

Entanglement Distribution - Towards a Suburban Quantum Network Link

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Abstract

Distributing quantum entanglement between distant nodes is crucial for future quantum networks. For that, quantum nodes are required to provide an efficient light-matter interface for entanglement generation, serve as a quantum memory allowing long-lived storage of quantum states, and have the possibility to connect to low-loss quantum channels. Here we present a neutral atom-based quantum node capable of sharing entanglement over long distances [1-2].

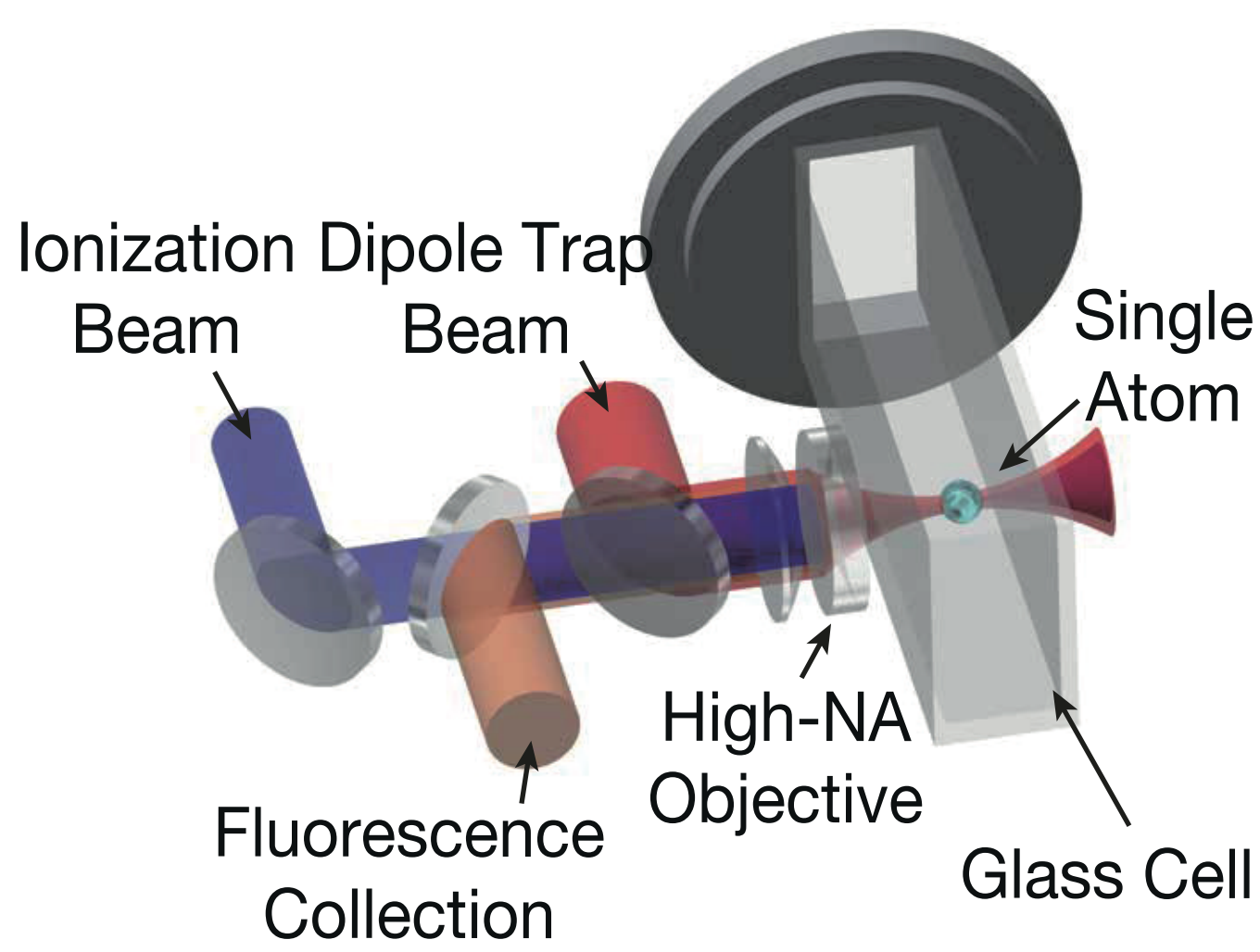
Our setup consists of single Rb-87 atoms trapped in optical dipole traps. First, entanglement is generated between the polarization of the photon and the Zeeman state of the atom. Then a state-selective Raman transfer changes the encoding of the atomic qubit in a combination of $F=1$ & $F=2$ hyperfine states [3]. The reduced sensitivity to magnetic fields in the new basis increases the atomic coherence time to 10 ms.

With a polarization-preserving quantum frequency conversion to telecom wavelengths minimizing the photon loss along optical fibers, we achieve the distribution of atom-photon entanglement over 101 km of spooled fibers with a fidelity of $\geq 70.8\%$ [2]. This crucial step of analyzing and evaluating our node paves the way for the realization of city-to-city scale quantum network links by incorporating another Rb-87 atom node at a 14 km distance [1, 2, 4].

Setup & Methods

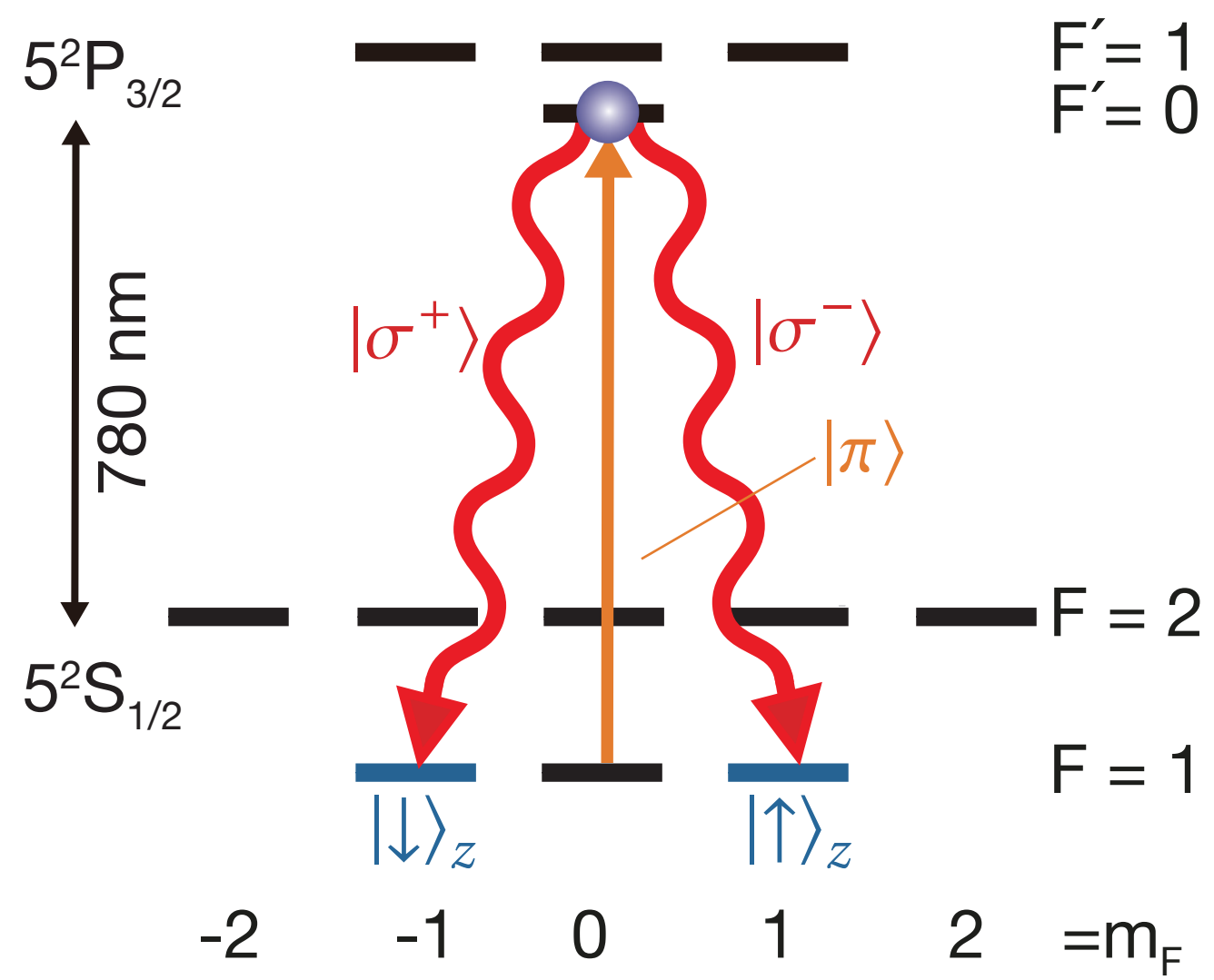
Single Atom Trap

Storing a single ⁸⁷Rb atom in a tightly focused optical dipole trap



Atom-Photon Entanglement

Entanglement from spontaneous decay on the D2 transition



$$|\Psi_{AP}\rangle = \frac{1}{\sqrt{2}} (|\downarrow\rangle_z |\sigma^+\rangle + |\uparrow\rangle_z |\sigma^-\rangle)$$

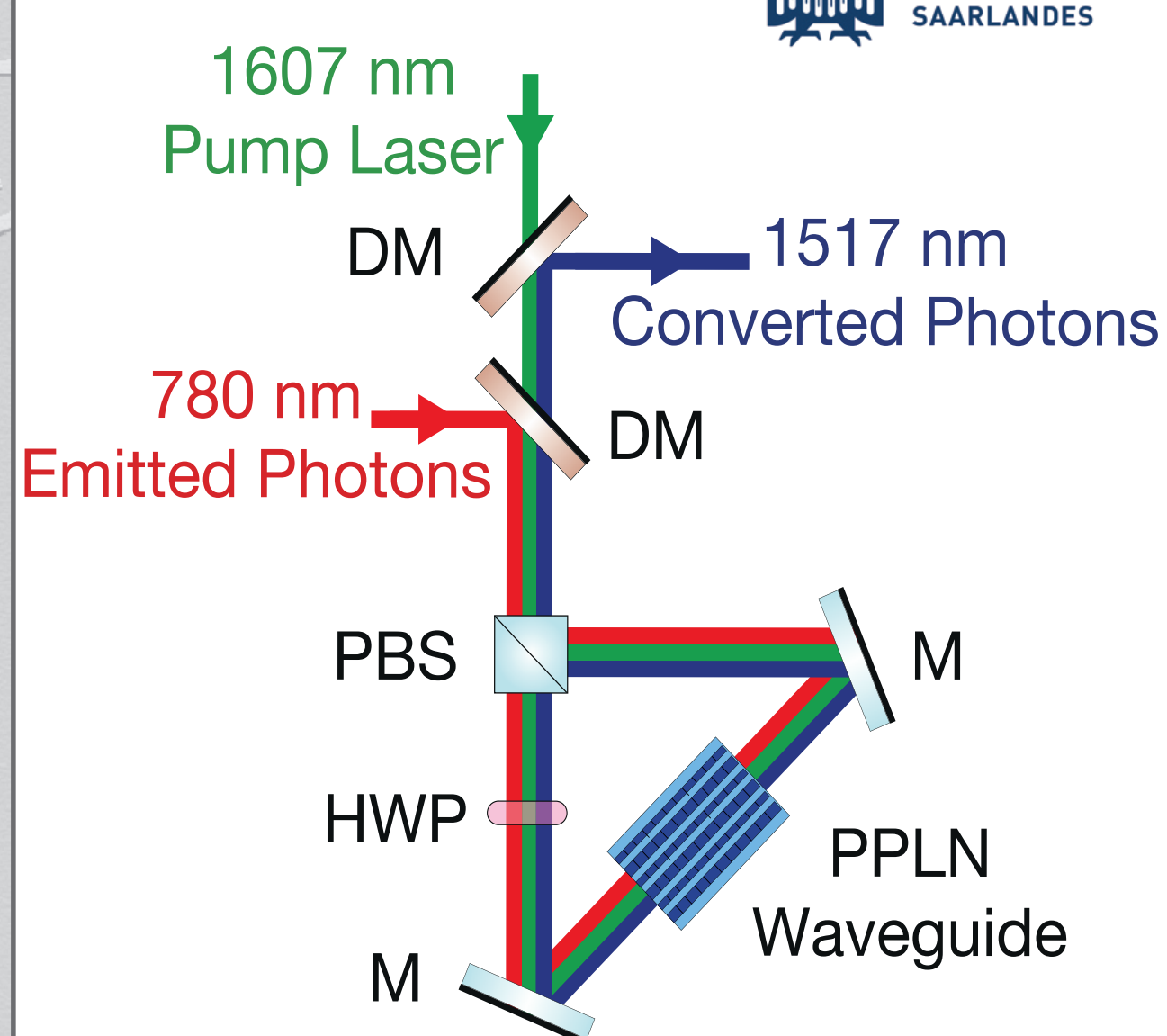
Atom-Atom Entanglement

Entanglement swapping between two atom-photon pairs at BSM in H/V basis results in an entangled atom-atom pair

$$|\Psi_{AA}^\pm\rangle = \frac{1}{\sqrt{2}} (|\uparrow\rangle_x |\downarrow\rangle_x \pm |\downarrow\rangle_x |\uparrow\rangle_x)$$

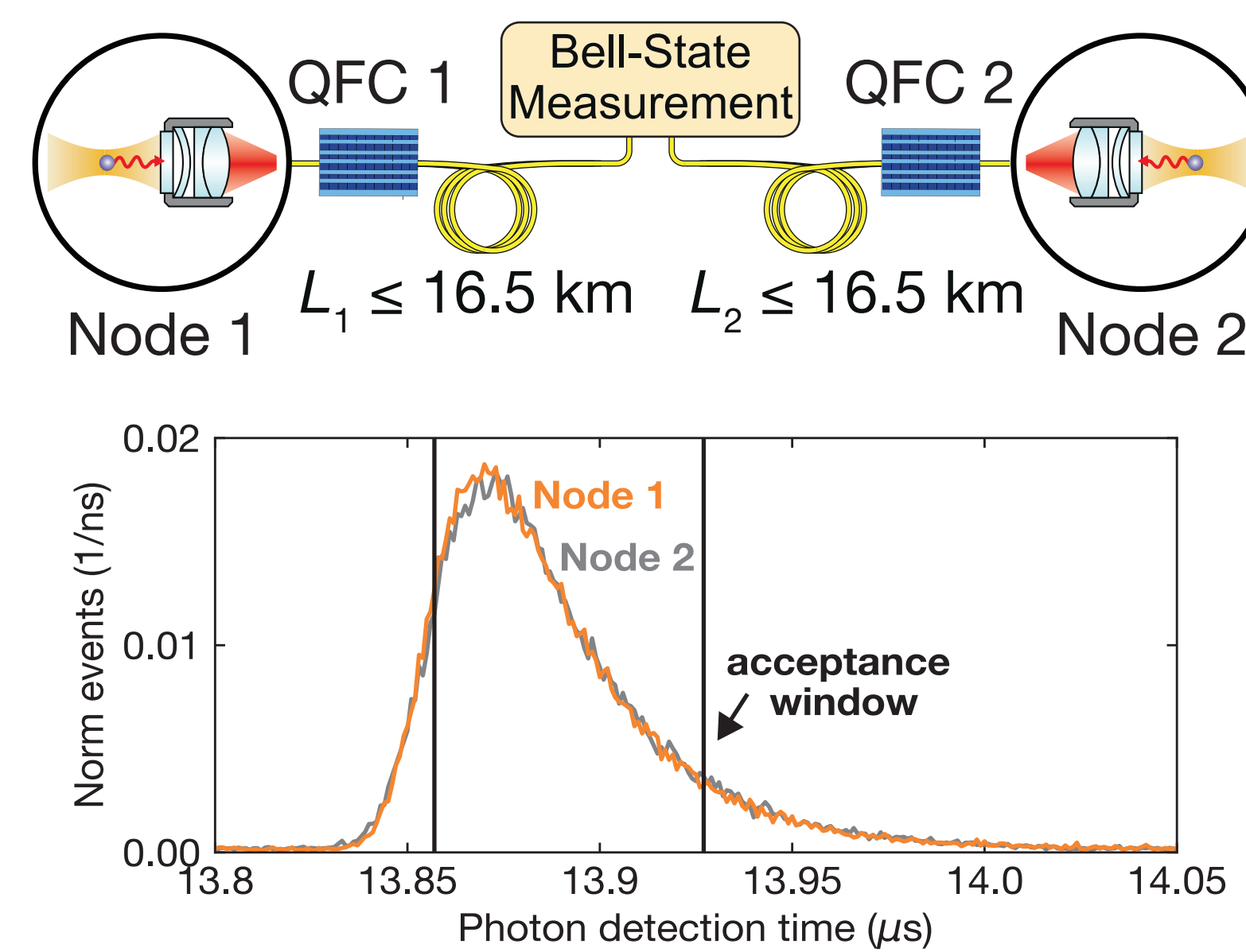
Atom-Atom Entanglement over 33 km Optical Fiber

QFC Setup



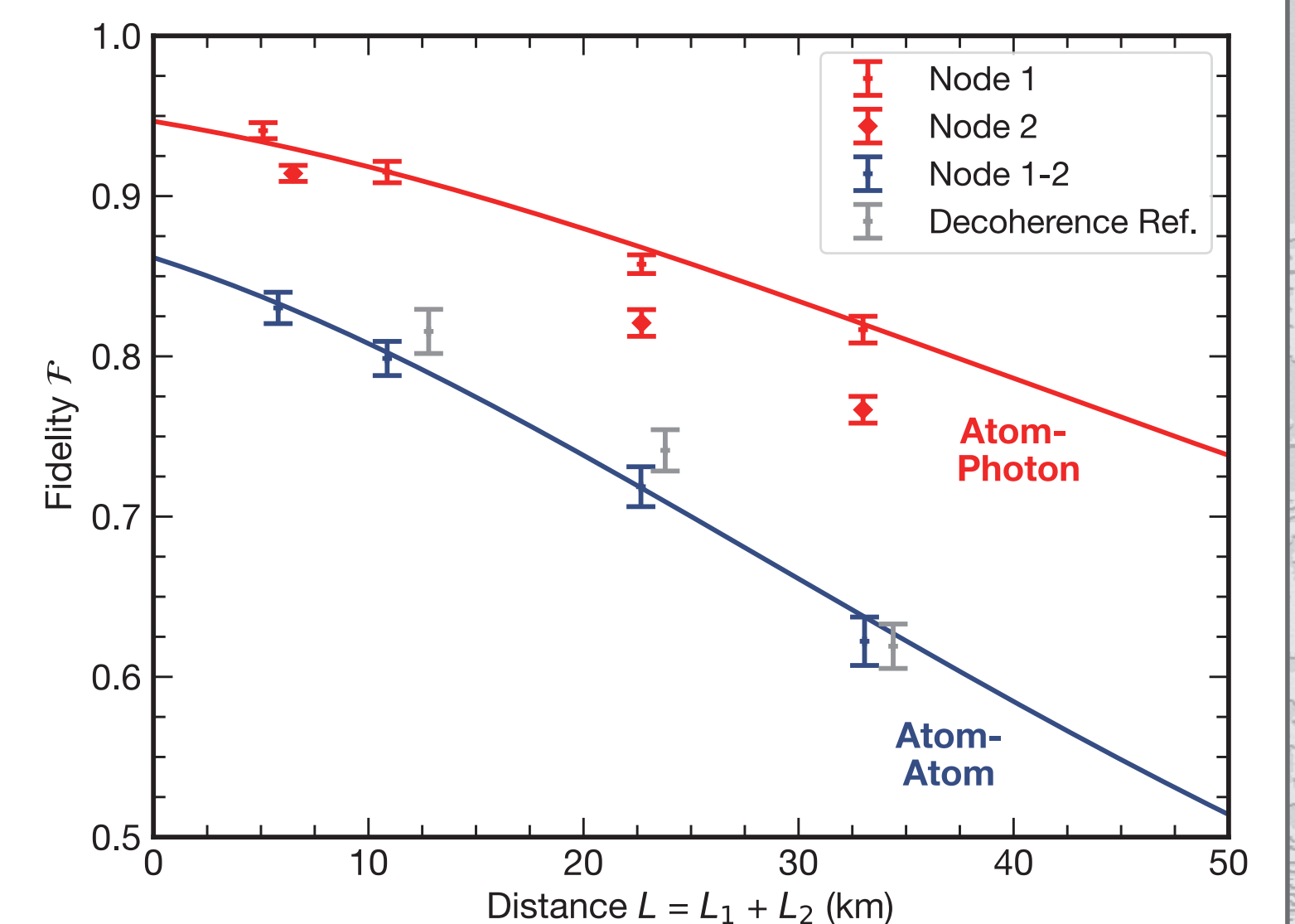
- Difference frequency generation $\omega_{1517\text{nm}} = \omega_{780\text{nm}} - \omega_{1607\text{nm}}$
- External device efficiency of 57%
- Spectral filtering with a cavity to 27 MHz FWHM

Entanglement Swapping



- Indistinguishable photons in spatial, temporal and spectral degree of freedom
- Two-photon interference based on the HOM effect, with an interference contrast of 95.5%.

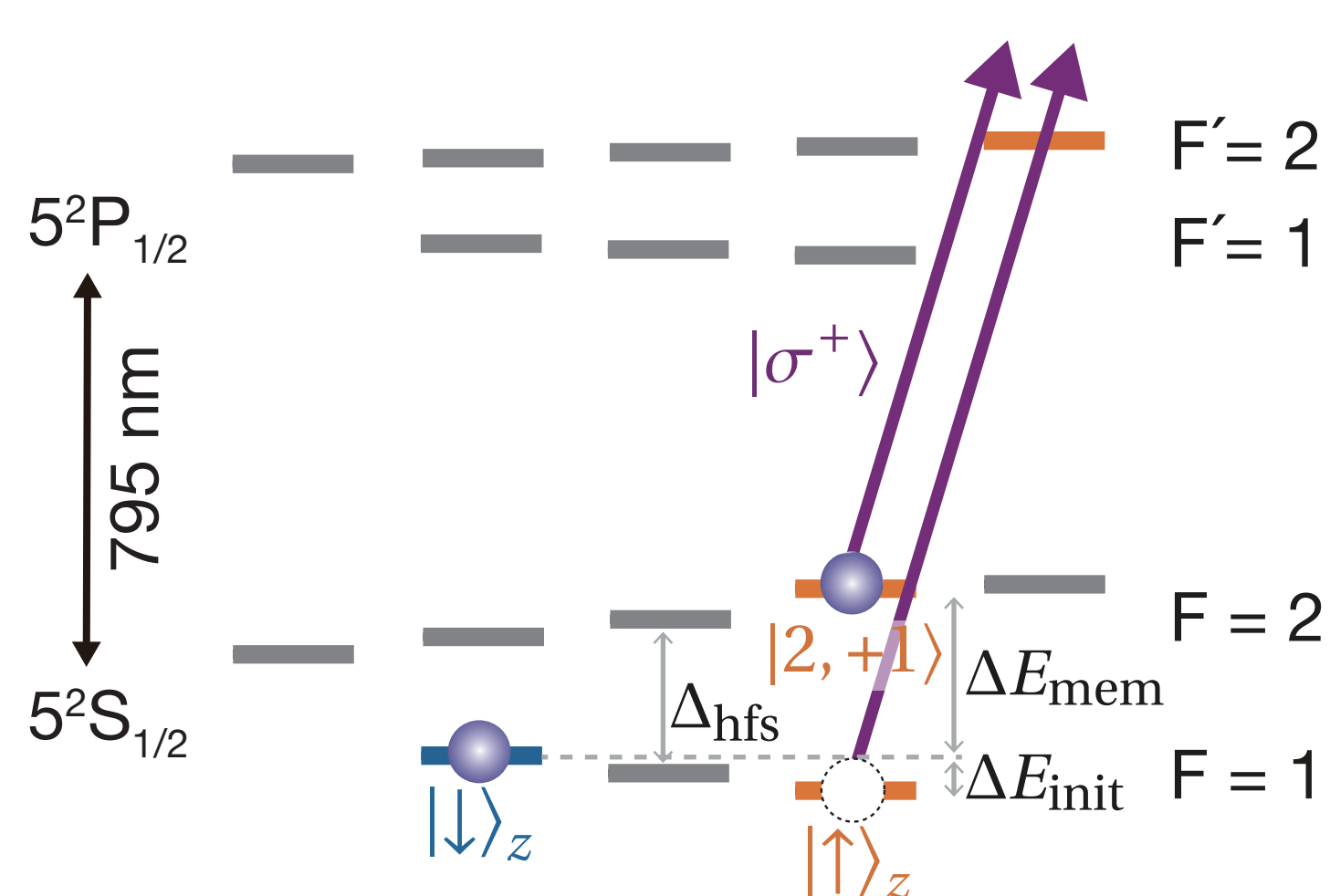
Atom-Atom Entanglement



- Measure spin states in linear bases X, Y and Z
- Fidelity estimation includes $m_F=0$ and is thus calculated by $\mathcal{F} \geq \frac{1}{9} + \frac{8}{9}\sqrt{V}$
- Event rate: 1/19 - 1/208 s⁻¹

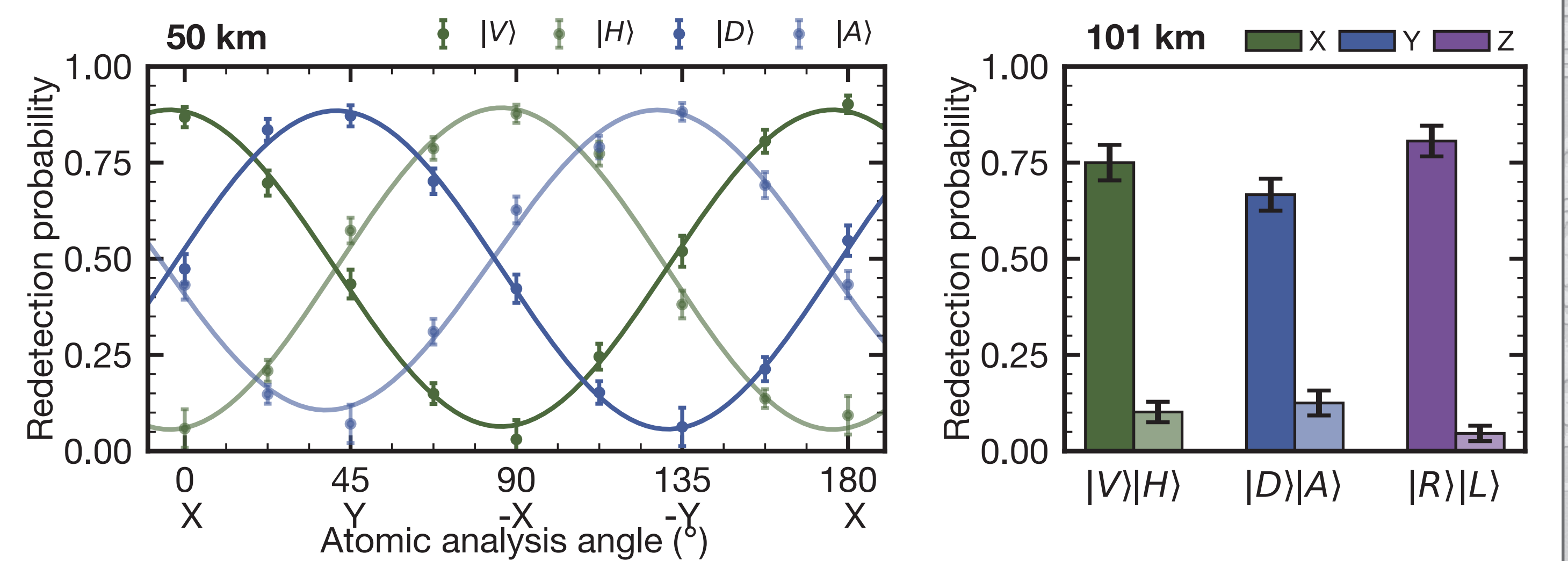
Atom-Photon Entanglement over 101 km Optical Fiber

State-Selective Raman Transfer



- Initial basis: $\Delta E_{\text{init}} = 2g_F \mu_B B_z$
- Memory basis: $\Delta E_{\text{mem}} = \Delta E_{\text{hfs}} + 2g_I \mu_B B_z$
- Field sensitivity: $g_I/g_F = 1/500$
- Increase of coherence time from 0.279(32) ms to 10.5(10) ms

Long Distance Atom-Photon Entanglement



- 6548 (656) events recorded over 25.2 (47.7) hours for fiber lengths of 50 km (101 km)
- Fidelity estimation includes $m_F=0$ and is thus calculated by $\mathcal{F} \geq \frac{1}{6} + \frac{5}{6}\sqrt{V}$
- 50 km: success probability 1.09×10^{-4} , event rate 1/14 s⁻¹, fidelity $84.8 \pm 1.1\%$
- 101 km: success probability 1.08×10^{-5} , event rate 1/262 s⁻¹, fidelity $70.8 \pm 2.4\%$

Collaborations

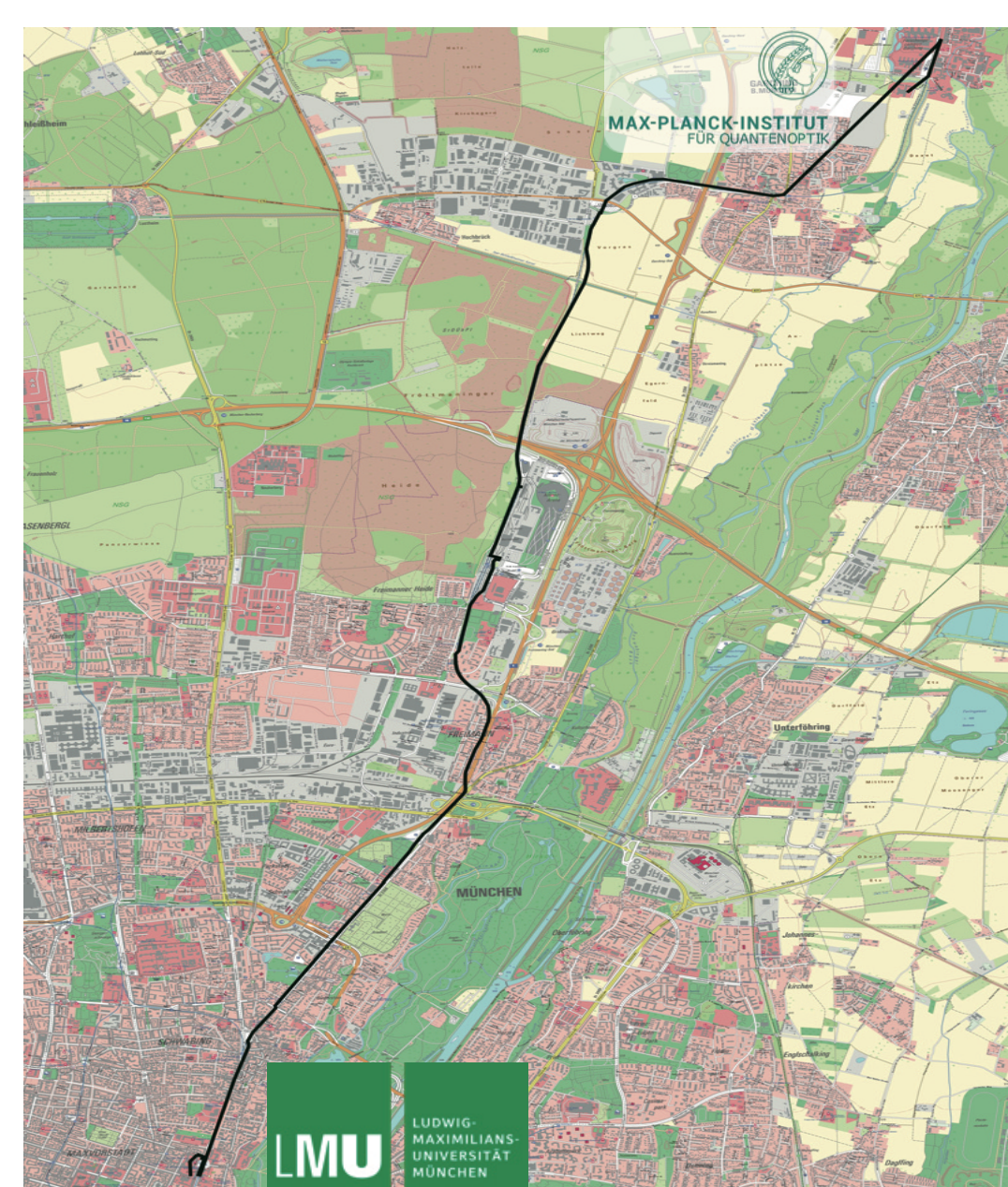
Maya Büki
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 Gerhard Rempe
 Matthias Bock
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References

- [1] T. van Leent et al., Nature **607**, 69-73 (2022)
- [2] Y. Zhou et al., PRX Quantum **5**, 020307 (2024)
- [3] M. Körber et al., Nature Photonics **12**, 18-21 (2018)
- [4] M. Brekenfeld et al., Nature Physics **16**, 647-651 (2020)

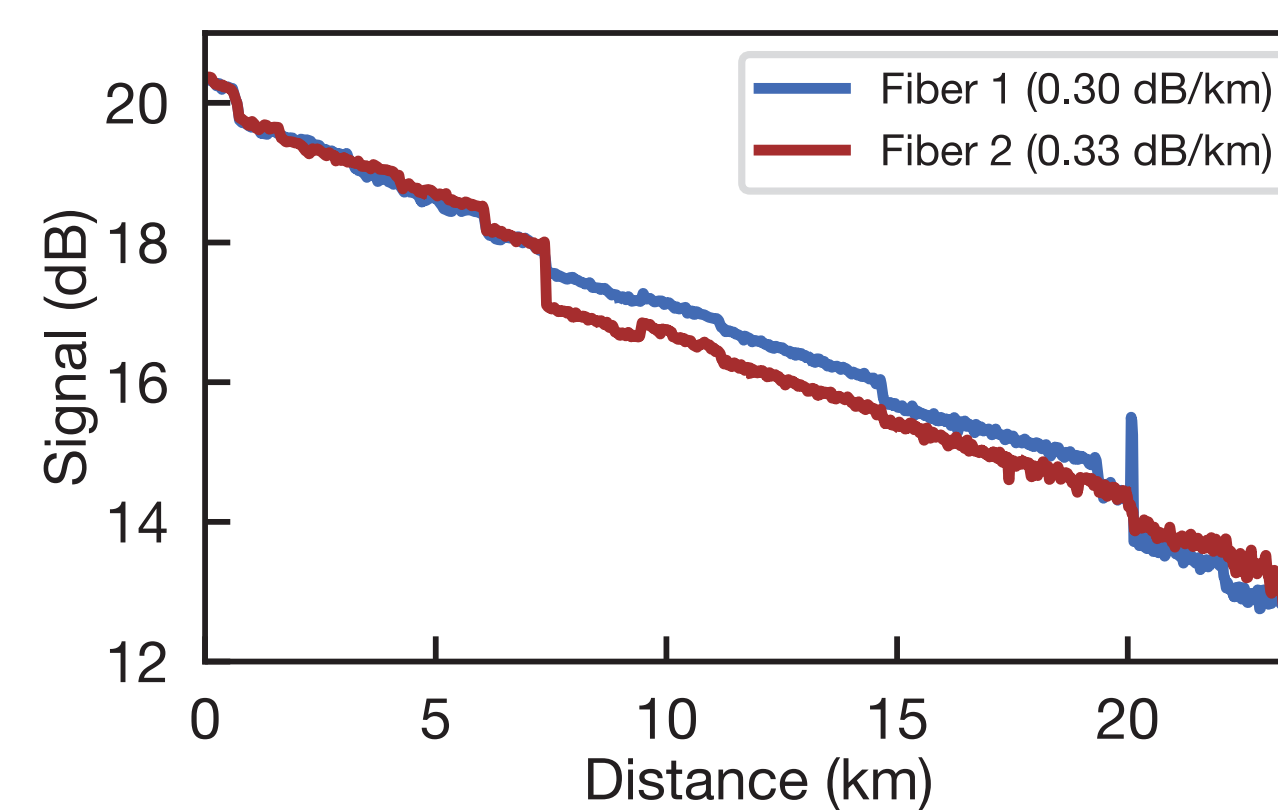
Towards a Suburban Quantum Network Link

LMU-MPQ Link



Geobasisdaten:
 Bayerische Vermessungsverwaltung

OTDR Measurement

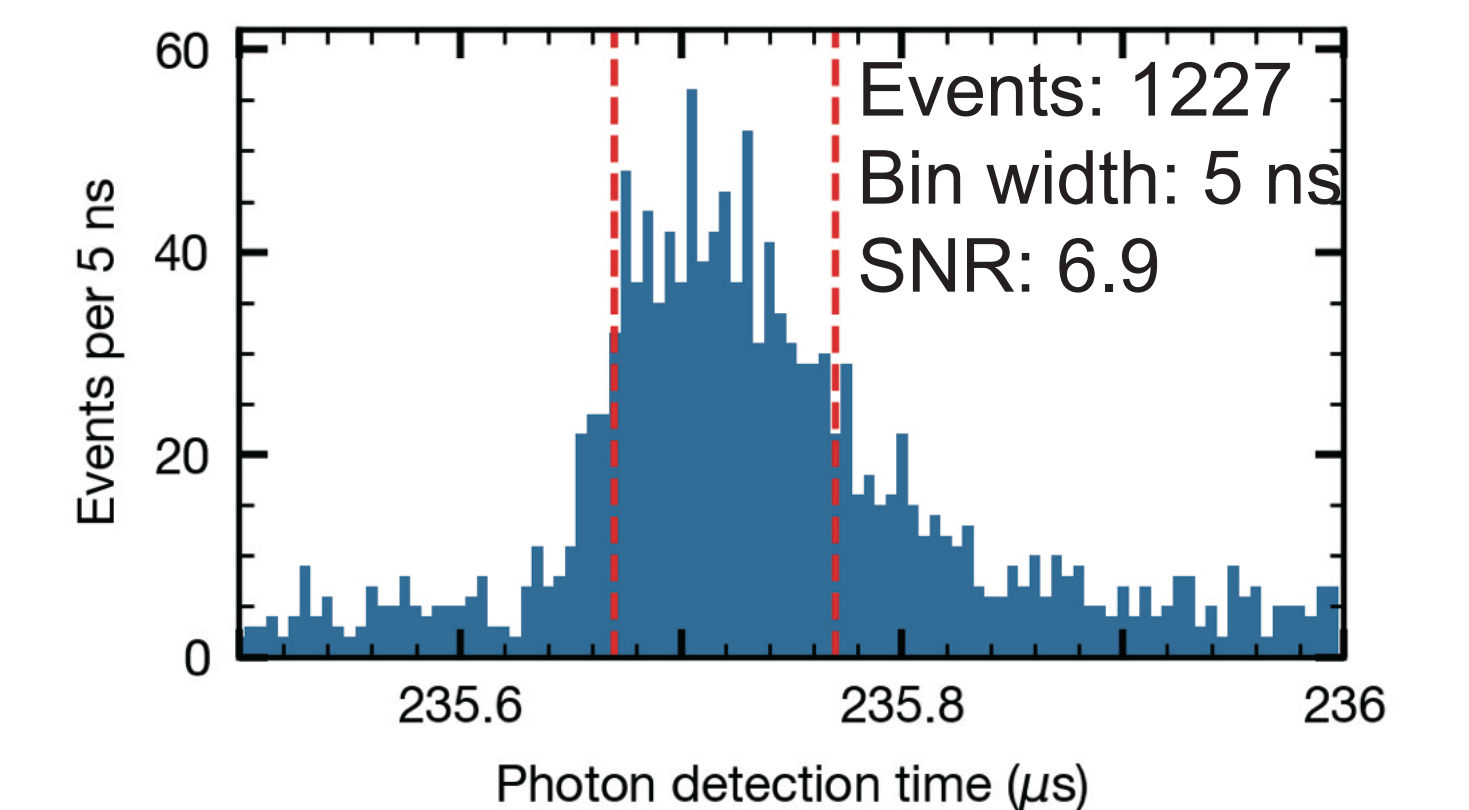


- Link length: 23.7 km
- Link loss: 0.30 dB/km @1550 nm
- Line-of-sight separation: 13.9 km

(In collaboration with Quantum Dynamics group)



Atom-Photon Entanglement



- LMU node sends photons to MPQ via the field-deployed fiber
 - Atom-atom entanglement via heralded photon absorption
- $$\frac{1}{\sqrt{2}} (|\downarrow\rangle_z |\sigma^+\rangle + |\uparrow\rangle_z |\sigma^-\rangle)_{\text{LMU}} |1, 0\rangle_{\text{MPQ}} \rightarrow \frac{1}{\sqrt{2}} (|\downarrow\rangle_z |\downarrow\rangle_z + |\uparrow\rangle_z |\uparrow\rangle_z)_{\text{Atom}} |\pi\rangle_{\text{Herald}}$$