Quantum communication – state-of-the-art and challenges

Wolfgang Tittel

University of Geneva*, Geneva Quantum Center, Schaffhausen Institute of Technology, Delft Technical University

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QuTech KAVLI INSTITUTE of Nanoscience Delft UNIVERSITÉ DE GENÈVE SIT GENEVA QUANTUM CENTRE

Outline

- Two types of quantum networks
- How to overcome transmission loss
- Towards quantum repeaters: sources and memories
- Outlook: A future (?) Swiss quantum communication infrastructure

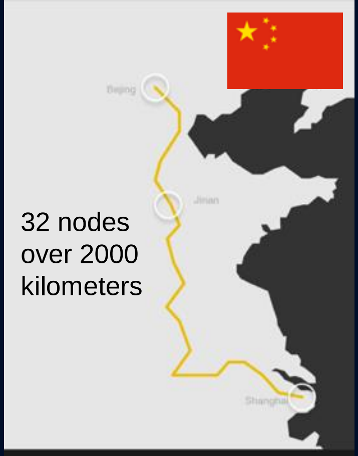
Quantum networks

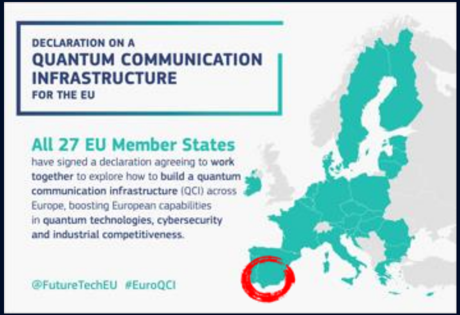
Trusted-node quantum networks

- Already implemented (China) and under development (Euro QCI)
- Allows QKD within restricted security paradigm

Repeater-based quantum networks

- Not yet ready, but rapid progress (e.g. QIA)
- For QKD with end-to-end quantum security, blind and networked quantum computing as well as distributed quantum sensing





Quantum repeater - how to mitigate loss

Goal: Overcome the exponential scaling of photon transmission over a long (lossy) quantum channel

Note: multiplexing does not lead to better scaling

Solution

1) Break long link into shorter *elementary links.*

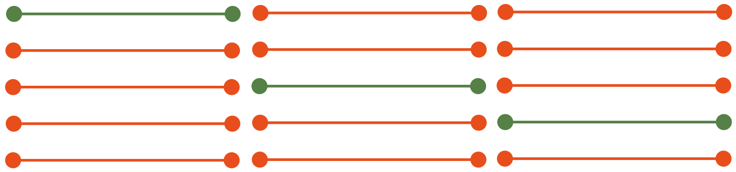
2) Distribute *heralded and long-lived entanglement* across each elementary link.

3) Multiplex distribution (any degree of freedom) to make it efficient.

4) Mode mapping based on feed-forward info allows connecting “good” links using Bell-state measurements.

Exponential scaling

Same scaling



Better scaling

No need for photons to travel *in one go* over the entire link.

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

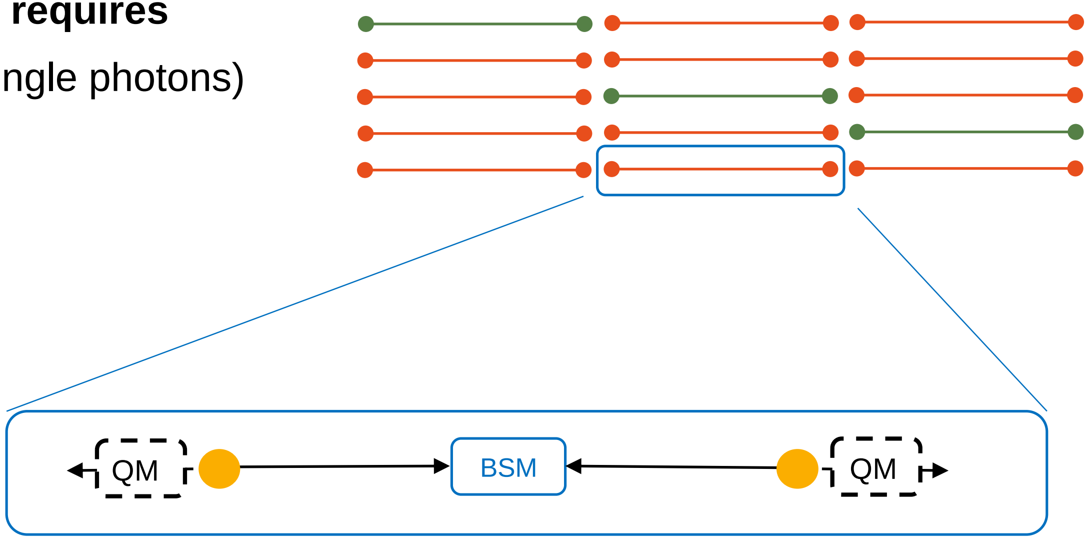
Quantum repeater components

One of the simplest repeater designs requires

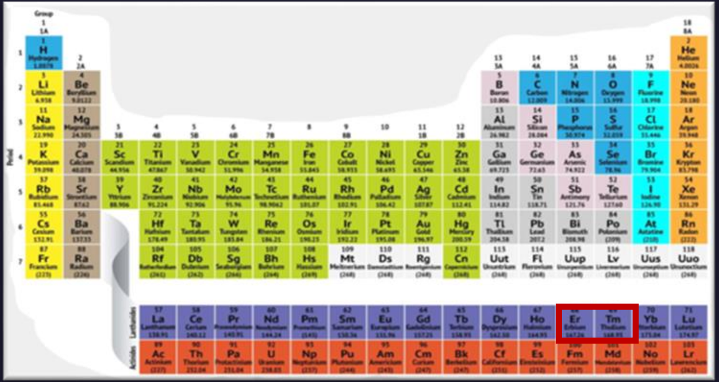
1) Sources of entangled photons (or single photons)
2) Quantum memory for light
3) Bell-state measurement
4) Compatible components

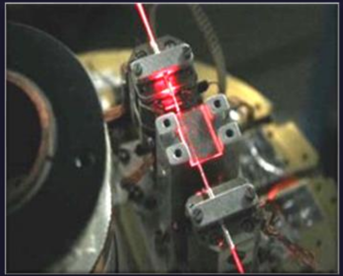
   - incl. with telecom fibers

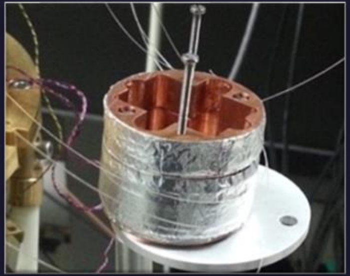
   - and satellite links



Rare-earth-ion-doped crystals

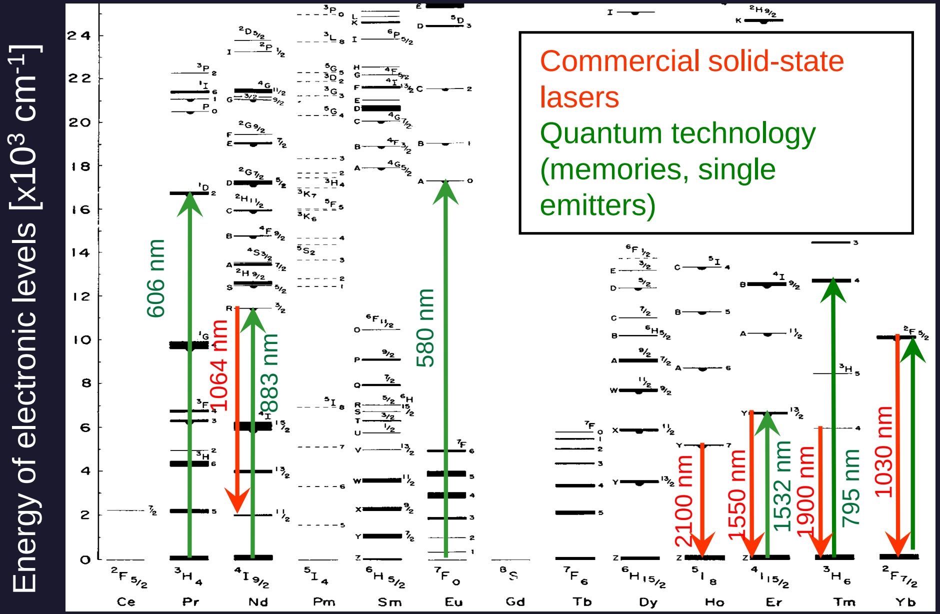






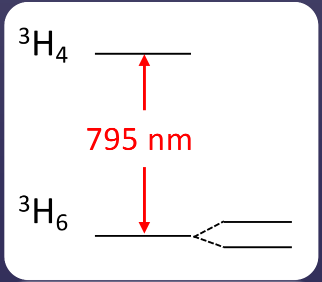
Saglamyurek, WT *et al*., Nature 469, 512-515 (2011).

Saglamyurek, WT *et al*., Nature Phot. 9, 83 (2015).

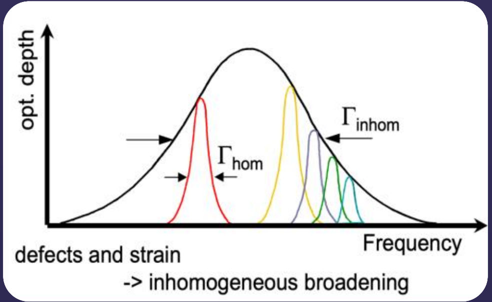


G.H. Dieke, Spectra and Energy Levels of Rare Earth Ions in Crystals, Wiley Interscience, New York,

Rare-earth crystals: a brief introduction



Simplified level structure of Tm^{3+}-doped crystals



1) Transitions in the visible and near infrared
-> quantum communication

2) $\Gamma_{inhom} \approx$ 100 MHz – 500 GHz
-> *broadband quantum memory*

3) Excited states with very long lifetimes (ms)

4) At T< 2 K: $\Gamma_{hom}^{opt} \approx$ 50 Hz – 100 kHz -> T_2 = 4 ms
-> *high-capacity & long-lived quantum memory*

5) At T< 2 K: ground states with long T_1 (d) and T_2 (h)
-> *long-lived quantum memory and qubits*

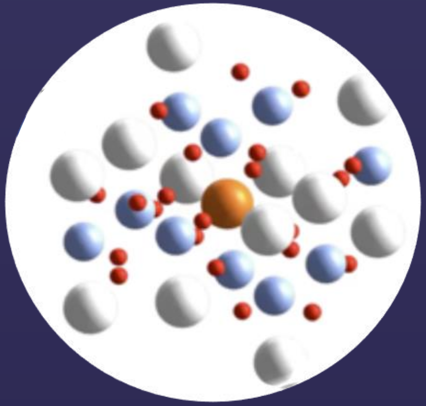
6) Electric dipole-dipole interaction between close ions
-> *quantum computing*

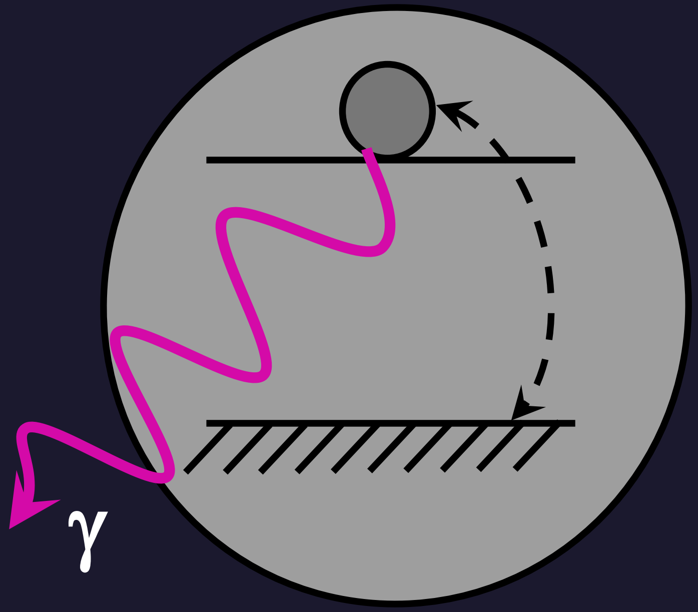
Promising for optical quantum memory and QIP. But not for sources.

Creating single photons (1)

- Photons will be emitted into random directions

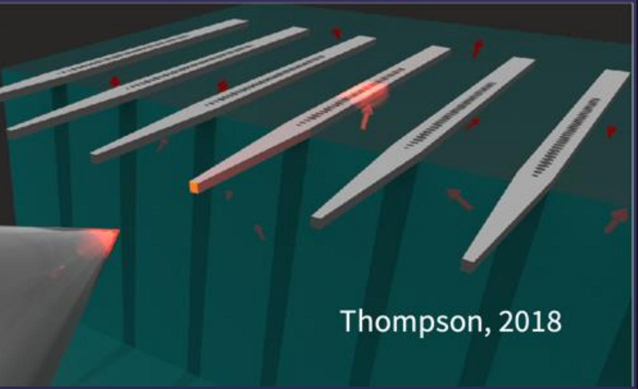
- The long optical lifetimes in rare-earth ions make observing single photons difficult

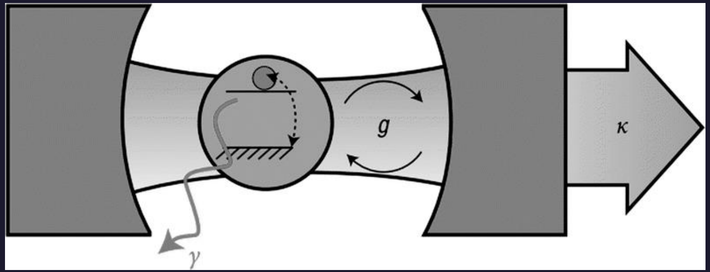




Creating single photons (2)

- Nano (photonic crystal) cavities allow increasing the emission rate (Purcell effect)
- This allows creating single photon sources and optical readout of spin qubits.





For κ >> g >> γ (weak coupling regime):

$$\gamma' = F_P \gamma_0$$

γ_0: vacuum emission rate

$$F_P = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q}{V}$$ Purcell factor

for atom in max field region

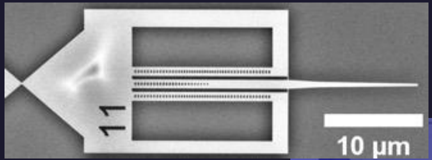
Quality factor

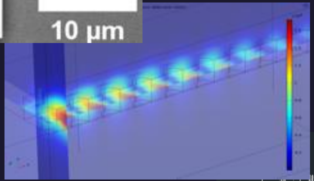
$$Q = \frac{\nu}{\Delta\nu}$$

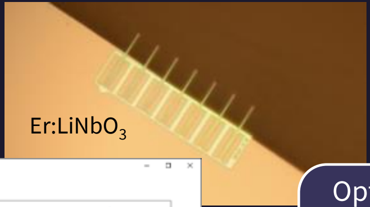
Mode volume

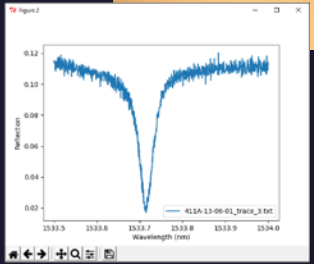
$$V = \int d^3\mathbf{r} \frac{\epsilon(\mathbf{r})|\,E(\mathbf{r})\,|^2}{max\{\epsilon(\mathbf{r})|\,E(\mathbf{r})\,|^2\}}$$

Single-photon sources using REIs – fabrication cycle









Design and Simulations

Patterning:
E-beam lithography

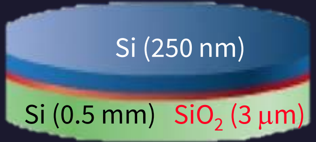
Patter transfer:
Cryo-etching

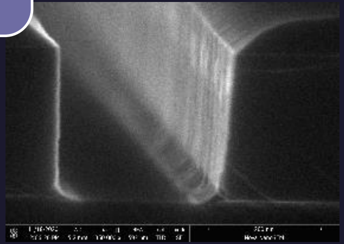
Under-cutting:
Hydrofluoric acid

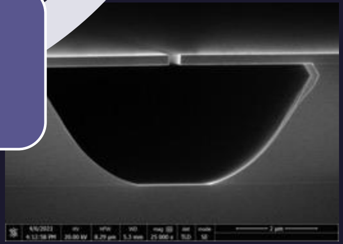
Inspection:
Optical microscope & SEM

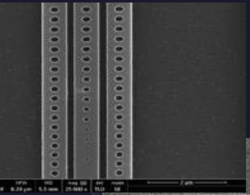
Optical characterization in air, and after transfer on Er:$LiNbO_3$, at T=293K and T=4K

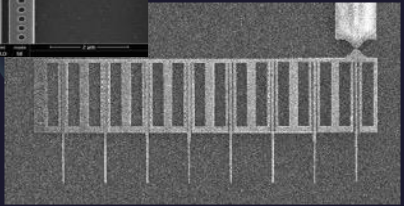
Spectra and quality factor





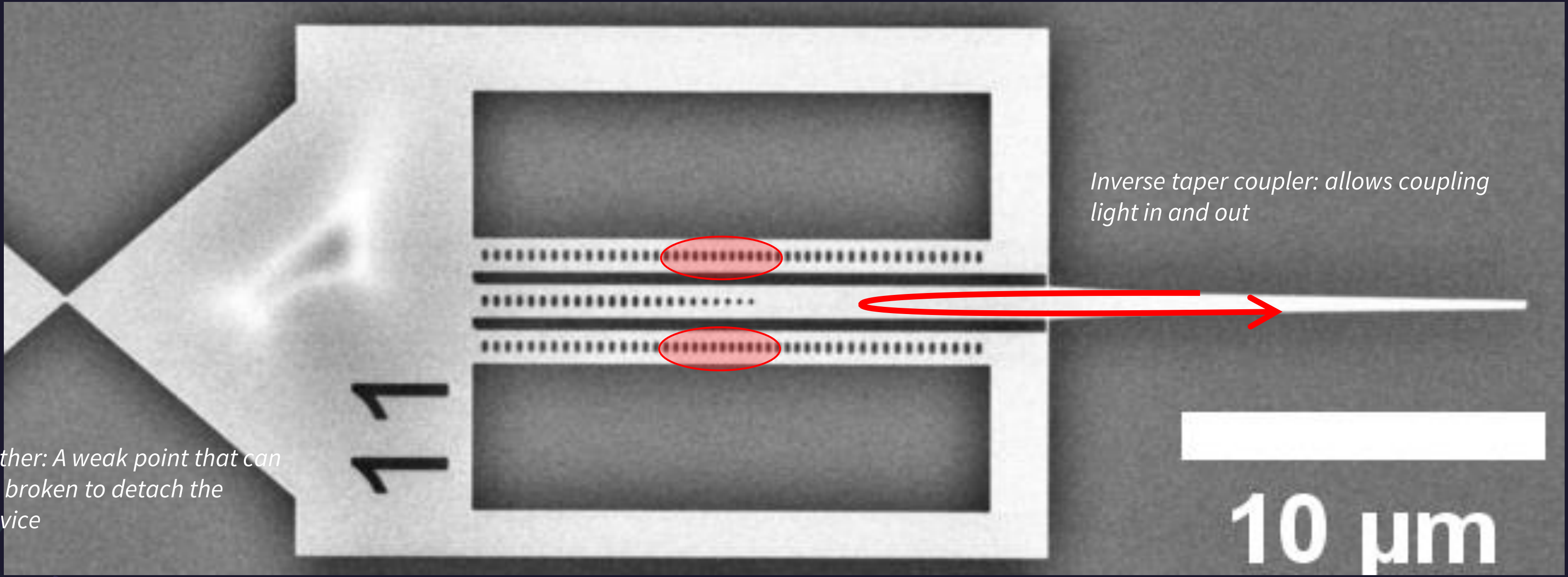






Design

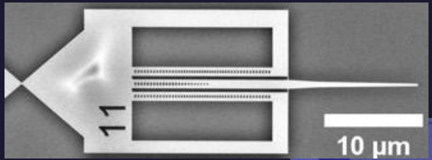
A “bus” waveguide (with Bragg reflector): couples to 2 nanobeam cavities

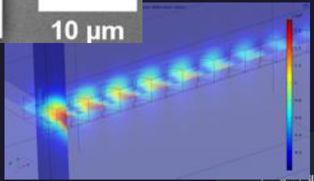


Tether: A weak point that can be broken to detach the device

Based on S.M. Meenehan *et al*. *Phys. Rev. A* 90, 011803(R) (2014)

Single-photon sources using REIs – fabrication cycle





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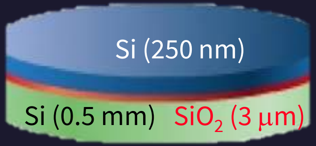
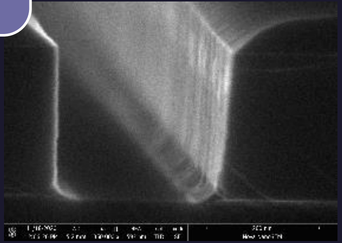
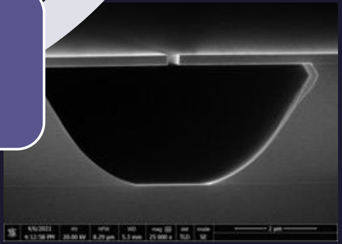


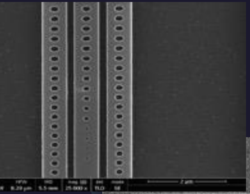
Patter transfer:
Cryo-etching

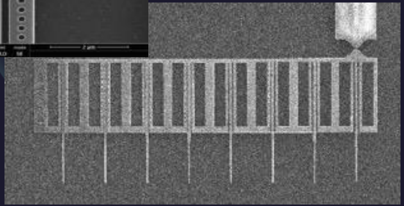


Under-cutting:
Hydrofluoric acid



Inspection:
Optical microscope & SEM





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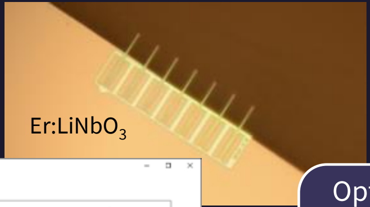
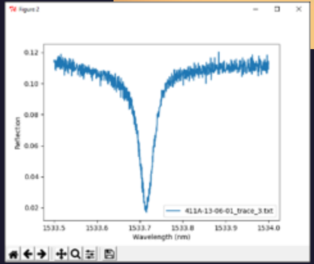
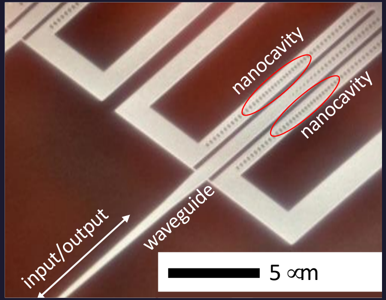


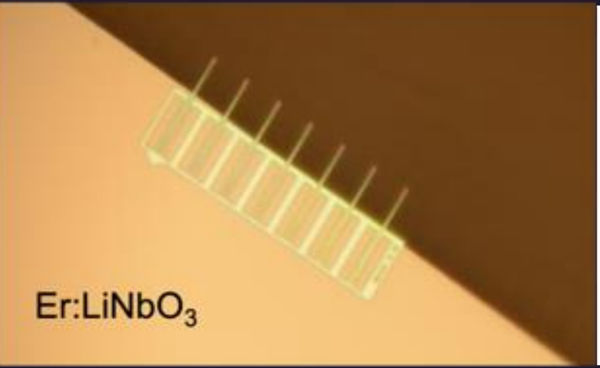


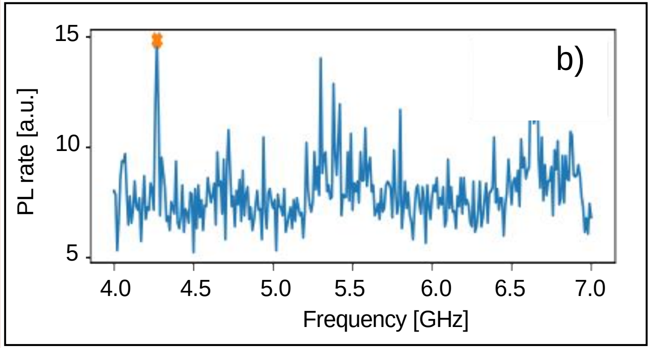
Purcell-enhanced emission (ongoing)

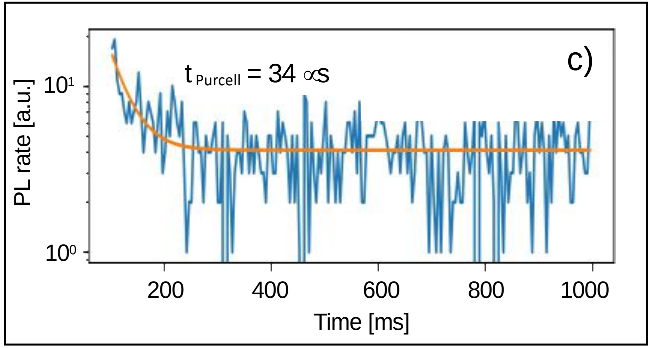


- Si cavity on 0.005% $Er:LiNbO_3$
- Observation of isolated photoluminescence lines. Individual ions?
- 60-fold reduction of decay constant from 2 ms
- T_1 lifetimes of around 1 μsec and radiatively limited emission ($T_1=T_2/2$) seem possible

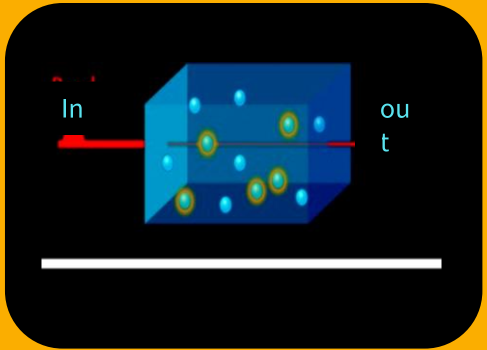
  -> single- (and entangled-) photon sources, QI processing nodes



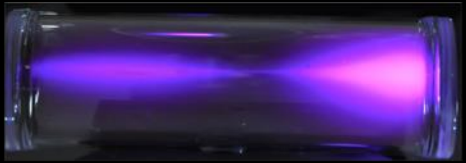




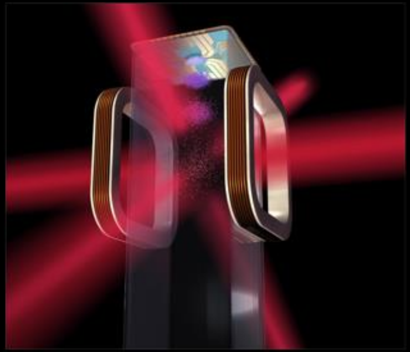
How to store photonic quantum states in a multiplexed manner? Use large ensembles of atoms



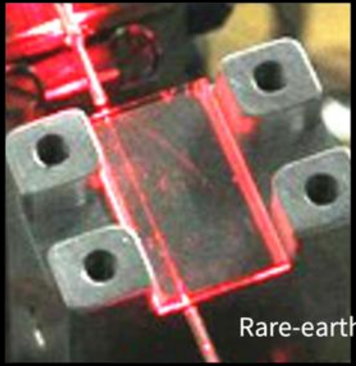
$$|\psi'\rangle = \mathbb{1}|\psi\rangle$$



Room-temperature vapor



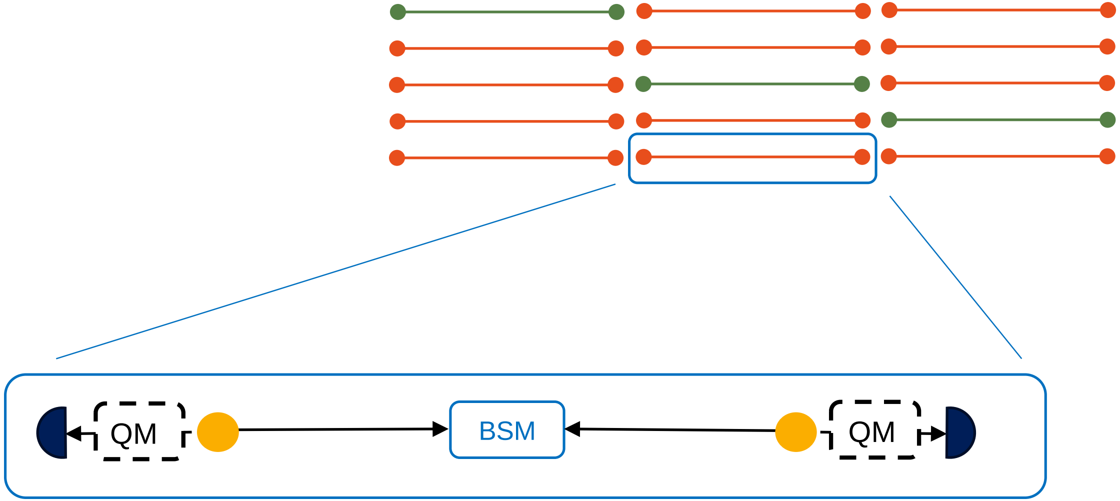
Laser-cooled atoms



Rare-earth crystals

Quantum memory requirements

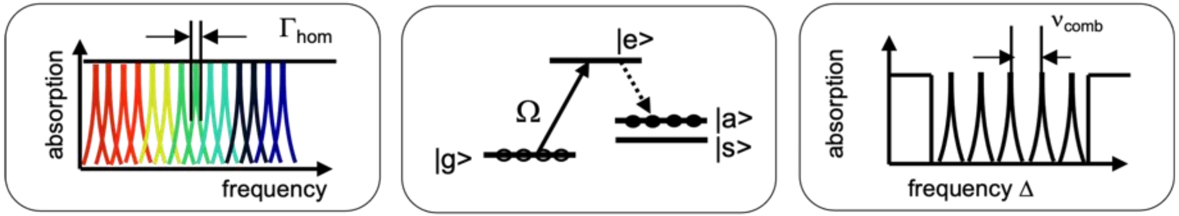
1) **Large storage efficiency**
2) **Sufficient storage time**
3) Fidelity ->1
4) Feed-forward mode mapping
5) High multiplexing capacity
6) Wavelength of operation
7) Bandwidth per qubit
8) Integrability

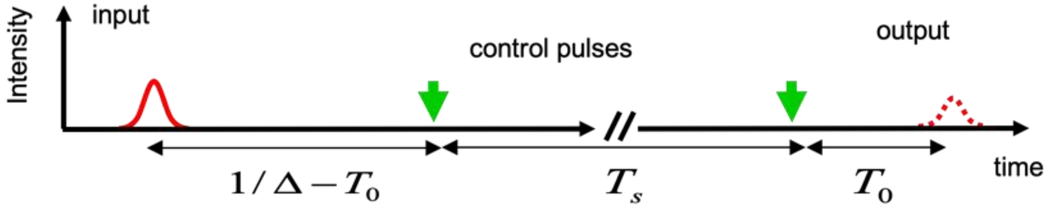


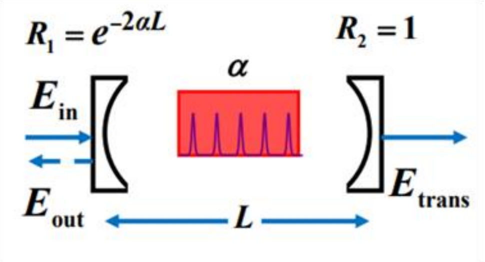
Necessary criterion for QM: storage efficiency better than using a fiber creating same delay

The atomic frequency comb (AFC) protocol in rare-earth crystals

- Rare-earth crystals and atomic frequency combs (AFC)







- 2-level AFC protocol with fixed storage time: $\tau=1/\nu_{comb}$
- Feed-forward mode-mapping possible using external devices
- Well suited for multiplexing
- Efficiency limited by T_2^{opt} :

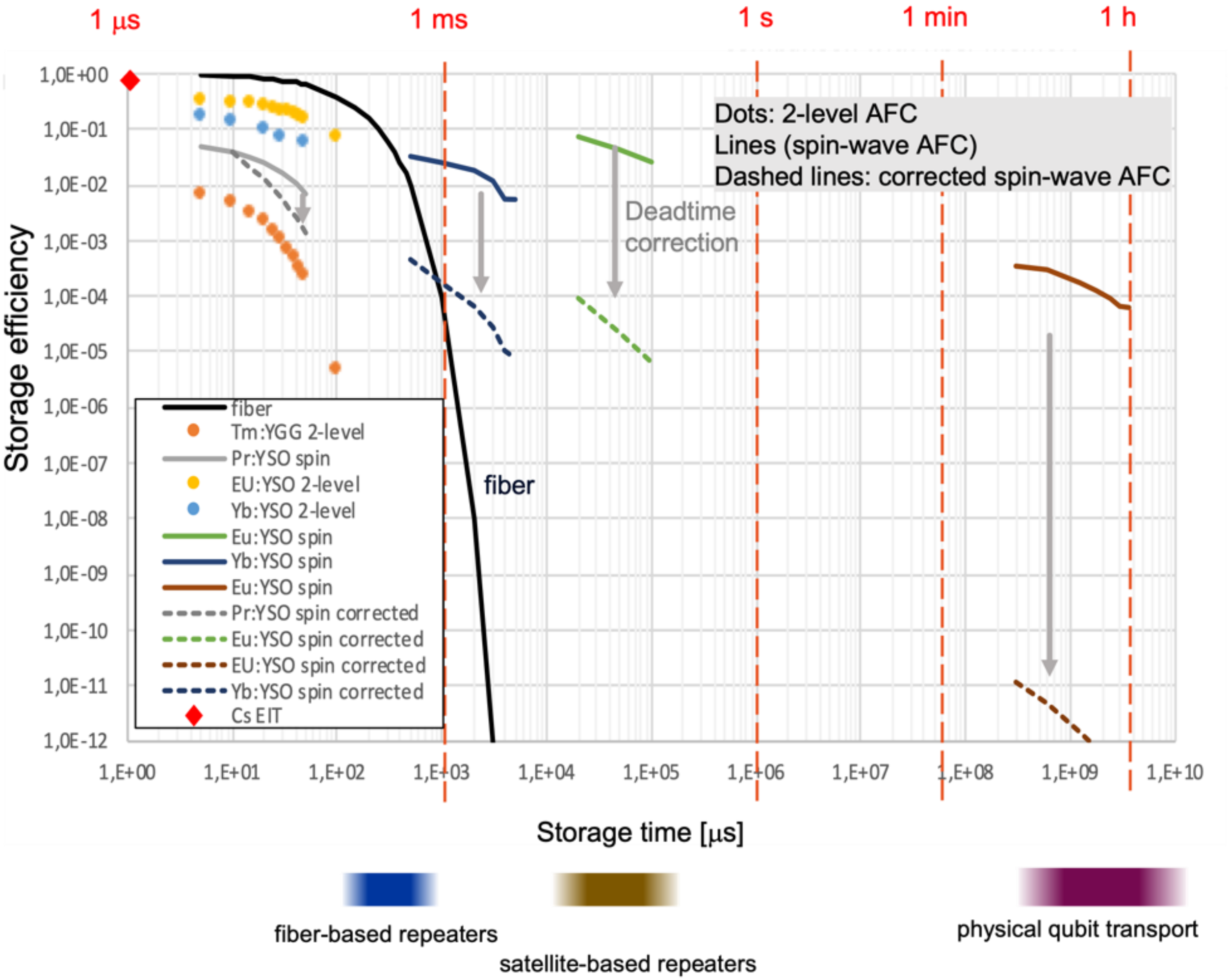
- Extension to spin-wave storage allows memory-internal read-out on demand
- Storage time (efficiency) then limited to spin level broadening (<- refocusing pulses)

- Impedance-matched cavities allow high-efficiency storage despite small optical depth αL

M.Afzelius et al. Phys. Rev. A **79**, 052329 (2009); N Sinclair, WT *et al.*, PRL113, 053603 (2014); M. Afzelius and C. Simon, PRA 82, 022301 (2010).

QM: recent developments

- Comparing results taken under different conditions… But while not all experiments demonstrate quantum nature, all used a quantum protocol
- Three use cases (my definition)
  - Quantum repeaters for fiber networks
  - Quantum repeaters for satellite networks
  - Physical qubit transport
- 2-level AFC: not yet better than fiber, but close. Materials with sufficient T_2^{opt} and T_2^{spin} exist. Need to reduce technical noise.
- AFC spin-storage: scaling already better than fiber, but efficiencies still small. Reduced when considering deadtime.
- EIT-based storage: best efficiency, but longer storage required
- Heralded entanglement between two rare-earth crystals demonstrated in 2021

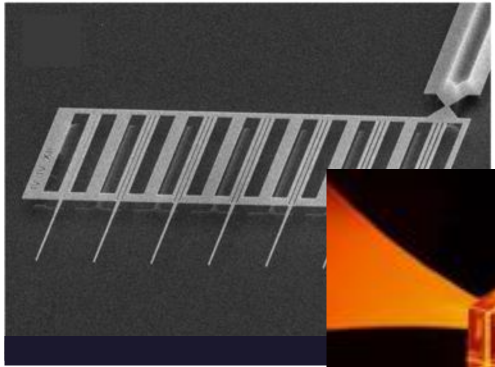


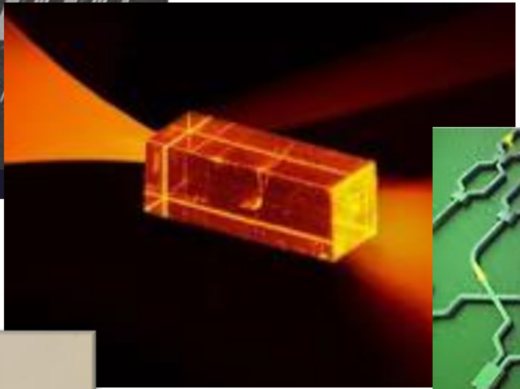
Outlook: Towards an integrated platform

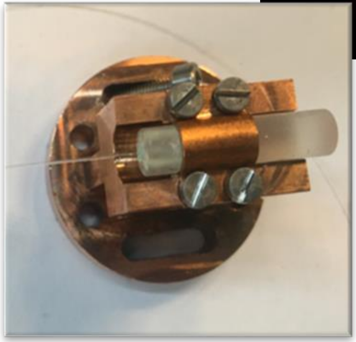
- Create single (and entangled) photons based on Purcell-enhanced emission from individual rare-earth ions

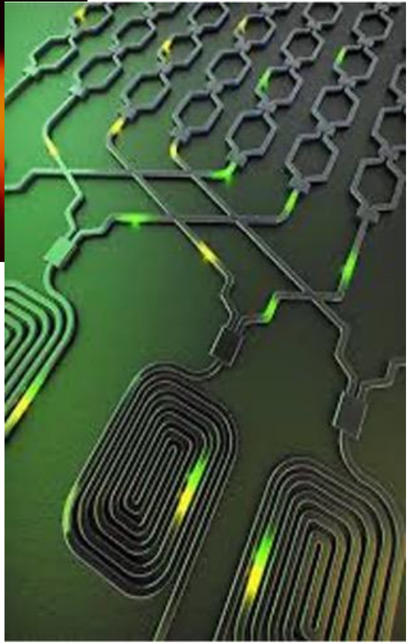
- Create compatible quantum memories based on large ensembles of rare-earth ions

- Exploit maturity of Si and SiN photonics to create integrated devices



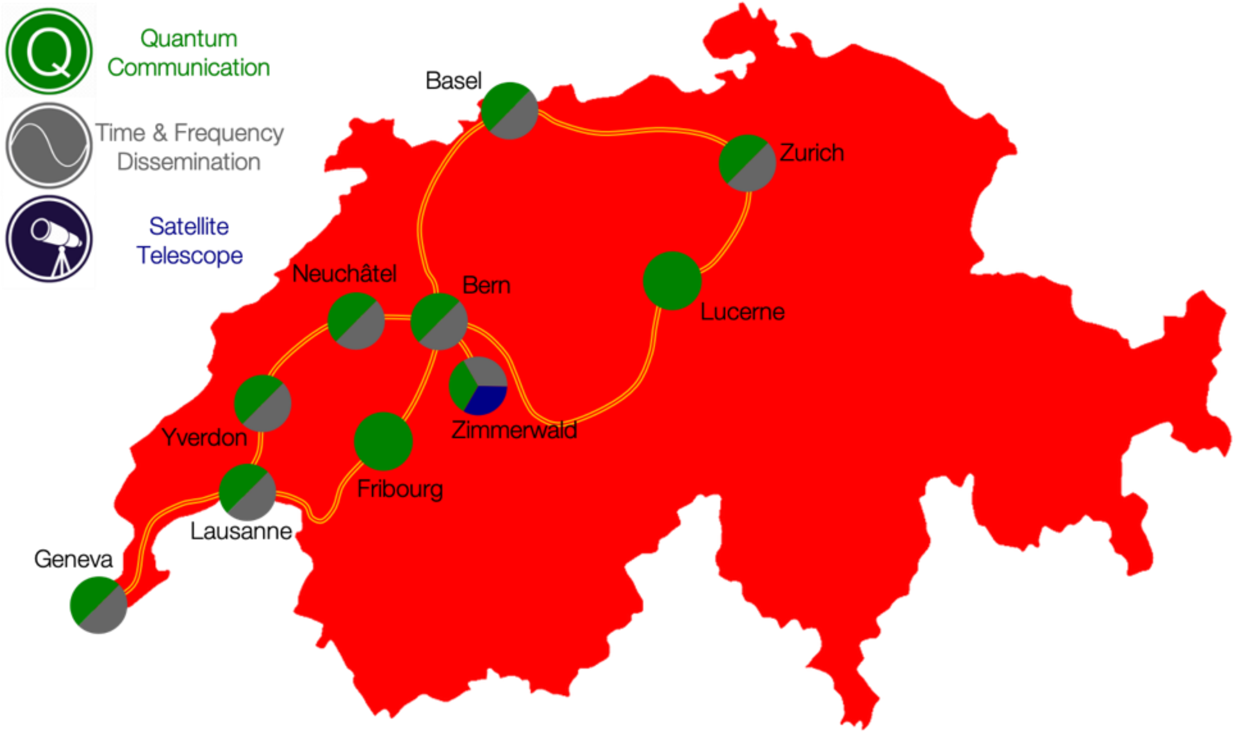






A Swiss QCI?

To be led by UniGe (if funded)
To explore and test
- QKD/Quantum Cryptography
- Quantum repeater technology
- Distributed Sensing & Metrology



Thank you!