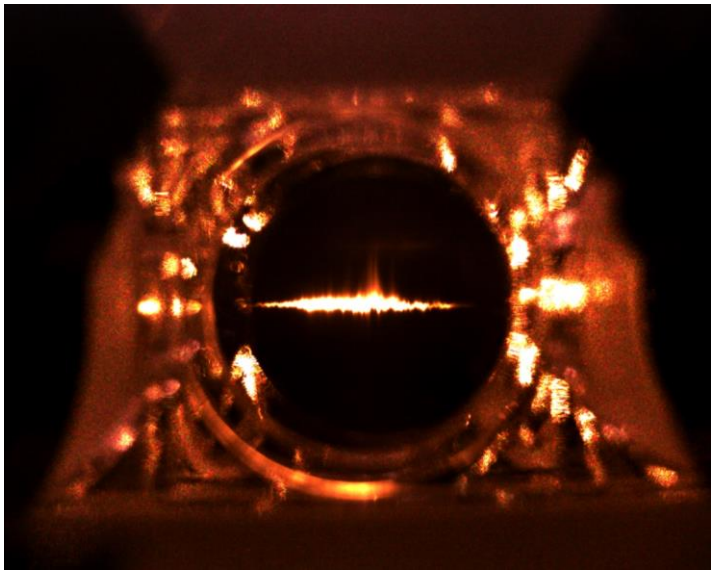
Multiplexed quantum memory with many functions:
entanglement generation and interferometric processing



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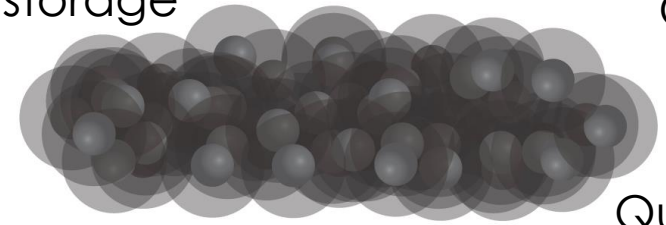
European Funds Smart Growth
Republic of Poland
FNP Foundation for Polish Science
European Union European Regional Development Fund

Multifunctional quantum memories

Photon spin-wave storage

Photon generation

Spin-wave interference

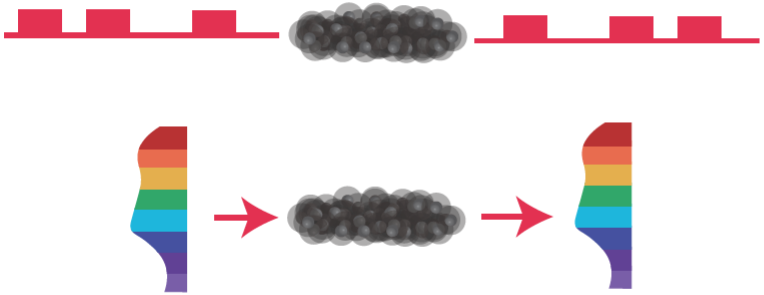


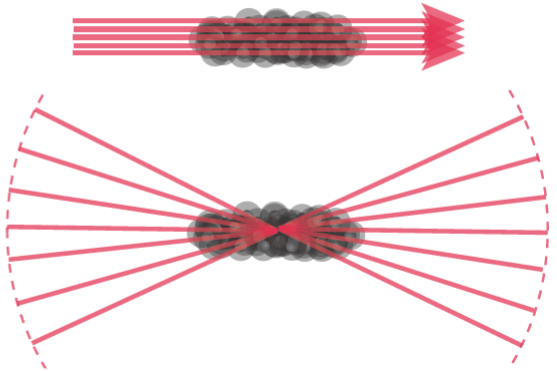
Quantum repeater

Error correction

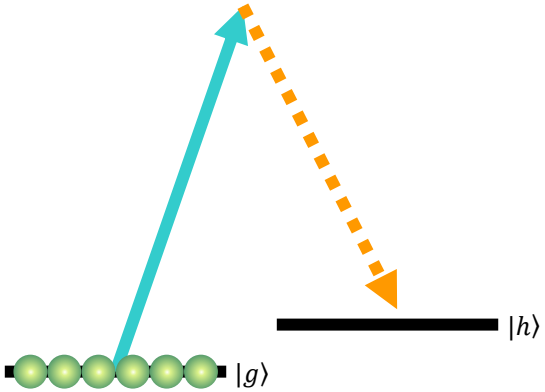
Quantum gates: linear, nonlinear

Qu**d**it storage: spatial, temporal

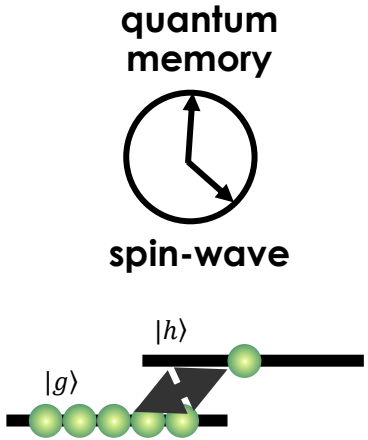


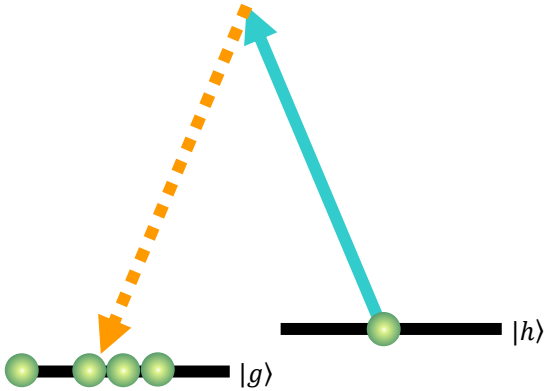


Raman interface



two-mode squeezed state
creation via off-resonant
Raman scattering



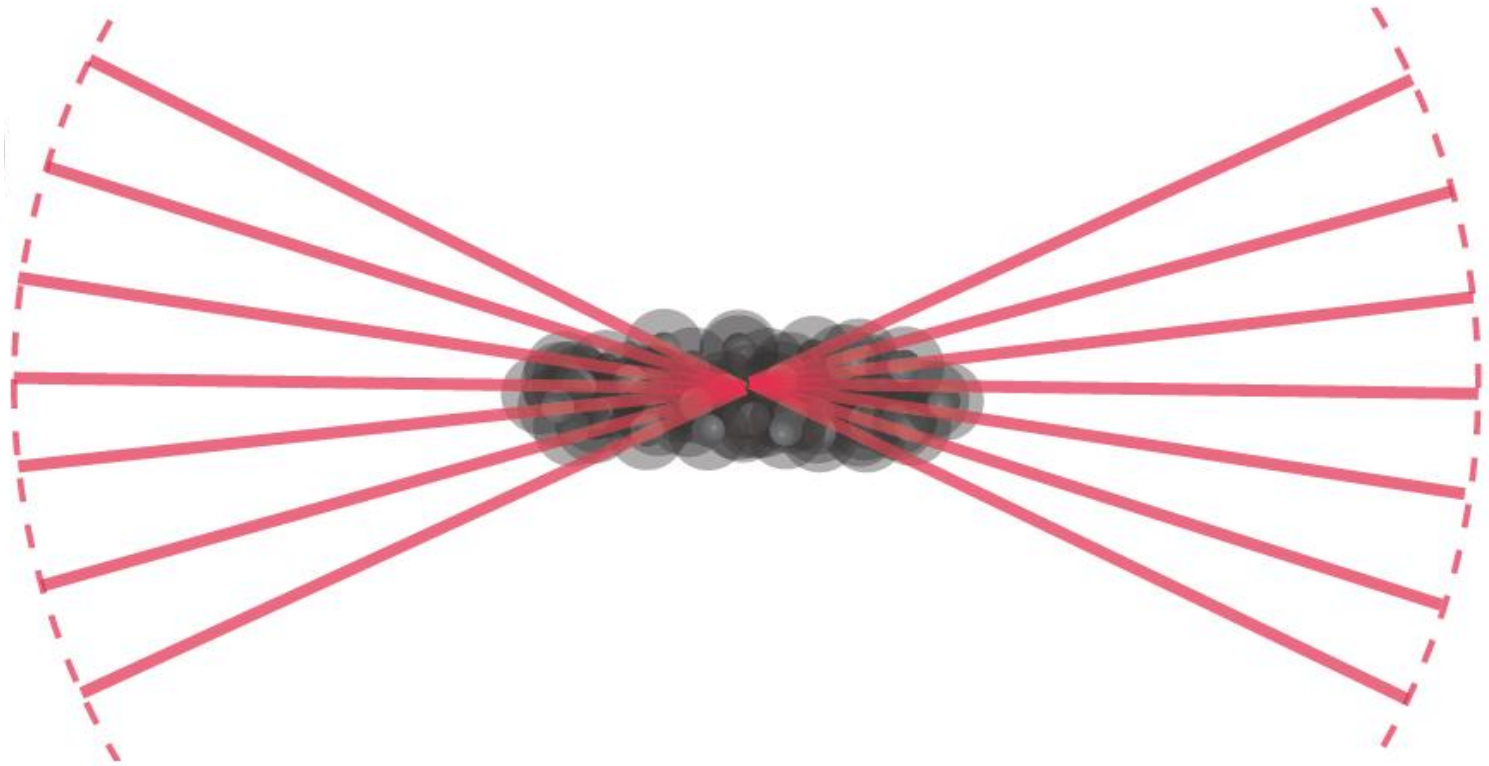


readout stage after storage time
results in **anihilation of spin-wave**

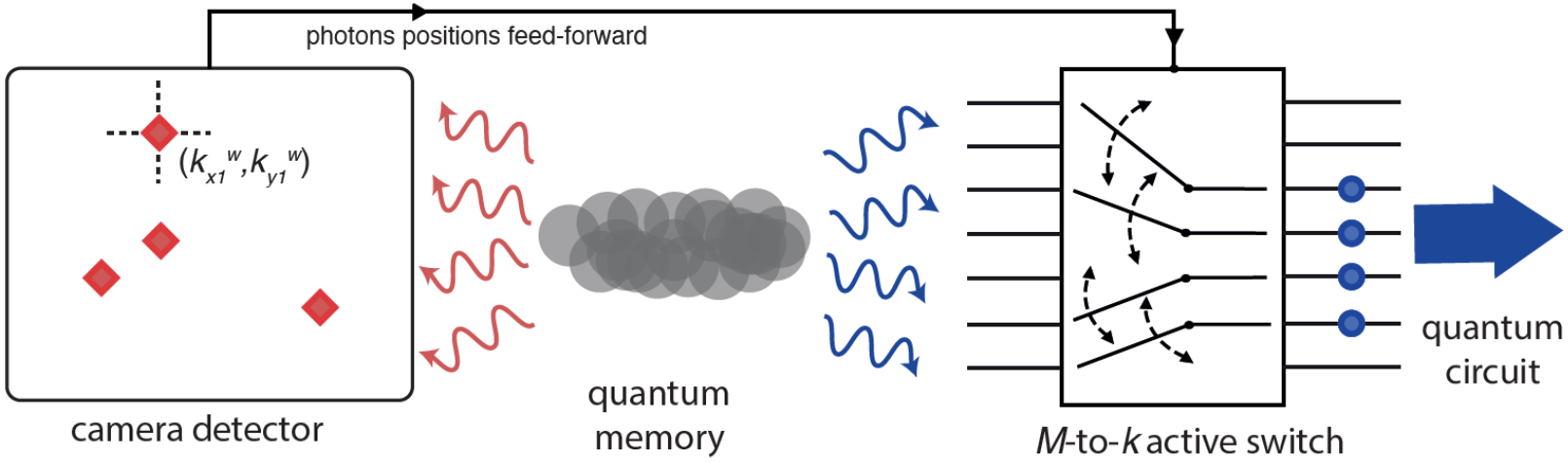
$$\frac{1}{\sqrt{N}}\left(e^{i\mathbf{K}\cdot\mathbf{r}_1}\left|\;\right\rangle + e^{i\mathbf{K}\cdot\mathbf{r}_2}\left|\;\right\rangle + e^{i\mathbf{K}\cdot\mathbf{r}_3}\left|\;\right\rangle + \dots\right)$$

$|g\rangle$
$|h\rangle$

Wavevector Multiplexing

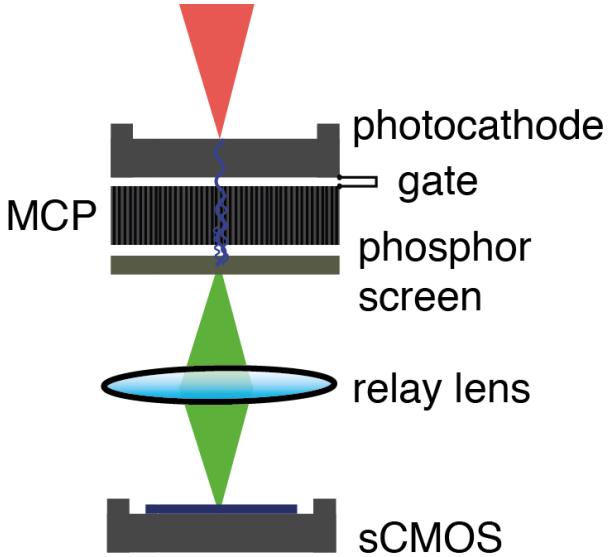


Deterministic single and multi-photons

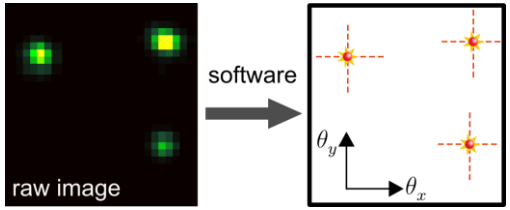


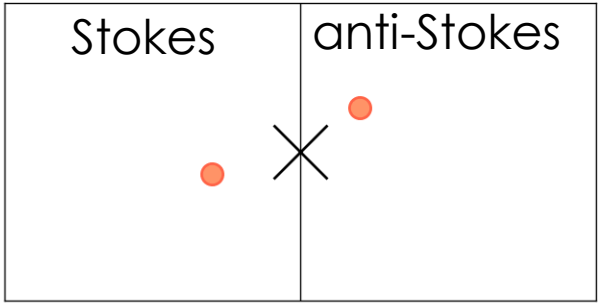
MP, M. Dąbrowski, M. Mazelanik, A. Leszczyński, M. Lipka, W. Wasilewski, Nat. Commun **8**, 2140 (2017)

I-sCMOS camera



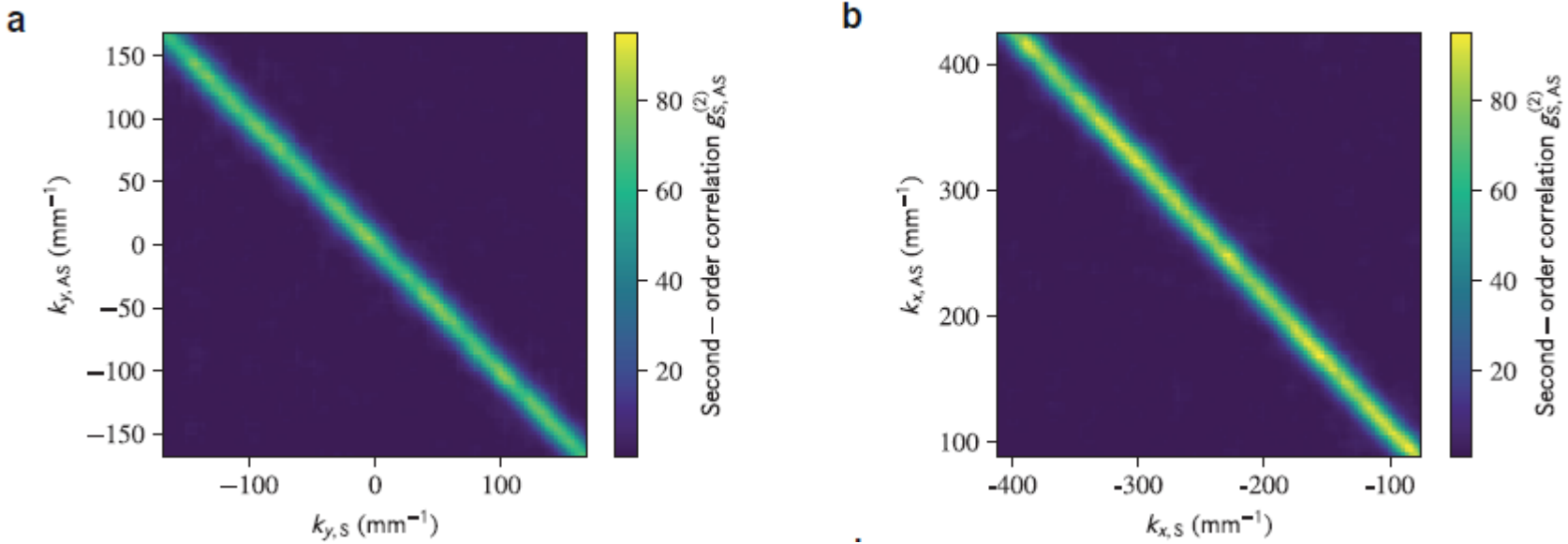
real-time image processing





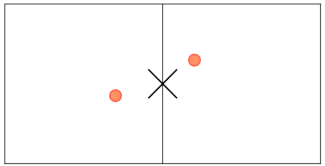
R. Chrapkiewicz, M. Jachura, K. Banaszek, W. Wasilewski, Nat. Photonics **10**, 576 (2016)
M. Jachura, R. Chrapkiewicz, W. Wasilewski, R. Demkowicz-Dobrzański, K. Banaszek, Nat. Commun. **7**, 11411(2016)
MP, M. Dąbrowski, M. Mazelanik, A. Leszczyński, M. Lipka, W. Wasilewski, Nat. Commun. **8**, 2140 (2017)

Photon number correlations



non-classical correlations

$$g^{(2)} = \frac{\langle n_S n_{AS} \rangle}{\langle n_S \rangle \langle n_{AS} \rangle} = 72 \pm 5 \gg 2$$



- **>500 modes**
- **>50 μs storage**

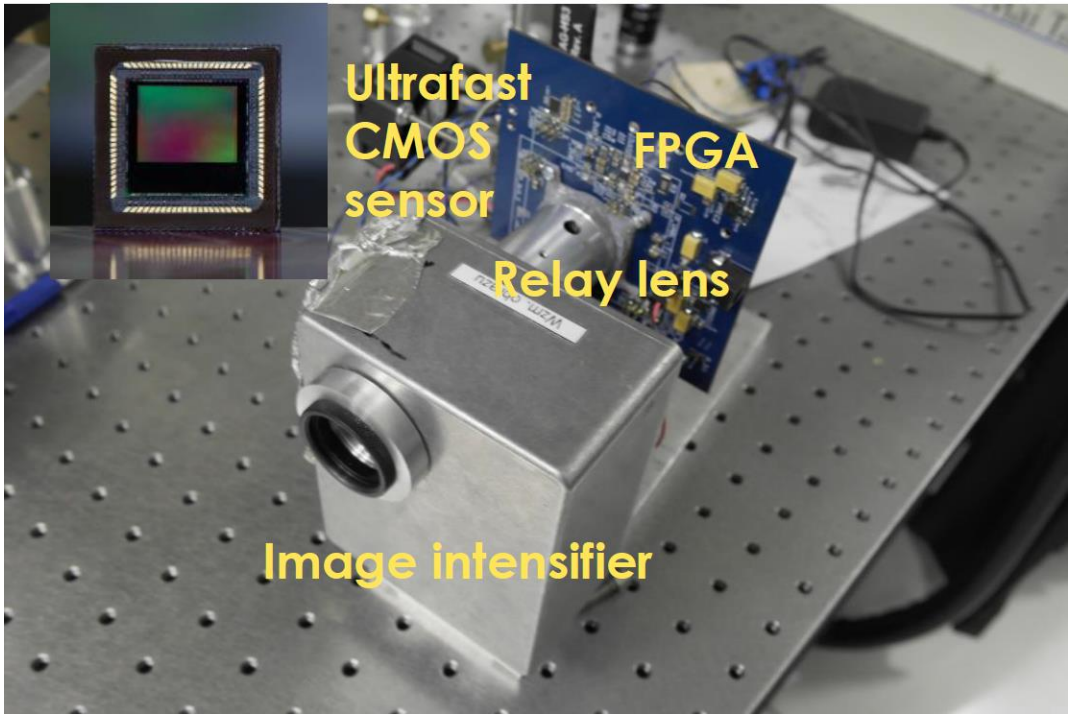
Nat. Commun **8**, 2140 (2017)

New system

Custom FPGA data processing

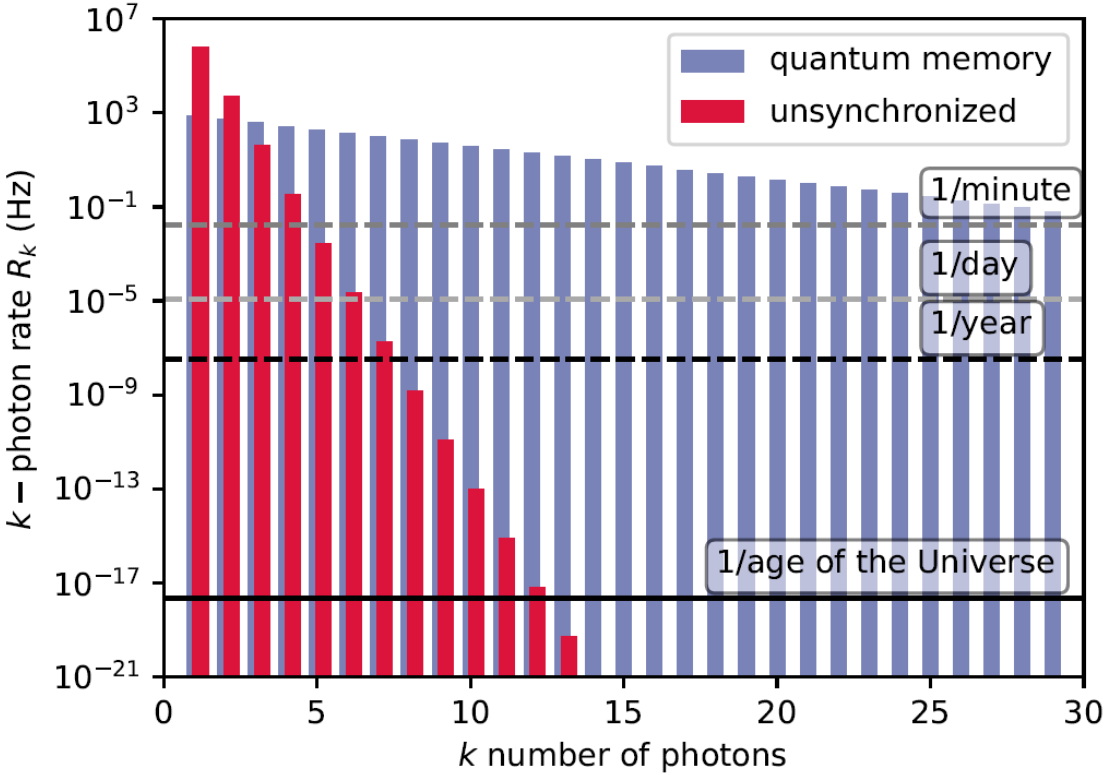
New custom high-voltage gating module

Now 100.000 frames per second, **~10 microseconds from detection to information**



arXiv:2101.03120, to appear in Optics Letters
https://doi.org/10.1364/OL.417658

Photon rate gains



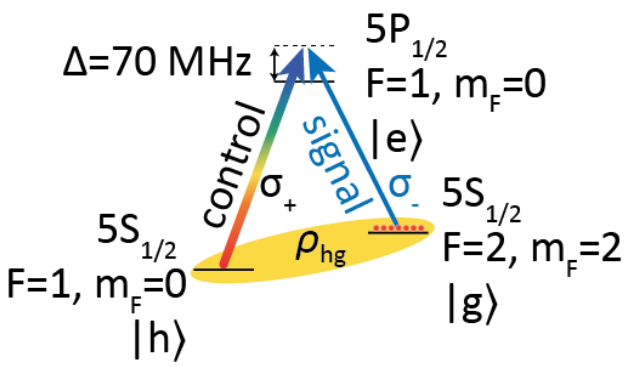
1 kHz rep. rate quantum memory

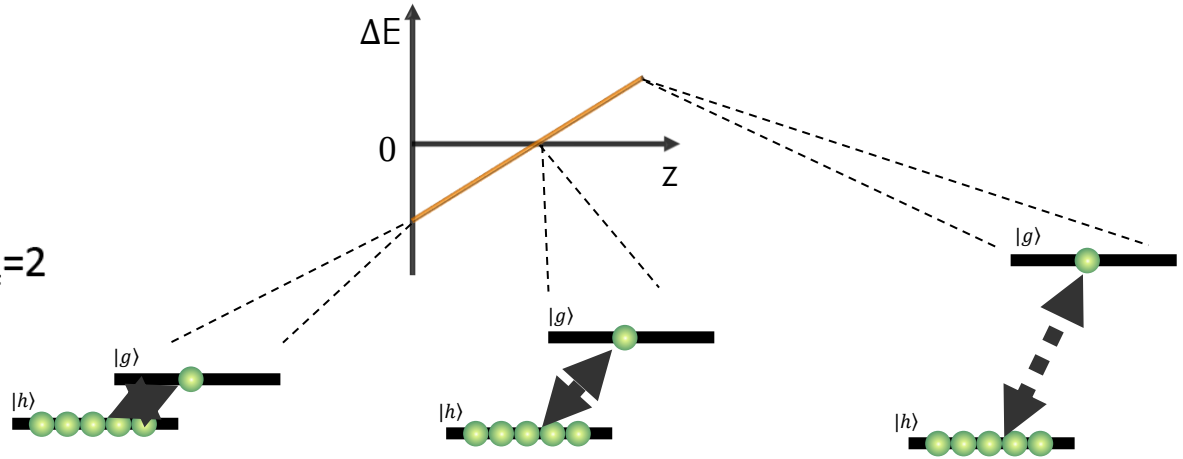
VS

80 MHz rep. rate SPDC

Temporal multiplexing

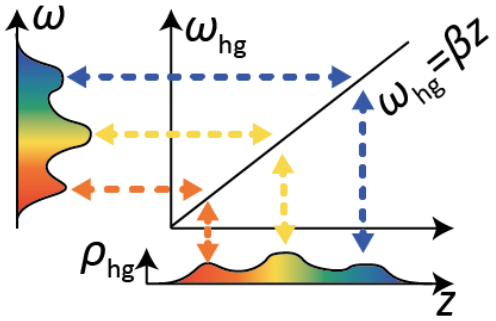
Gradient echo memory (GEM)





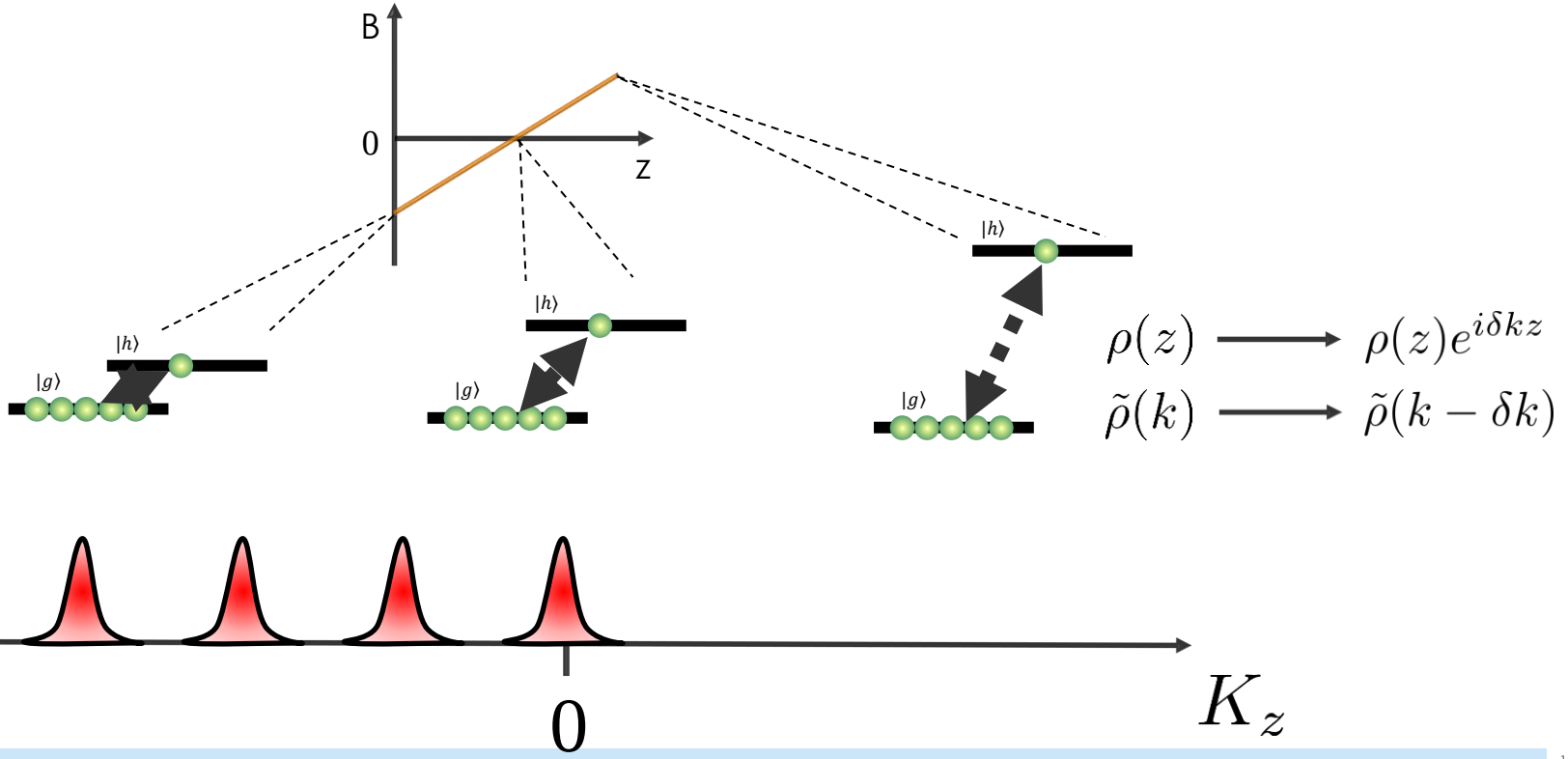
$$\frac{\partial \check{\rho}_{hg}(z,t)}{\partial t} = \frac{i}{\hbar}\frac{\Omega^*(t)dA(z,t)}{4\Delta - 2i\Gamma} - \frac{1}{2\tau}\check{\rho}_{hg}(z,t) + i\delta_{\mathrm{tot}}(z,t)\check{\rho}_{hg}(z,t),$$

$$\frac{\partial A(z,t)}{\partial z} = -i\frac{\hbar\Omega(t)\check{\rho}_{hg}(z,t)/d + A(z,t)}{2\Delta + i\Gamma}\frac{\Gamma}{2}gn(z),$$

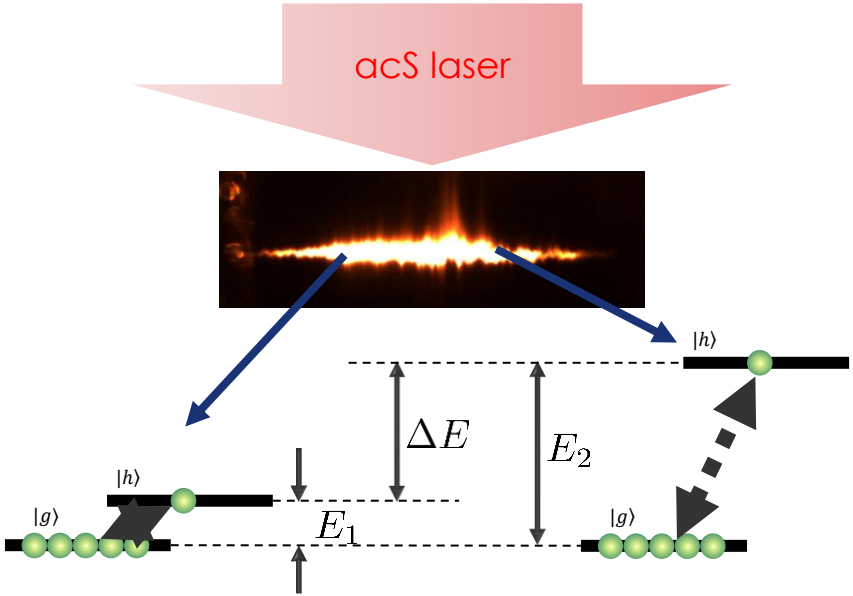


Hosseini et al., Nature 461, 241 (2009)

Spin-wave phase modulation (GEM)



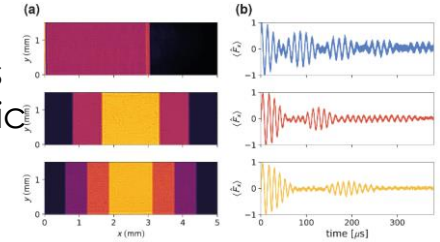
ac-Stark spin-wave phase modulation



$$\Delta\varphi(y,z) = \Delta E(y,z)T/\hbar$$

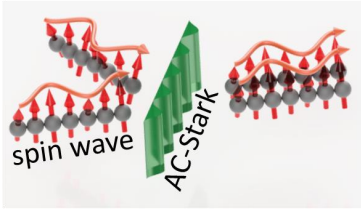
Differential phase accumulated during free evolution

Fictitious magnetic fields



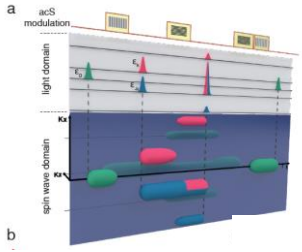
Opt. Lett. 43, 1147 (2018)

Spin-wave Hong-Ou-Mandel interference



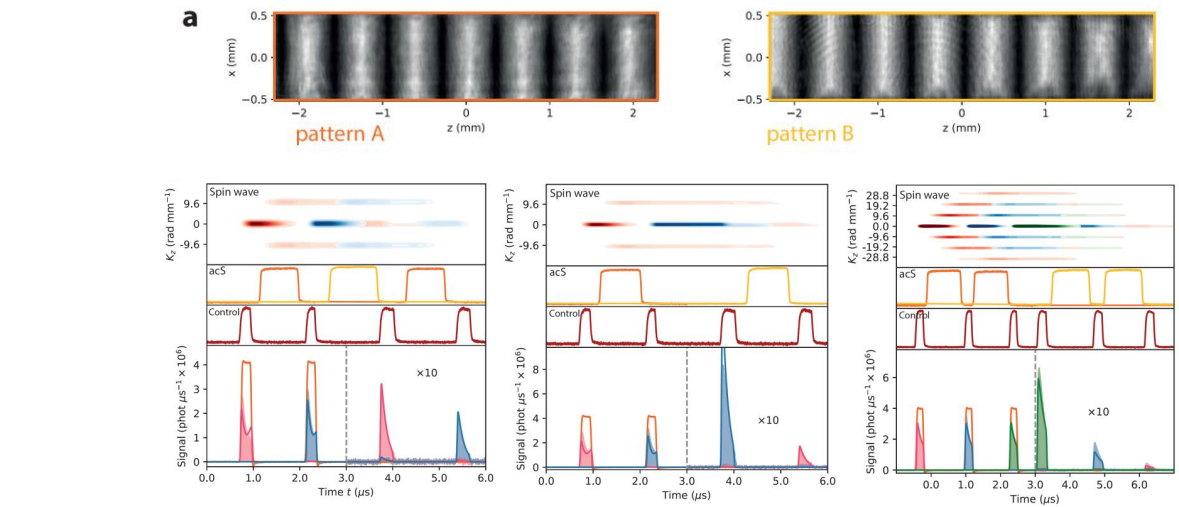
Phys. Rev. Lett. **122**, 063604 (2019)

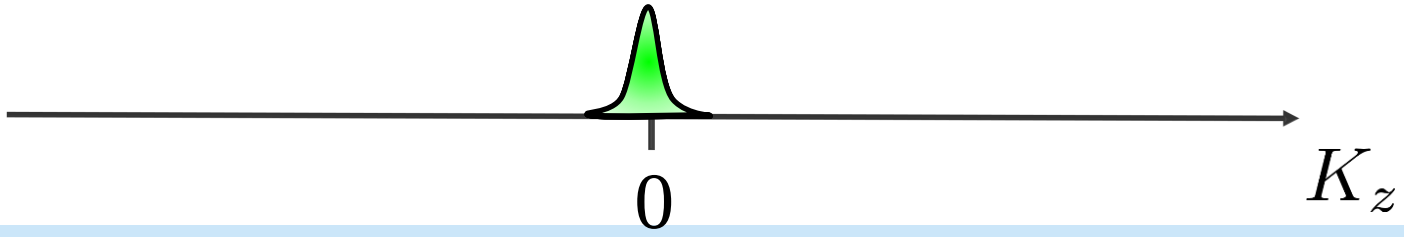
Spin-wave processor of stored optical pulses



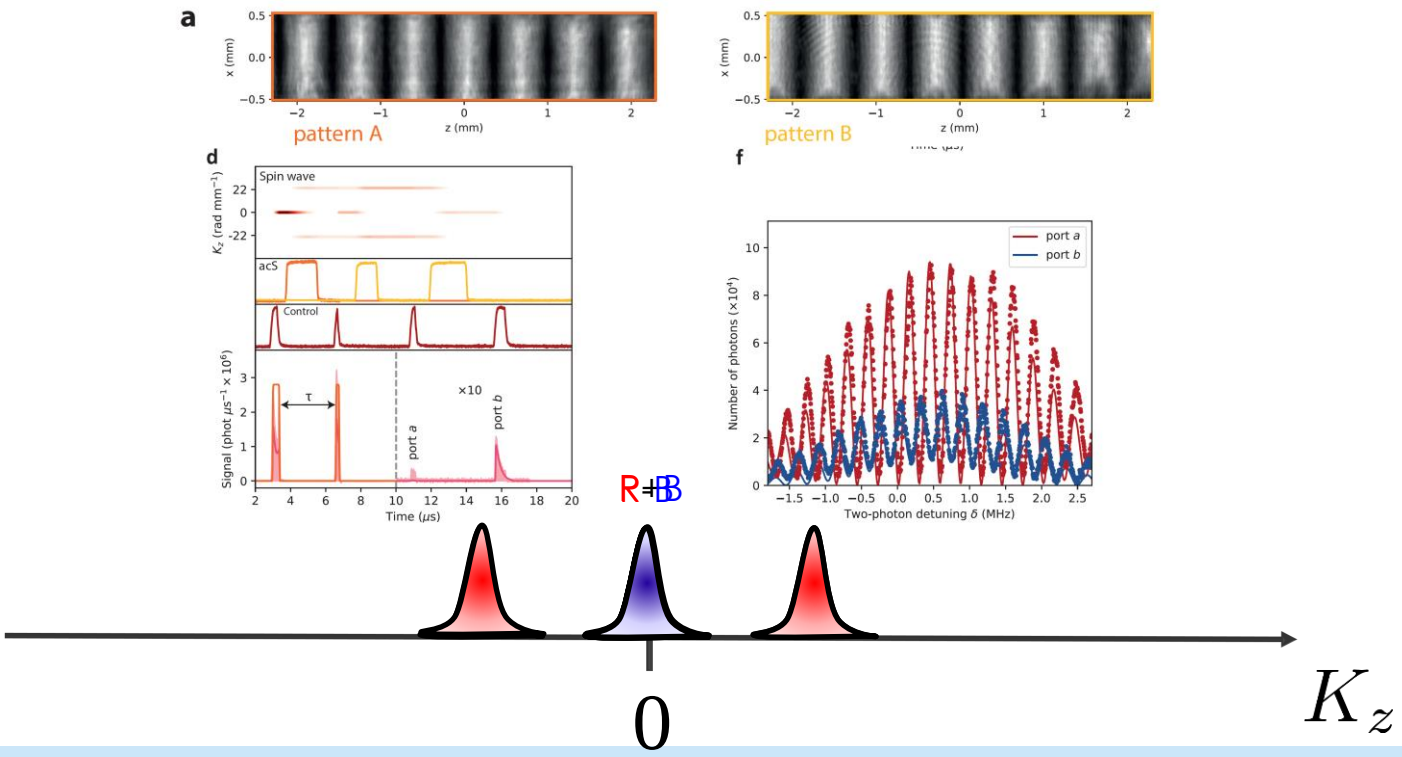
npj Quantum Information **5**, 22 (2019)

ac-Stark GEM

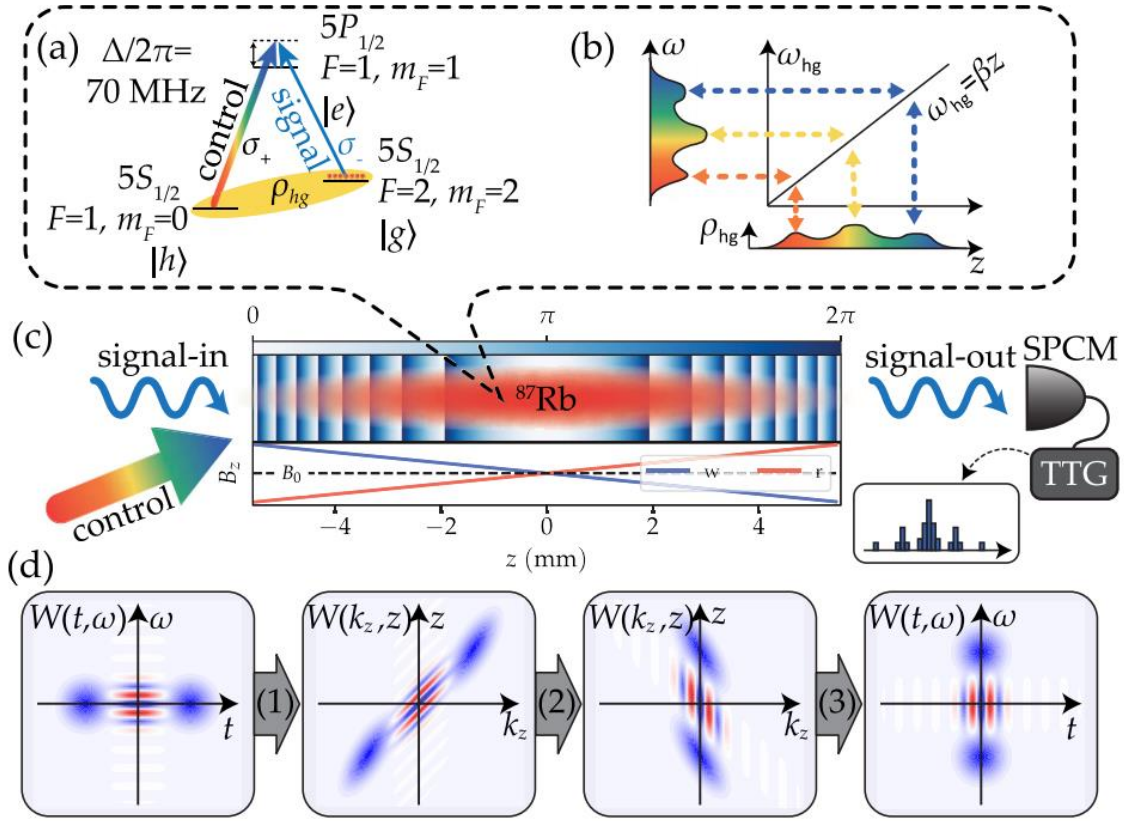

a
pattern A
pattern B
x (mm)
z (mm)
Spin wave
acS
Control
×10
Time t (μs)
Time (μs)
Signal (phot μs⁻¹ × 10⁶)
Kz (rad mm⁻¹)


0
K_z

Spin-wave splitter

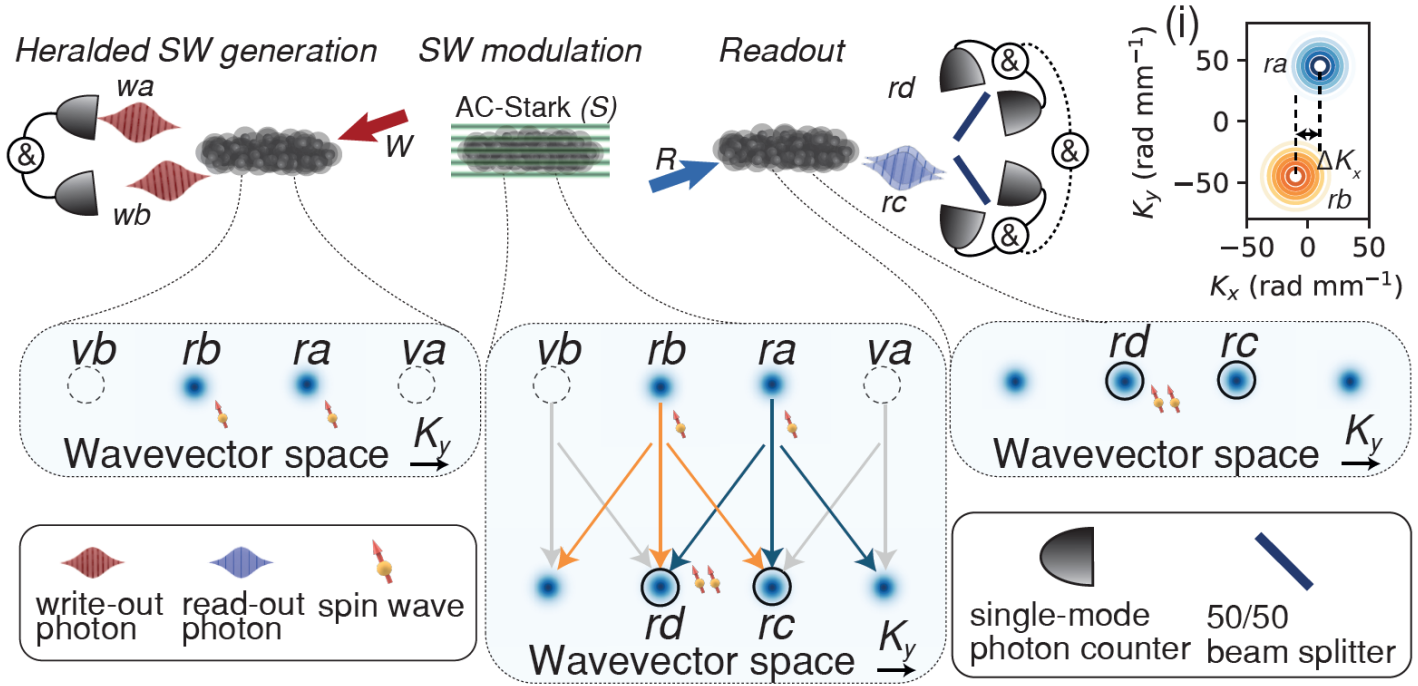


Combining magnetic and AC-S GEM



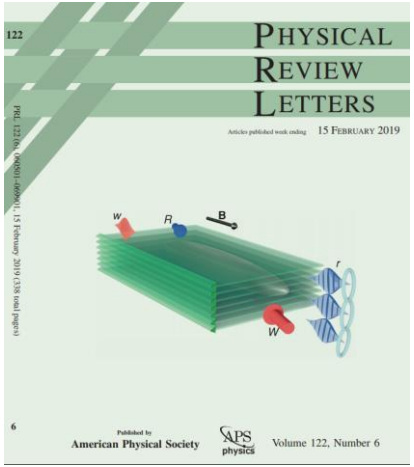
Optica 7, 203 (2020)

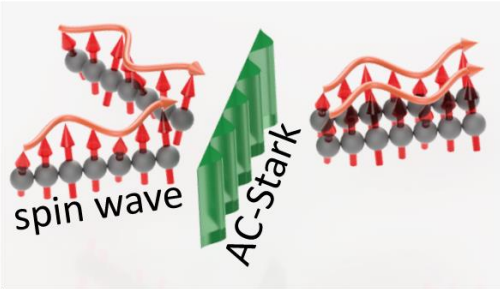
The three-way splitter

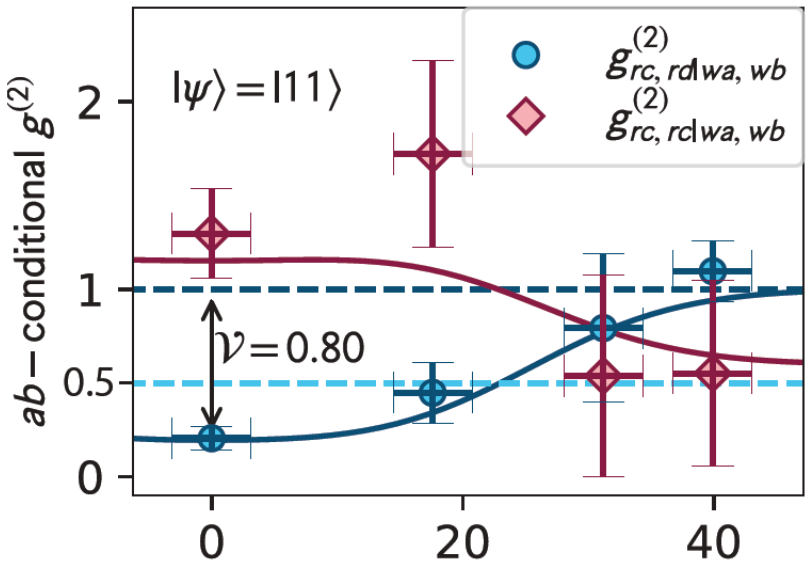


Phys. Rev. Lett. **122**, 063604 (2019)

Hong-Ou-Mandel interference



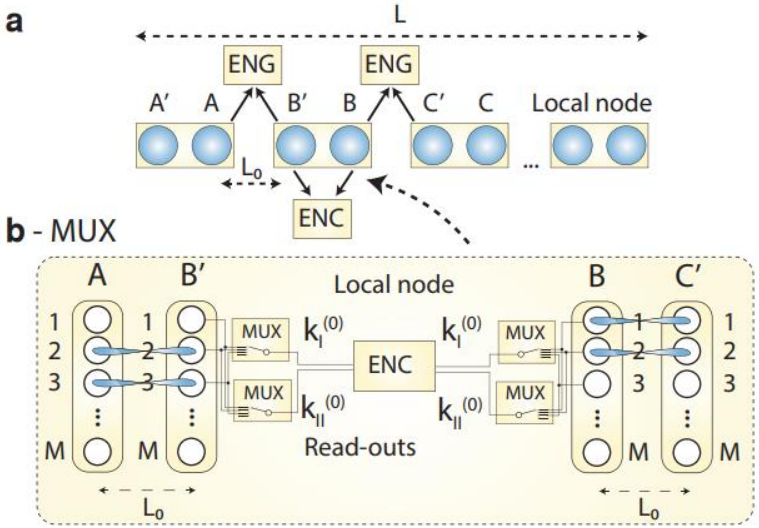




80% visibility at the moment limited by photon purity: with weak coherent states we observed interferometric visibility of >95%

Phys. Rev. Lett. **122**, 063604 (2019)

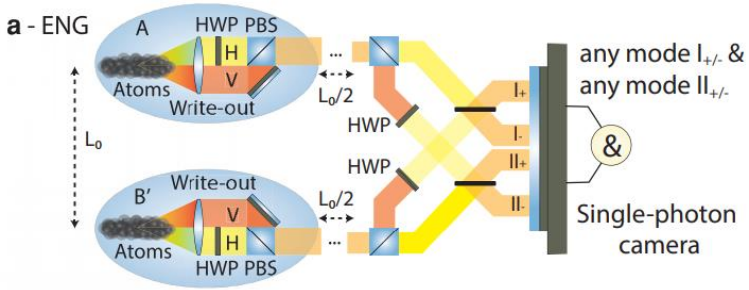
Quantum repeater with multiplexing

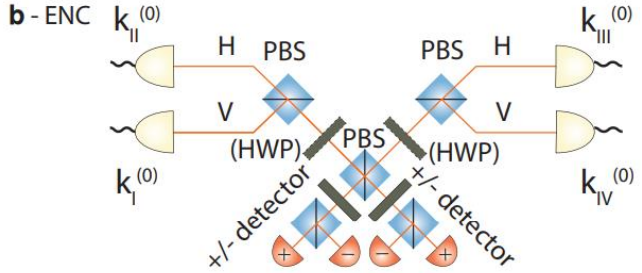


New Journal of Physics **23**, 053012 (2021)

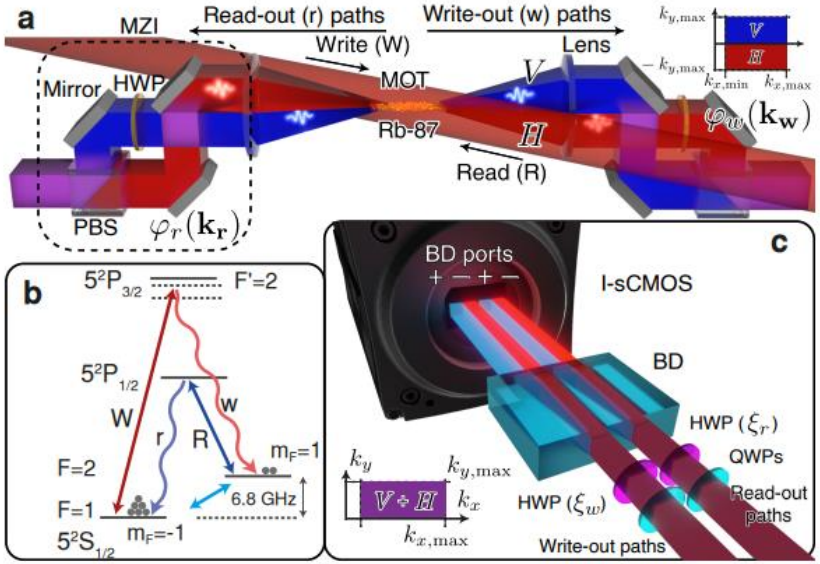
$$p_g^{(\mathrm{parallel})} = 1 - (1 - p_1)^M.$$

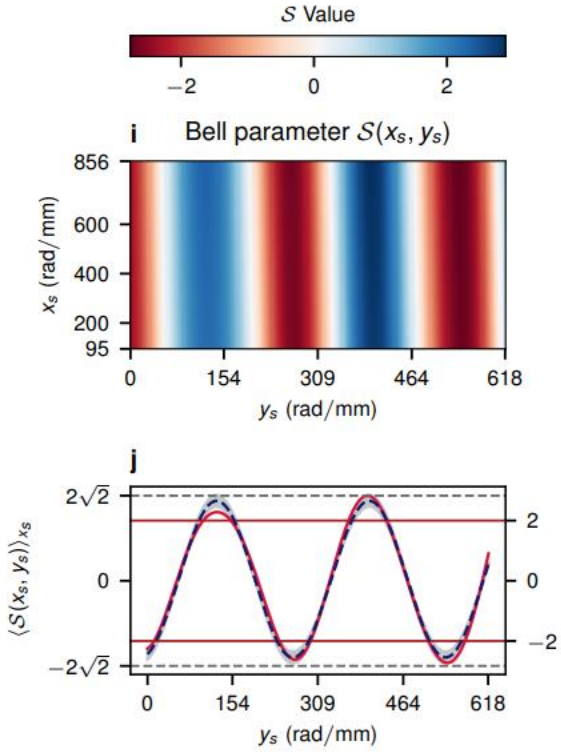
$$p_g = 1 - (1 - p_1)^{M^2}.$$





Towards experimental repeater

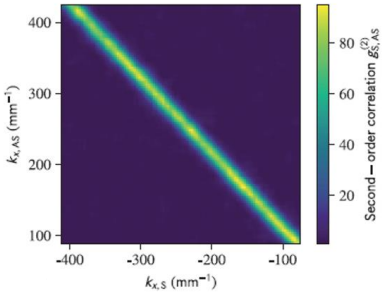


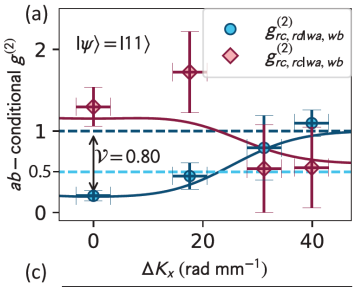


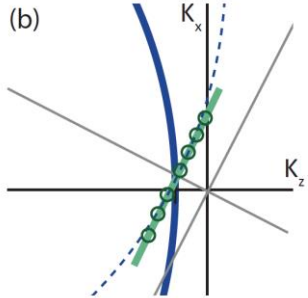
Communications Physics **4**, 46 (2021)

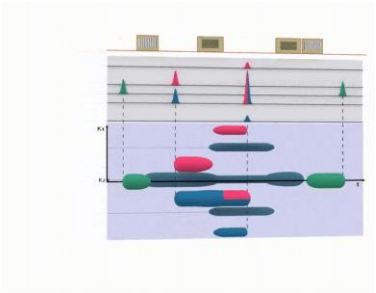
Atom-embedded photonic (co)processor

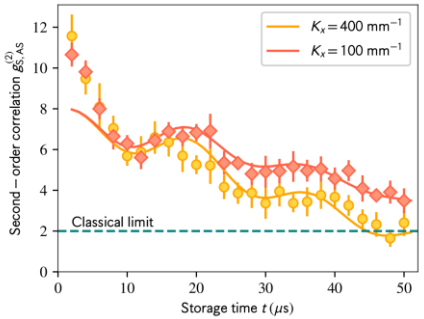
- Wavevector-multiplexed quantum memory
- Spin-wave-based interferometric processor for stored light
- Multiplexed quantum repeaters



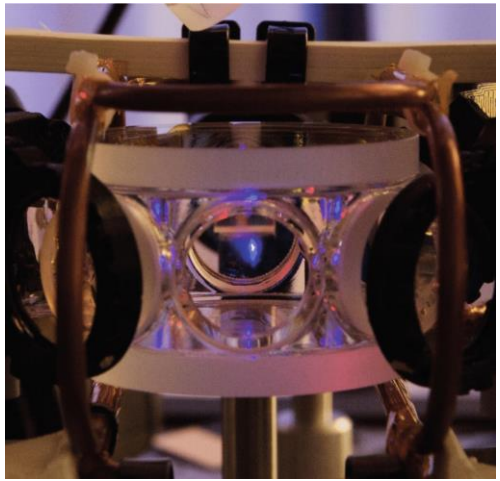




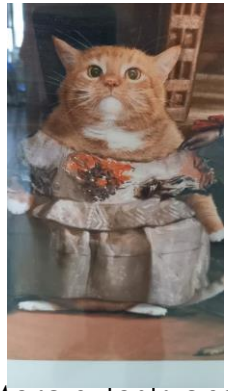




Thank You



QOT Centre for Quantum Optical Technologies
qot.uw.edu.pl



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Michał Parniak

PhD Students:
Mateusz Mazelanik, Michał Lipka
Students:
Sebastian Borówka, Tomasz Szawełło, Uliana Pylypenko, Marcin Jastrzęnski, Stanisław Kurzyna, Bartosz Niewelt, Jan Nowosielski, Krzysztof Lasocki, Pavel Halavach
Alumni:
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Theory Collaborators: Konrad Banaszek, Rafał Demkowicz-Dobrzański

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