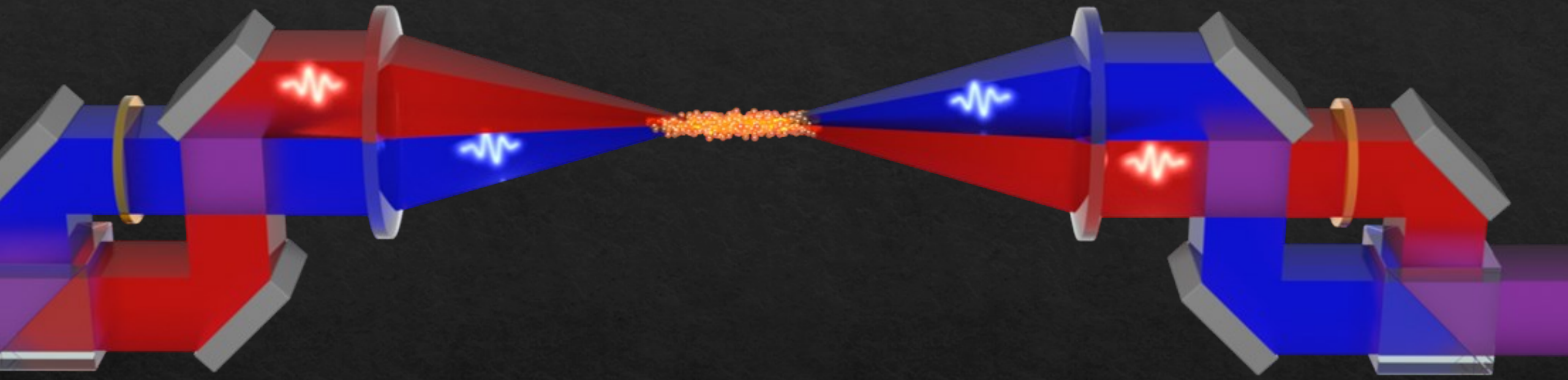


Generation of polarization entanglement in wavevector-multiplexed atomic quantum memory

Michał Lipka, Mateusz Mazelanik, Adam Leszczyński, Wojciech Wasilewski, Michał Parniak

Centre for Quantum Optical Technologies and Faculty of Physics, University of Warsaw

"Current Trends in Quantum Information", Friday, May 21, 2021

Diamentowy Grant

European Funds Smart Growth | Republic of Poland | FNP Foundation for Polish Science | European Union European Regional Development Fund

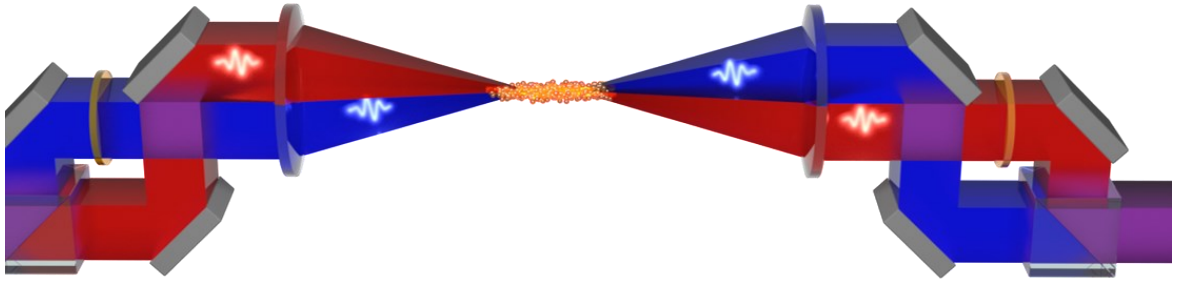
The "Quantum Optical Technologies " project is carried out within the International Research Agendas programme of the Foundation for Polish Science co-financed by the European Union under the European Regional Development Fund.

Overview

Experiment

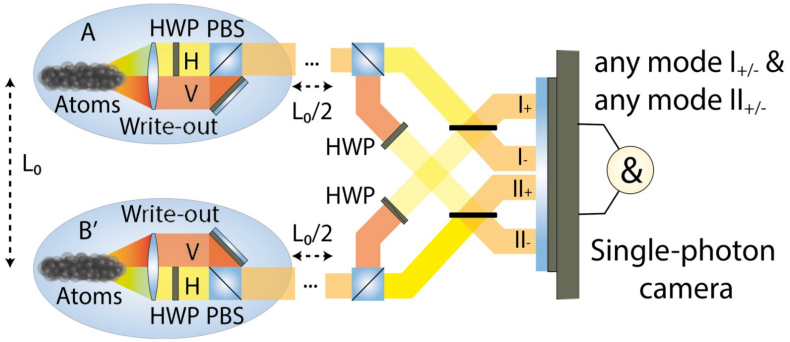
Theory

Experiment: Generation of entanglement in 500 modes



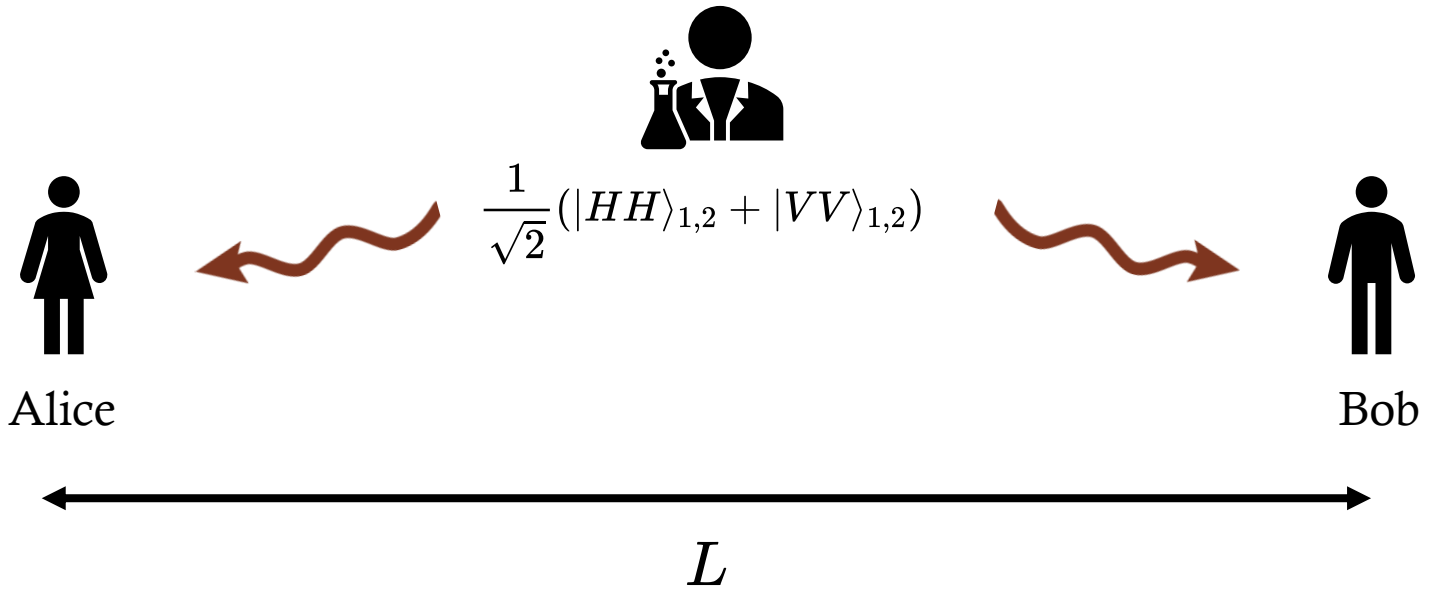
Commun Phys **4,** 46 (2021)

Theory: 5000 modes + performance as a quantum repeater



New J. Phys. **23** 053012 (2021)

Entanglement generation



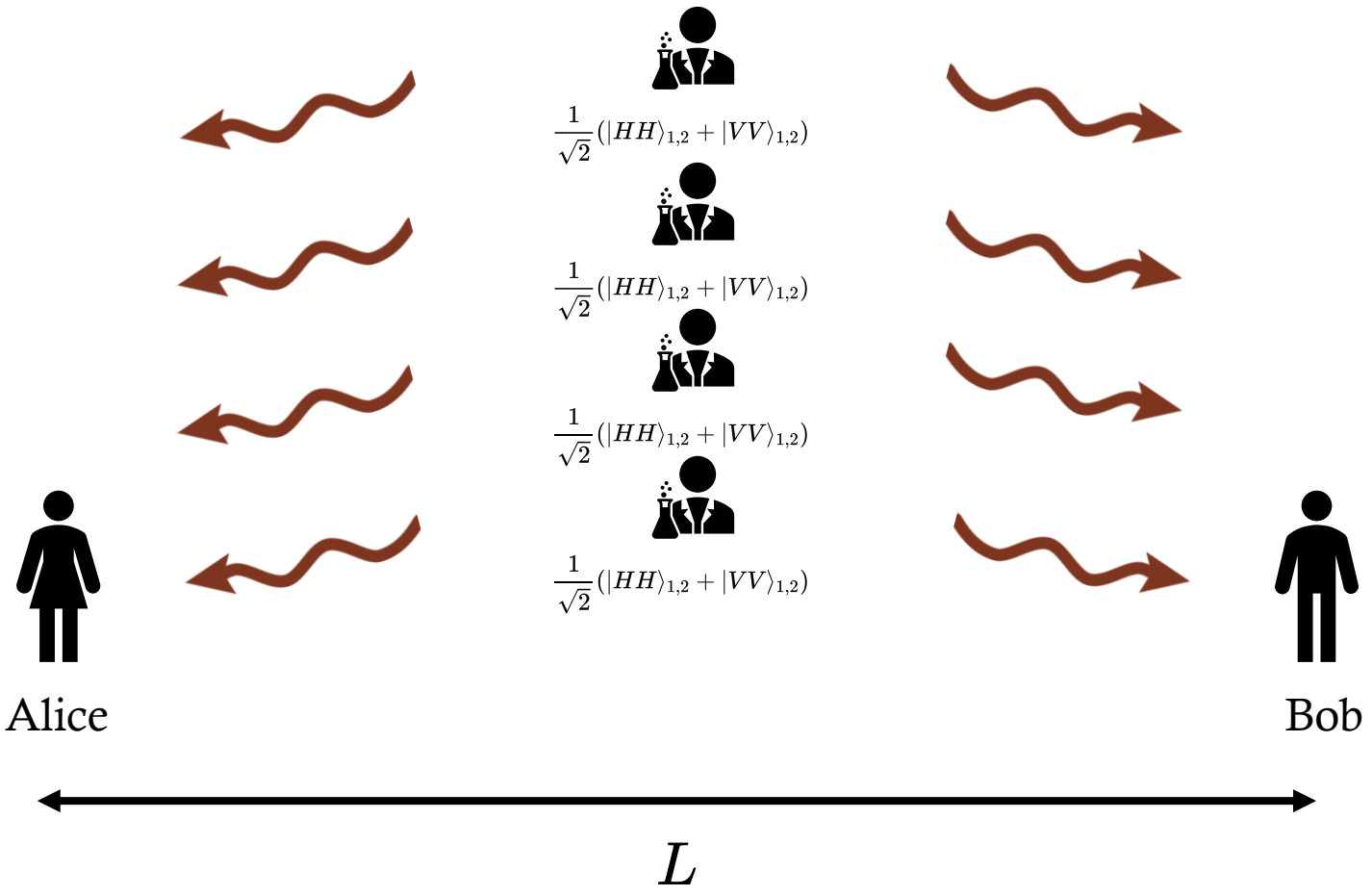
Transmission loss: $e^{-\alpha L}$

Telecom @ 100 km = 99% loss

Parallel

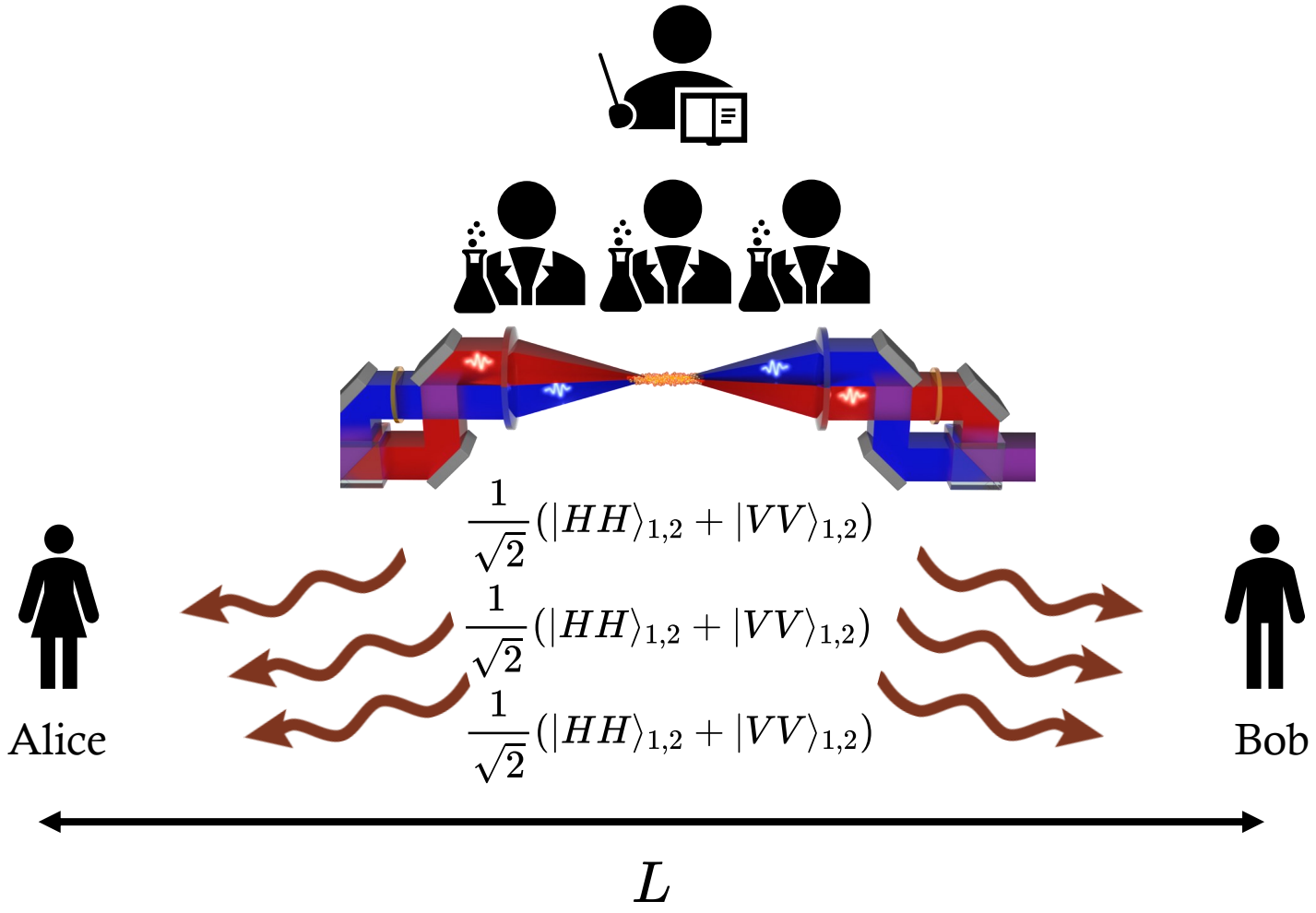
Feasible?

$ $ $



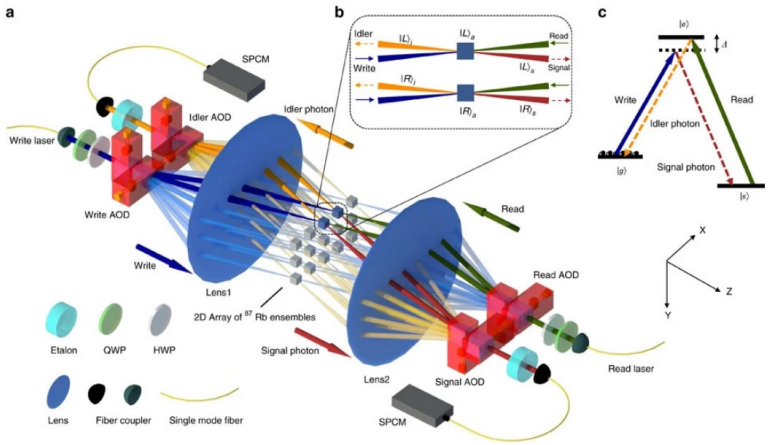
Multimode platform

Wavevector-multiplexed quantum memory (WV-MUX-QM)



One of many

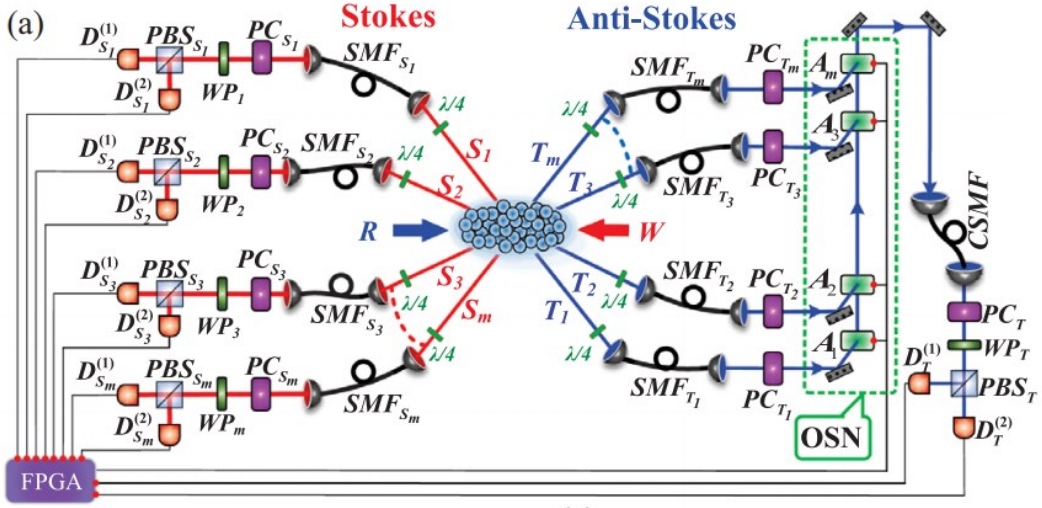
- Spatial modes
- Temporal modes
- Spectral modes
- Wavevector modes
- Orbital angular momentum (OAM)
- hybrid



Experimental realization of a multiplexed quantum memory with 225 individually accessible memory cells

Y-F Pu, N. Jiang, W. Chang, H-X Yang, C. Li & L-M Duan

Nature Communications **8**, Article number: 15359 (2017) | Cite this article



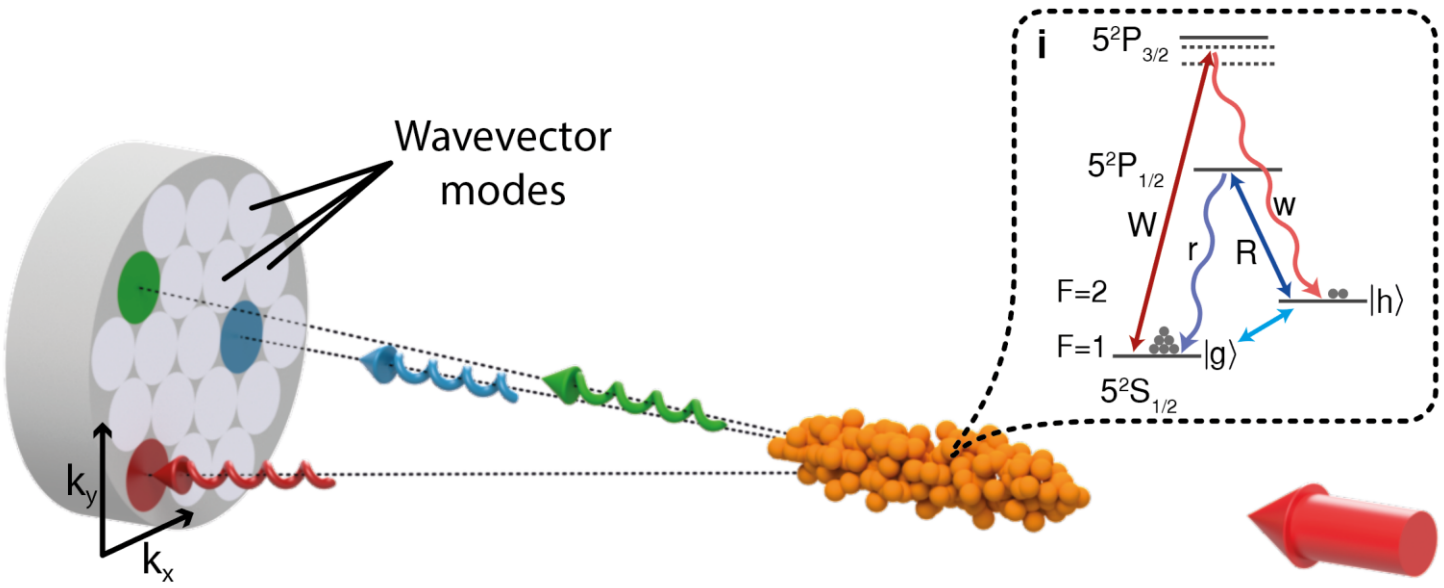
PRL **119,** 130505 (2017) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2017

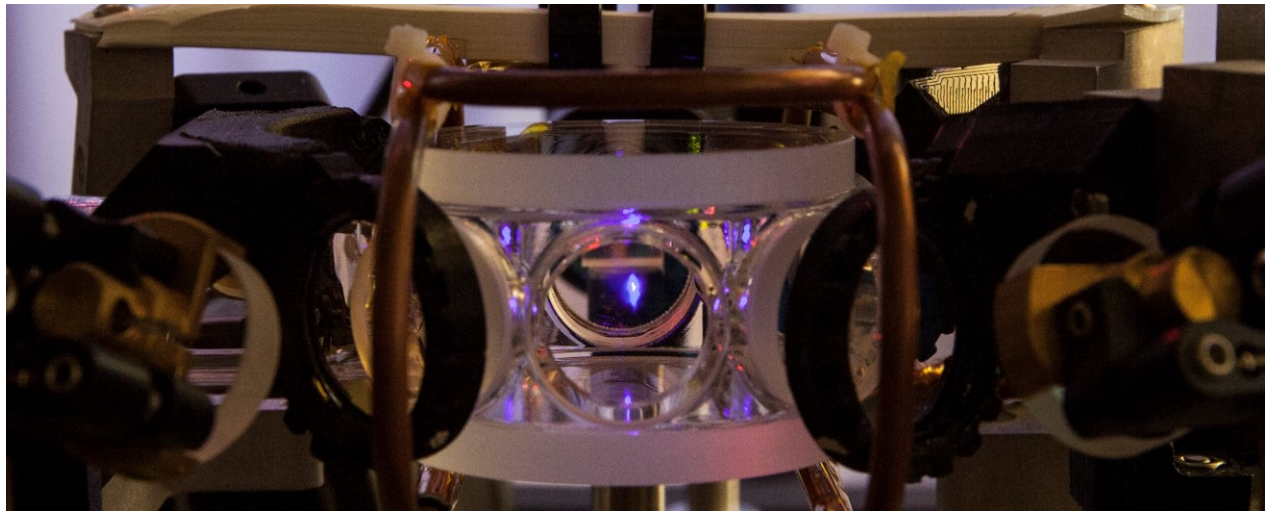
Spatial Multiplexing of Atom-Photon Entanglement Sources using Feedforward Control and Switching Networks

Long Tian, Zhongxiao Xu, Lirong Chen, Wei Ge, Haoxiang Yuan, Yafei Wen, Shengzhi Wang, Shujing Li, and Hai Wang*
The State Key Laboratory of Quantum Optics and Quantum Optics Devices, Collaborative Innovation Center of Extreme Optics, Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, People's Republic of China
(Received 26 December 2016; published 29 September 2017)

Wavevector modes

Wavevector-multiplexed quantum memory (WV-MUX-QM)



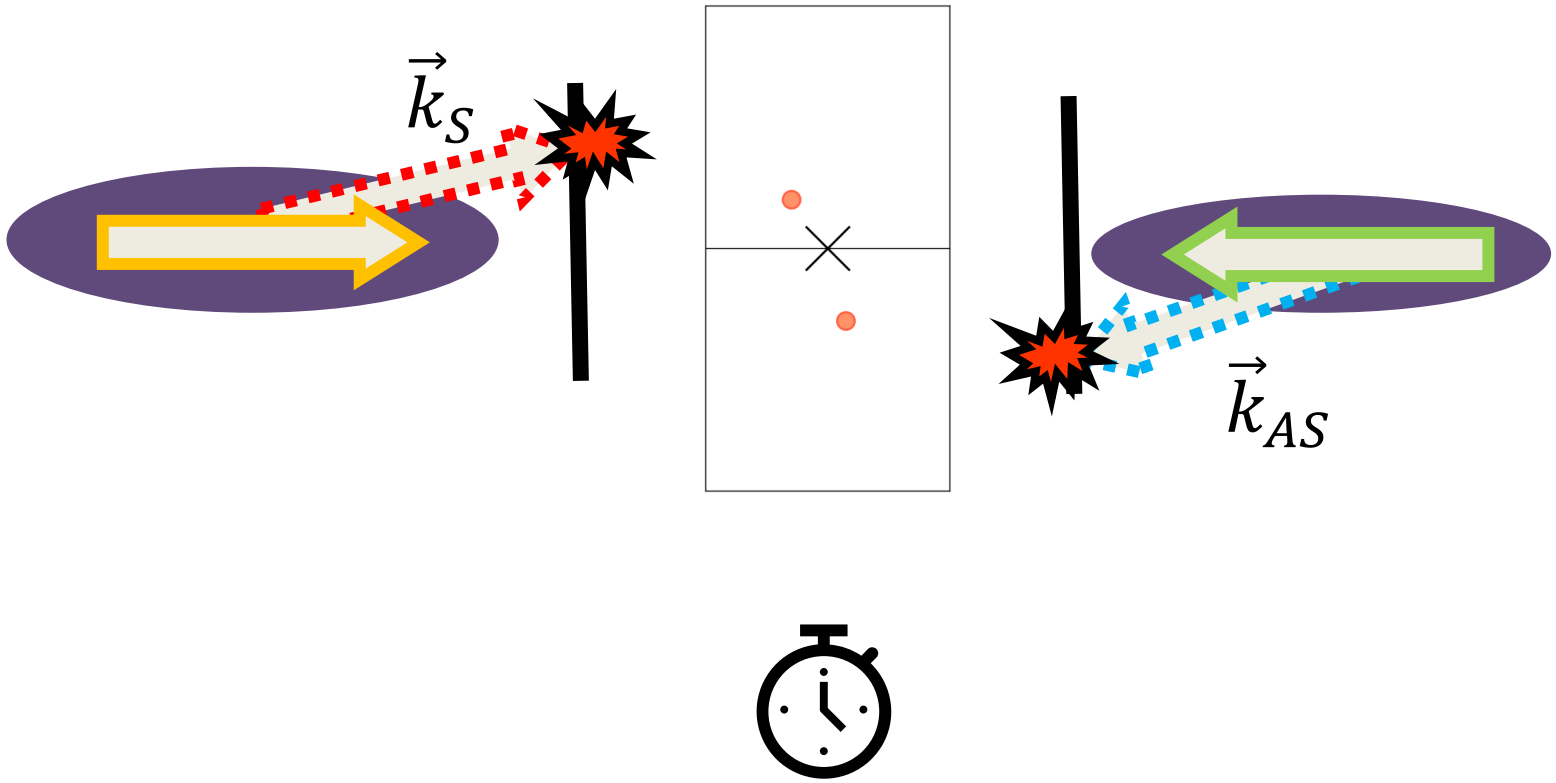


Correlated wavevectors

Write photon

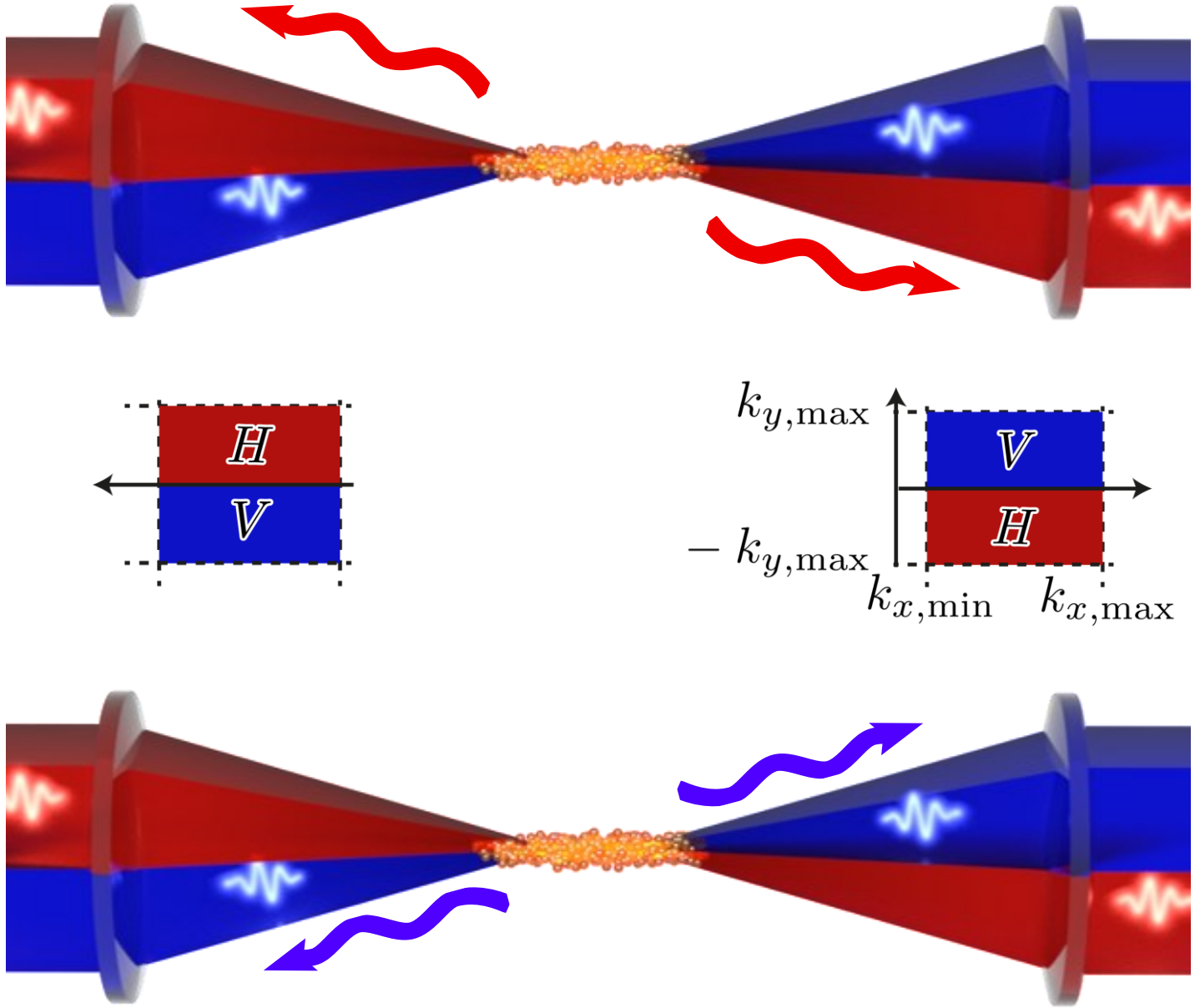
storage (delay)

Read photon



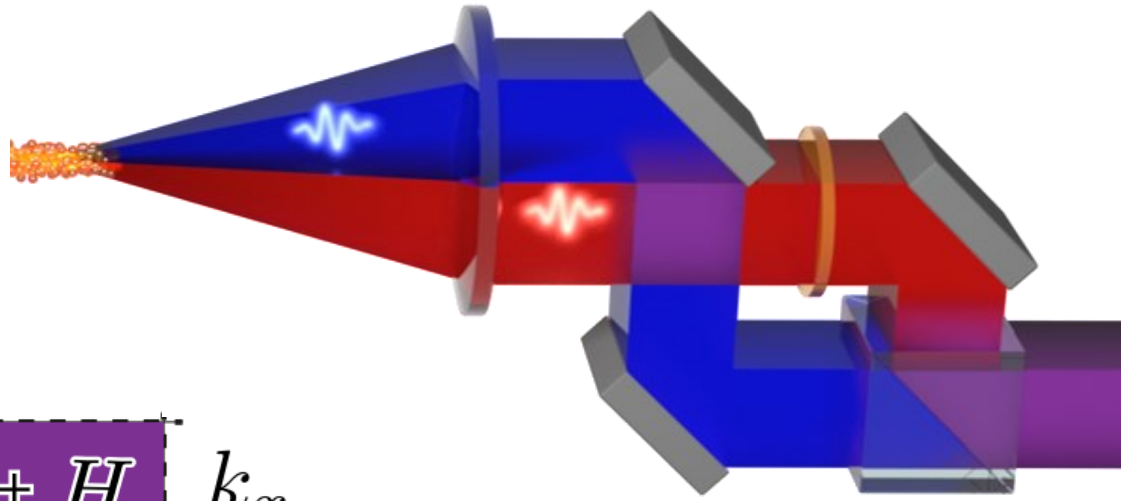
Wavevector modes

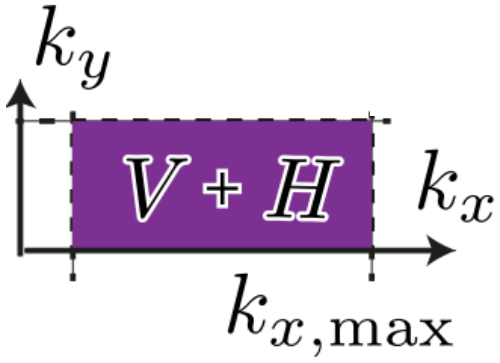
- Coherent modes
- Superposition of H and V
- Correlated write-out and read-out (HH + VV)

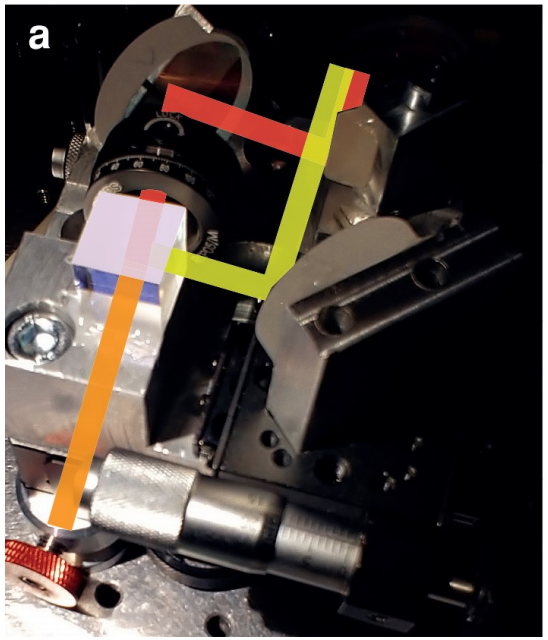


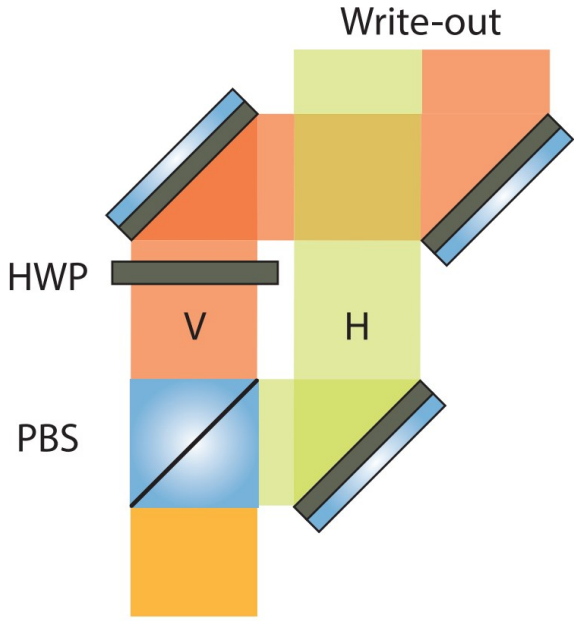
Mode converter

Pair of wavevector modes to orthogonal polarizations with a single wavevector



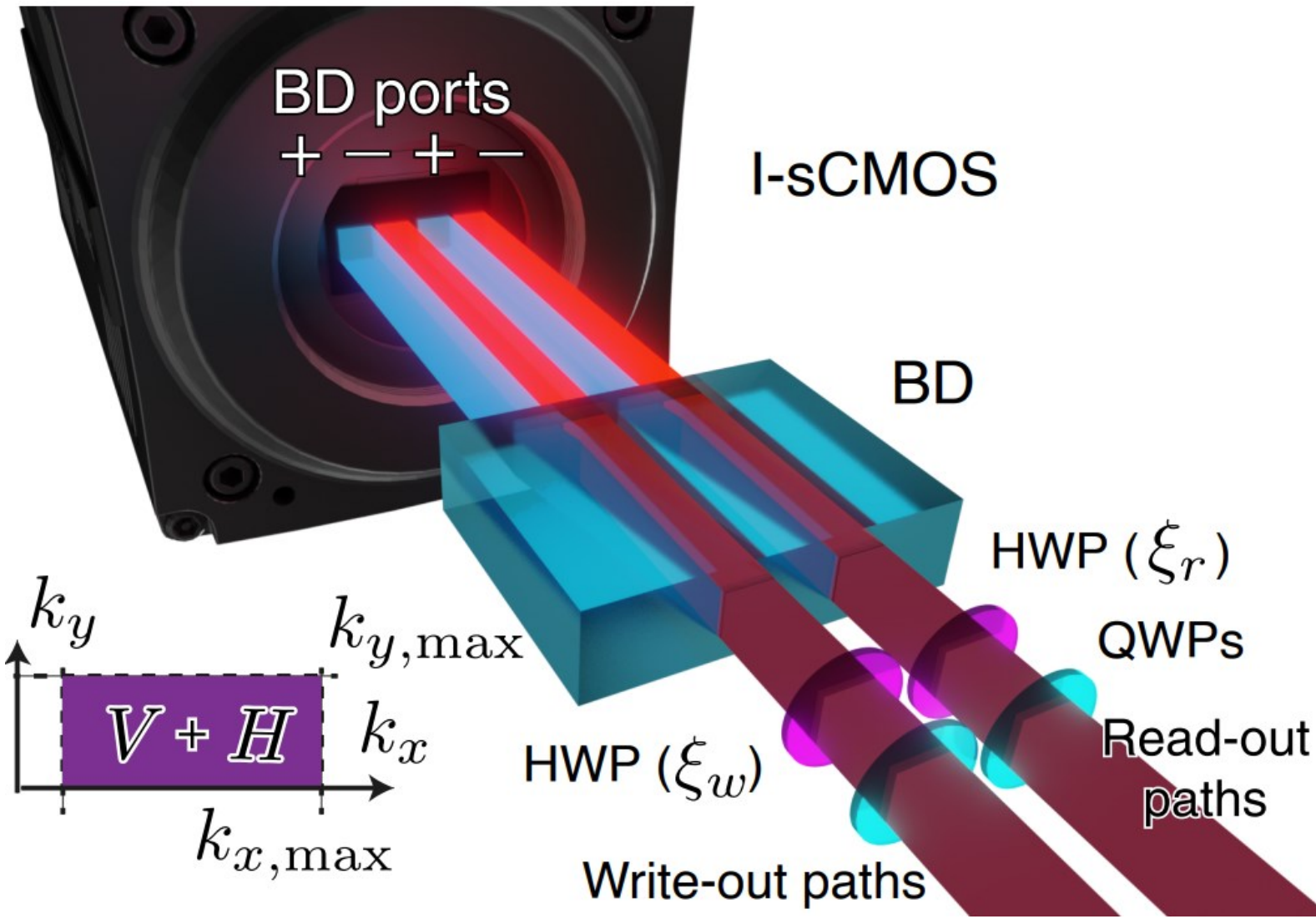






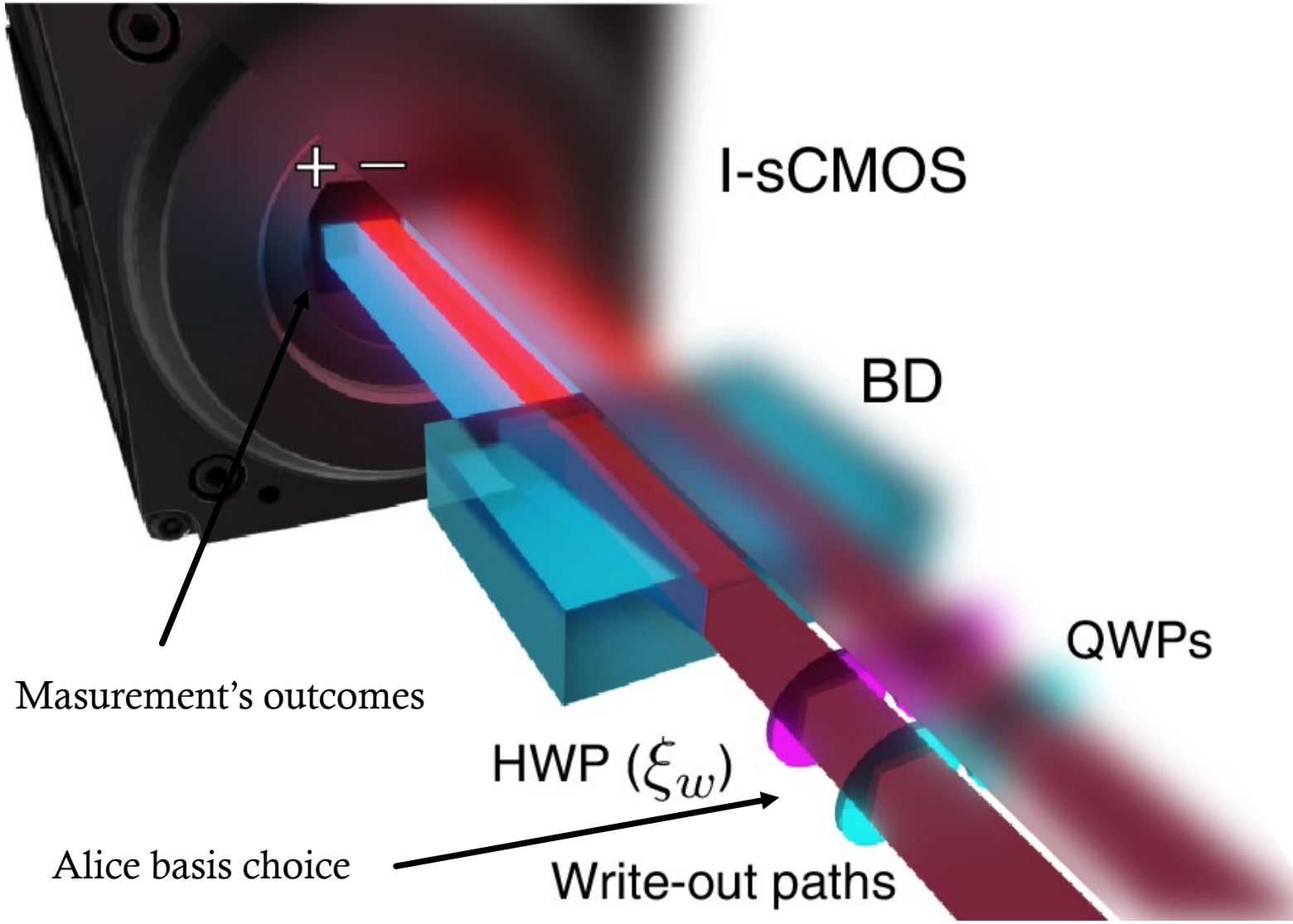
Bell measurement

With wavevector resolution



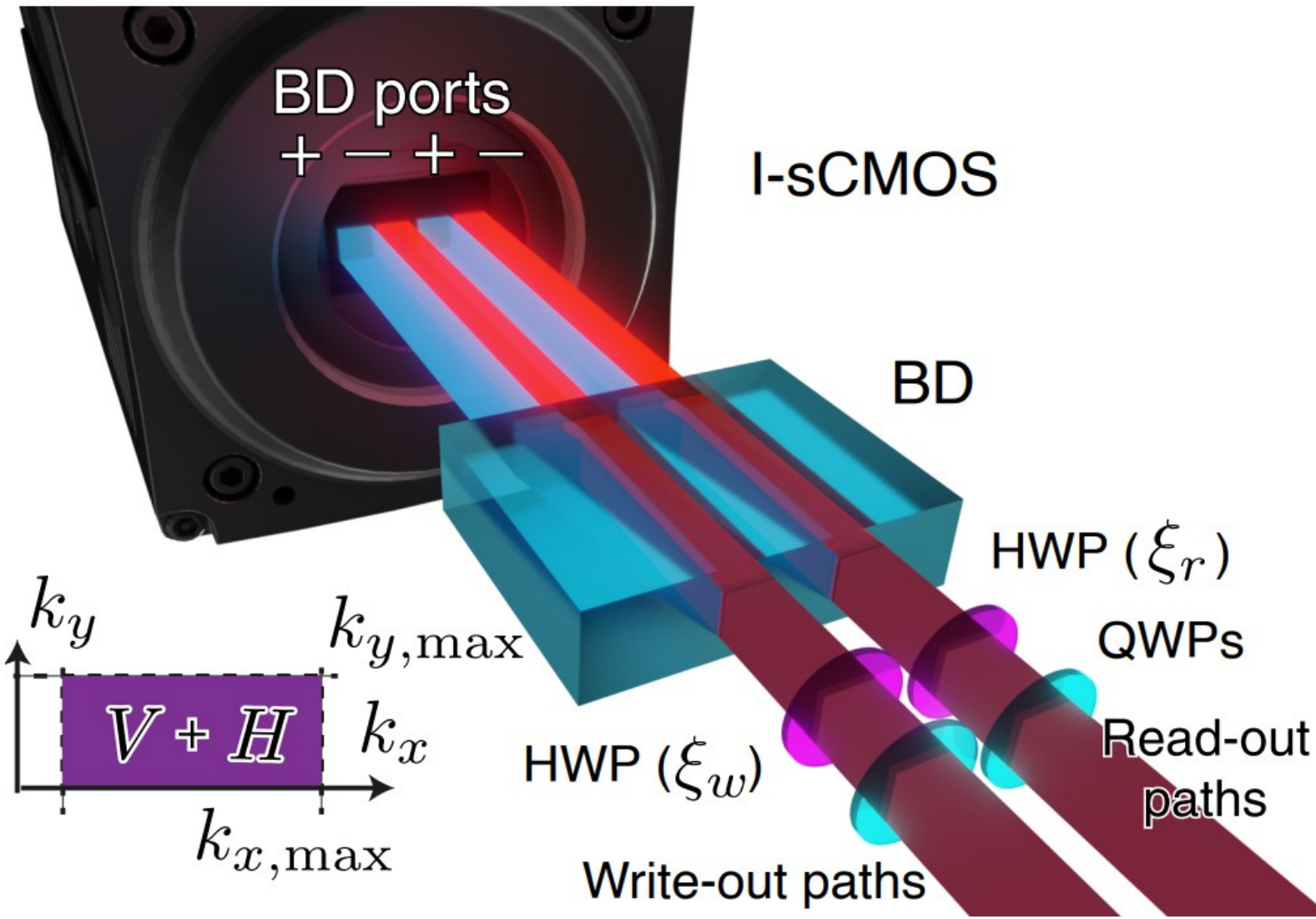
Bell measurement

With wavevector resolution



Bell measurement

With wavevector resolution

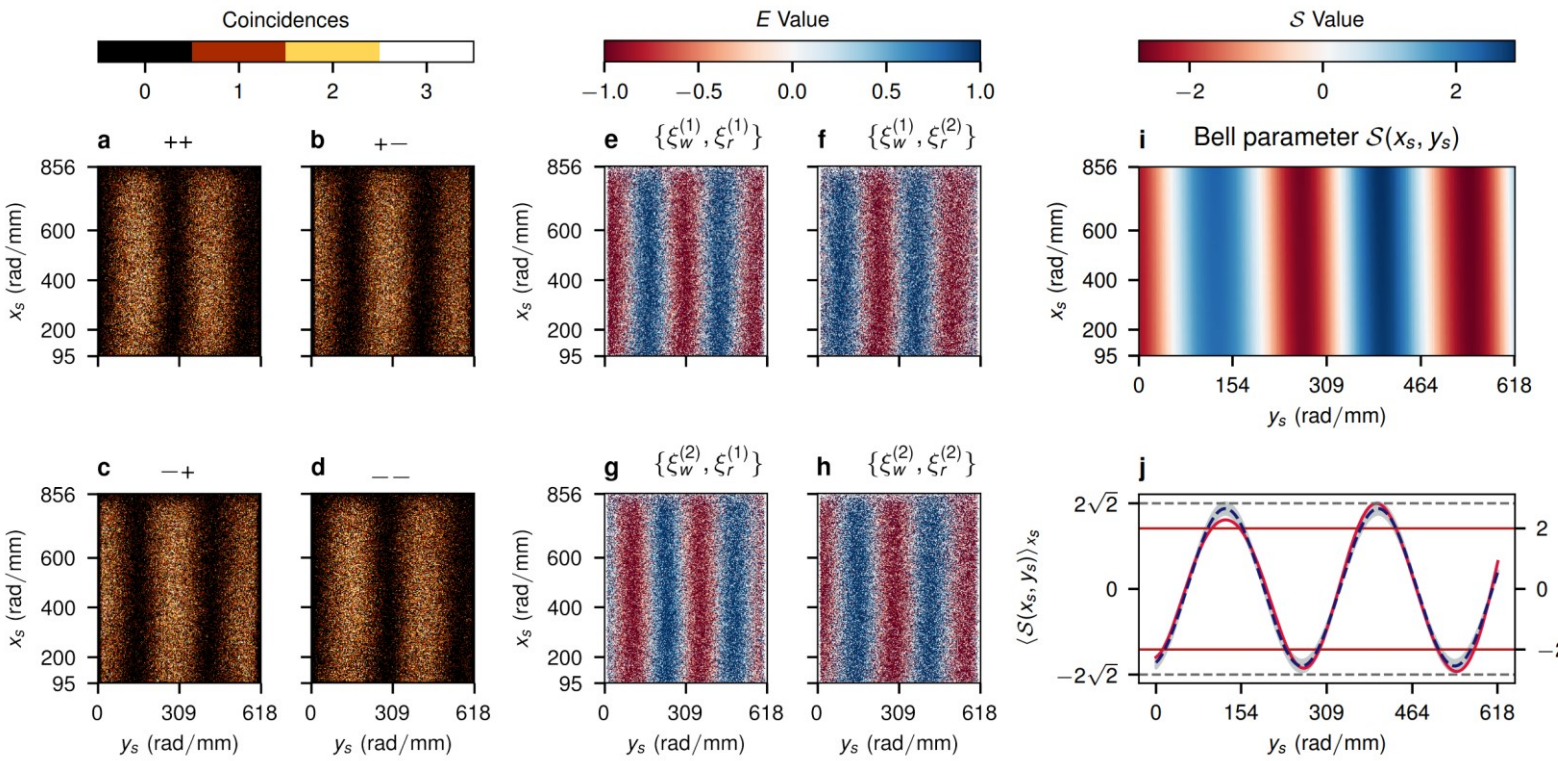


CHSH violation

Clauser, Horne, Shimony, Holt

In 500 modes,

In 250 modes after 45 us delay



$$E = \frac{N_{++} - N_{+-} - N_{-+} + N_{--}}{N_{++} + N_{+-} + N_{-+} + N_{--}}$$

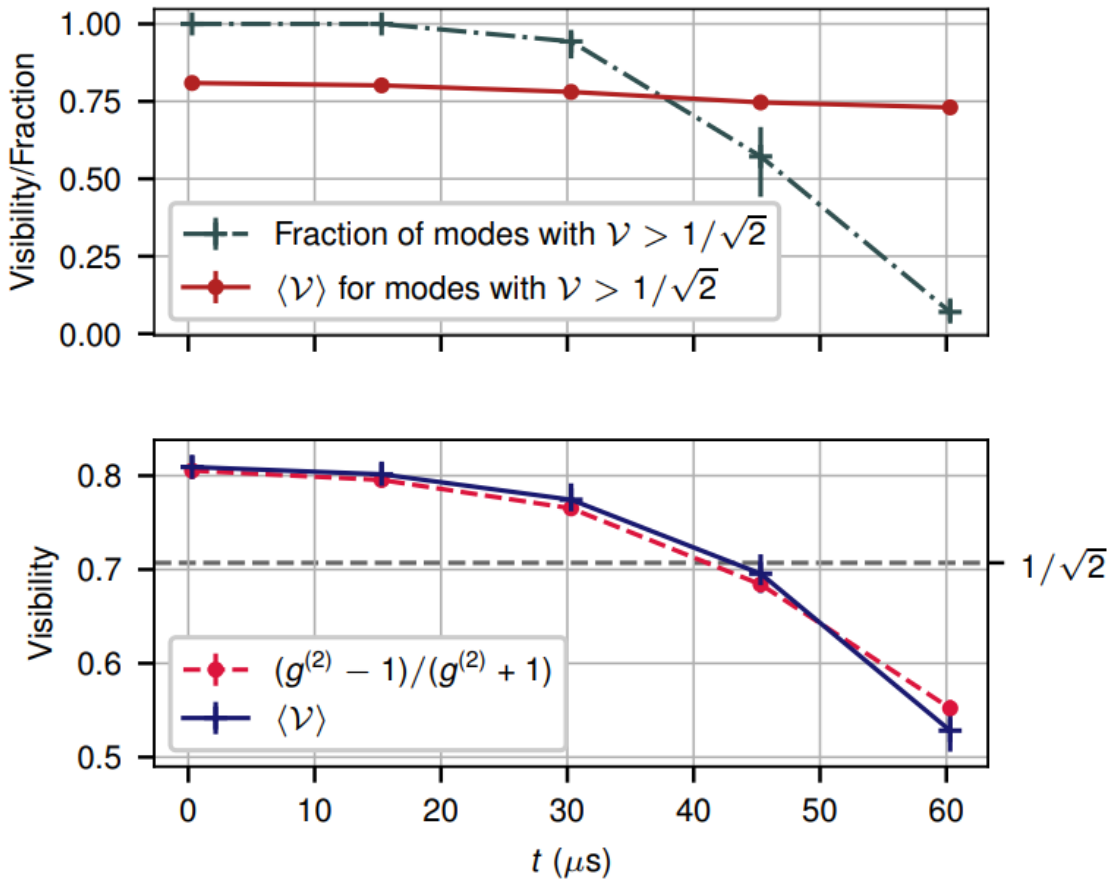
Commun Phys **4,** 46 (2021)

CHSH violation

Clauser, Horne, Shimony, Holt

In 500 modes,

In 250 modes after 45 us delay



Visibility $\mathcal{V} = \frac{|\mathcal{S}|}{2\sqrt{2}}$

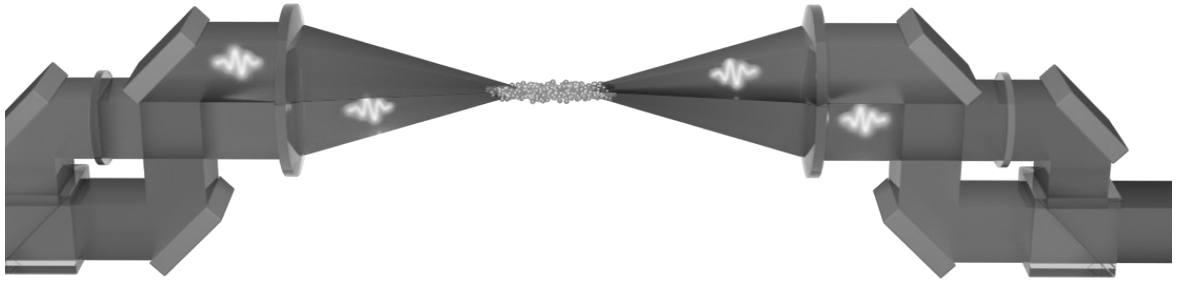
CHSH violation $\mathcal{V} > 1/\sqrt{2}$

Overview

Experiment

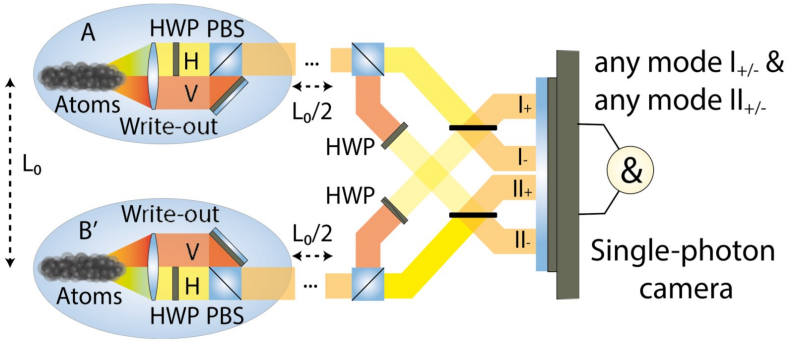
Theory

Experiment: Generation of entanglement in 500 modes



Commun Phys **4,** 46 (2021)

Theory: 5000 modes + performance as a quantum repeater



New J. Phys. **23** 053012 (2021)

Quantum Repeaters

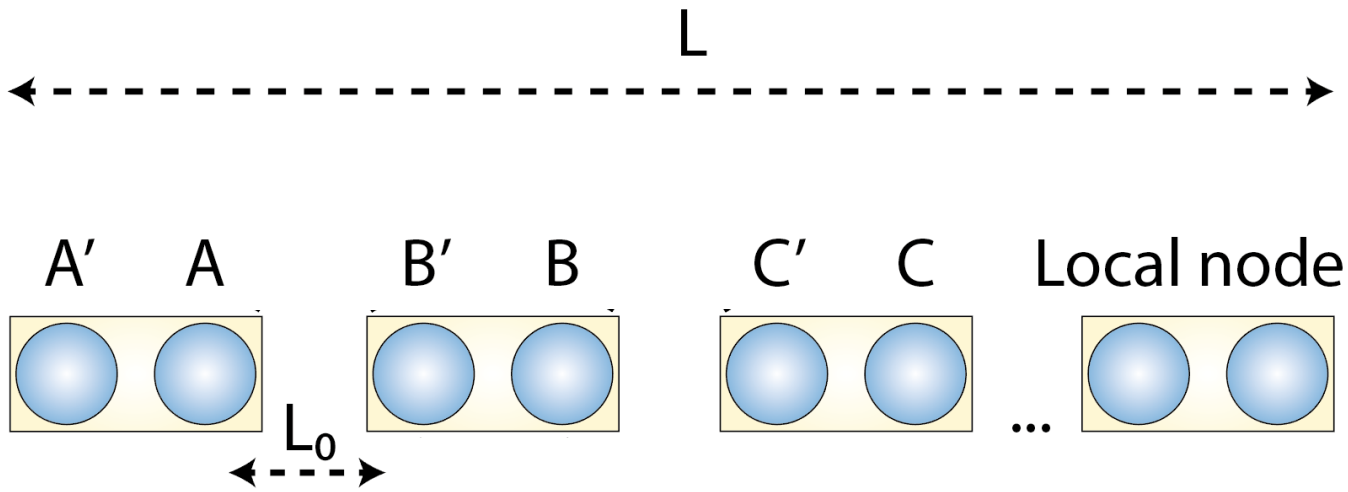
- Near-term: DLCZ, two-photon (BDCZ), …
- Error-correcting
- Others?

Quantum Repeaters

- Near-term: DLCZ, two-photon (BDCZ), …
- Error-correcting
- Others?

Quantum repeater network

Make final parties share an entangled state

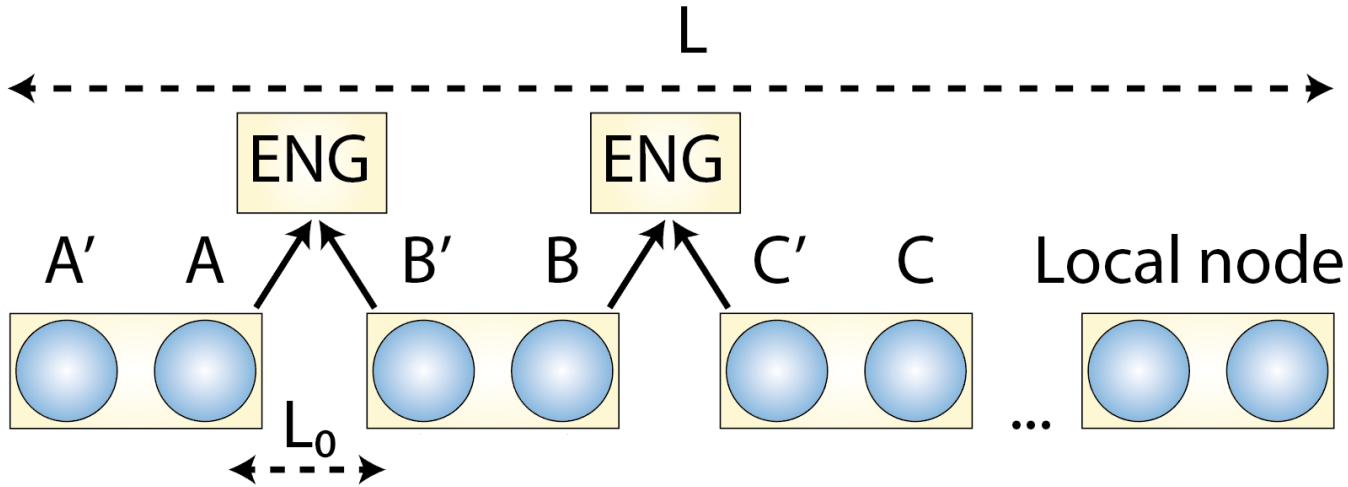


Transmission loss:

$$e^{-\alpha L}$$

Quantum repeater network

Entanglement generation (ENG) between neighbours



Transmission loss:

Direct over L

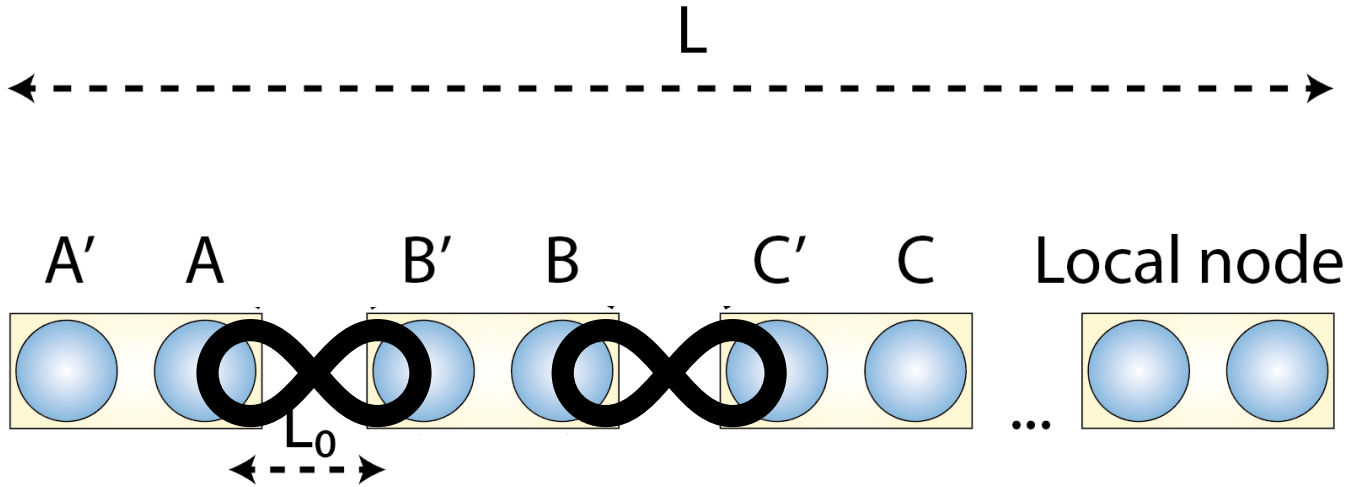
$$e^{-\alpha L}$$

ENG transmission
N nodes

$$1-(1-e^{-\alpha L/N})^N \approx Ne^{-\alpha L/N}$$

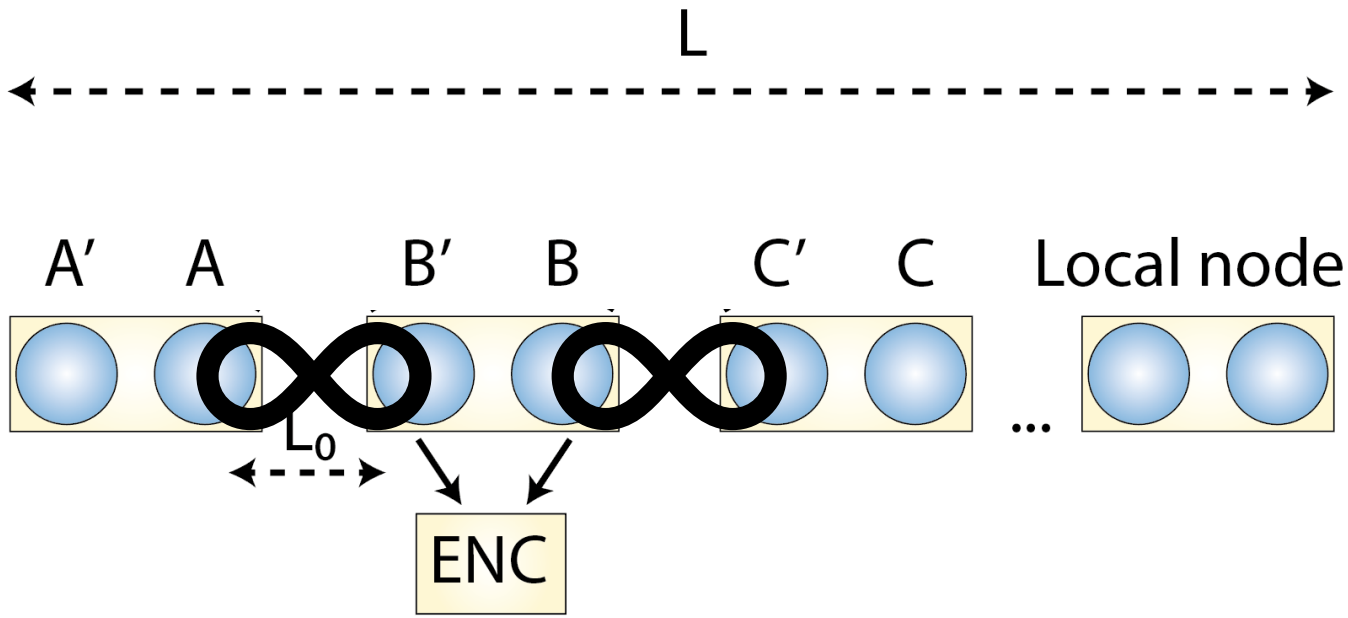
Quantum repeater network

We are lucky, ENGs succeeded



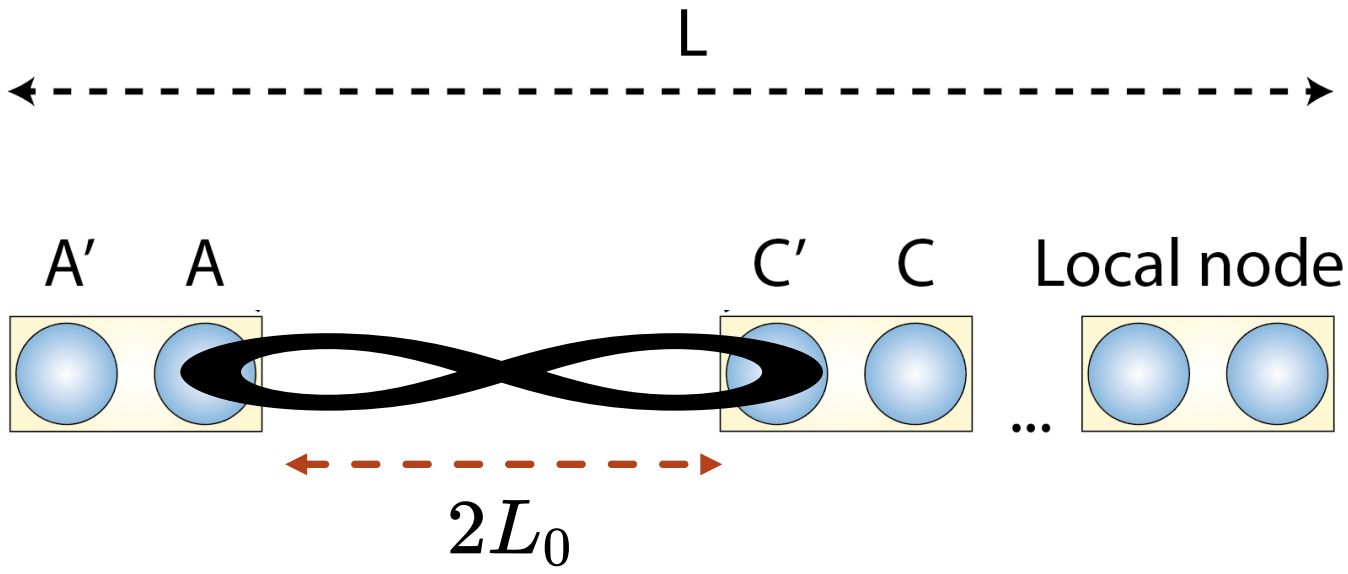
Quantum repeater network

Entanglement connection (ENC) at local nodes



Quantum repeater network

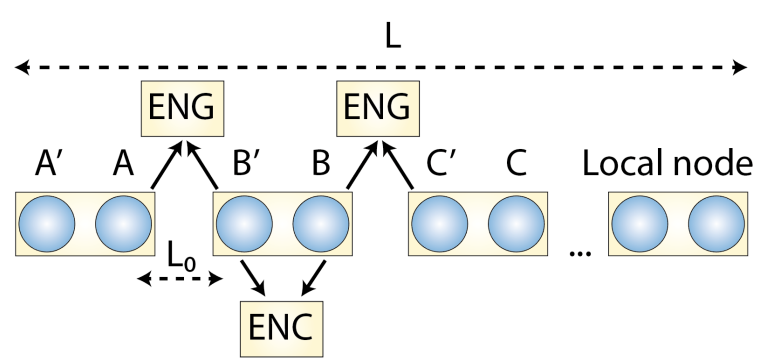
Entanglement connection (ENC) at local nodes



Multiplexing

Better performance scaling

More technically demanding



Single-mode, end-to-end success probability

$$p_1 \equiv 1 - (1 - p_1)$$

Parallel, M channels

$$M[1 - (1 - p_1)] = Mp_1$$

Multiplexed ENC

$$1 - (1 - p_1)^M \overset{p_1 \ll 1}{\approx} Mp_1$$

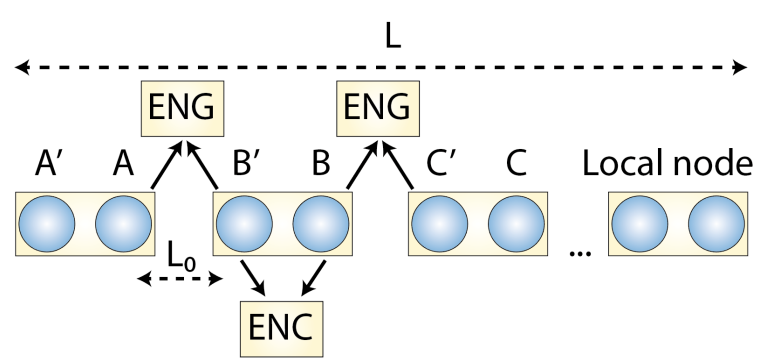
Multiplexed ENC + ENG

$$1 - (1 - p_1)^{M^2} \overset{p_1 \ll 1}{\approx} M^2 p_1$$

Multiplexing

Better performance scaling

More technically demanding



Single-mode, end-to-end success probability

$$p_1 \equiv 1 - (1 - p_1)$$

Parallel, M channels

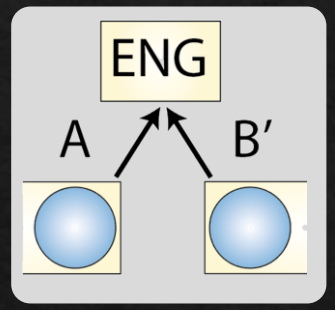
$$M[1 - (1 - p_1)] = Mp_1$$

Multiplexed ENC

$$1 - (1 - p_1)^M \overset{p_1 \ll 1}{\approx} Mp_1$$

Multiplexed ENC + ENG

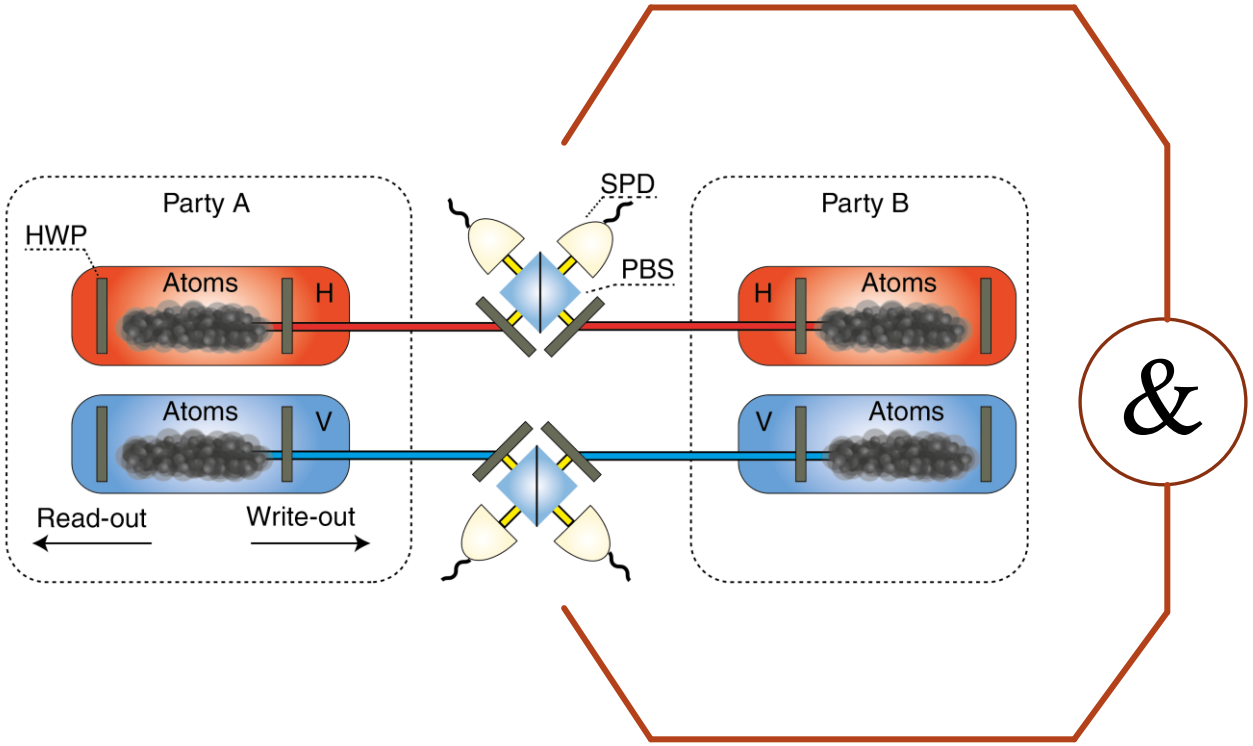
$$1 - (1 - p_1)^{M^2} \overset{p_1 \ll 1}{\approx} M^2 p_1$$



Two-photon protocol

Entanglement generation (ENG)

Single-mode



Coincidence detection:

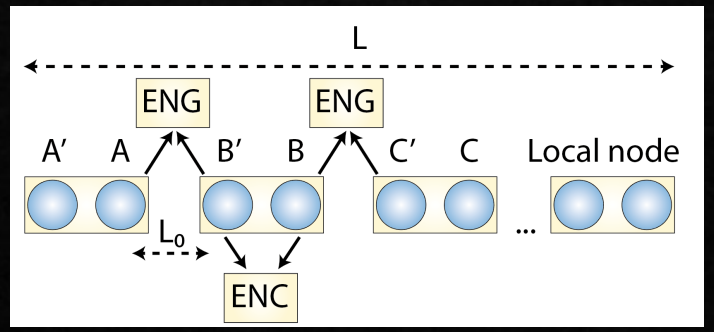
$$\frac{1}{2}(\hat{S}^{\dagger}_{A,H}+e^{i\varphi}\hat{S}^{\dagger}_{B,H})(\hat{S}^{\dagger}_{A,V}+e^{i\varphi}\hat{S}^{\dagger}_{B,V})$$

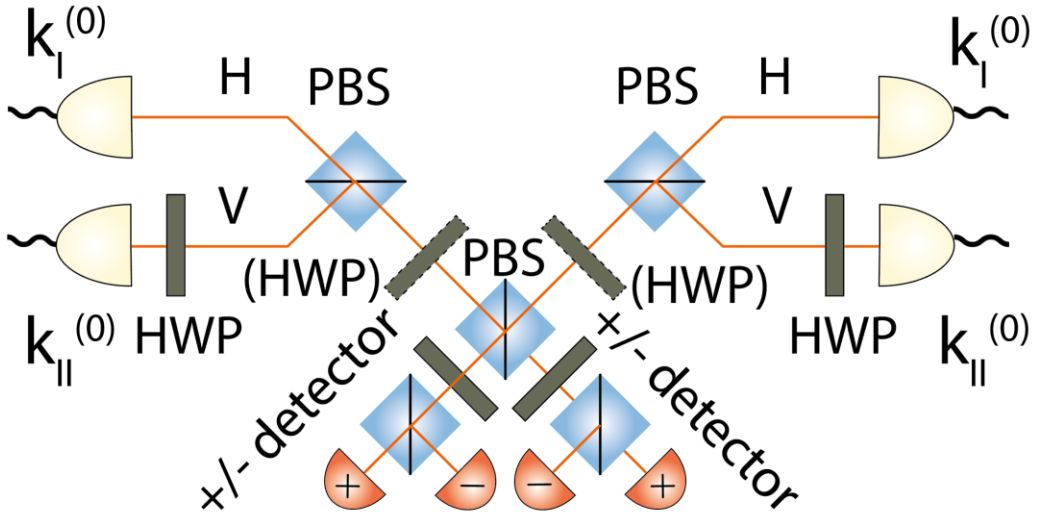
Further post-selection (at ENC):

$$\frac{1}{\sqrt{2}}(\hat{S}^{\dagger}_{A,H}\hat{S}^{\dagger}_{B,H}+\hat{S}^{\dagger}_{A,V}\hat{S}^{\dagger}_{B,V})$$

Two-photon ENC

Post-select 1/8th of the cases

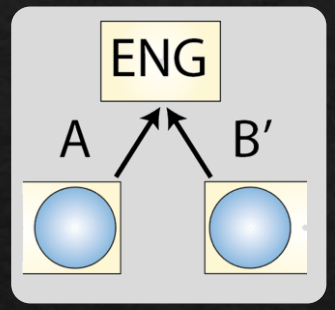




$$\frac{1}{2}(\hat{S}^{\dagger}_{A,H}+e^{i\varphi}\hat{S}^{\dagger}_{B',H})(\hat{S}^{\dagger}_{A,V}+e^{i\varphi}\hat{S}^{\dagger}_{B',V})$$

$$\frac{1}{2}(\hat{S}^{\dagger}_{B,H}+e^{i\tilde{\varphi}}\hat{S}^{\dagger}_{C',H})(\hat{S}^{\dagger}_{B,V}+e^{i\tilde{\varphi}}\hat{S}^{\dagger}_{C',V})$$

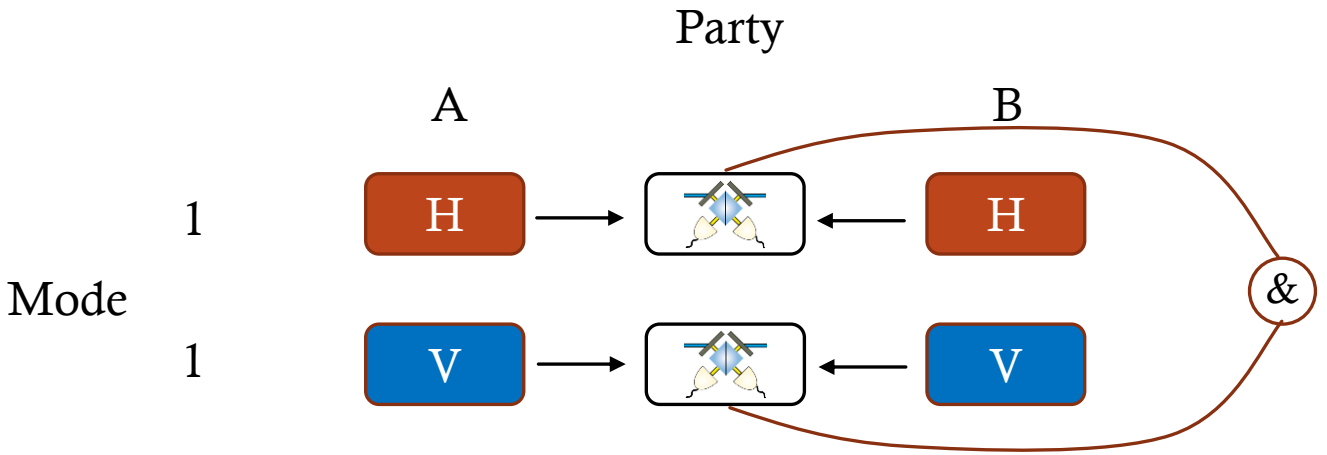
$$\frac{1}{\sqrt{2}}(\hat{S}^{\dagger}_{A,H}\hat{S}^{\dagger}_{C',H}+\hat{S}^{\dagger}_{A,V}\hat{S}^{\dagger}_{C',V})$$

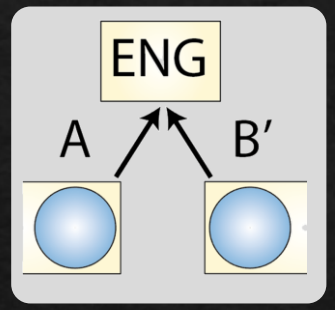


Single-mode ENG

Coincidences:

(@H and @V)



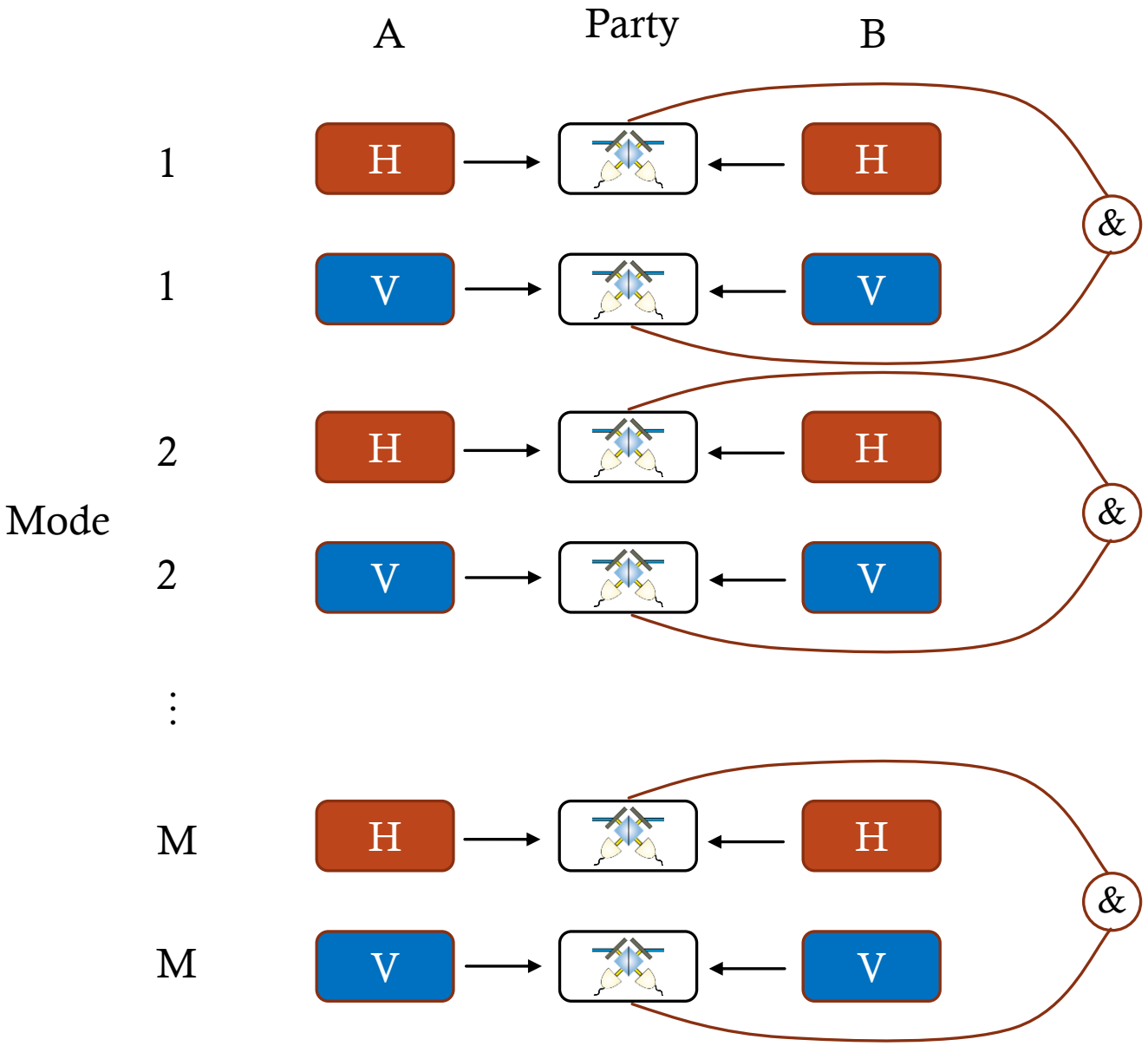


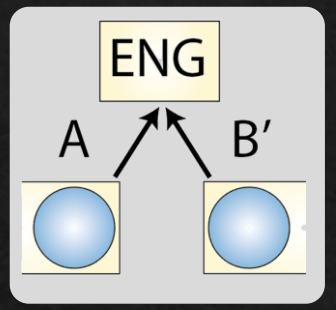
Parallel ENG

Coincidences:

(@H and @V) for any mode index

M possibilities





Multiplexed ENG

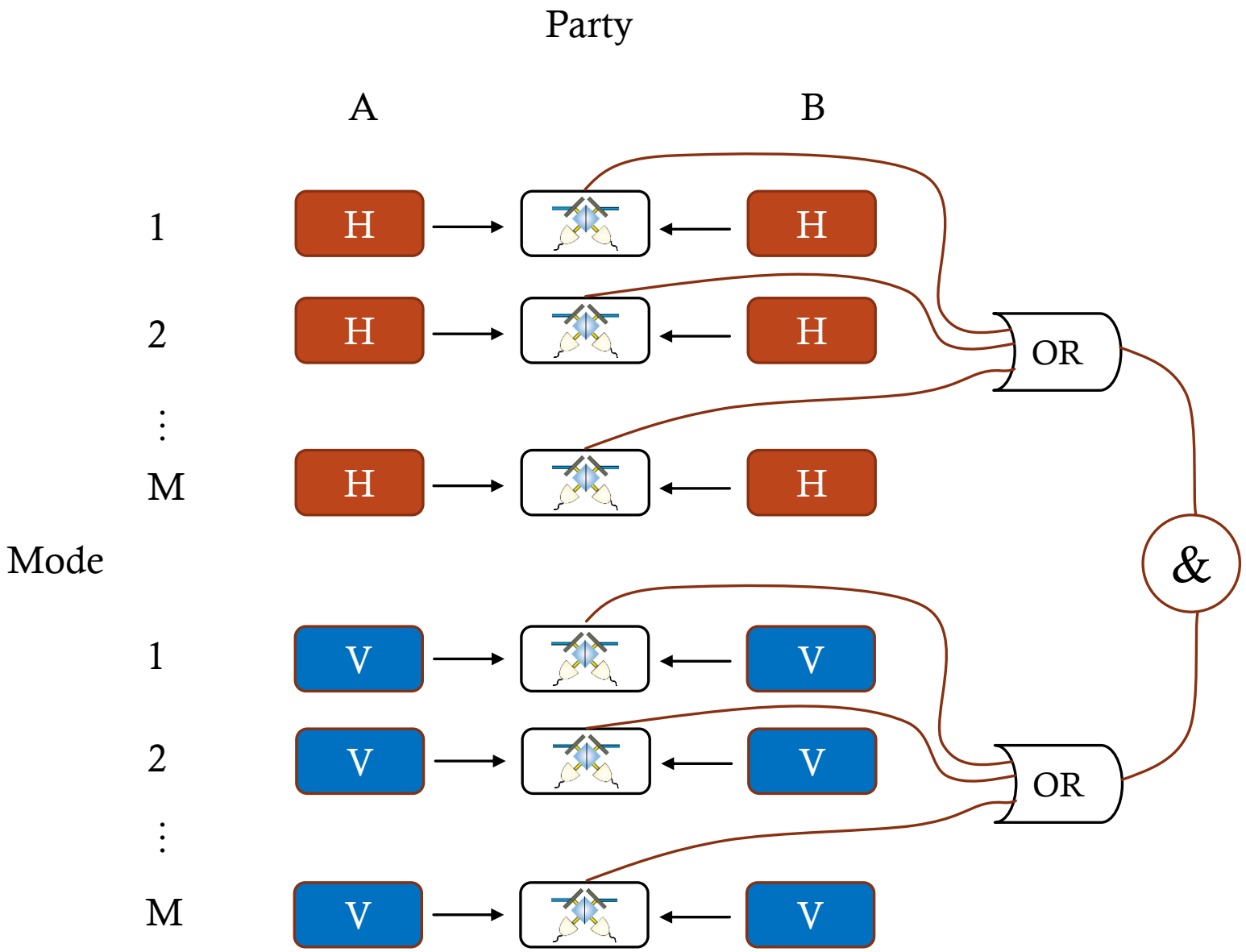
Coincidences:

(@H for any mode index)

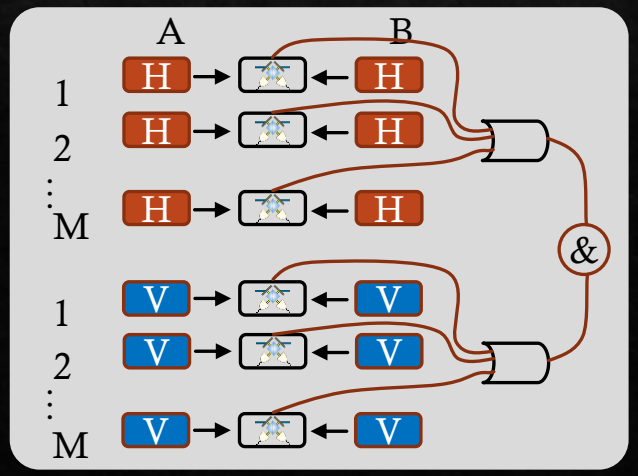
And

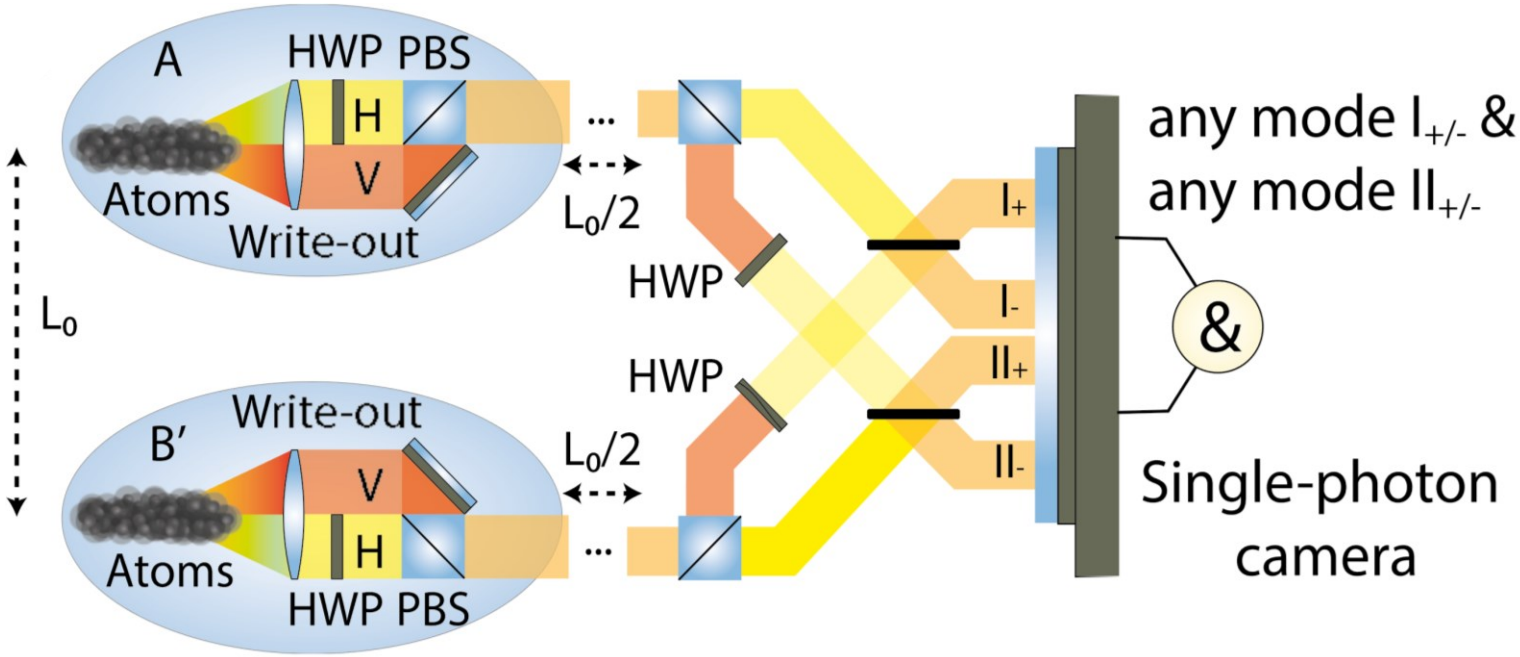
(@V for any mode index)

M(M-1) possibilities!



Multiplexed ENG





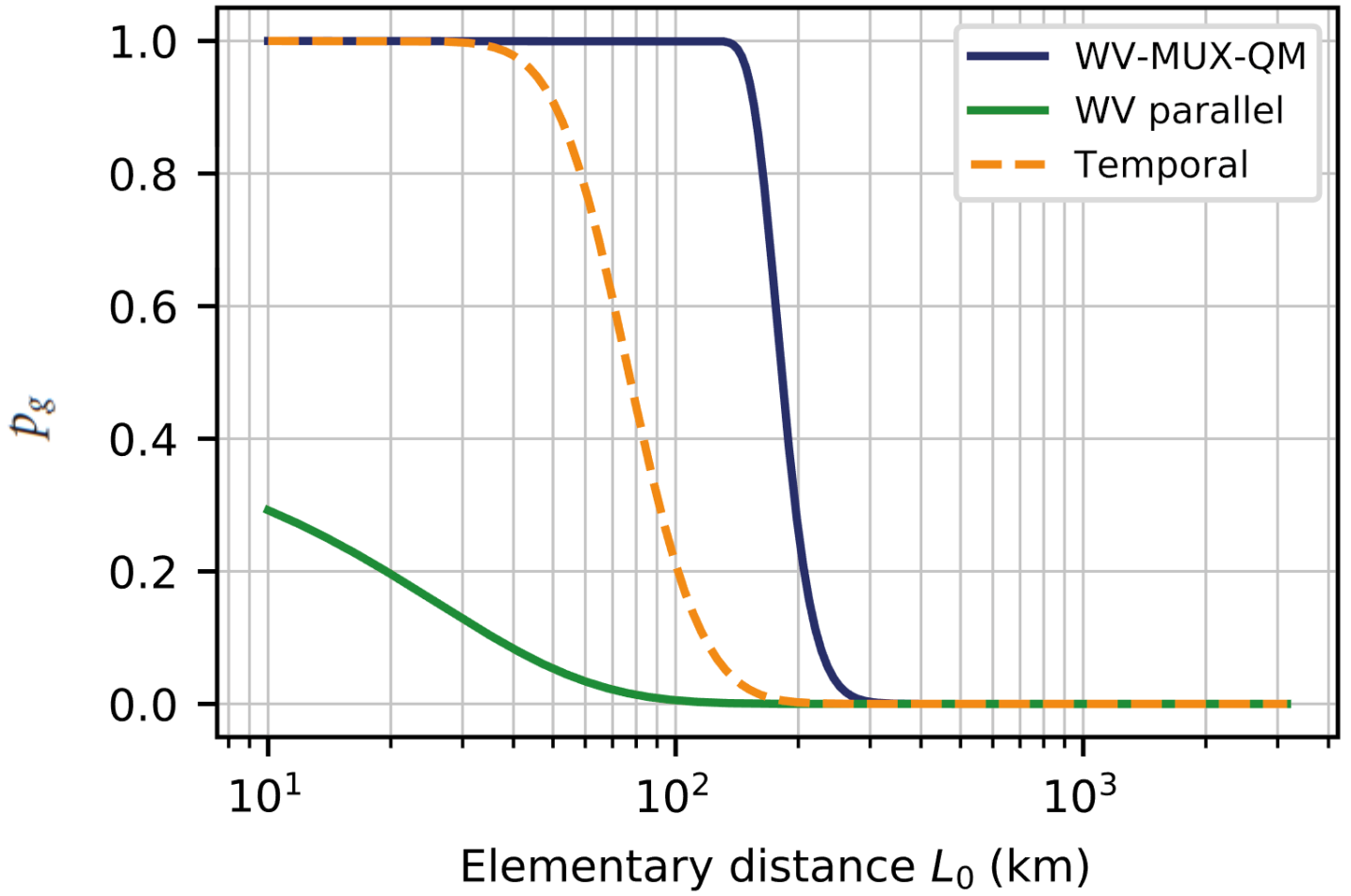
ENG success

Probability vs internode distance

Wavevector multiplexed (5000 modes)

Wavevector parallel

Temporal parallel



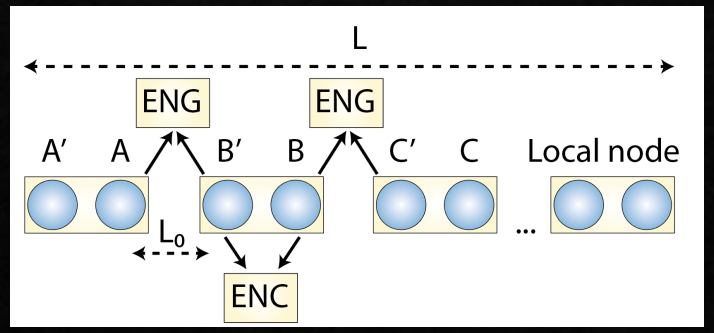
$$p_1 = (\chi \eta_m \eta_t)^2$$

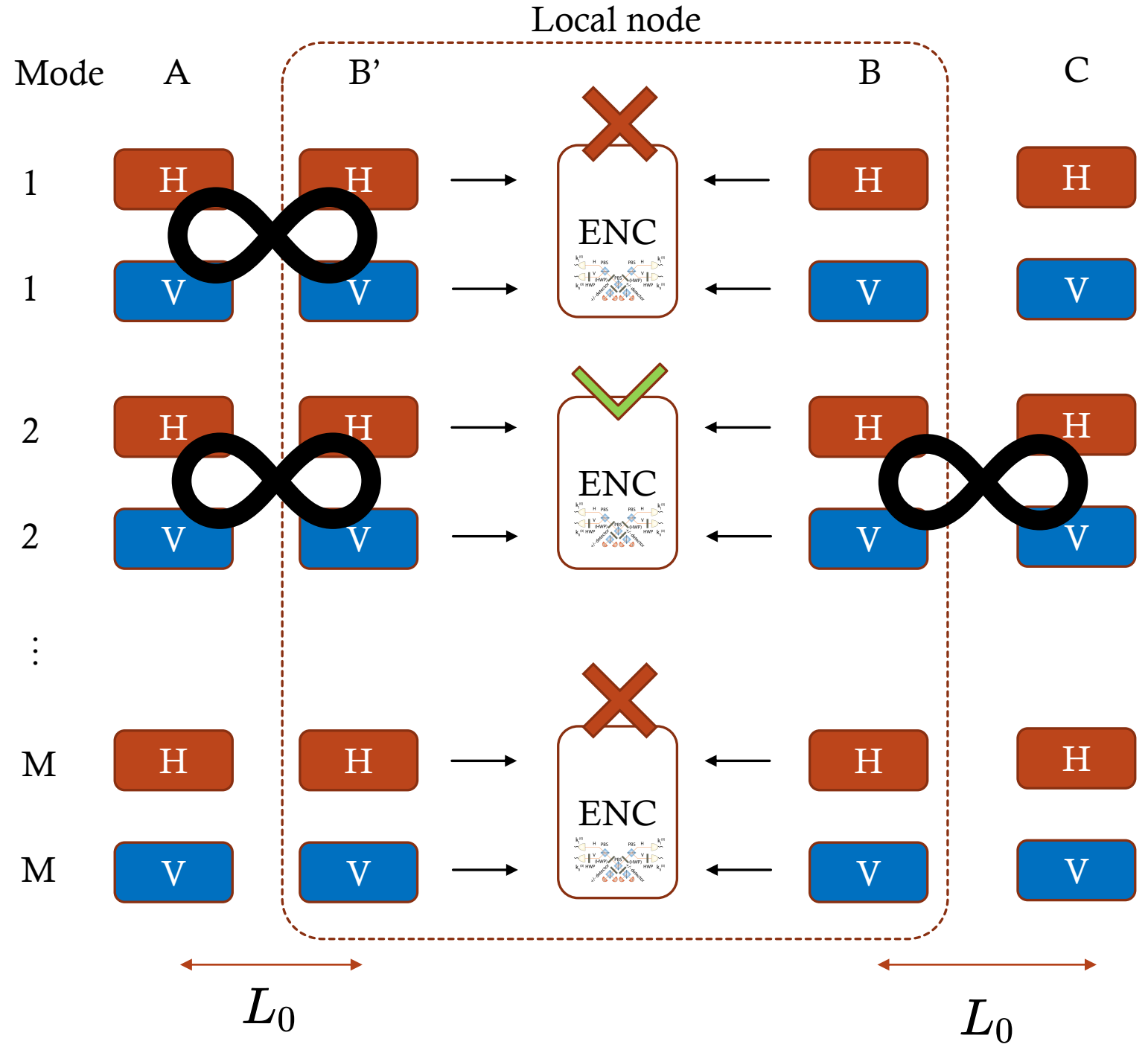
$$p_g^{(\text{parallel})} = 1 - (1 - p_1)^M$$

$$p_g = 1 - (1 - p_1)^{M^2}$$

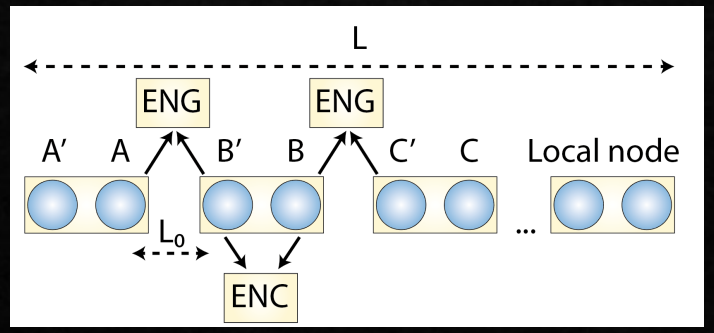
New J. Phys. **23** 053012 (2021)

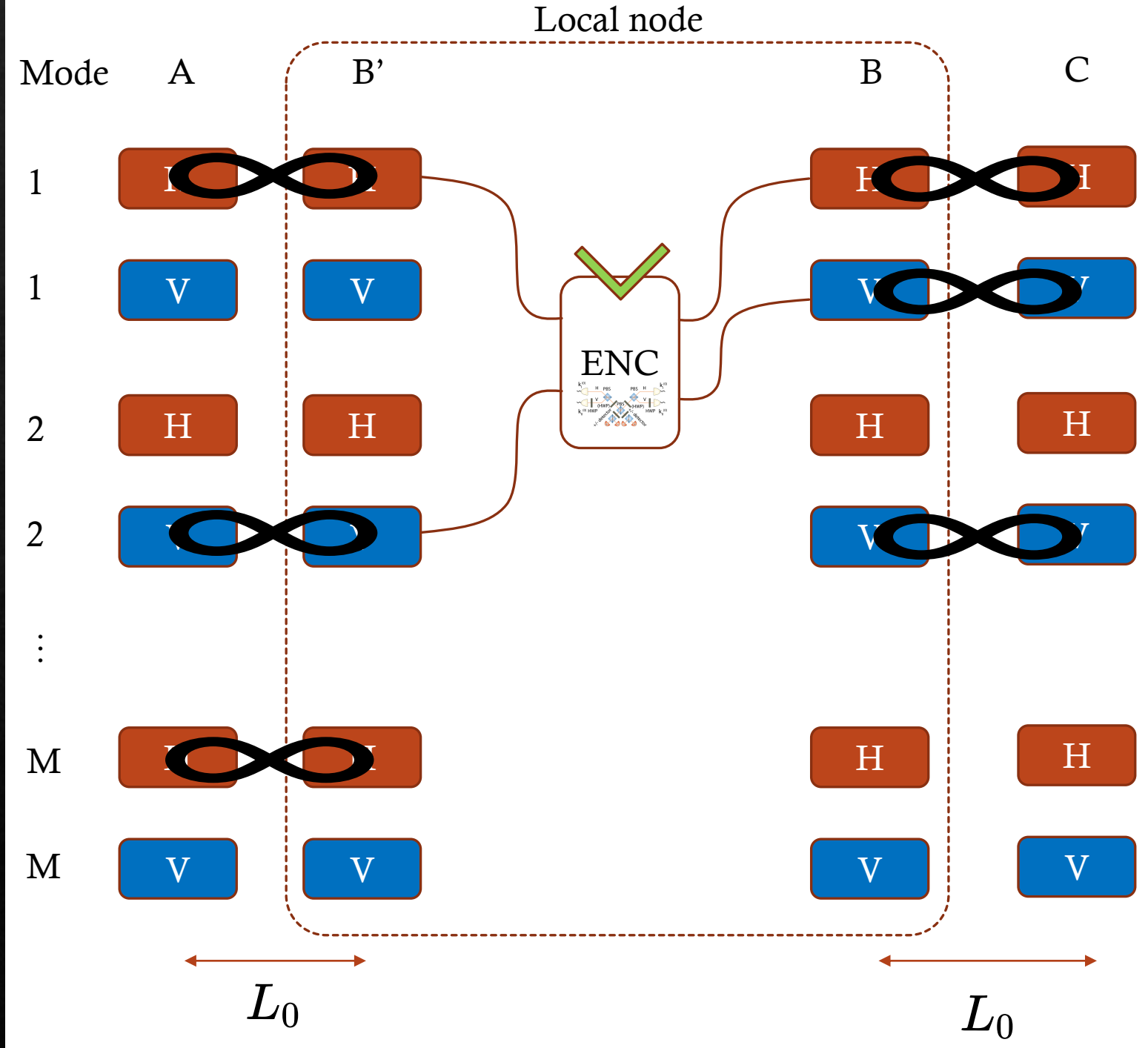
Parallel ENC





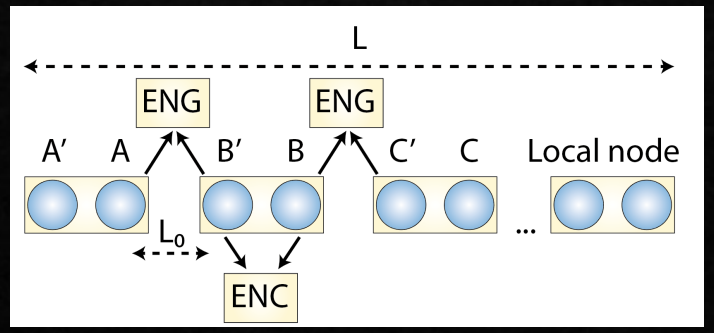
Multiplexed ENC



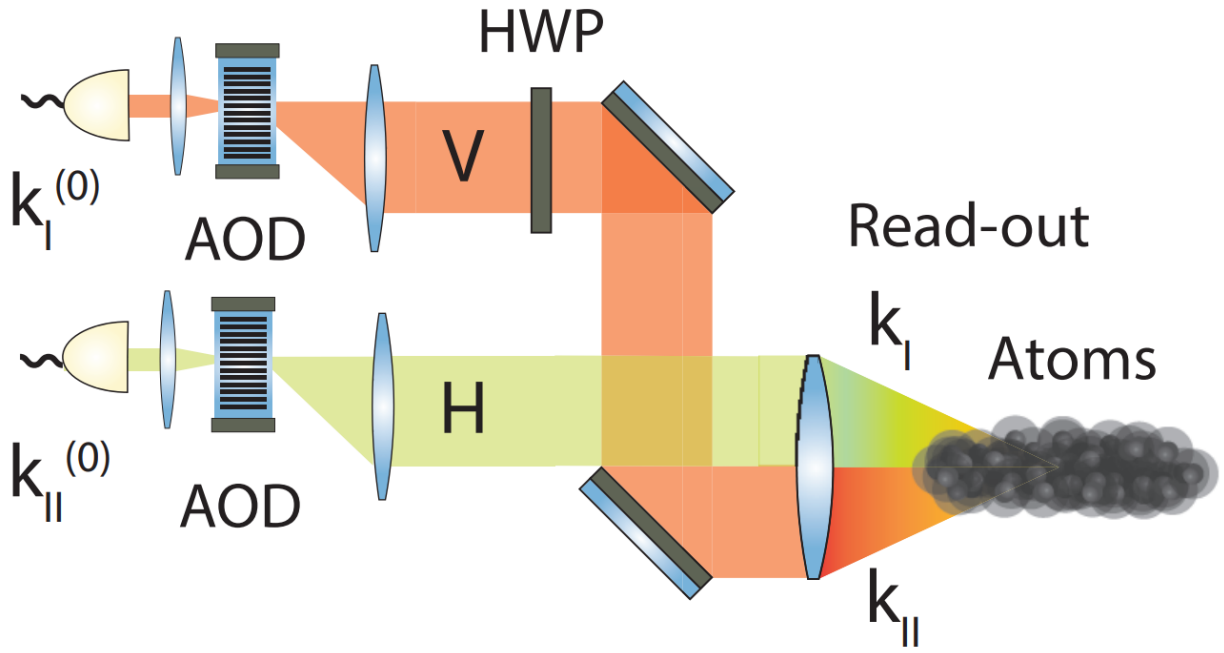


Multiplexed ENC

Mux readout to single-mode ENC

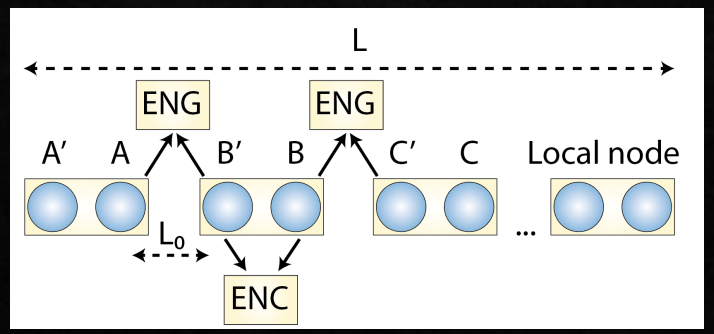


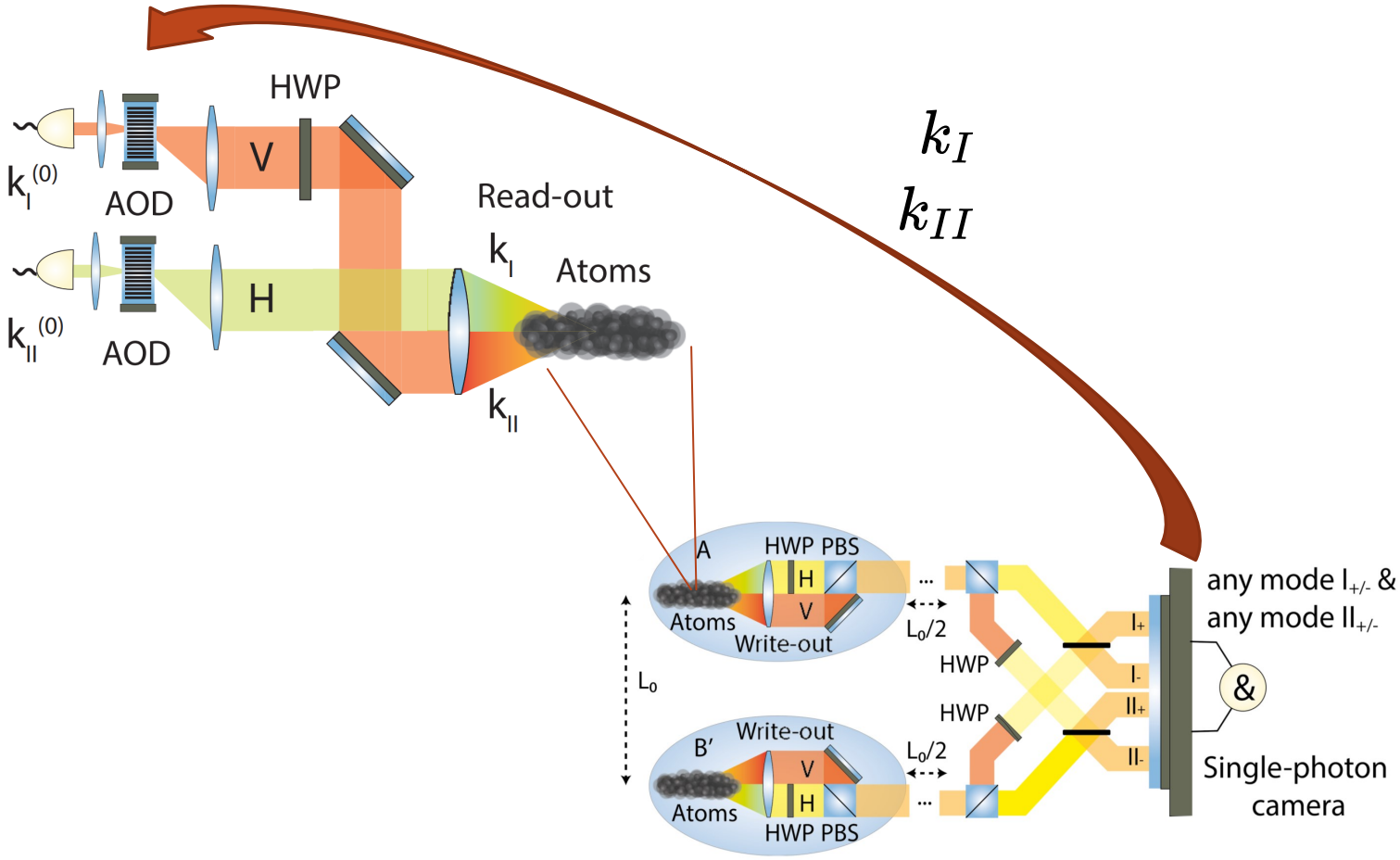
Readout multiplexing (particular solution)



Multiplexed ENC

Info from multimode ENG





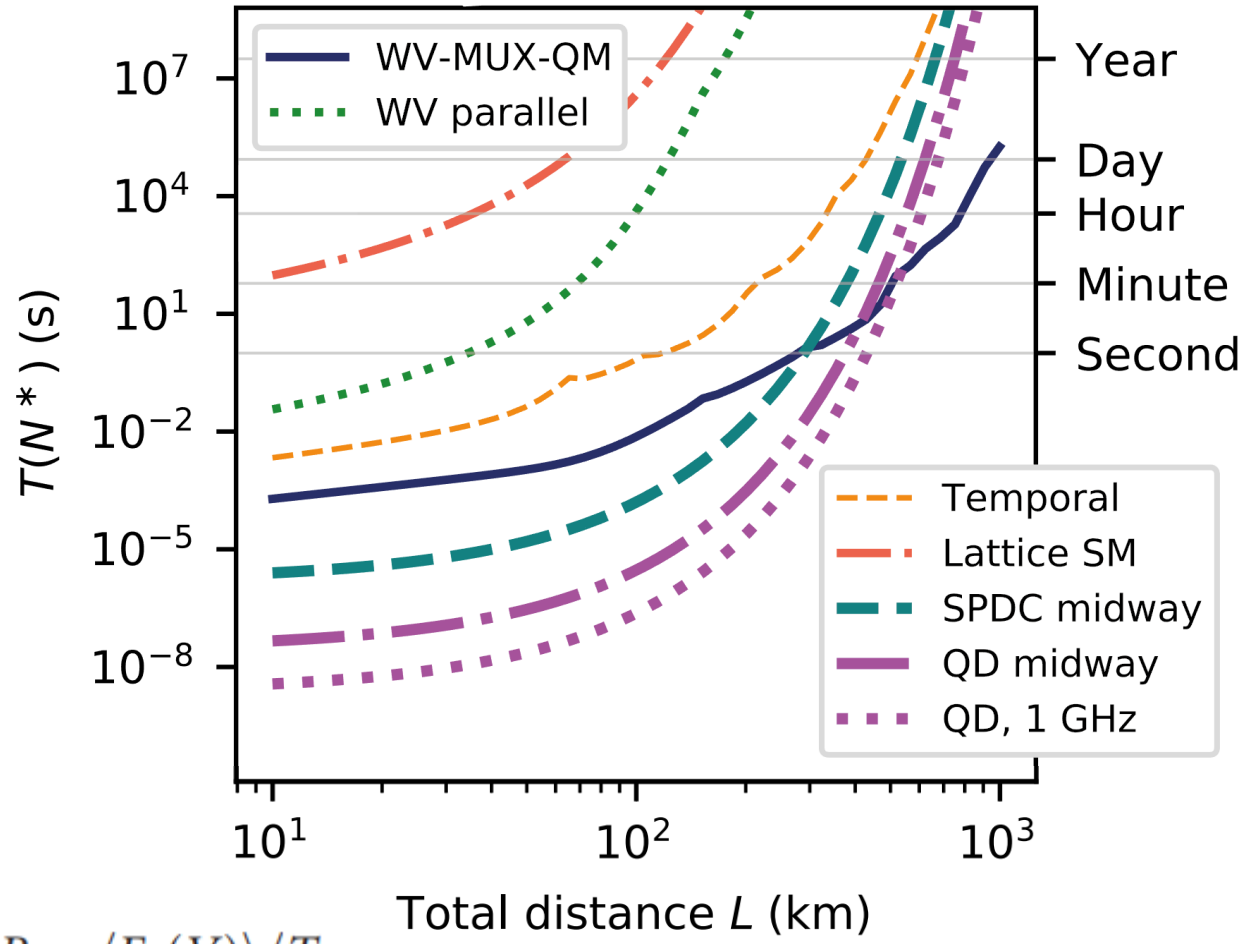
$$\frac{1}{2}(\hat{S}^{\dagger}_{A,H,\mathbf{k_I}} + \exp(i\phi)\hat{S}^{\dagger}_{B',V,\mathbf{k_I}})(\hat{S}^{\dagger}_{A,V,\mathbf{k_{II}}} + \exp(i\phi)\hat{S}^{\dagger}_{B',H,\mathbf{k_{II}}})|\mathrm{vac}\rangle$$

Performance

Quality = Entanglement of formation

Maximize: Quality * Average time per success / n.o. nodes

Figure of merit: Quality *Average time per success



$$R = \langle E_F(V) \rangle / T_{tot}.$$

$$Q(N, L) = R(N, L)/N,$$

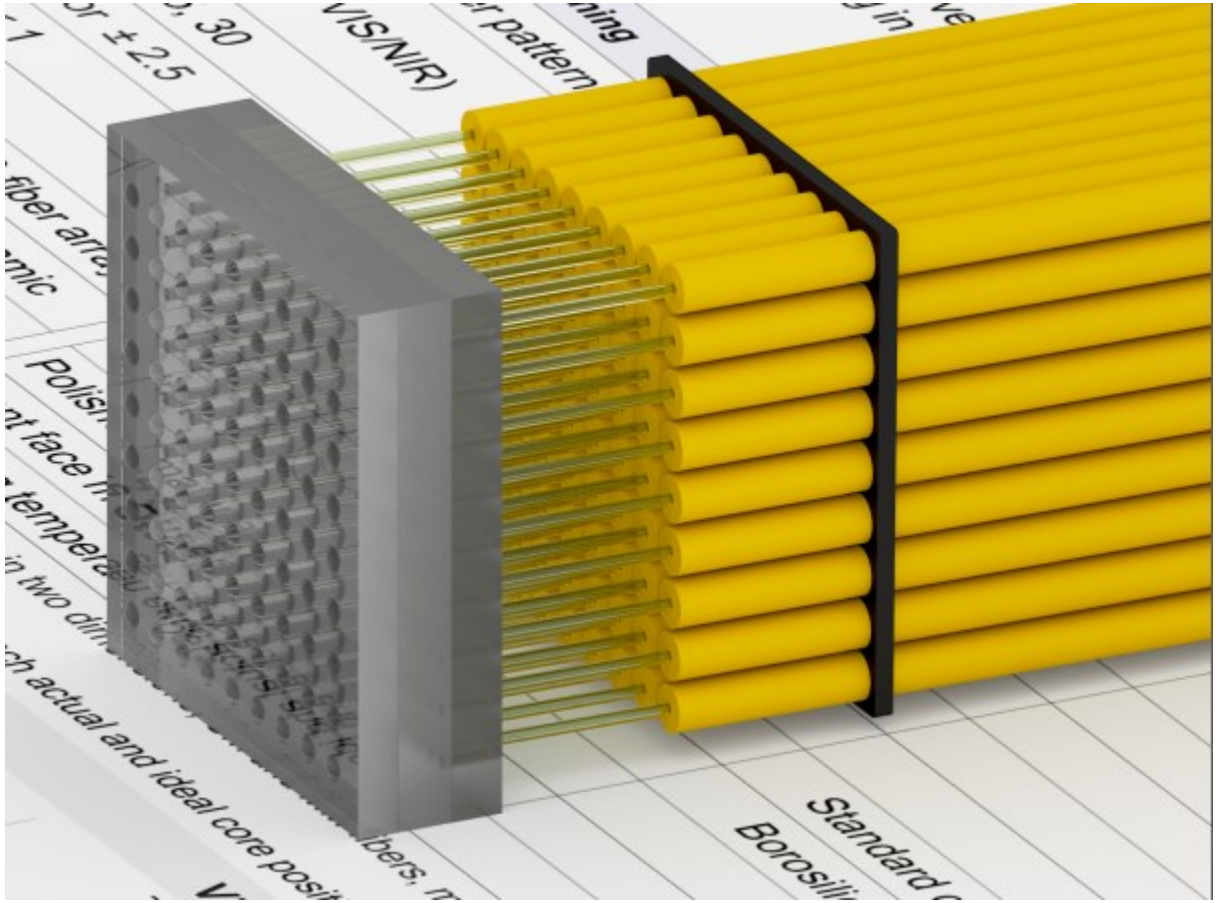
$$N^*(L) = \arg\max_N Q(N, L).$$

New J. Phys. **23** 053012 (2021)

Fiber Coupled Microlens Array

12 x 12

+ Single-mode fiber bundles, off-the-shelf
600 fibers / bundle



SQS Vlaknova optika a.s.

Summary

- Multiplexing ENC and ENG gives better scaling with number of modes
- Mostly experimentally feasible but transferring 5000 modes coherently is challenging!
- Wavevector multiplexing (not necessarily in atomic systems) can slightly enhance near-term repeaters while we struggle with efficiency and coherence time of quantum memories