Quantum network technology

The second life of rare-earth crystals

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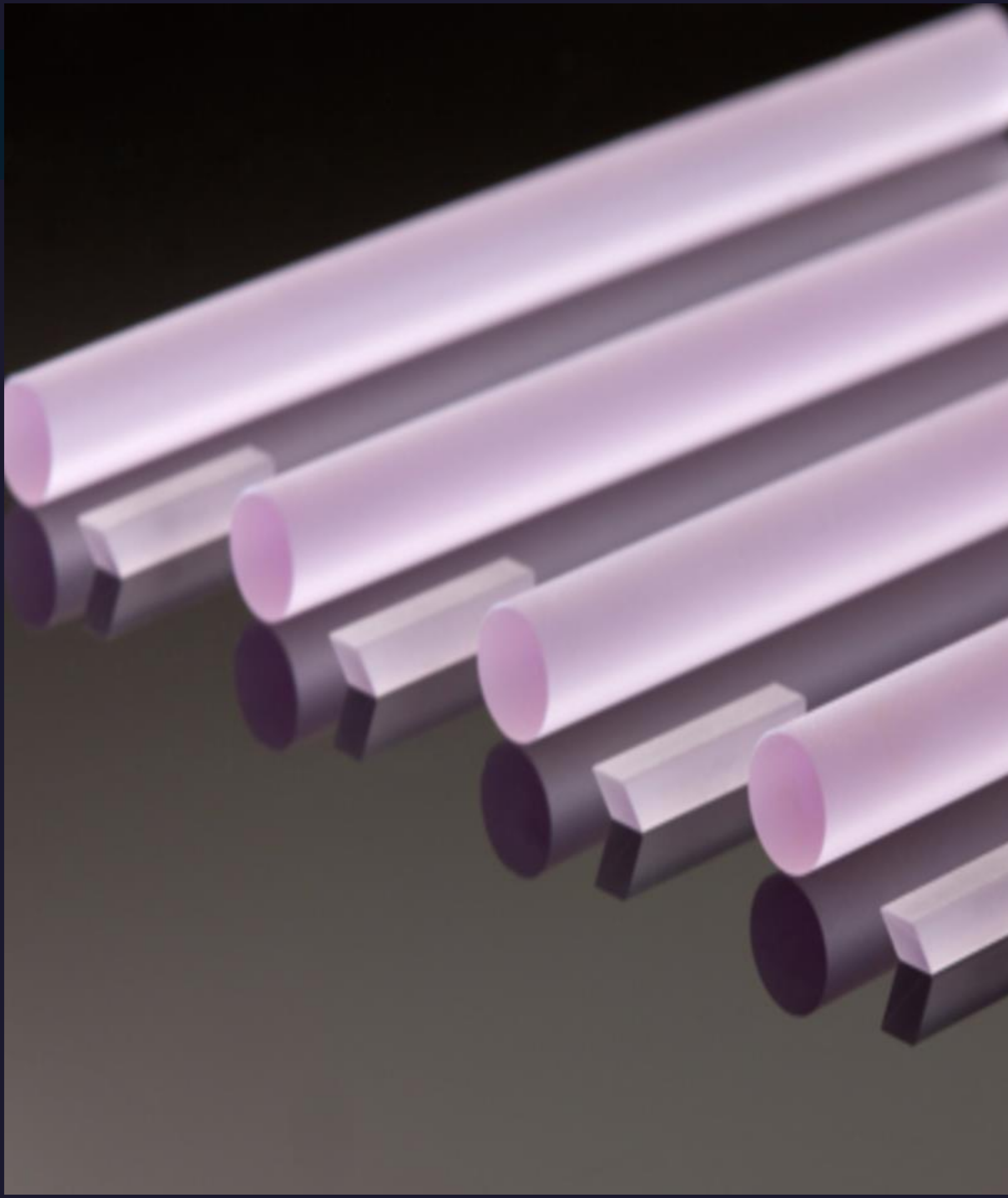
Constructor Institute of Technology & Constructor University

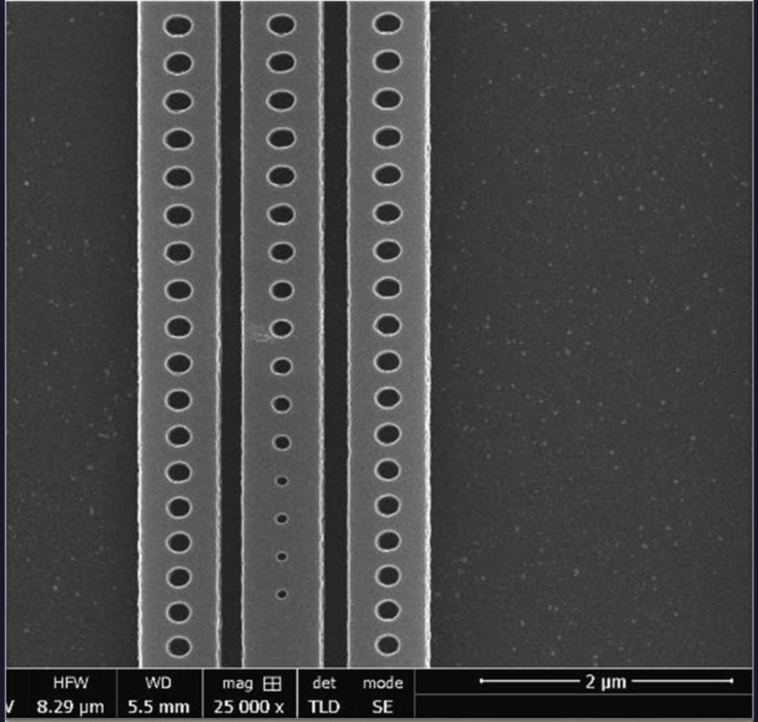


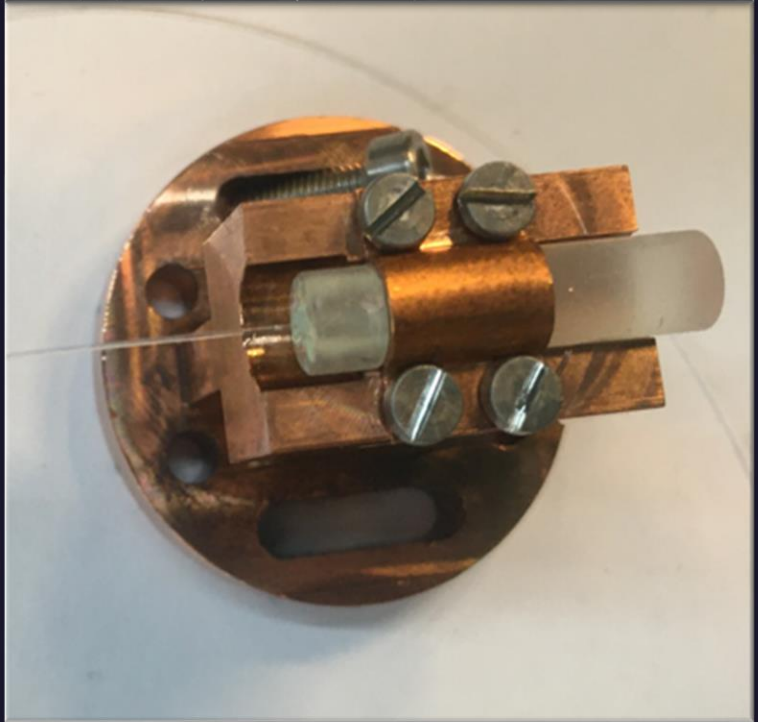
Elements of a quantum network

- Interacting centers for matter-based qubits
- Individual optical centers for single and entangled photons
- Large ensembles for high-capacity, feed-forward-controlled optical quantum memories
- For compatibility and scalability, these components should be based on the same type of defect and be on-chip integrable using standard photonics technology.

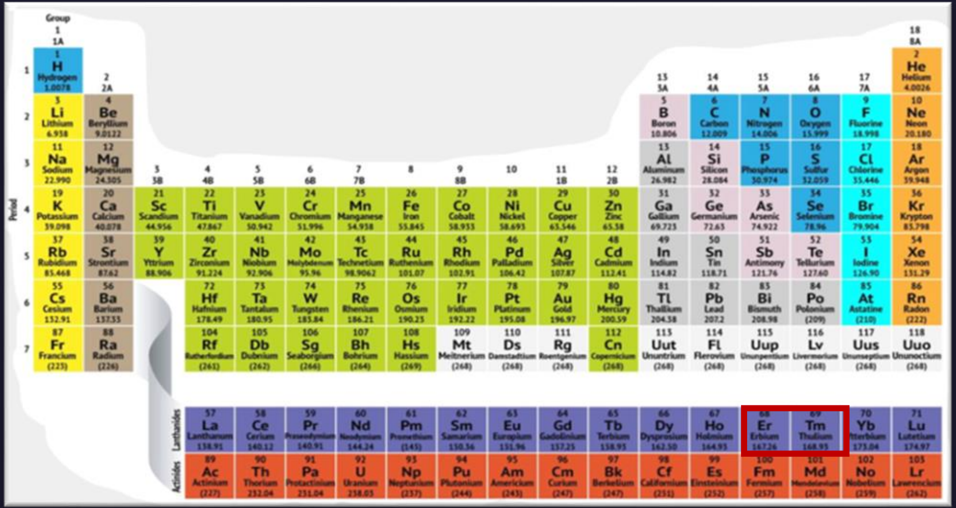
Outline

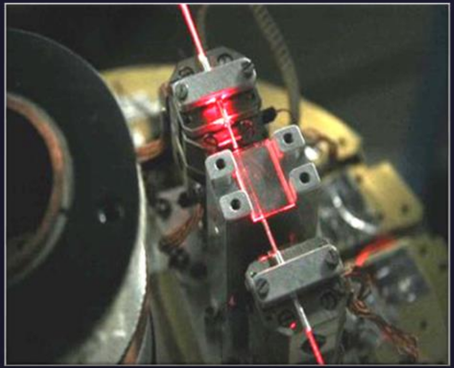
- Rare-earth ion-doped crystals
- Single photons based on individual rare-earth ions
- Optical quantum memory using ensembles of rare-earth ions
- Outlook and conclusion

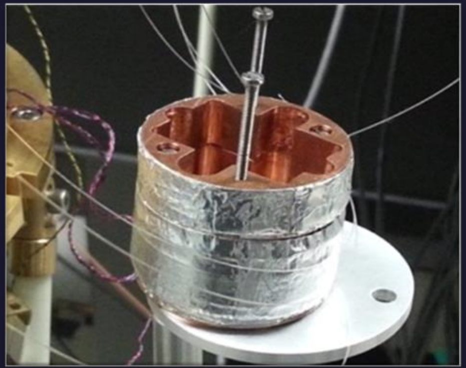




Rare-earth ion-doped crystals

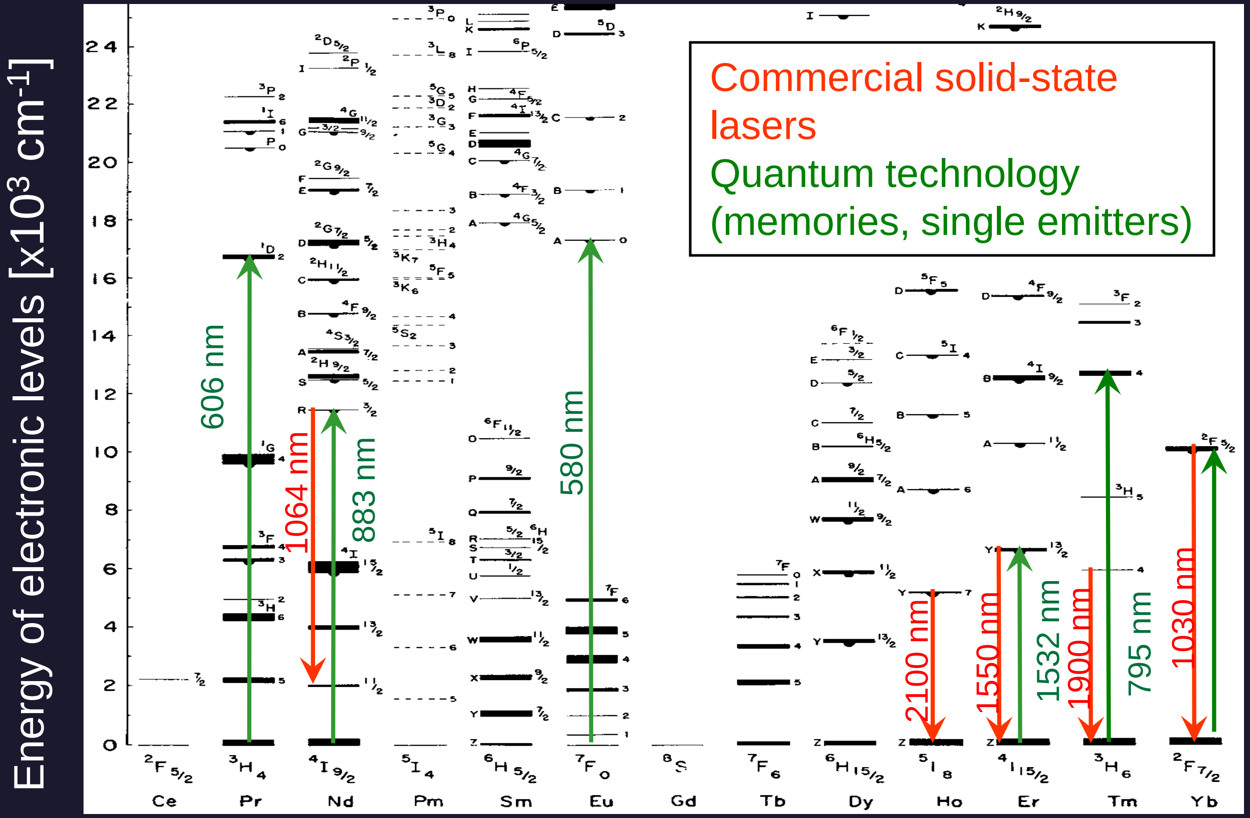






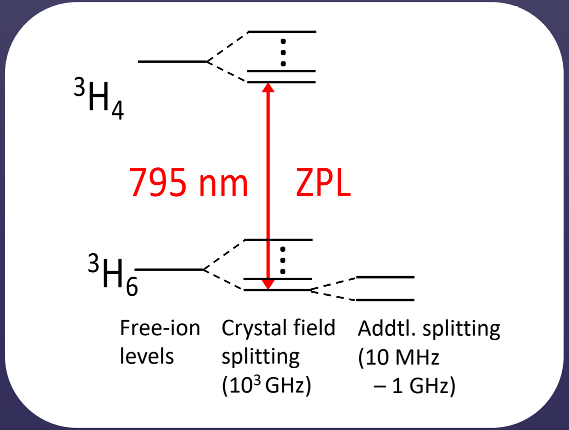
Saglamyurek, WT *et al.*, Nature 469, 512-515 (2011).

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

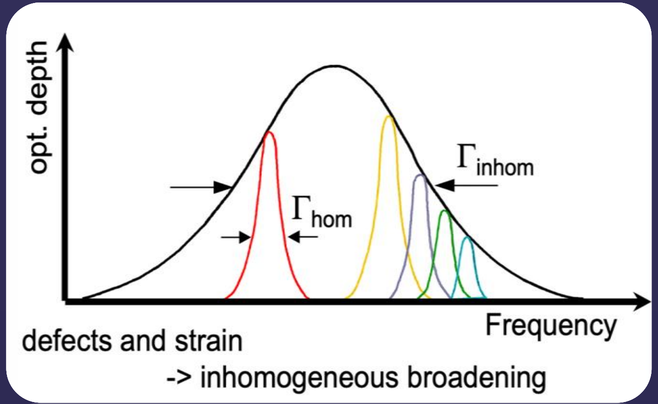


G.H. Dieke, Spectra and Energy Levels of Rare Earth Ions in Crystals, Wiley Interscience, New York, 1968.

Rare-earth crystals: a brief introduction



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



1) Transitions (zero-phonon lines) 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)
-> *difficult to observe single-photon emissions*

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

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

6) Electric dipole-dipole interaction between neighboring ions
-> *quantum gates*

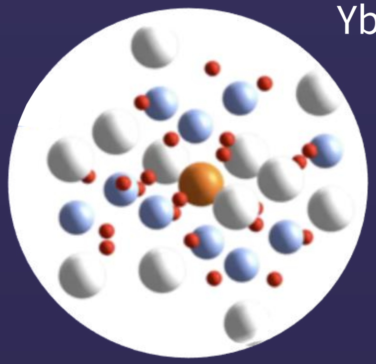
Promising for optical quantum memory and QIP. But not for single-photon emitters.

How to create a single photon? Spontaneous emission from a single emitter

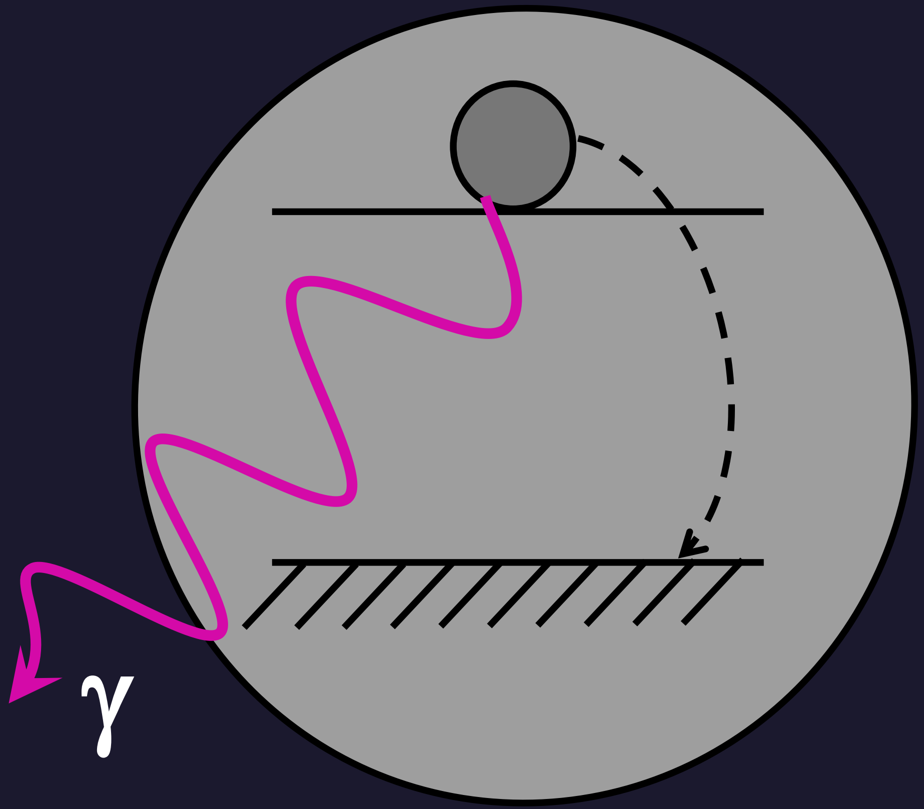
- The long optical lifetimes in rare-earth ions result in very small decay rates

- Photons will be emitted into random directions

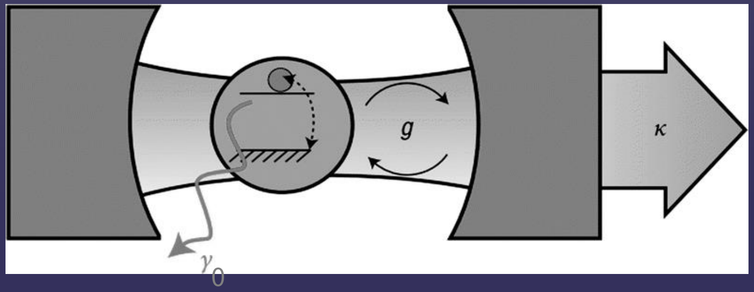
Yb:YVO_4



Single rare-earth ion



Creating (and observing) single photons



$$g = \frac{\mu_{eg}}{\hbar}\sqrt{\frac{\hbar\omega}{2\varepsilon_M V_{mode}}}$$

For $\kappa >> g >> \gamma_0$ (weak coupling regime):

$$\gamma' = F_P \gamma_0$$

γ_0: vacuum emission rate

$$F_P = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q}{V}\left|\frac{E(\mathbf{r})}{E_{max}}\right|^2$$ Purcell factor

for atom in max field region

Quality factor

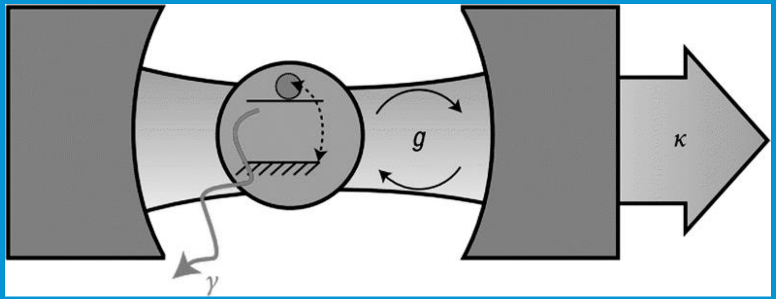
$$Q = \frac{\nu}{\Delta\nu}$$

Mode volume

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

Needed: cavity with small V and large Q

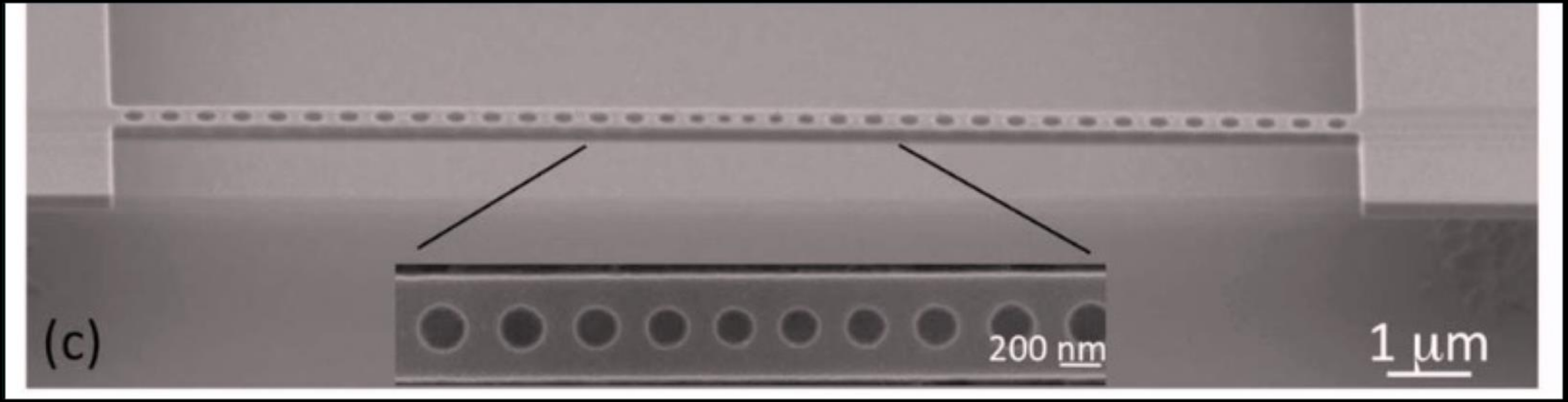
The Purcell effect: atom-light interaction in the weak coupling regime

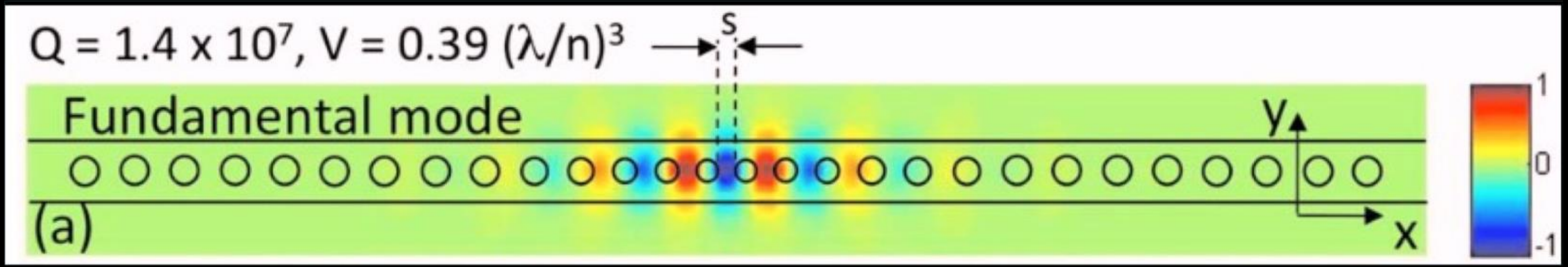


$$g = \frac{\mu_{eg}}{\hbar}\sqrt{\frac{\hbar\omega}{2\varepsilon_M V_{mode}}}$$

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

Nano-photonic crystal cavities



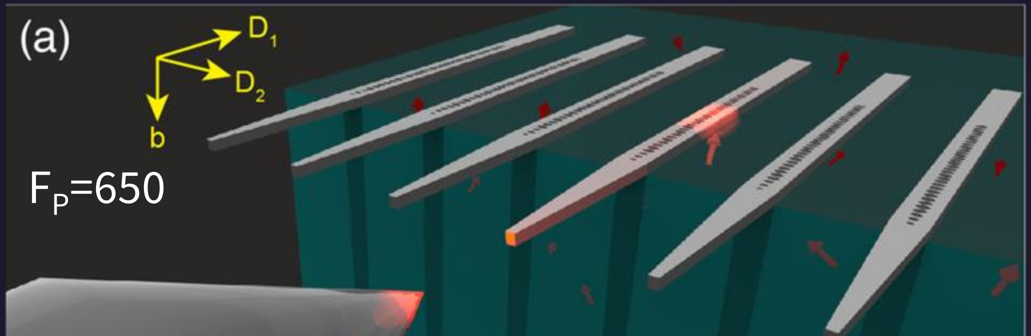


Deotare et al. *Appl. Phys. Lett.* 94, 121106 (2009)

Single photons from individual rare-earth ions

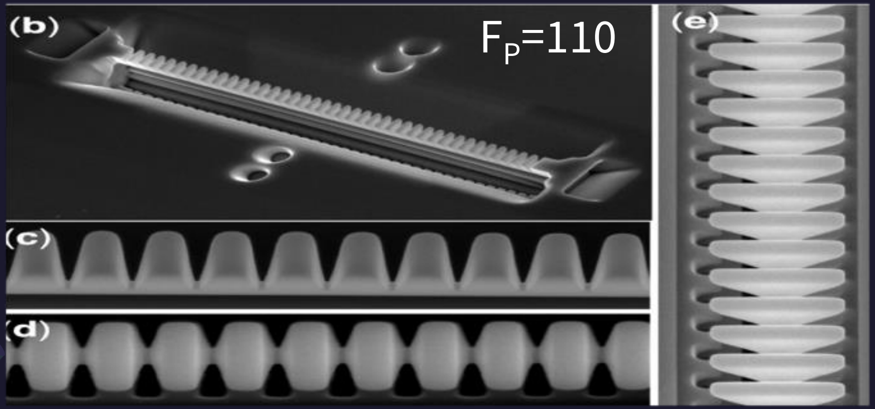
- **Purcell-entangled light-matter interaction** has enabled the observation of true single photons from individual rare-earth ions coupled to nanocavities.

Heterogeneous approach



Thompson group: Silicon photonic crystal (nano) cavity stamped on top of Er:YSO (PRL 2018)

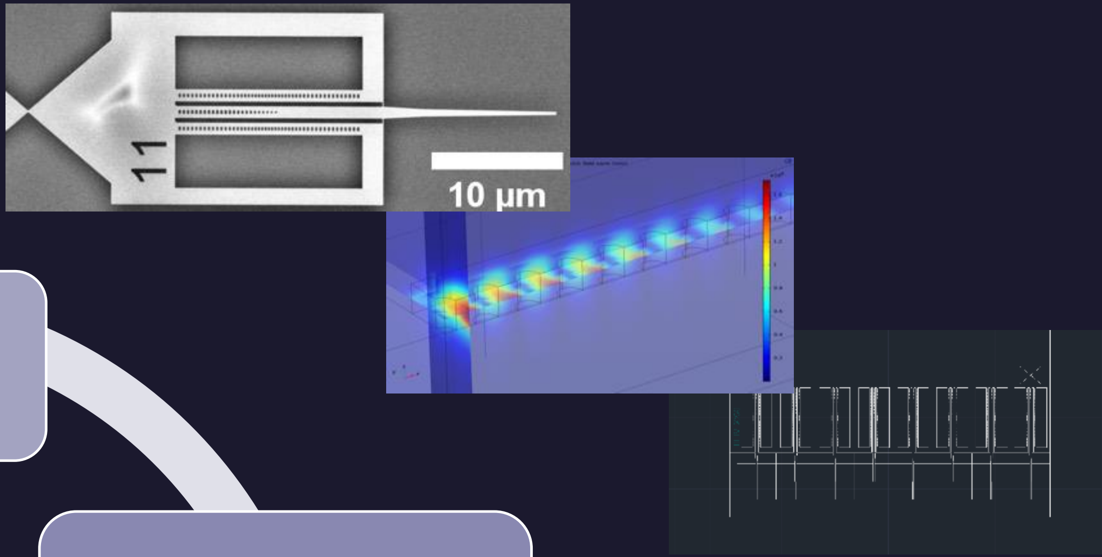
Homogeneous approach



Faraon group: photonic crystal nano-cavity milled out of $Nd:YVO_4$ (PRL 2018)

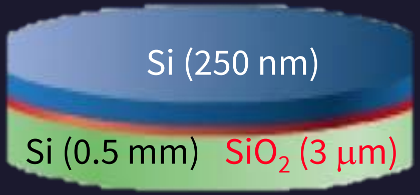
A single-photon source based on Er:$LiNbO_3$

Design and Simulations



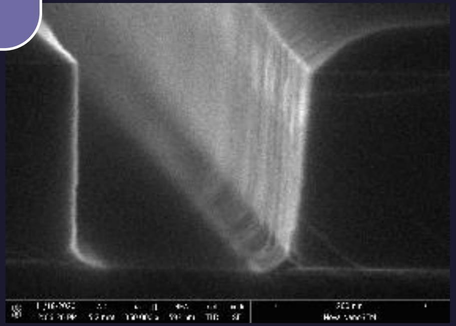
Patterning:

E-beam lithography



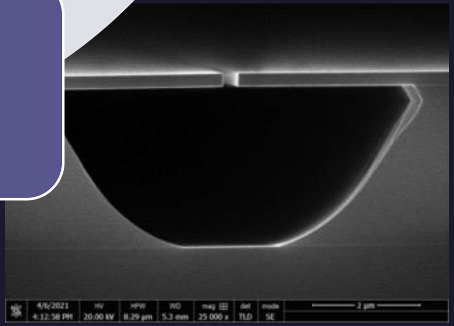
Patter transfer:

Reactive ion etching



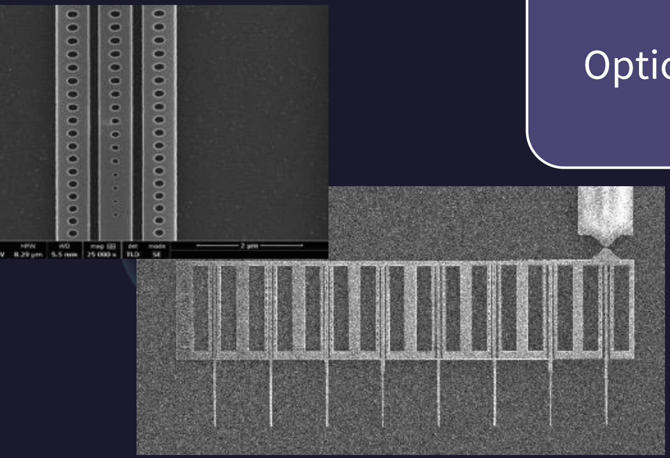
Under-cutting:

Hydrofluoric acid



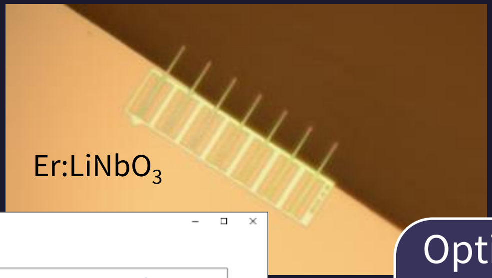
Inspection:

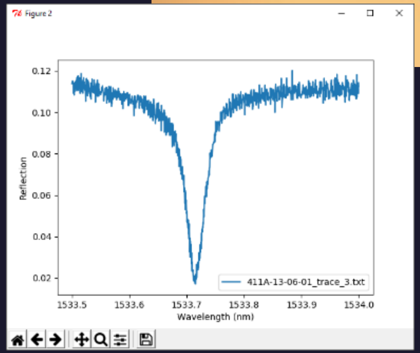
Optical microscope & SEM



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

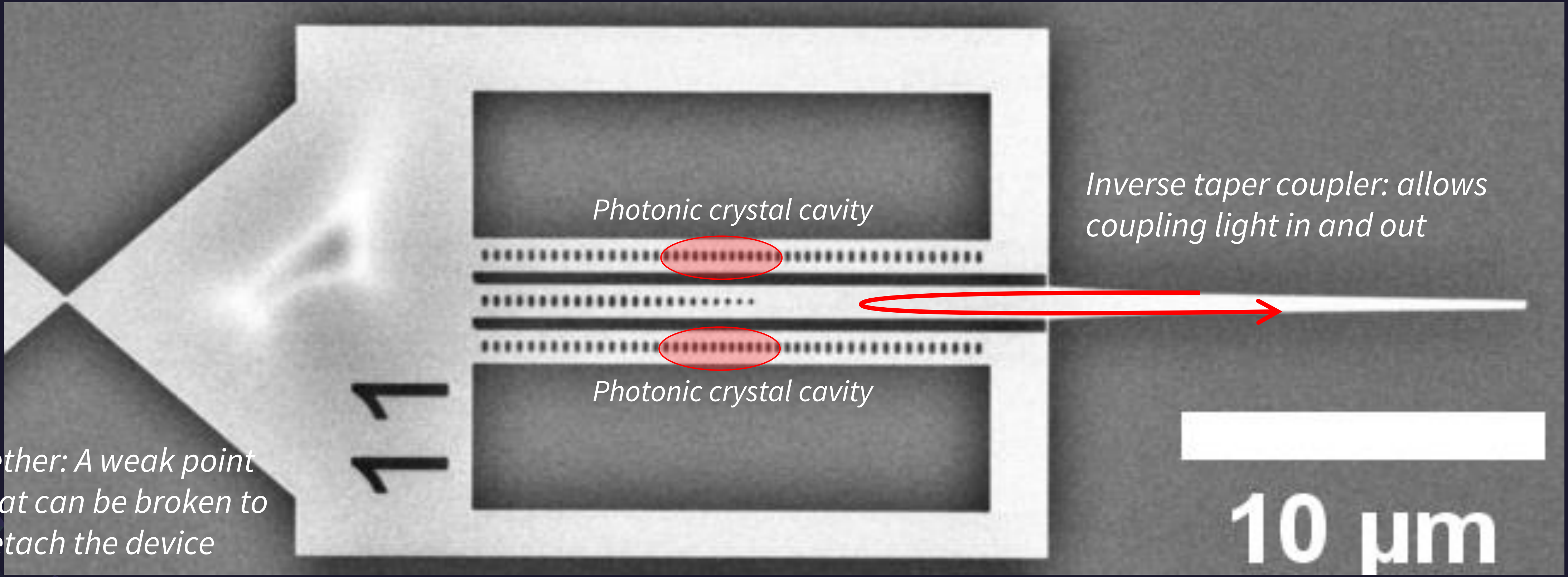
Spectra and quality factor





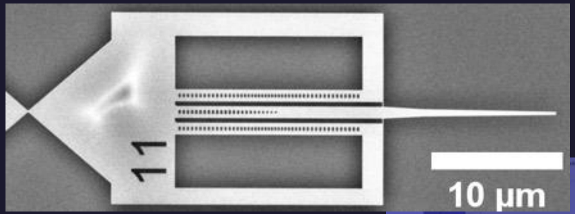
Design

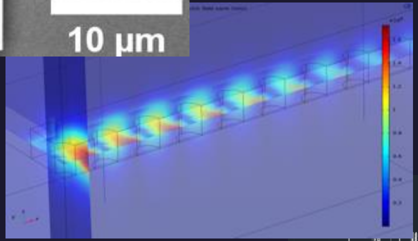
A "bus" waveguide (with Bragg reflector): couples to 2 nanobeam cavities

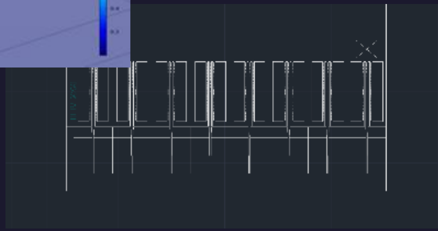


Joint work with Gröblacher group

A single-photon sources based on $Er:LiNbO_3$







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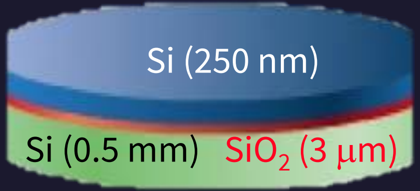
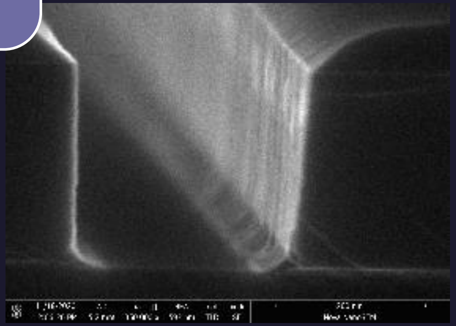


Patter transfer:

Reactive ion etching



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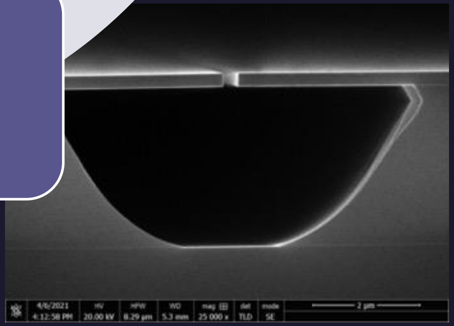

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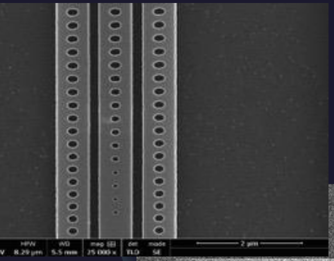

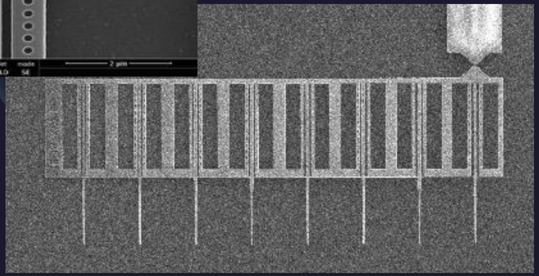

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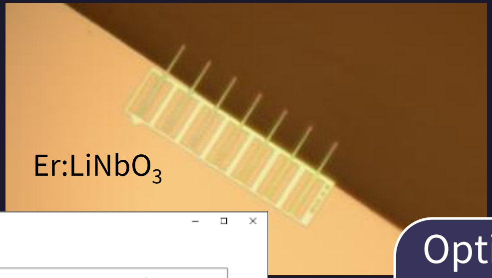
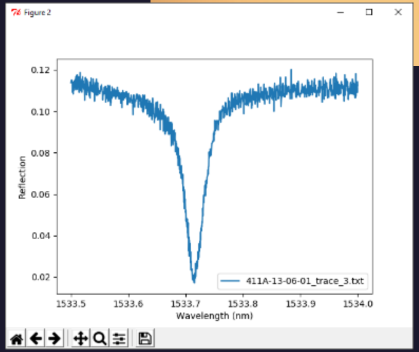
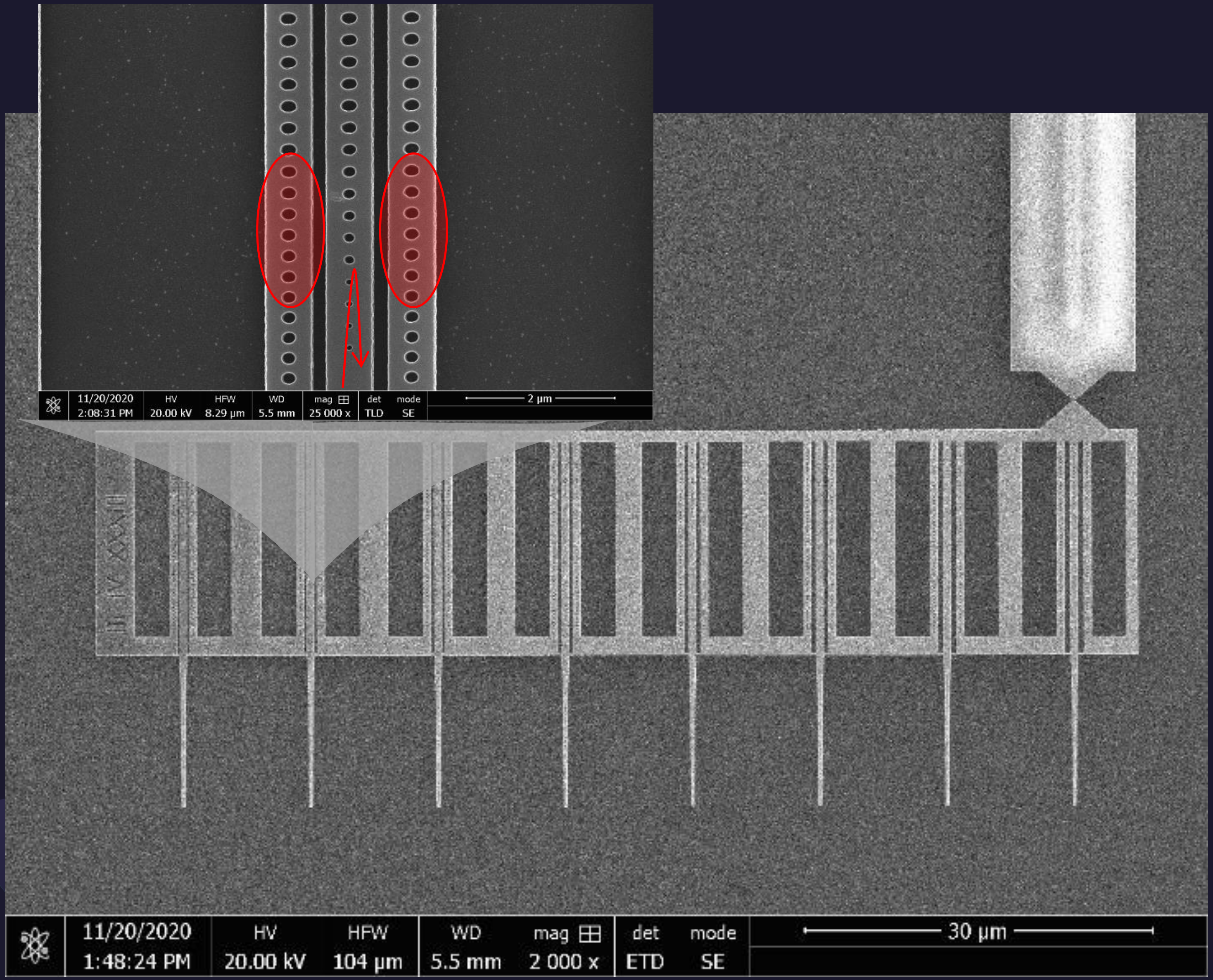




Cavity characterization

Mode volume	calculated	0.1 μm^3
Quality factor (on Er: $LiNbO_3$)	measured	50 000
Purcell factor ($E=E_{max}$, $\beta=1$)	predicted	1 000

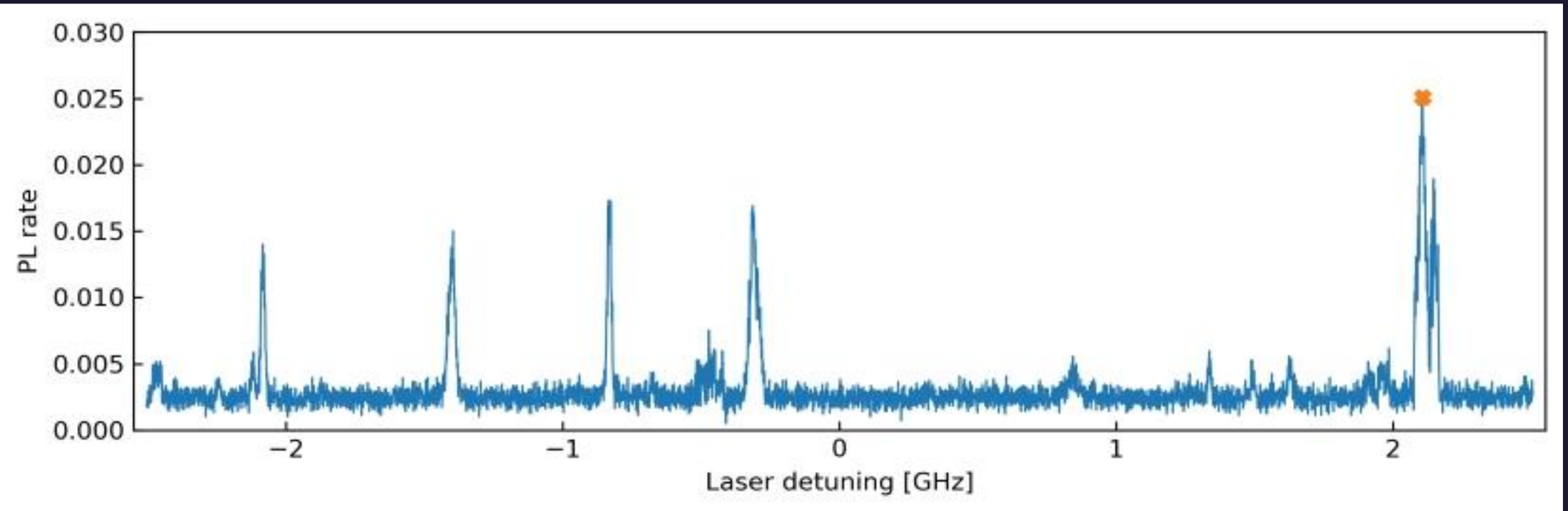
$$F_P = \frac{3}{4\pi^2}\left(\frac{\lambda}{n}\right)^3 \frac{Q}{V}$$ Purcell factor

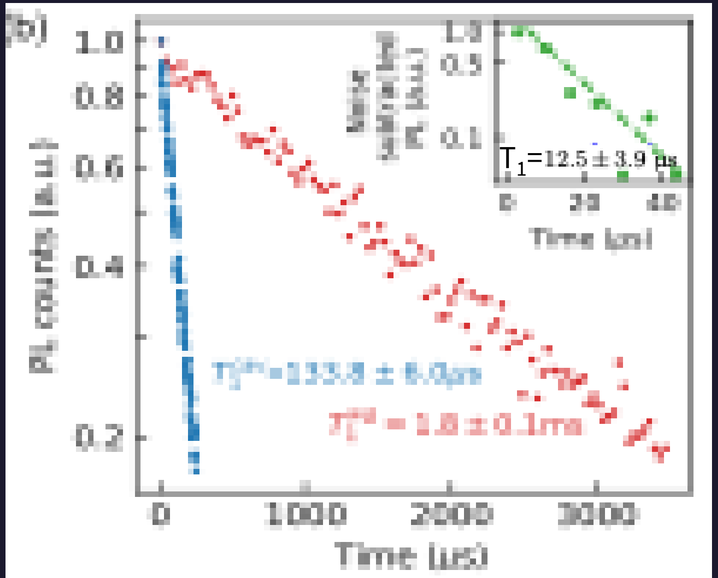


Purcell-enhanced emission

- Si cavity on 0.005% $Er:LiNbO_3$
- T approx. 50 mK
- Observation of isolated photoluminescence lines off line-center
- 13-fold(144-fold) reduction of decay constant from 1.8 ms to 134 µs (12.5 µs)
- T_1 <10 µsec and radiatively limited emission (T_1=T_2/2) seem possible
  -> Fourier-limited photons

Joint work with Gröblacher group, TU Delft

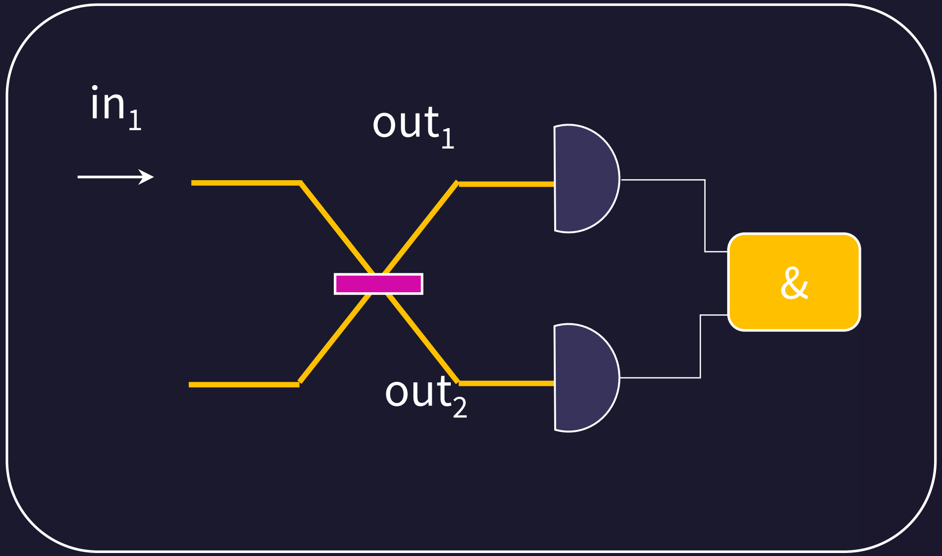




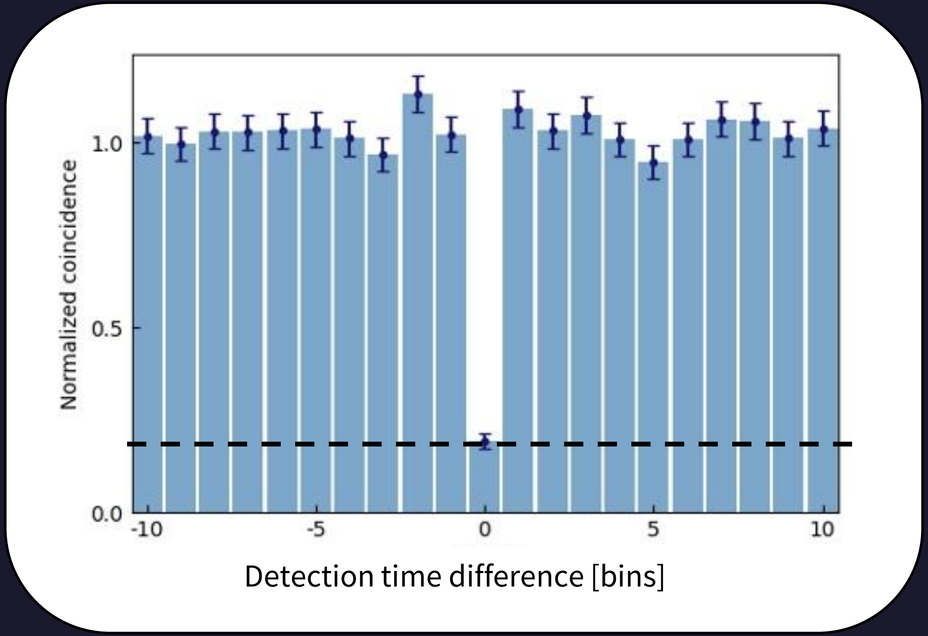
Purcell-enhanced emission

- Measurement of auto-correlation coefficient shows non-classical (single-photon) nature of emissions and confirms interaction with individual erbium ions
  - -> single-photon source and possibility for qubit read-out

$g^2(0) = 0.190 +- 0.02$

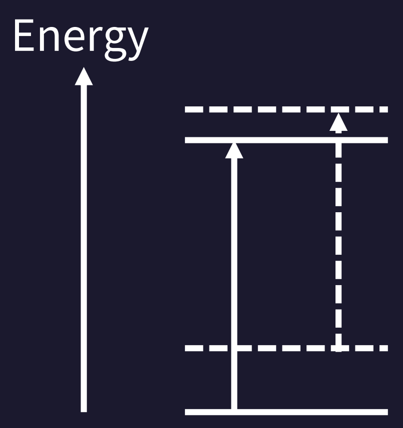


Experimental setup



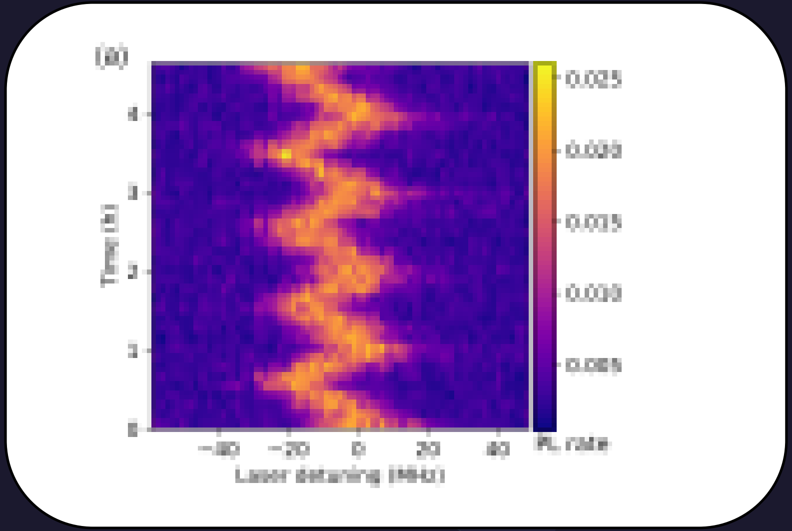
Joint work with Gröblacher group, TU Delft

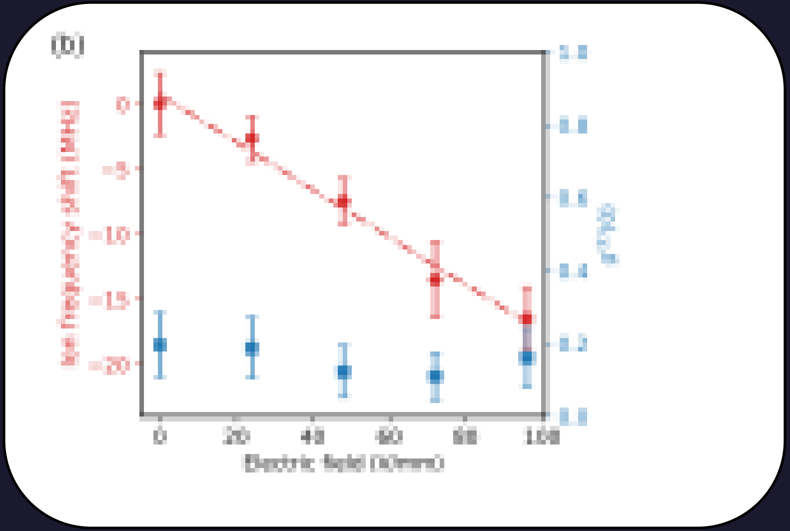
Purcell-enhanced emission



$\Delta\nu = (\vec{d}_e - \vec{d}_g)\vec{E} / h$

- Demonstration of Stark tunability of single ion
- Single-photon character not affected
- Feedback mechanism to counter spectral diffusion
    - -> indistinguishable single photons
    - -> distant spin-spin entanglement
    - -> heralded entangled photon pairs

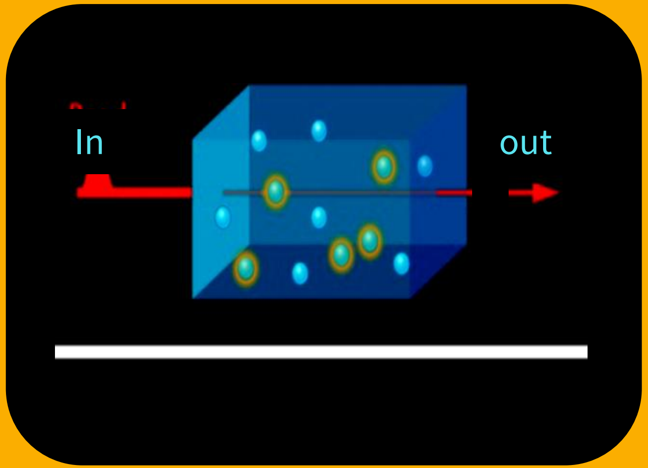




Joint work with Gröblacher group, TU Delft

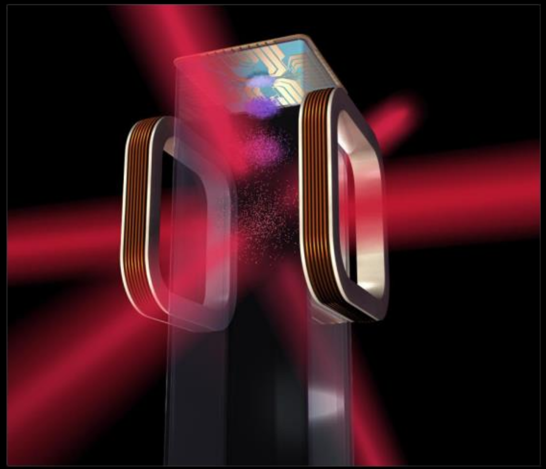
Y. Yu et al., Phys. Rev. Lett. ***131****, 170801 (2023)*

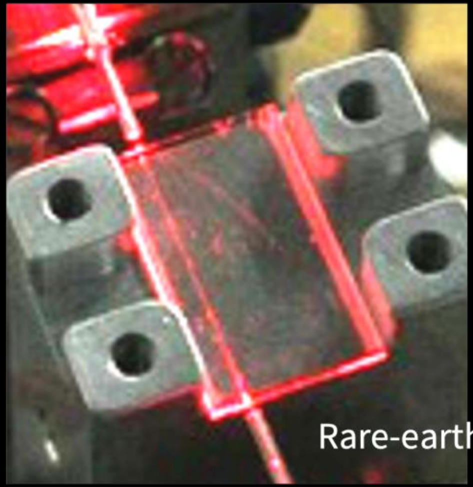
How to store photonic quantum states in a <u>multiplexed</u> manner? Use large ensembles of atoms



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

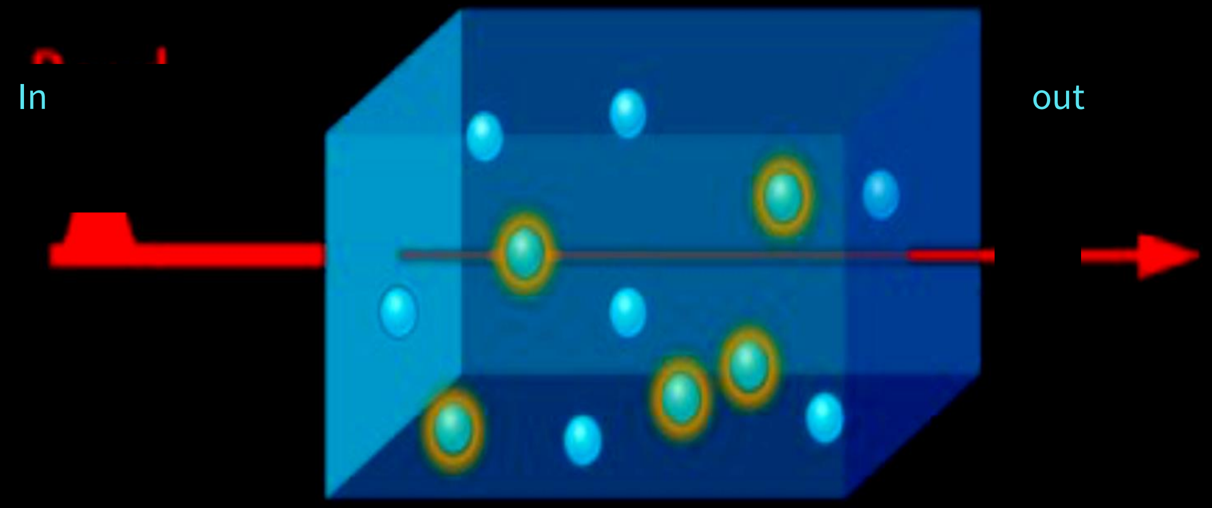

Room-temperature vapor


Laser-cooled atoms


Rare-earth crystals

How to store photonic quantum states in a <u>multiplexed</u> manner?

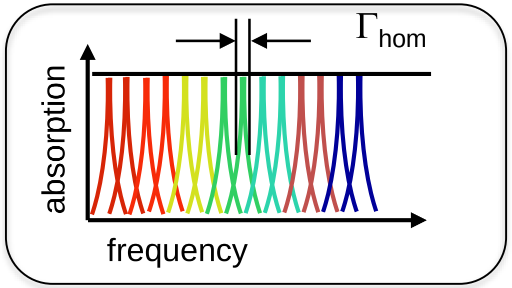
Use large ensembles of atoms

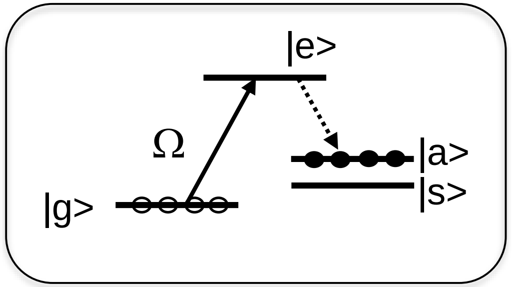


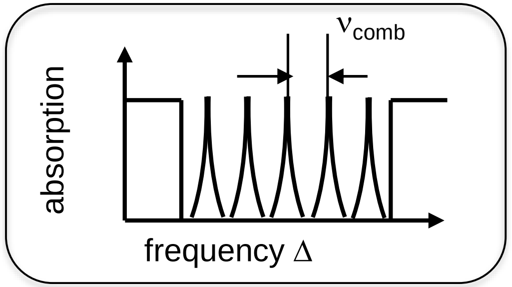
$$|\psi'\rangle = \mathbb{1}|\psi\rangle$$

Photon echo quantum memory (AFC)

1. Preparation of an atomic frequency comb







2. Absorption of a photon -> fast dephasing

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

<u>Experiments</u>: Geneva, Lund, Paris, Calgary, Delft, Barcelona, Hefei, Caltech

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

-> Re-emission of photonic qubits with unity efficiency* and fidelity
-> Possibility tu use control pulses for on-demand read-out (if needed)

* requires phase matching or cavity

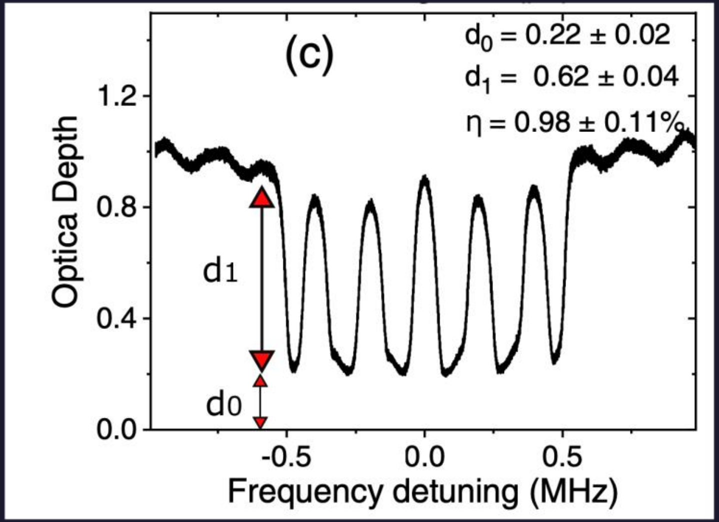
Needed: inhomogeneously broadened transition, long-lived auxiliary state, narrow homogeneous linewidth

M. Afzelius *et al.* PRA 79, 052329 (2009)

Towards efficient quantum memory

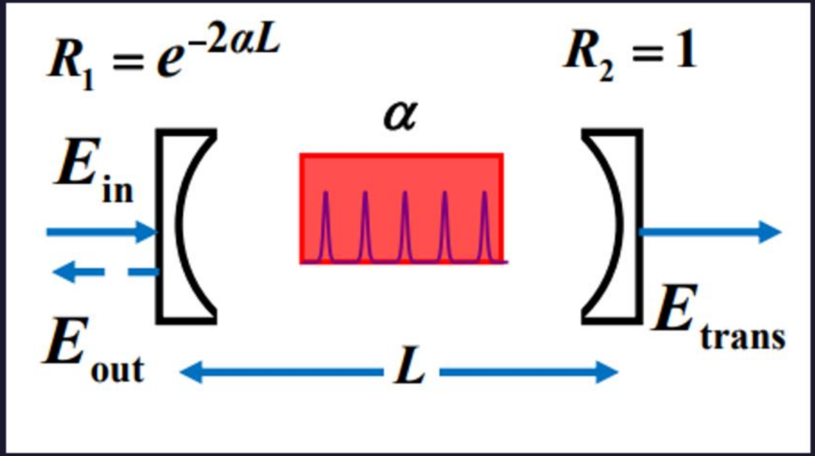
The efficiency of the AFC quantum memory is limited by its optical depth

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



Using an impedance-matched cavity allows in principle to increase the efficiency to 1 despite small single-pass absorption $e^{-\alpha l}$

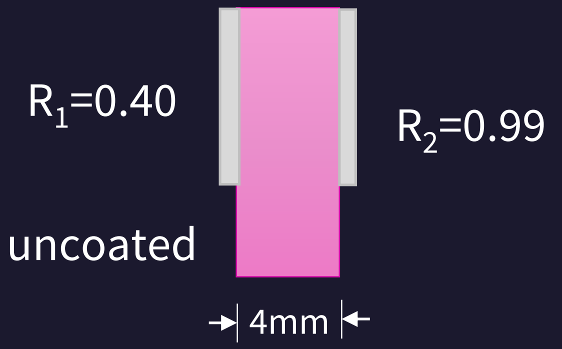
Condition: $R_1 = e^{-2\alpha l} R_2$ with $R_2 = 1$

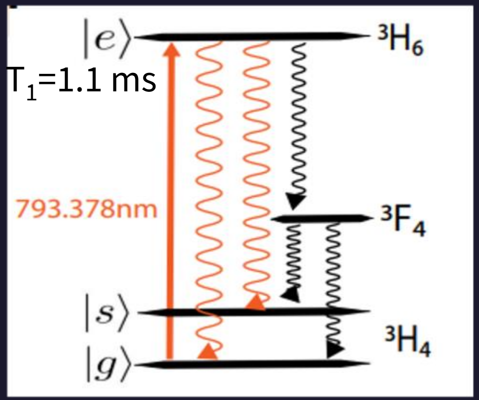


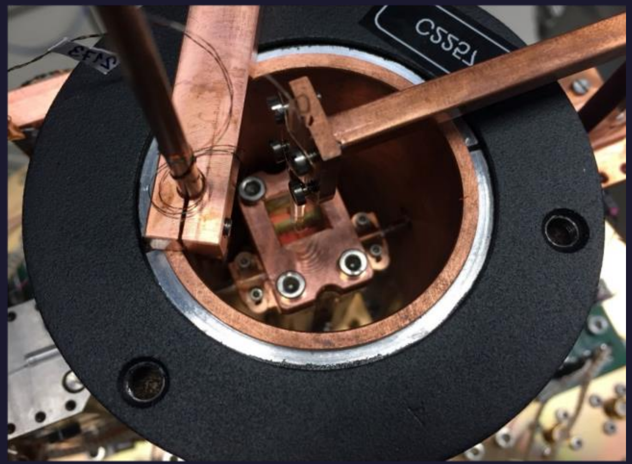
M. Afzelius and C. Simon, Phys. Rev. A 82, 022310 (2010)

Towards efficient quantum memory

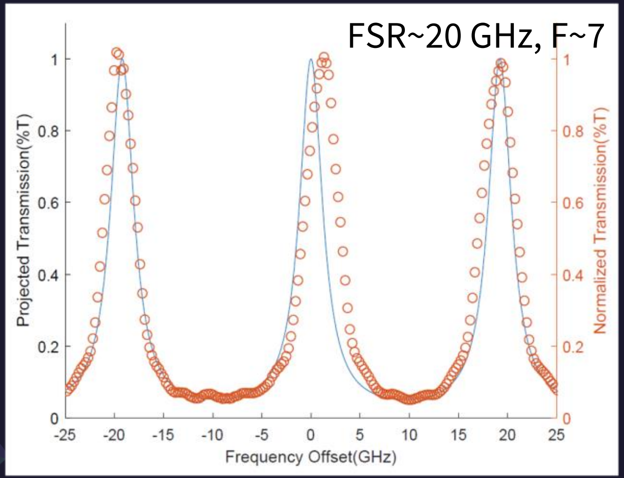
Reflection-coated $Tm:Y_3Al_5O_{12}$ (YAG) crystal



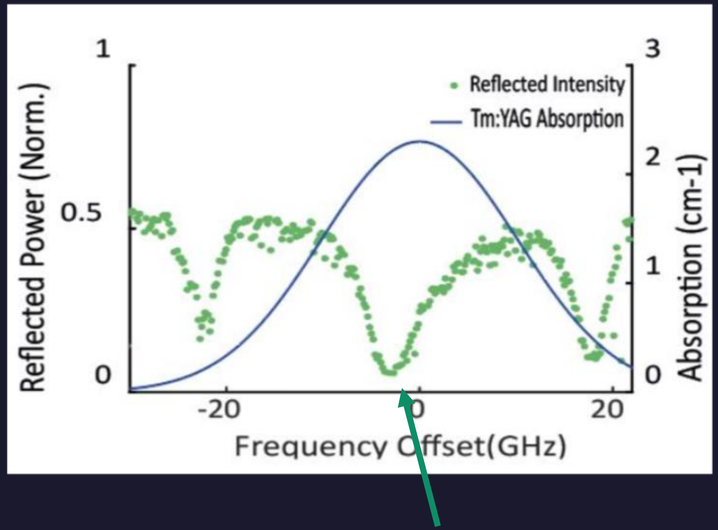




Cavity transmission spectrum
(outside Tm resonance)



Cavity reflection spectrum
(within Tm resonance)

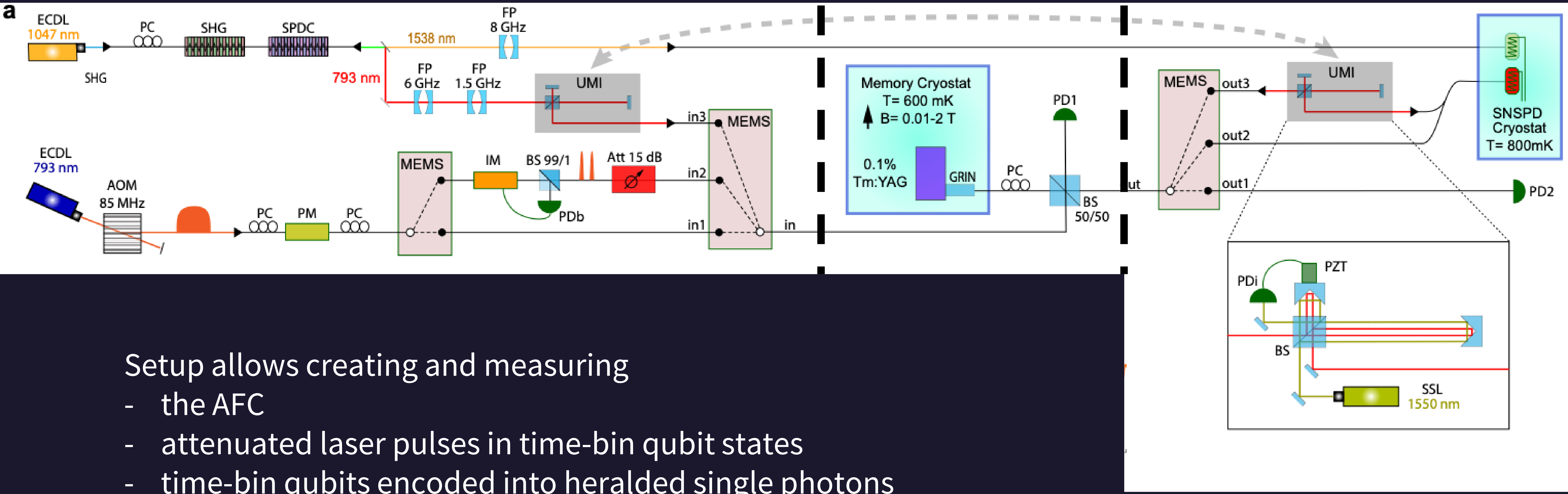


Almost impedance-matched!

J. Davidson, WT et al., PRA 101, 042333 (2020)

Towards efficient quantum memory

Preparation of light Quantum memory detection



Setup allows creating and measuring

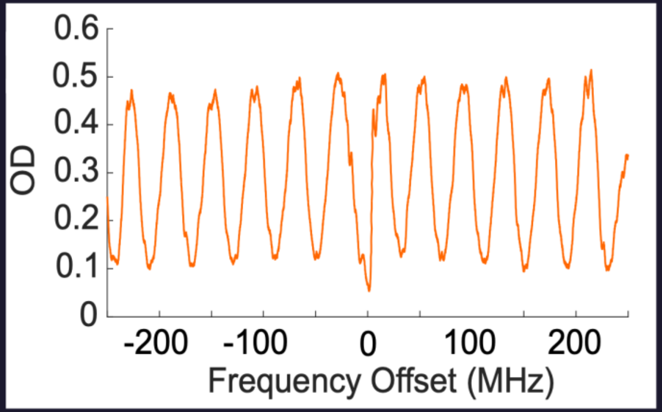
- the AFC
- attenuated laser pulses in time-bin qubit states
- time-bin qubits encoded into heralded single photons

$$|\psi\rangle = \alpha|e\rangle + \beta e^{i\phi}|l\rangle$$

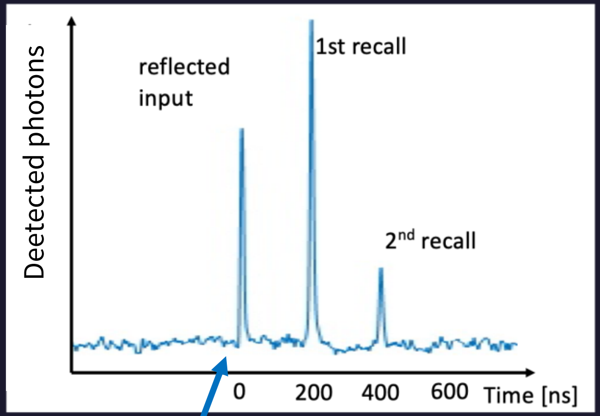
J. Davidson, WT et al., PRA 101, 042333 (2020)

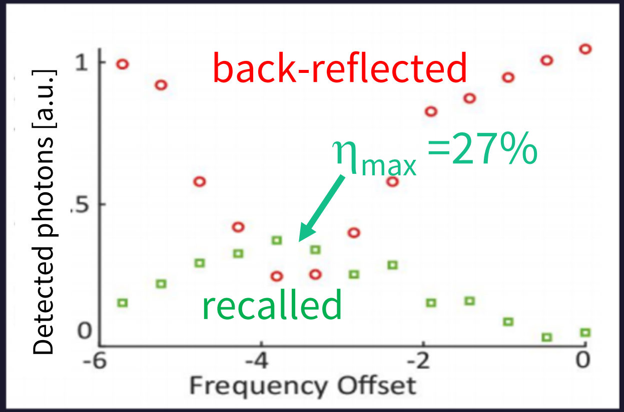
Results

AFC created using the non-coated part of the crystal. η~1%



AFC-based storage of attenuated laser pulses (μ=0.7) using coated part of crystal





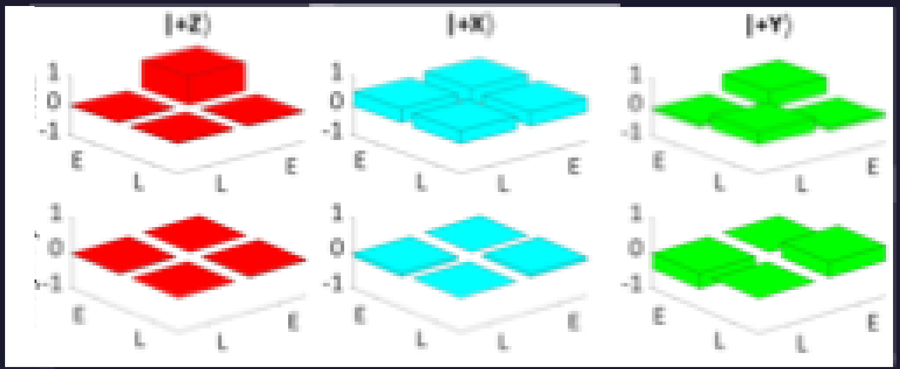
Imperfect impedance matching

J. Davidson, WT et al., PRA 101, 042333 (2020)

More Results

Measurement of **non-classical cross-correlations** with photon pairs before and after storage:
$g^{(2)}_{before}$=61.8 ±3.8, $g^{(2)}_{after}$ = 9.1 ±1.2

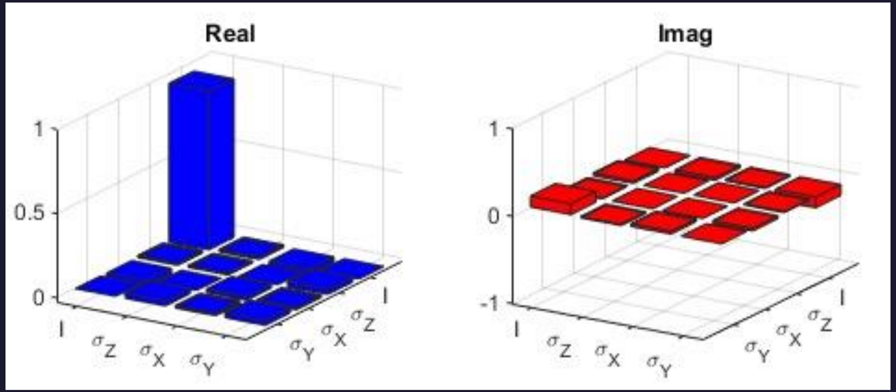
Quantum state tomography of time-bin qubits encoded into heralded single photons

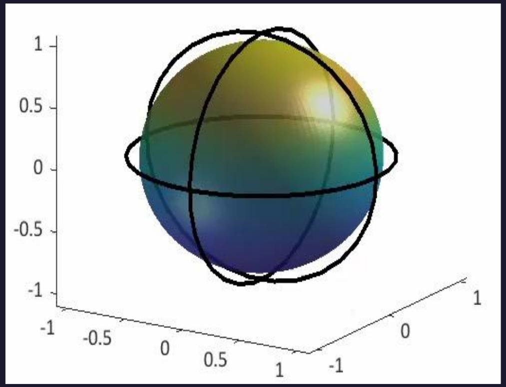


-> F=(85 ± 1)% >> 0.66

Quantum process tomography of time-bin qubits encoded into attenuate laser pulses (μ=0.7)

$$\rho_{out} = \sum_{m,n=0}^{3} \chi_{mn}\sigma_m\rho_{in}\sigma_n^\dagger$$

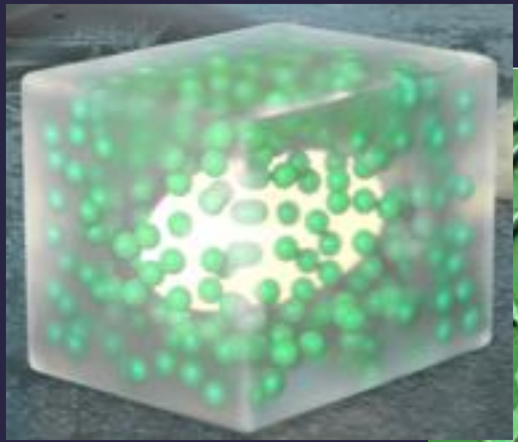


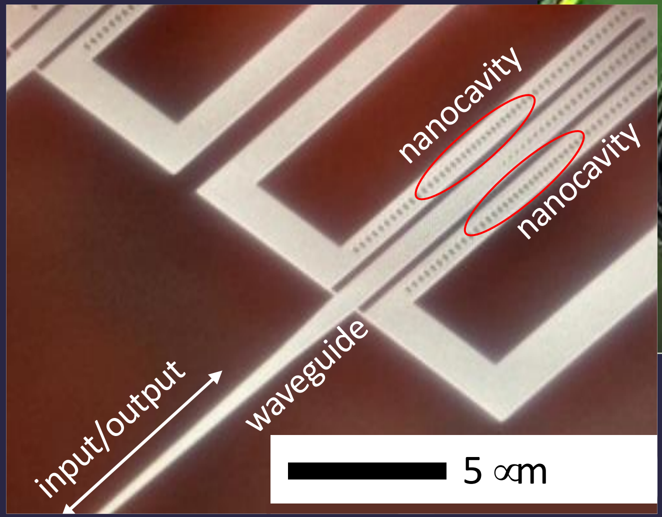


J. Davidson, WT et al., PRA 101, 042333 (2020)

Towards fully quantum-enabled networks based on an integrated platform

- **Single (and soon? entangled) photons** based on Purcell-enhanced emission from single rare-earth ions
- Compatible **quantum memories** based on large ensembles of rare-earth ions
- **(Quantum computing nodes** using interacting rare-earth ions coupled to nano-cavities for readout)
- Exploit maturity of Si/SiN/$LiNbO_3$ photonics (foundries) to create **compatible, scalable** and **integrated quantum network technology**
- More **fundamental research into materials, protocols, applications**,…





Thank you!

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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

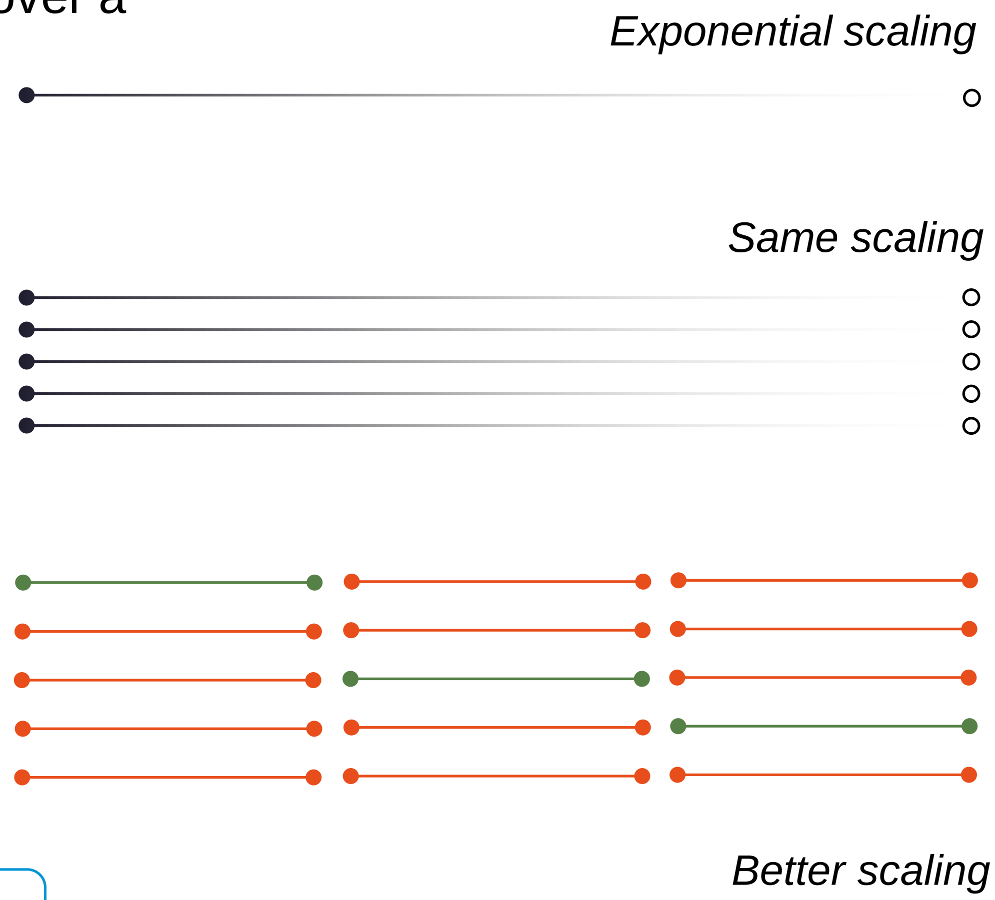
Solution

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.

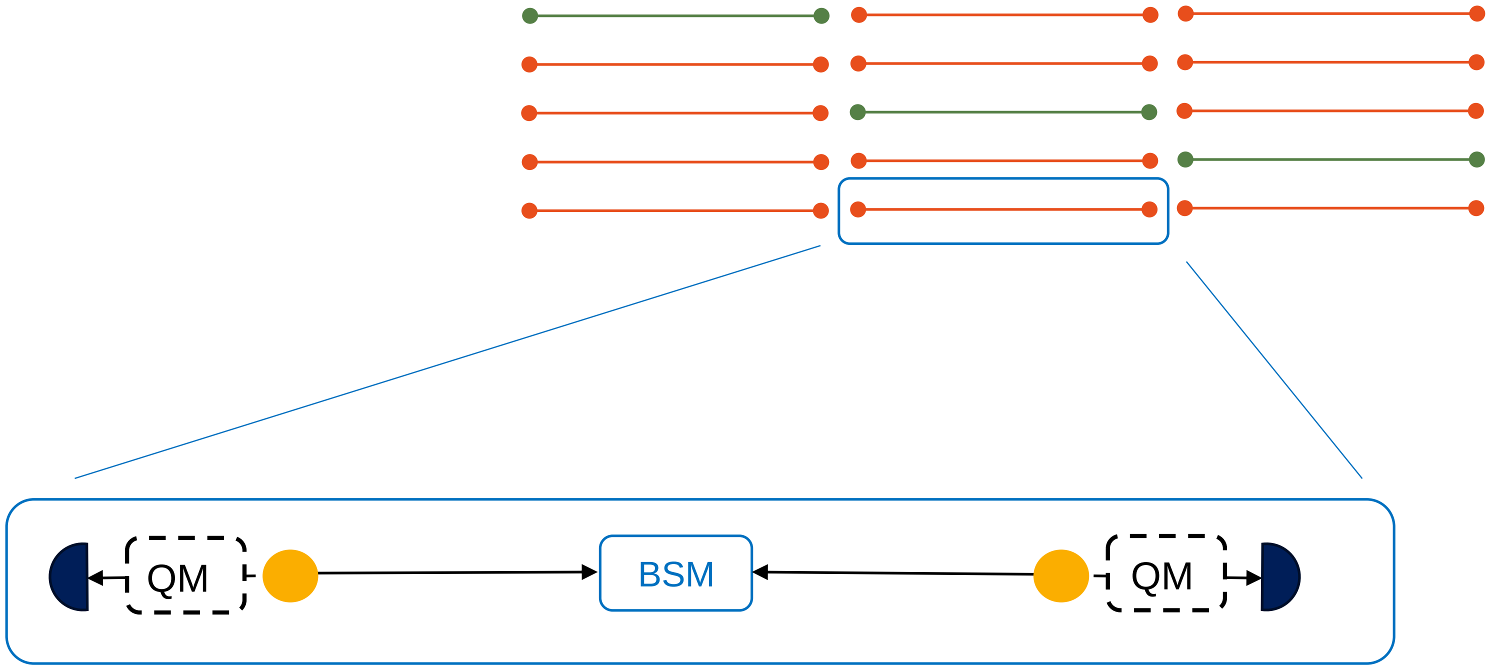


No need for photons to travel *in one go* over the entire link.

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

Quantum 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



State-of-the-art

- **Comparing results taken under different conditions**… But while not all experiments demonstrate quantum nature, all used a quantum protocol
- **2-level AFC**: not yet better than fiber, but close. Materials with sufficient T_2^{opt} for τ = 1ms exist. Need to reduce technical noise and add cavities.
- **AFC spin-storage**: scaling already better than fiber, but efficiencies still small. Materials with sufficient T_2^{spin} exist. Need to improve efficiency of π-pulses and noise and to add cavities.
- **Three use cases (**assuming sufficient multiplexing)
  - Quantum repeaters for fiber networks
  - Quantum repeaters for satellite networks
  - Physical qubit transport