12} = \big(|00\rangle_{12} - |11\rangle_{12}\big)/\sqrt{2}$$

- Individual measurements allow establishment of secret (classical) bits (QKD)
- Joint measurement with a third qubit allows transmitting its quantum state via quantum teleportation



Quantum communication and distance

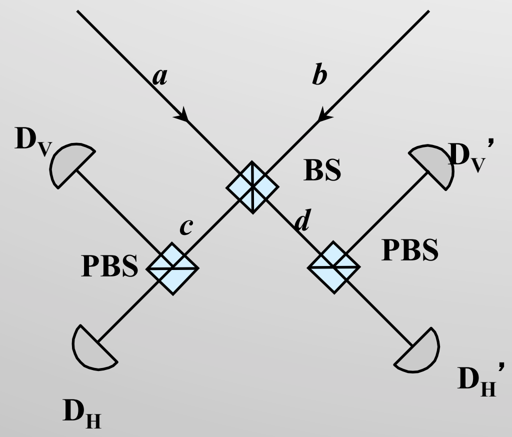
- the probability for transmission of entangled photons across an optical fibre decreases exponentially with distances
- amplifiers, used in classical communications, are not suitable in the quantum context (no-cloning theorem)
- and yet, a quantum repeater allows improving the scaling



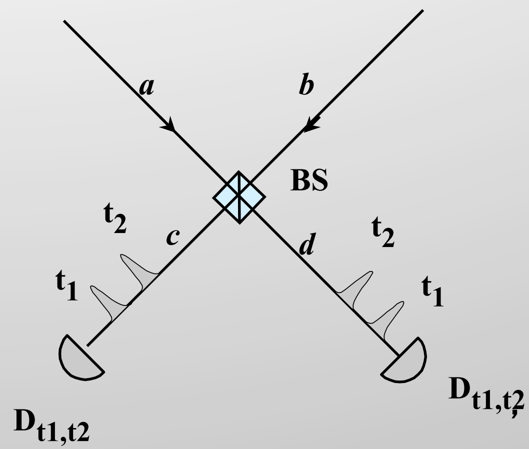
HJ Briegel, W Dür, JI Cirac, P Zoller, Phys. Rev. Lett. 81, 5932 (1998)

Key ingredient: projection onto Bell states

polarization qubits



time-bin qubits



$$|0\rangle_a |1\rangle_b \rightarrow (i\,|0\rangle_c + |0\rangle_d)\,(|1\rangle_c + i\,|1\rangle_d) = i\,|0\rangle_c |1\rangle_c - |0\rangle_c |1\rangle_d + |1\rangle_c |0\rangle_d + i\,|0\rangle_d |1\rangle_d$$

$$|1\rangle_a |0\rangle_b \rightarrow (i\,|1\rangle_c + |1\rangle_d)\,(|0\rangle_c + i\,|0\rangle_d) = i\,|0\rangle_c |1\rangle_c - |1\rangle_c |0\rangle_d + |0\rangle_c |1\rangle_d + i\,|0\rangle_d |1\rangle_d$$

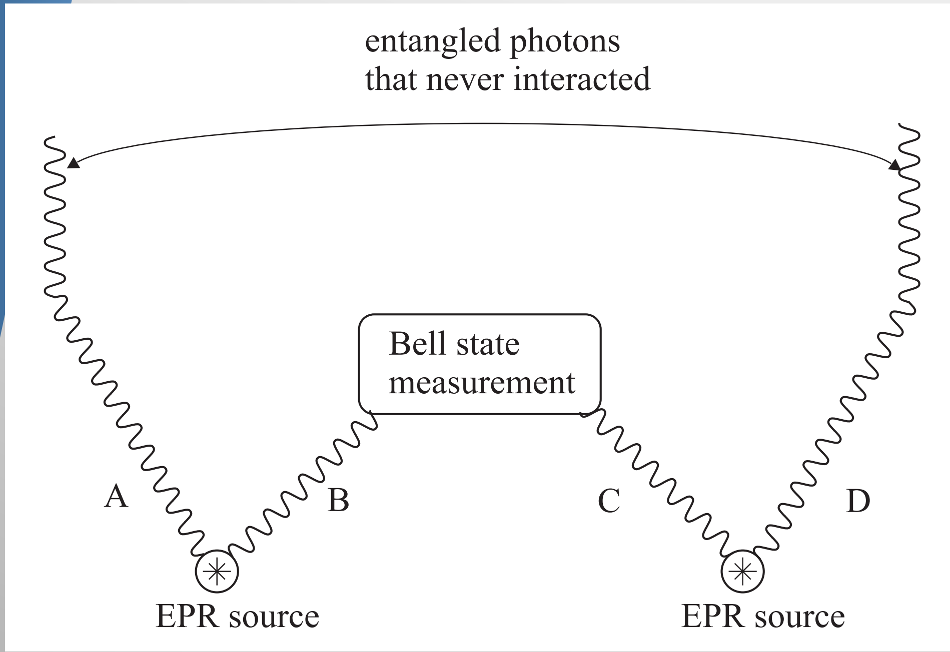
$$\Rightarrow \boxed{\begin{aligned} |\psi^-\rangle &= |0\rangle_a |1\rangle_b - |1\rangle_a |0\rangle_b \rightarrow -|0\rangle_c |1\rangle_d + |1\rangle_c |0\rangle_d \\ |\psi^+\rangle &= |0\rangle_a |1\rangle_b + |1\rangle_a |0\rangle_b \rightarrow i\,|0\rangle_c |1\rangle_c + i\,|0\rangle_d |1\rangle_d \end{aligned}}$$

requires photons B and C to be indistinguishable

Bell state measurement only 50 % efficient (lin. optics, no addtl. photons)

N. Lütkenhaus *et al.*, PRA **59**, 3295 (1999).

Key ingredients: entanglement swapping



$$|\phi^+\rangle_{AB} = \left(|00\rangle_{12} + |11\rangle_{12}\right)/\sqrt{2}$$

$$|\phi^-\rangle_{CD} = \left(|00\rangle_{12} - |11\rangle_{12}\right)/\sqrt{2}$$

$$|\psi^-\rangle_{BC} = \left(|01\rangle_{12} - |10\rangle_{12}\right)/\sqrt{2}$$

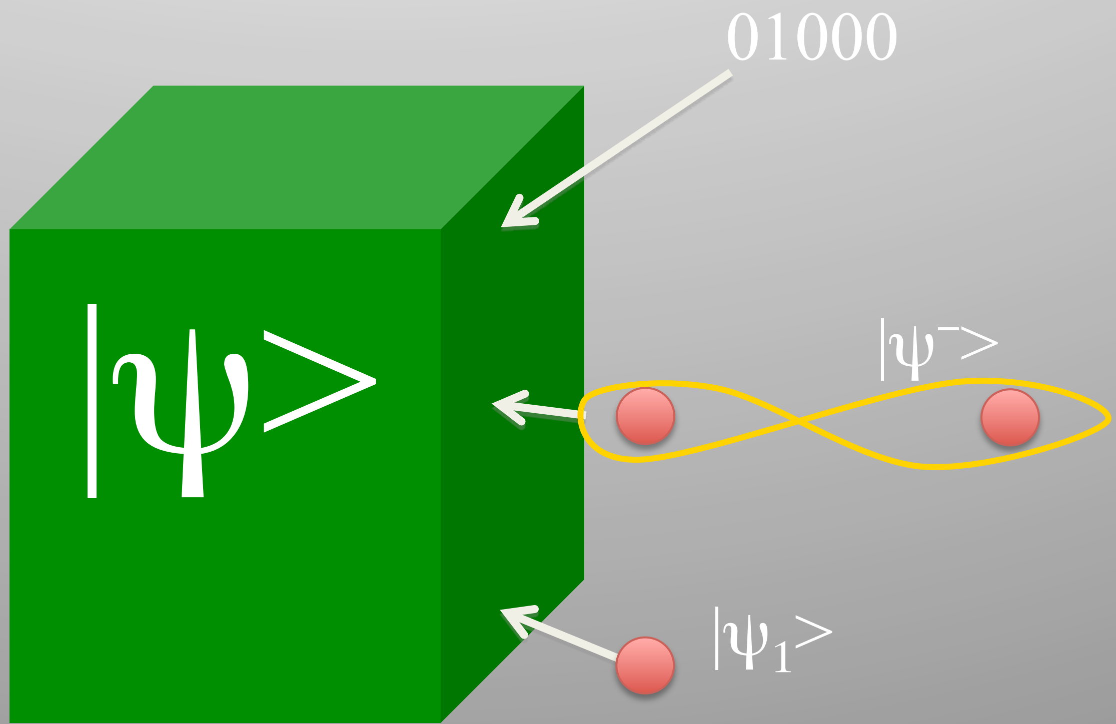
$$|\psi^+\rangle_{AD} = \left(|01\rangle_{12} + |10\rangle_{12}\right)/\sqrt{2}$$

- Start with entangled pairs (A,B) and (C,D)
- Projecting (B,C) onto a Bell state results in <u>heralded</u> <u>entanglement</u> between A and C

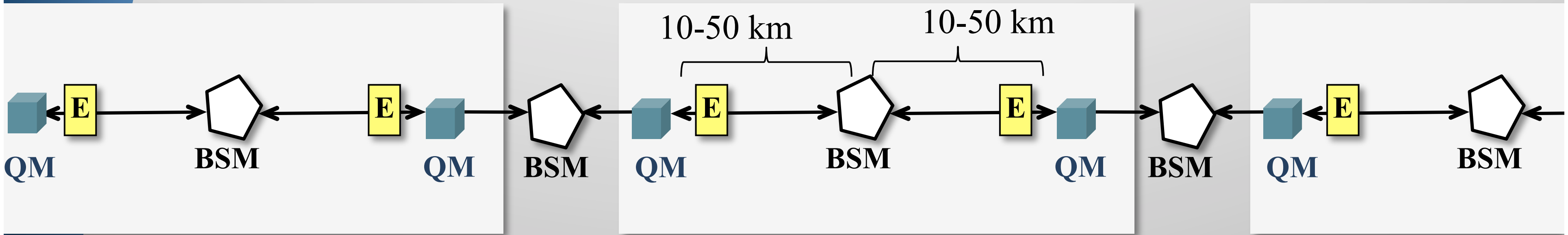
$$|\psi\rangle_{ABCD} = |\phi^+\rangle_{AB}|\phi^-\rangle_{CD} = |\psi^-\rangle_{BC}|\psi^+\rangle_{AD} + \ldots$$

Key ingredients: quantum memory for light

$$|\psi'\rangle = \mathbb{1}|\psi\rangle$$

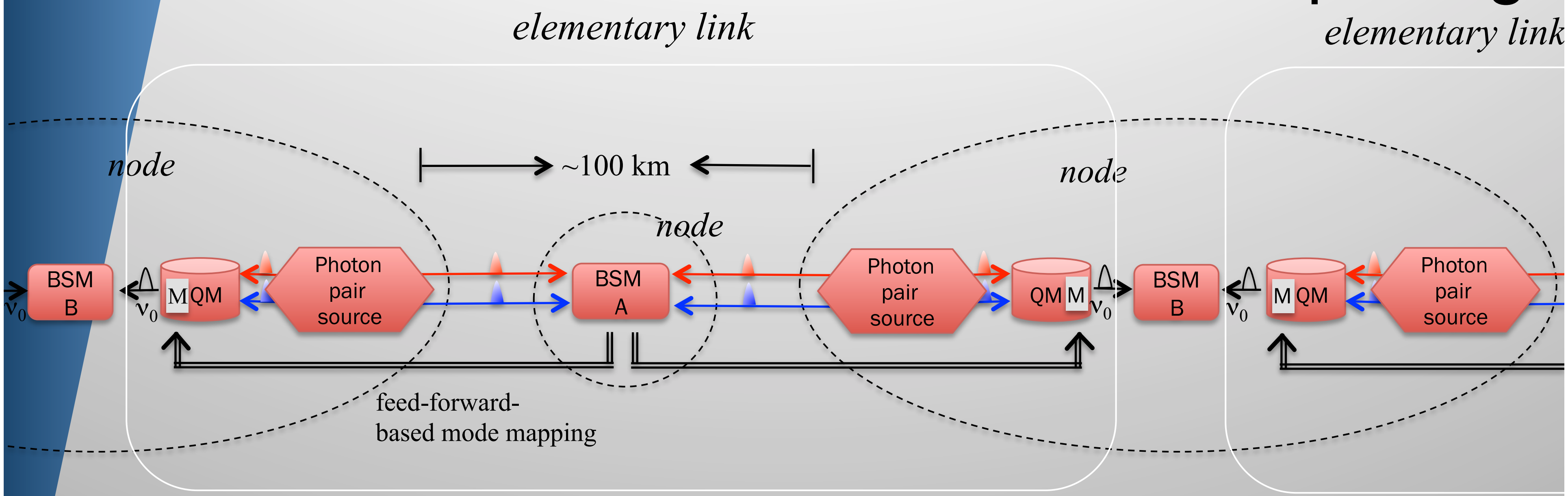


Quantum repeater



- Split long distance into elementary links
- Create heralded entanglement via swapping over elementary links
- Connect elementary links using second swapping operation
- Improvement of scaling is achieved by decoupling transmissions over elementary links.

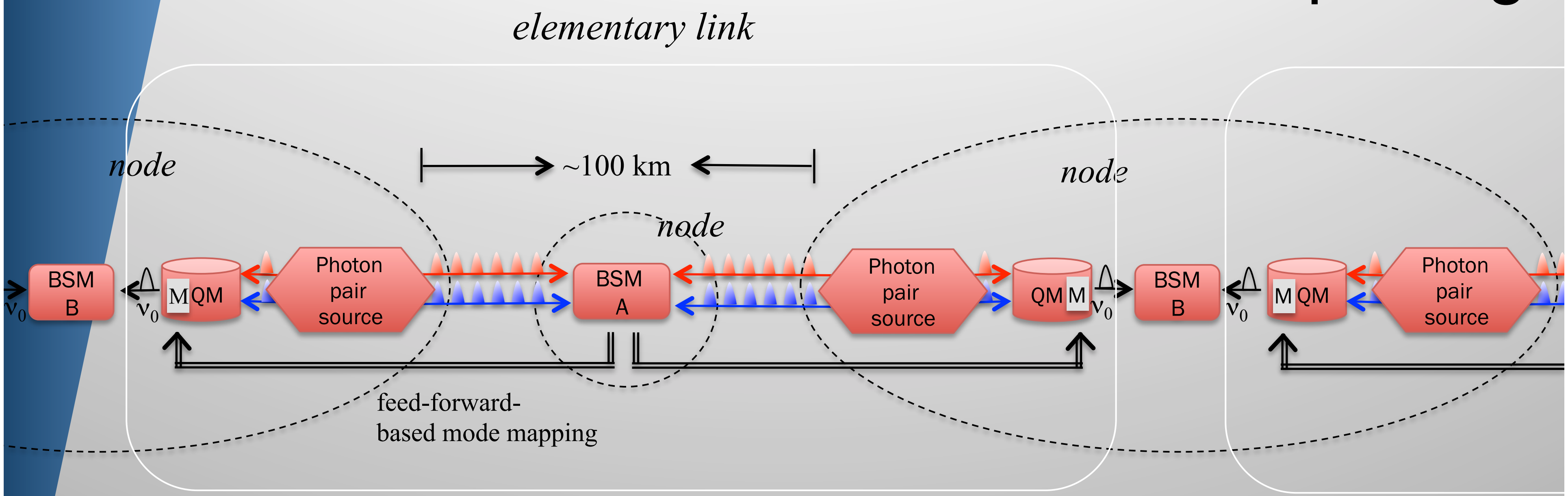
Quantum repeater based on spectral multiplexing



- Heralding of entanglement through BSM A
- Many spectral modes, P_{EL} ->1
- Feed-forward-based mode-mapping M (requires $\tau_{mem} = L_{EL}/\mathrm{v}$)
- Connection of ELs by BSM B
- No entanglement distillation

N. Sinclair, WT *et al.*, Phys. Rev. Lett. **113**, 053603 (2014), S. Guha, WT *et al.*, arXiv:1404.7183

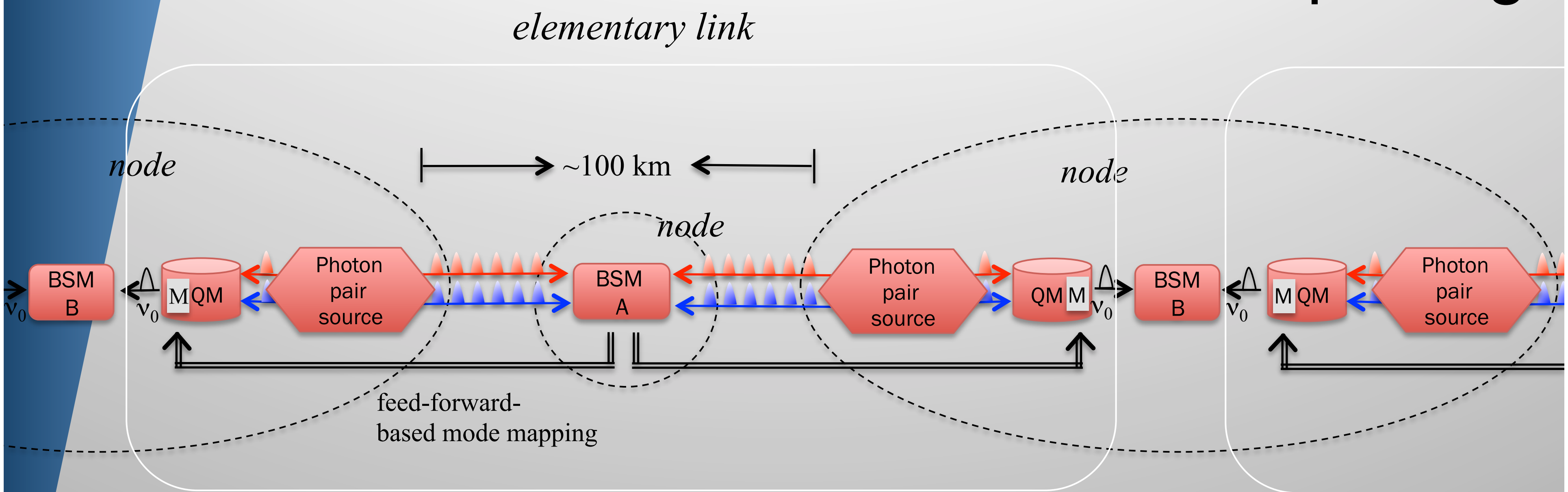
Quantum repeater based on spectral multiplexing



- Heralding of entanglement through BSM A
- Many spectral modes, P_{EL} ->1
- Feed-forward-based mode-mapping M (requires $\tau_{mem} = L_{EL}/\mathrm{v}$)
- Connection of ELs by BSM B
- No entanglement distillation
- High clock rate $1/\tau_{qubit}$, not limited by round-trip time L_{tot}/v or L_{EL}/v

N. Sinclair, WT *et al.*, Phys. Rev. Lett. **113**, 053603 (2014), S. Guha, WT *et al.*, arXiv:1404.7183

Quantum repeater based on spectral multiplexing



Photon pair source:
- Spectrally (spatially, temp., pol.) multiplexed (1000 modes), high-rate emissions
- # modes determined by elementary link loss
- Only one member per pair has to be at telecom λ

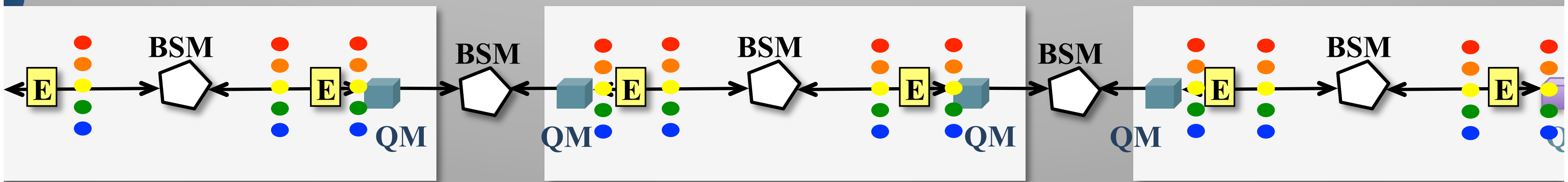
Memory:
- Storage of multiplexed (spectral, temporal, polarization and spatial modes) qubits
- Storage time given by elementary link length (500 μsec for 100 km)
- Feed-forward-based mode mapping may be performed internally or through external circuits
- Fixed storage time is sufficient

BSM:
- Linear optics based
- Limited efficiency of BSM A can be compensated by more modes
- Limited efficiency of BSM B impacts final rate and scaling

Detectors:
- In BSM A: Mode resolved and at telecom λ
- Modest rates per channel
- In BSM B: High-rate, but only one channel

System performance - assumptions

- Frequency-multiplexed photon-pair sources with fibre coupling efficiency per photon of 90%
- Fibre loss of 0.2 dB/km
- Quantum memories with 90% efficiency, Γ_{tot} = 300 GHz (-> R_{clock}= f(# of bins)), and ~500 μsec storage time (-> 100 km elem. link length)
- (Frequency-resolved) detectors with 90% efficiency

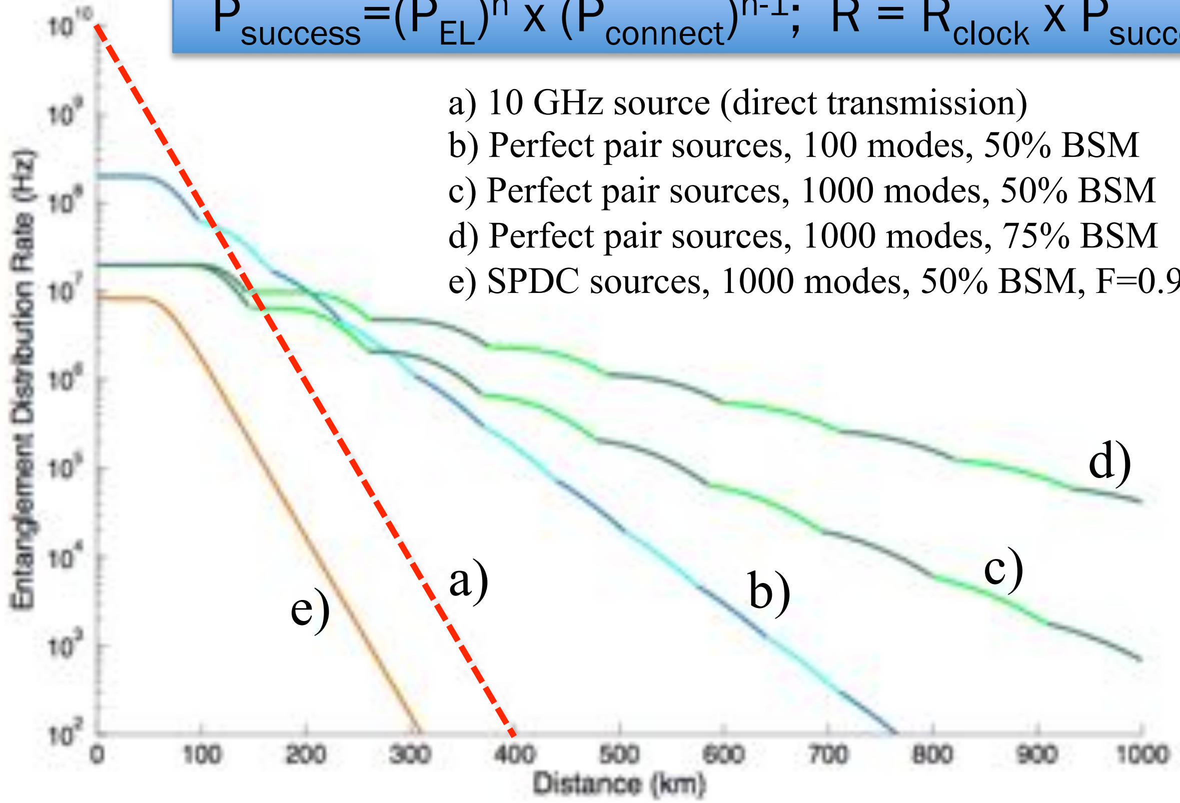


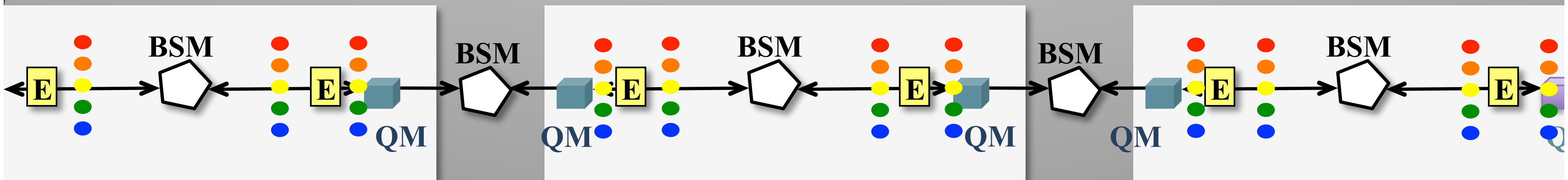
N. Sinclair *et al.*, Phys. Rev. Lett. **113**, 053603 (2014)

System performance

- for given number of elementary links, rate remains ~ constant as total distance increases until P_{EL} drops below 1
- adding another elementary link decreases rate, reflecting limited BSM efficiency
- SPDC sources without additional features not useful

$$P_{success}=(P_{EL})^n \times (P_{connect})^{n-1}; \quad R = R_{clock} \times P_{success}$$





N. Sinclair *et al.* PRL (2014), S. Guha *et al*., arXiv:1404.7183, M. Takeoka, S. Guha, M. Wilde, Nature Comm. 5, 5235 (2014)
S. Guha *et al*., arXiv:1505.03470

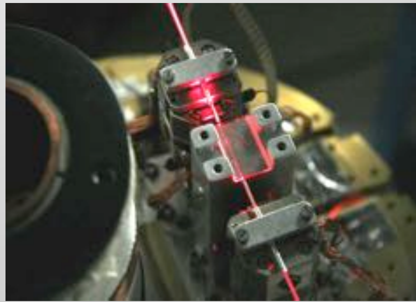
Solid state quantum memory

- Compared to atomic vapors, optical centers in solids do not move

  -> allows potentially for longer storage times

  -> no laser cooling necessary

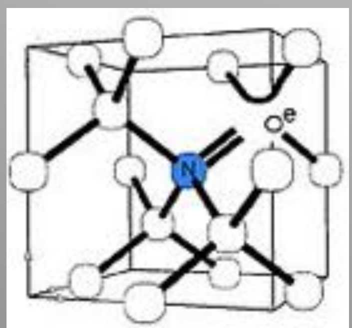
  -> compact and robust devices

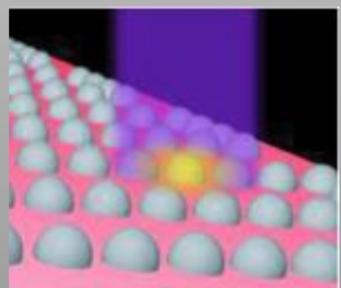


- Many possibilities (color centers in diamond, RE ions in crystals, quantum dots,..)

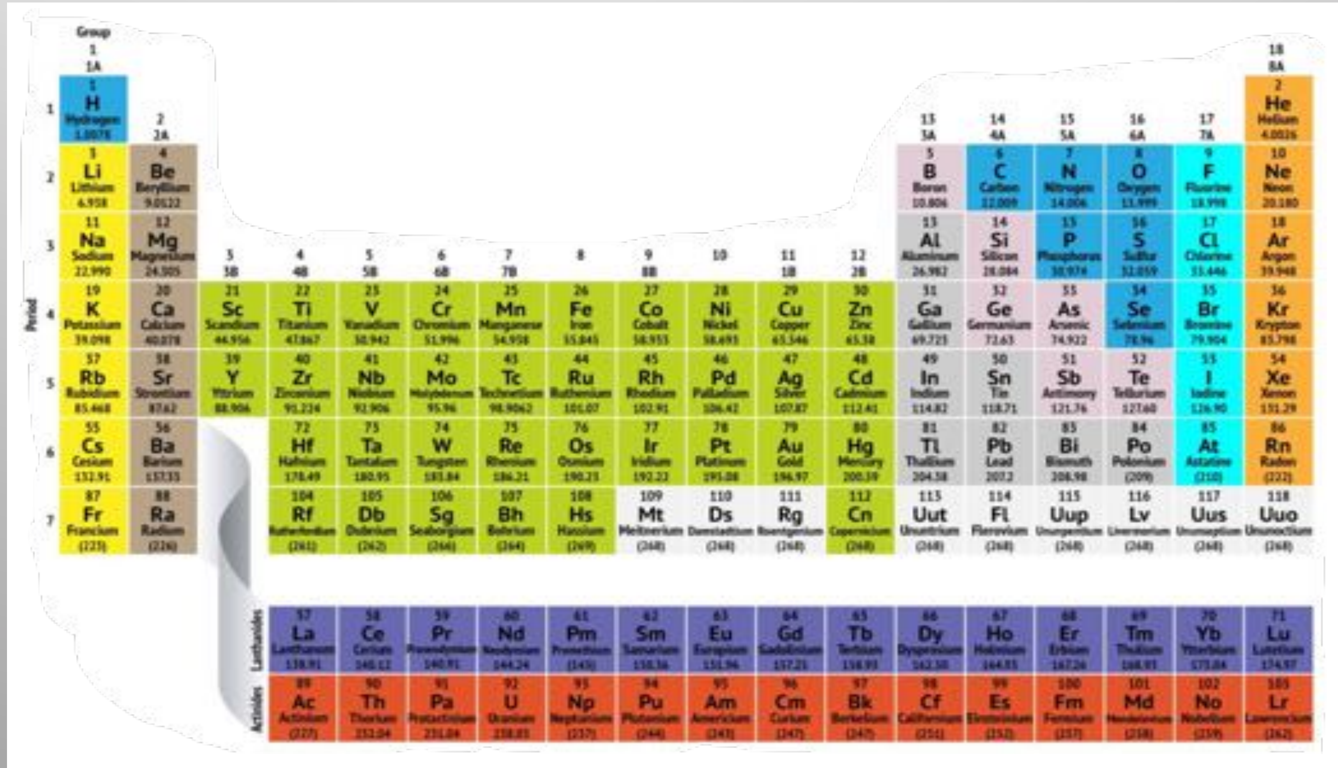
- More degrees of freedom to explore (and master)

- More spectroscopy needed

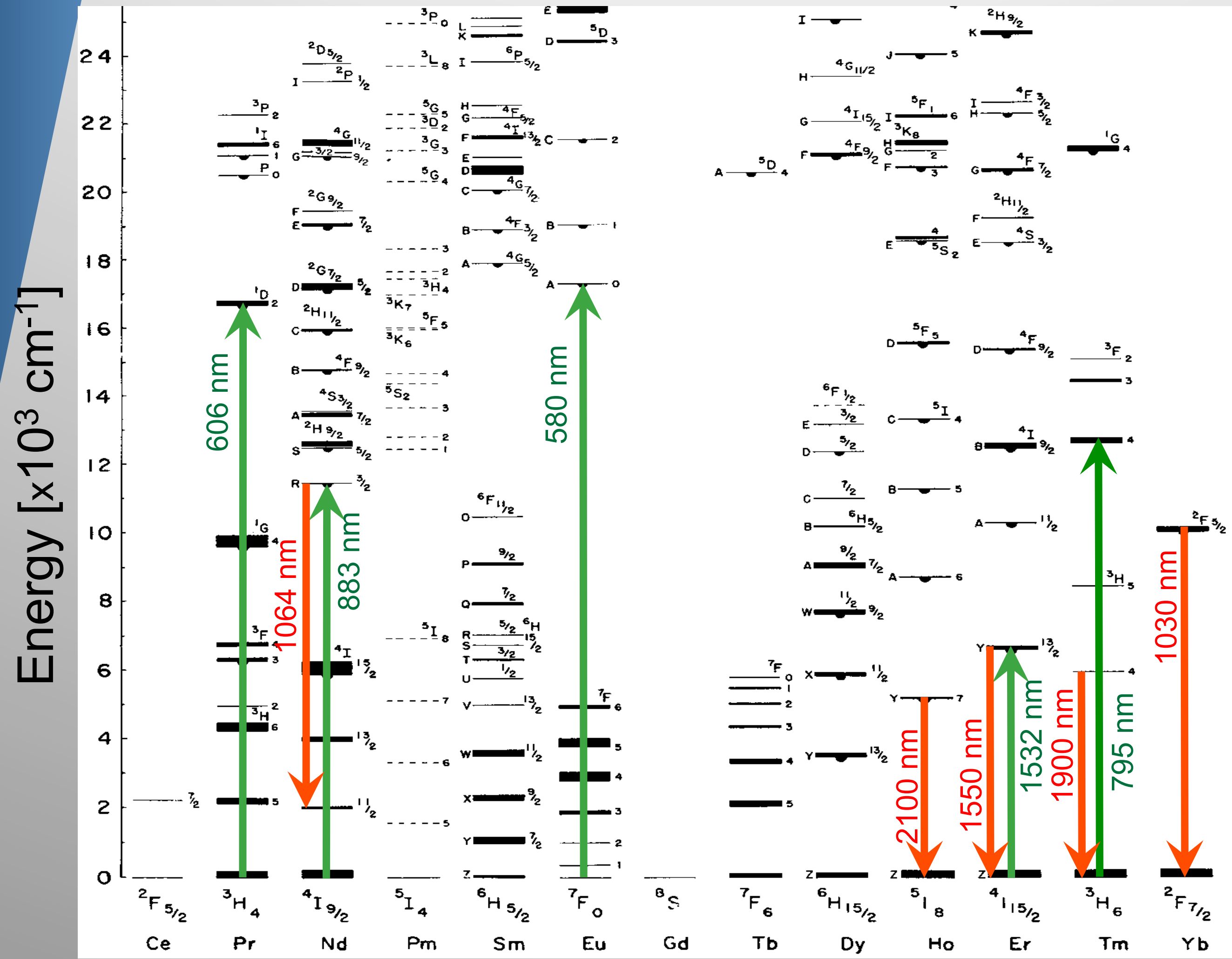




Rare-earth-ion doped crystals



Rare-earth-ion doped crystals

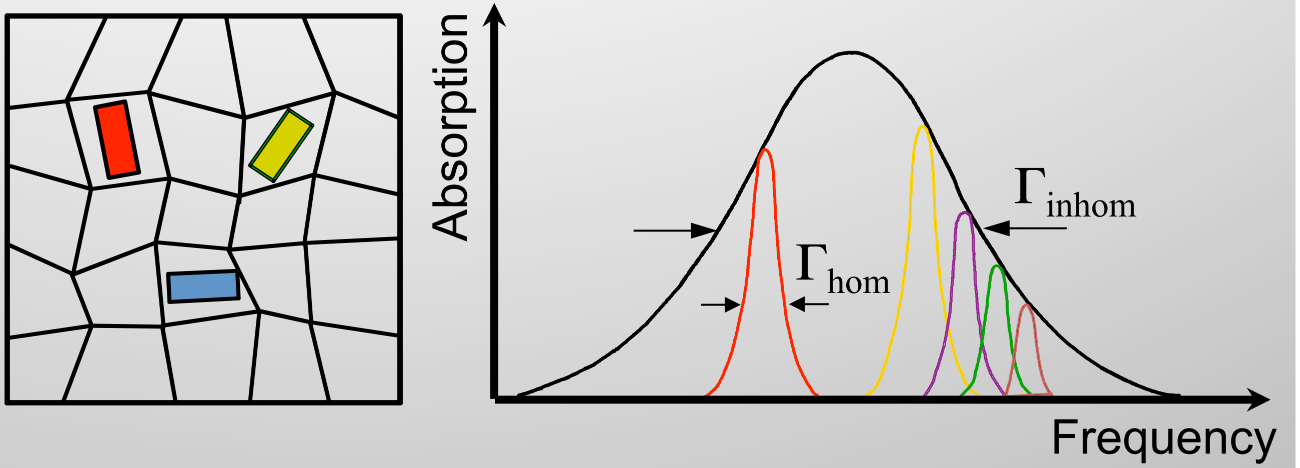


Commercial Solid State Lasers

Quantum memory

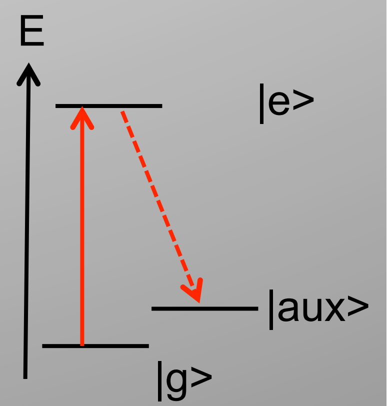
G.H. Dieke, Spectra and Energy Levels of Rare Earth Ions in Crystals, Wiley Interscience, New York, 1968.

Rare-earth-ion (RE^{3+}) doped crystals



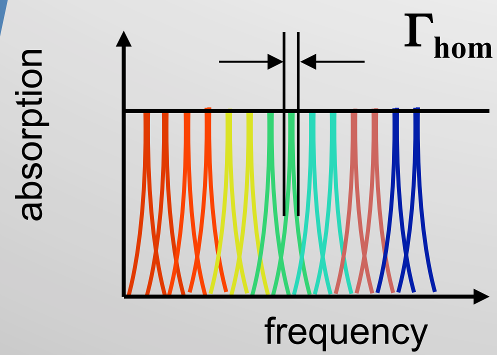
defects and strain -> inhomogeneous broadening

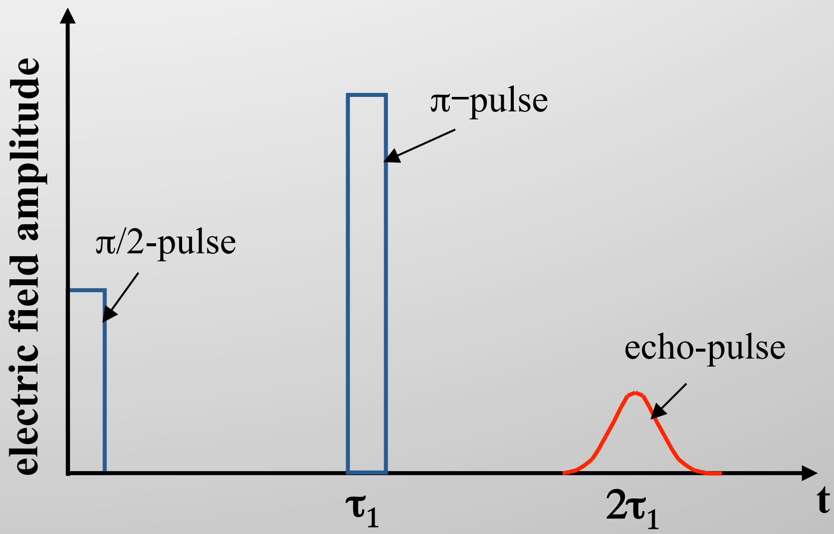
- 4f-4f transitions in the visible and NIR
- Energy levels barely affected by host material
- (almost) parity-forbidden transitions result in long optical T_1
- at 2 K: $\Gamma_{hom} \approx$ 50 Hz – 100 kHz, T_2 up to 4 ms
- $\Gamma_{inhom} \approx$ 100 MHz – 500 GHz
- at 2 K: ground state levels with up to hour-long T_1 (allowing spectral hole burning) and sec-long T2

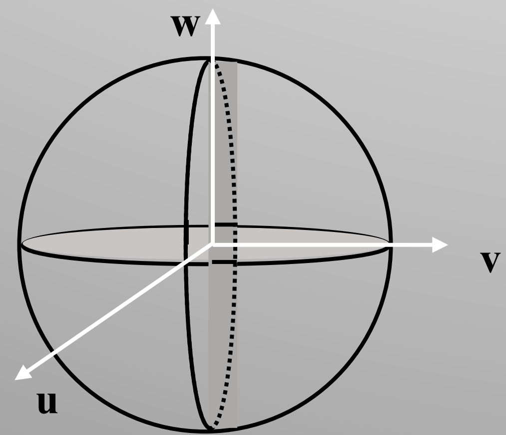


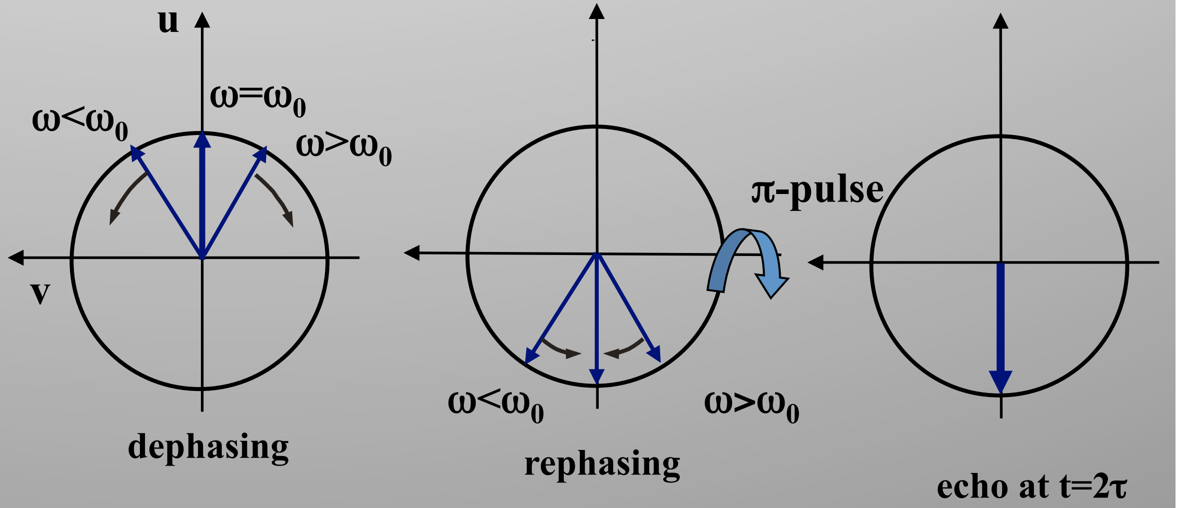
-> Suitable for quantum memory

Storage of light using two-pulse photon-echoes







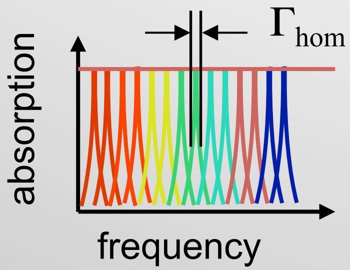


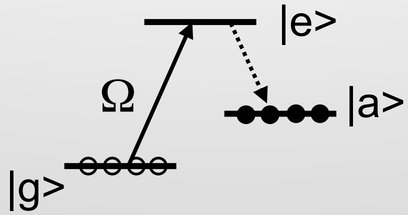
allows data storage! (but not quantum)

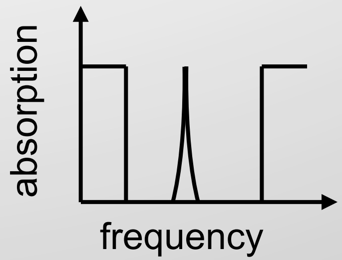
Kurnit, Abella & Hartmann, Phys. Rev. Lett. (1964), Mossberg, Opt. Lett. (1982)

Photon-echo quantum memory (CRIB)

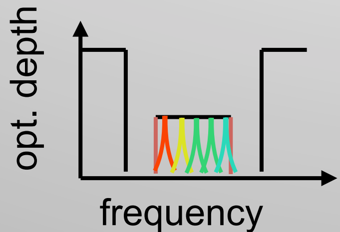
1. Preparation of an optically thick, single absorption line







2. Controlled reversible inhomogeneous broadening (CRIB)



(interaction with external electric field)

Experiments: Canberra, Geneva

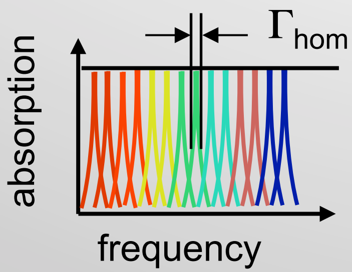
3. Absorption of light in arbitrary quantum state -> fast dephasing $\phi_i = \Delta_i t$
4. Reduction of broadening to zero
5. Phase matching: $\phi(z) = -2kz$; $E_{in} \propto e^{ikz} \rightarrow E_{out} \propto e^{-ikz}$
6. Re-establishment of broadening, with reversed sign $\Delta_i \text{ -> } -\Delta_i \ \forall\ i$

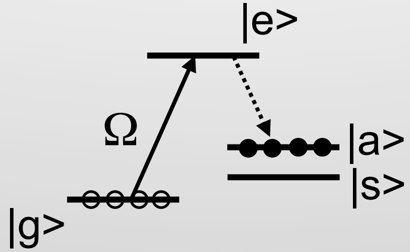
-> Time reversed evolution of atomic system and re-emission of light in backward direction with unity efficiency and fidelity

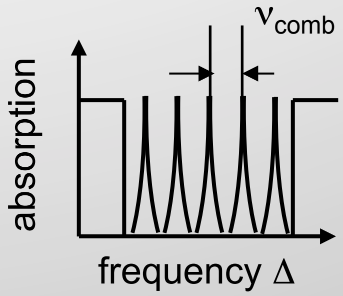
Moiseev *et al.*, PRL (2001); Nilsson *et al.*, Opt. Comm. (2005); Kraus, WT *et al.*, PRA(2006); Alexander *et al.*, PRL (2006)

Photon echo quantum memory (AFC)

1. Preparation of an atomic frequency comb







2. Absorption of a photon -> fast dephasing

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

3. Rephasing at $t = 1/\nu_{comb}$: $2\pi\Delta_j t = 2\pi(n\nu_{comb})/\nu_{comb} = n\,2\pi$

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

-> Re-emission of photonic qubits with unity efficiency* and fidelity.

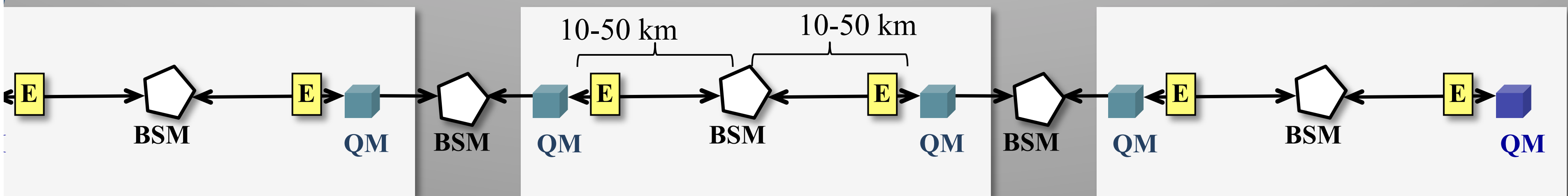
*some additional steps required

Needed: inhomogeneously broadened transition, long-lived auxiliary state, narrow homogeneous linewidth

Afzelius *et al.*, PRA (2009); De Riedmatten *et al.*, Nature (2008)

Conclusion

- The future will bring quantum networks that extend over large areas
- By decoupling transmissions over shorter (elementary) links, a quantum repeater improves the scaling of entanglement distribution with distance
- Building a quantum repeater requires work on many different components. While all basic elements have been demonstrated, more work is required to improve efficiencies, storage times, interfaces,…



Thank you

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