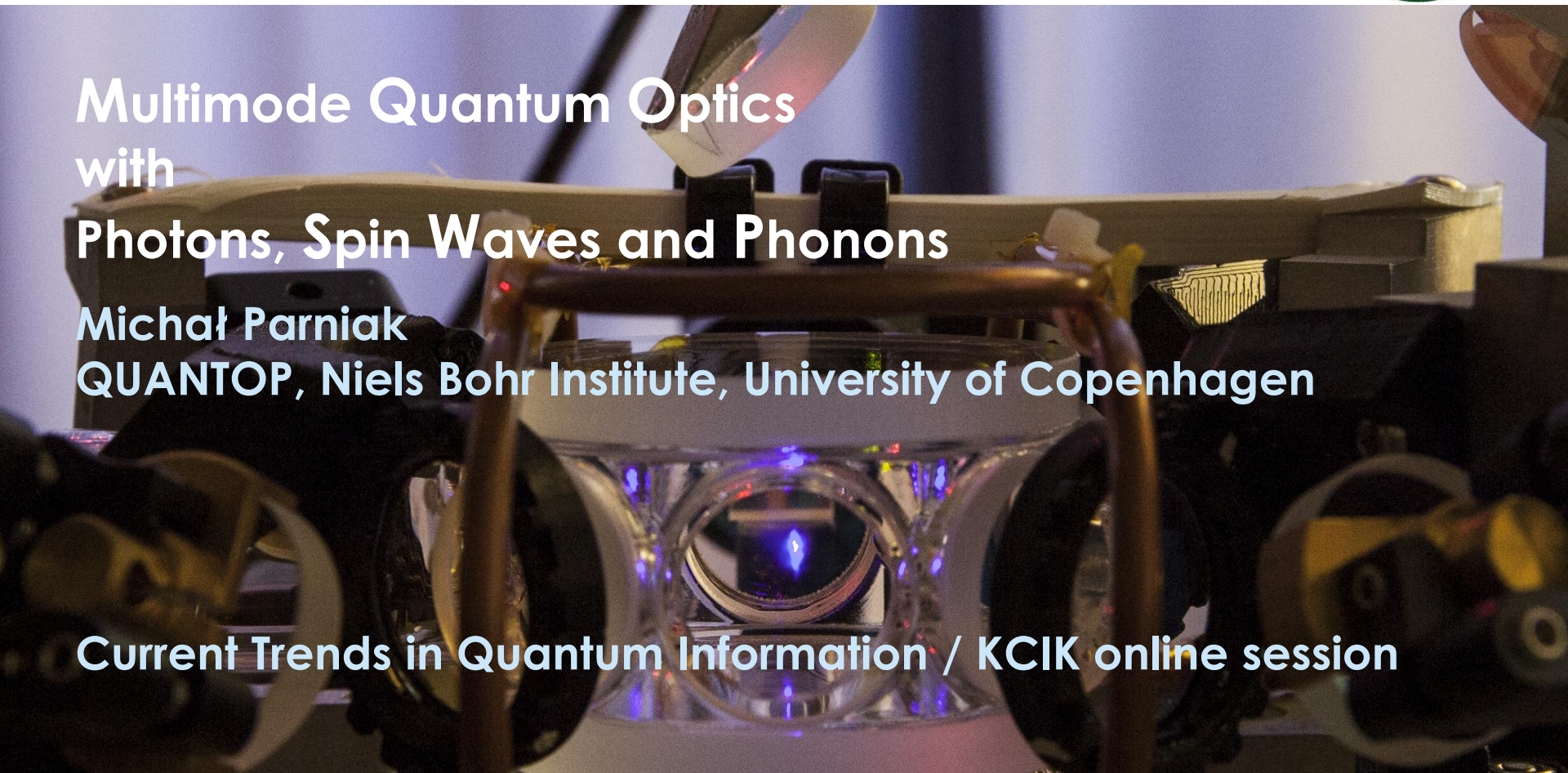


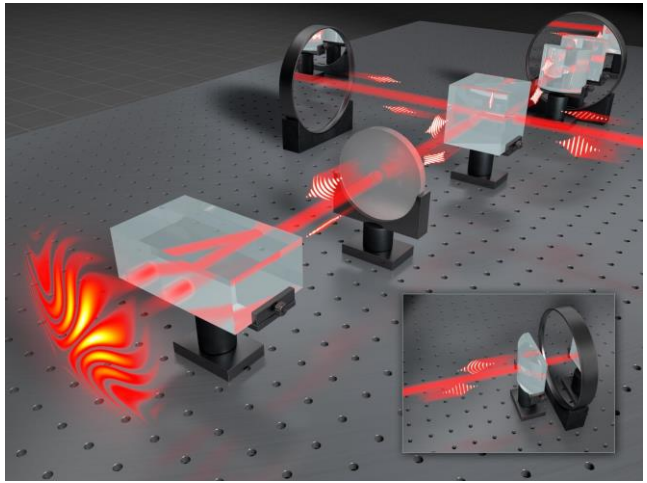
Multimode Quantum Optics with Photons, Spin Waves and Phonons

Michał Parniak
QUANTOP, Niels Bohr Institute, University of Copenhagen

Current Trends in Quantum Information / KCIK online session

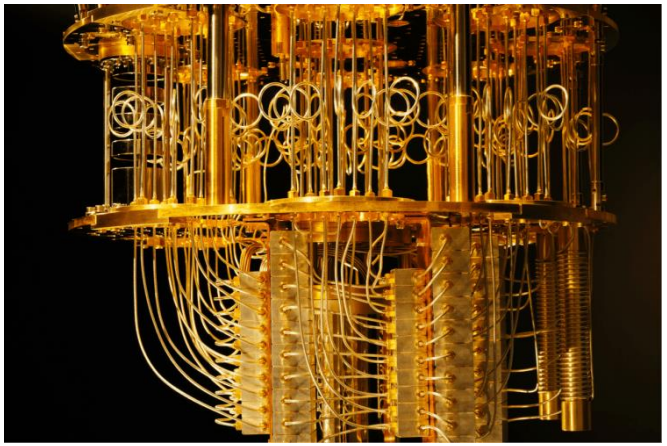
Quantum Platforms

Photonics



Single-Photon gates
Multi-Photon gates
Sources
Detectors

Material Systems



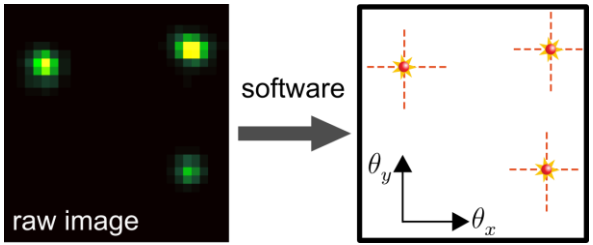
IBM

Ions
Superconducting circuits
Mechanical systems

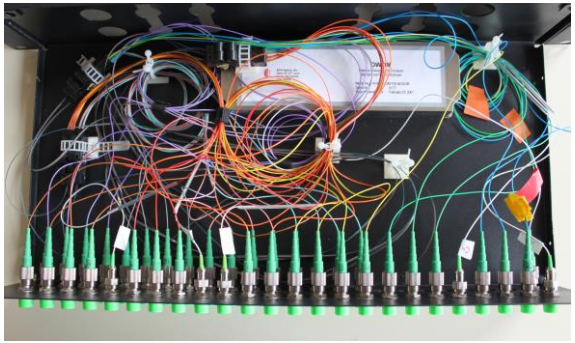
Degrees of freedom: space, time, polarization

Structured light

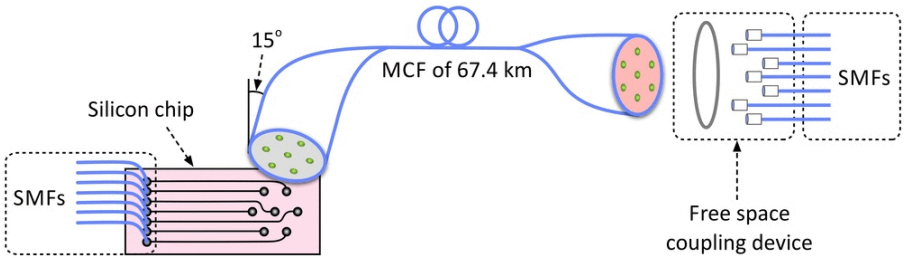
Spatial structure



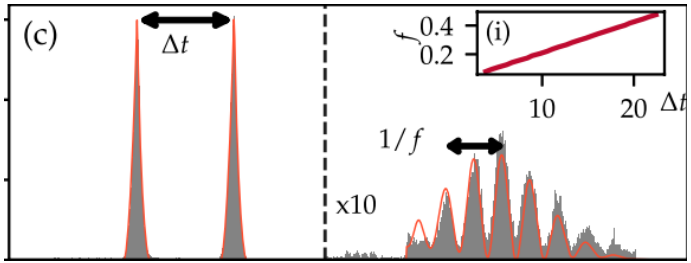
WDM



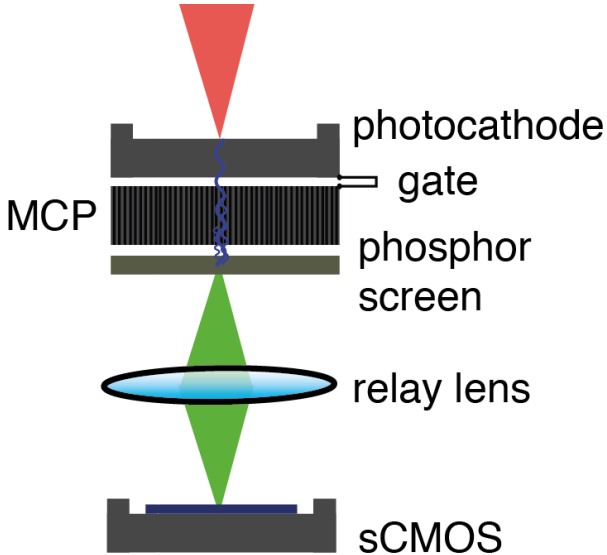
OAM, multicore fibres, space-division multiplexing

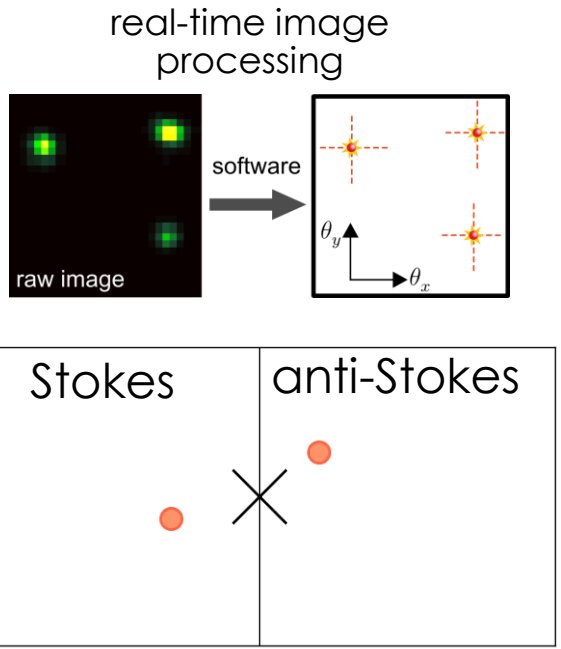


Time/frequency space



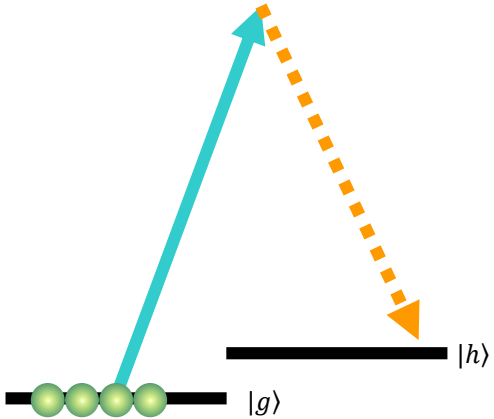
Intensified-sCMOS camera





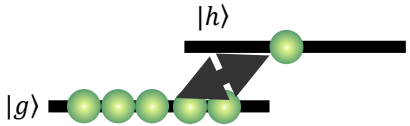
R. Chrapkiewicz, M. Jachura, K. Banaszek, W. Wasilewski, Nat. Photonics **10**, 576 (2016)
M. Jachura, R. Chrapkiewicz, W. Wasilewski, R. Demkowicz-Dobrzański, K. Banaszek, Nat. Commun. **7**, 11411(2016)
MP, M. Dąbrowski, M. Mazelanik, A. Leszczyński, M. Lipka, W. Wasilewski, Nat. Commun. **8**, 2140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

Raman interface

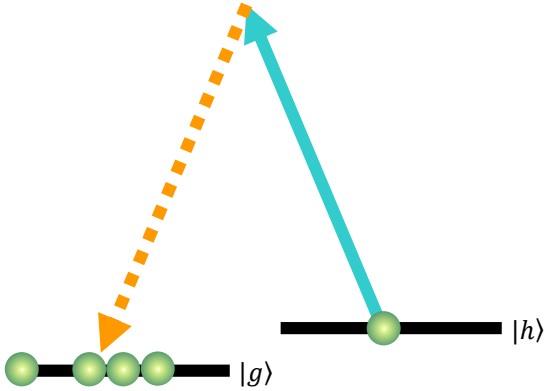


two-mode squeezed state
creation via off-resonant
Raman scattering

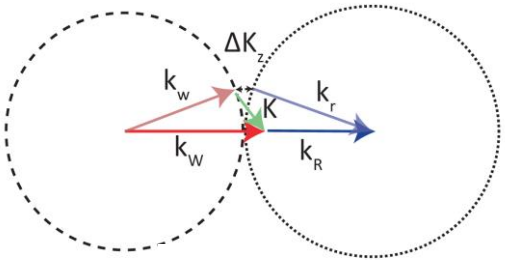
quantum memory



spin-wave



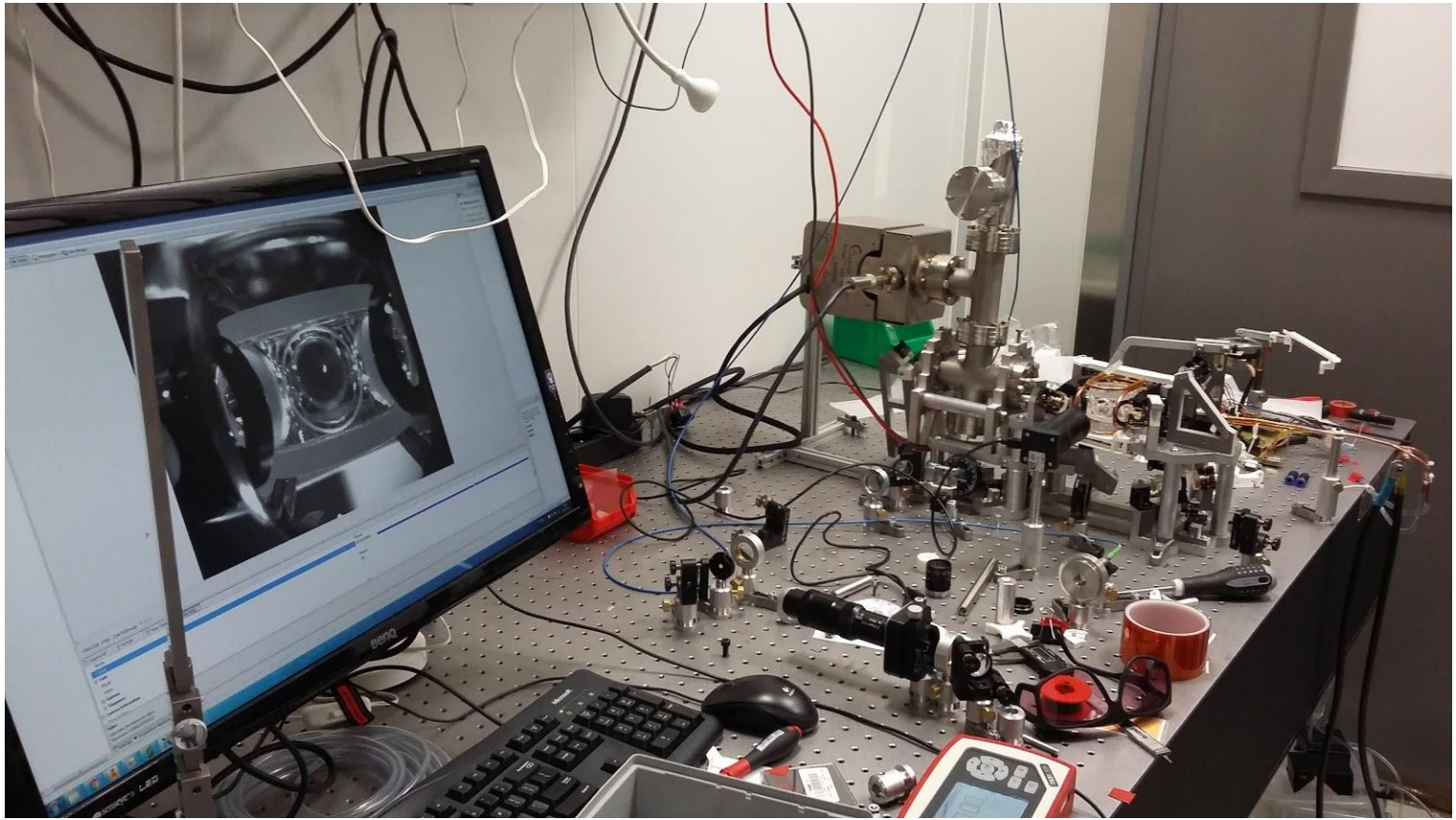
readout stage after storage time
results in **anihilation of spin-wave**



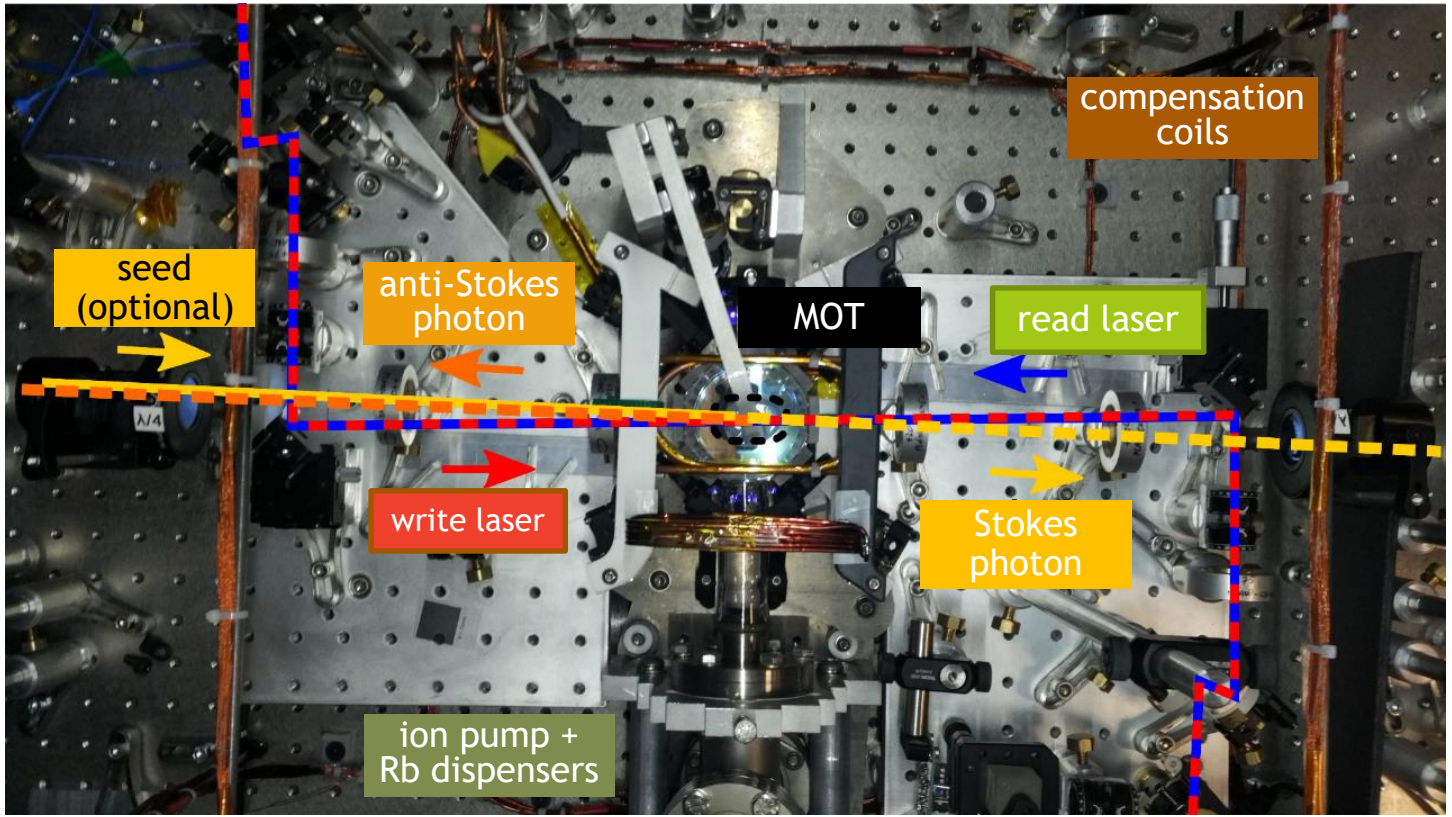
$$\frac{1}{\sqrt{N}}\left(e^{i\mathbf{K}\cdot\mathbf{r}_1}\left|\;\right\rangle + e^{i\mathbf{K}\cdot\mathbf{r}_2}\left|\;\right\rangle + e^{i\mathbf{K}\cdot\mathbf{r}_3}\left|\;\right\rangle + \dots\right)$$

$$\hat{S}^{\dagger}(\mathbf{K}) = N^{-1/2}\sum_n^N \exp(i\mathbf{K}\cdot\mathbf{r}_n)|h_n\rangle\langle g_n|$$

History – first atoms trapped

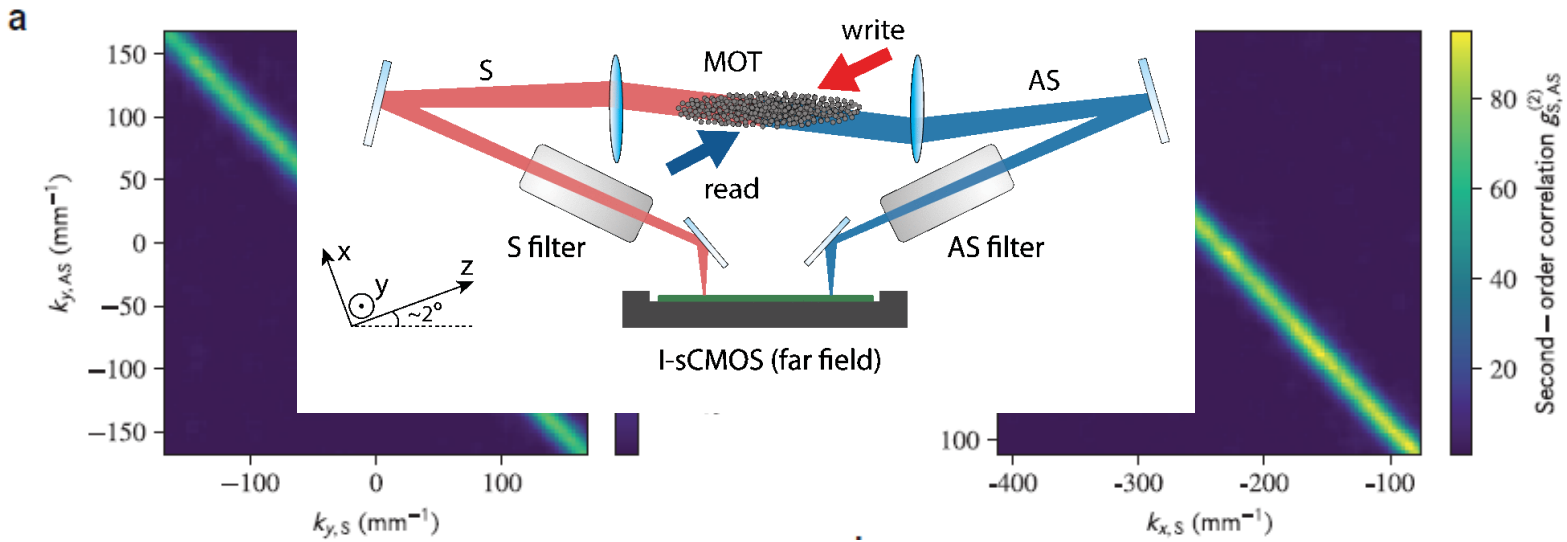


Experimental setup



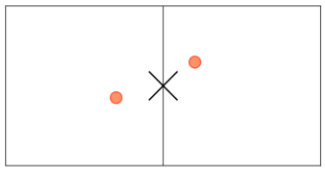
Nat. Commun **8**, 2140 (2017)

Photon number correlations



non-classical correlations

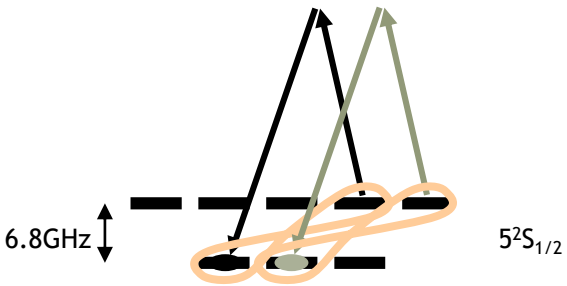
$$g^{(2)} = \frac{\langle n_S n_{AS} \rangle}{\langle n_S \rangle \langle n_{AS} \rangle} = 72 \pm 5 \gg 2$$



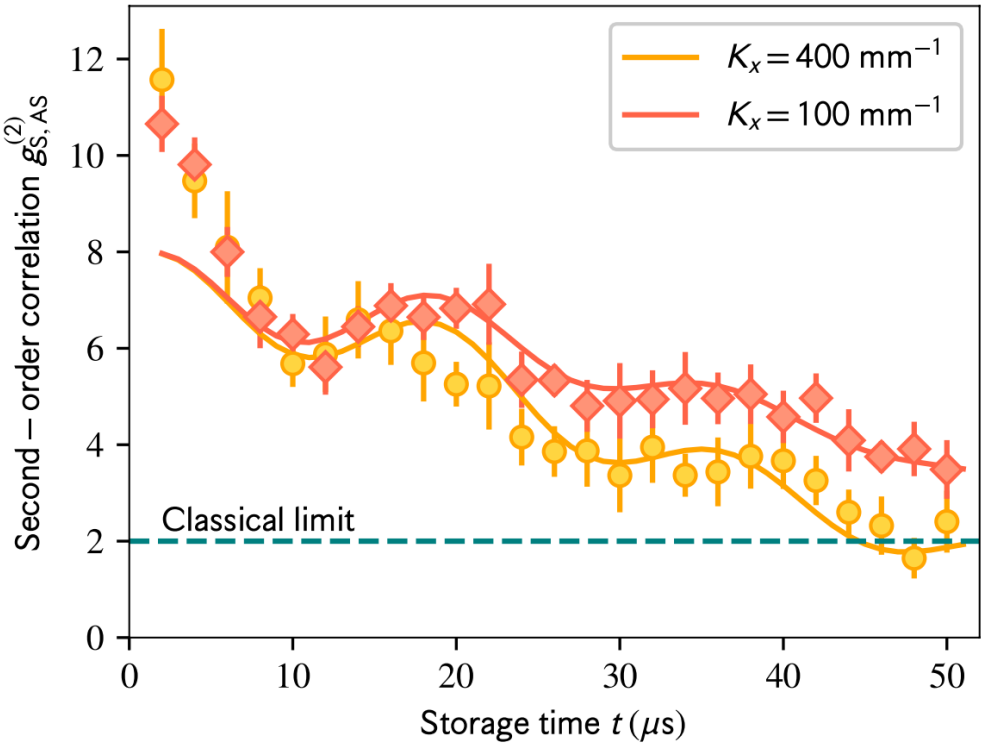
Nat. Commun **8**, 2140 (2017)

665 modes back in 2017; >2.000 modes now, with better imaging system; ~20.000 available fundamentally

Temporal evolution



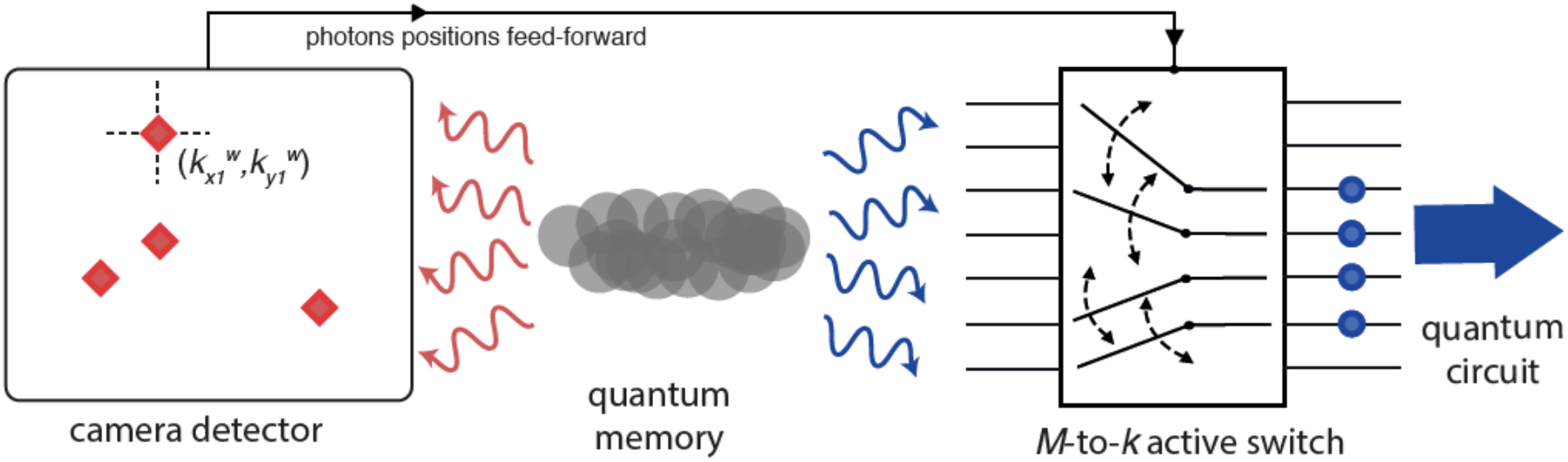
Oscillation between Zeeman sublevels engineered with optical pumping



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

Quasi-deterministic single and multi-photons

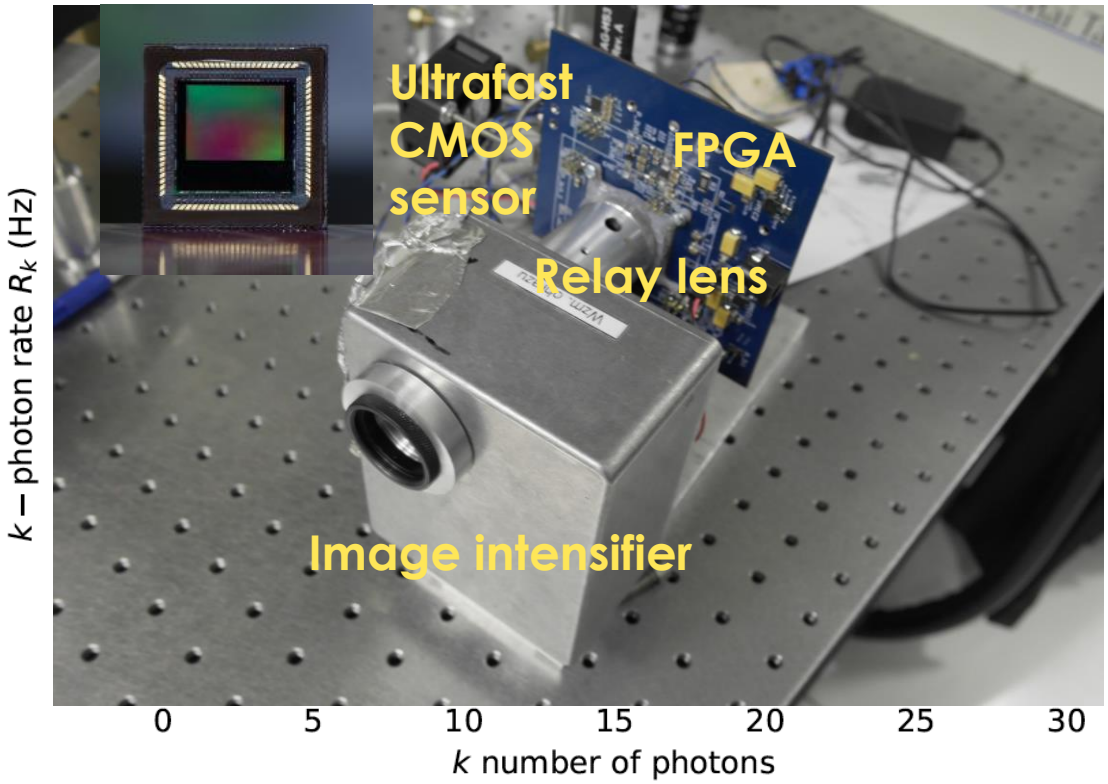
Enhancing photon rates via multiplexing



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

See also review by E. Meyer-Scott, C. Silberhorn & A. Migdall at Review of Scientific Instruments **91**, 041101 (2020)

Quasi-deterministic single and multi-photons: a bold estimate



4000-mode quantum memory with 20% heralding efficiency and 80% retrieval efficiency operating at 1 kHz* repetition rate

vs

k unsynchronized SPDC sources each at 80 MHz with 90% heralding efficiency**

p=1%, photon detection efficiency 90%

* We will go up to 70 kHz with a new camera

** Optimistic even with comparison to Phys. Rev. Lett. **121**, 250505 (2018)

Ac-Stark effect on spin waves

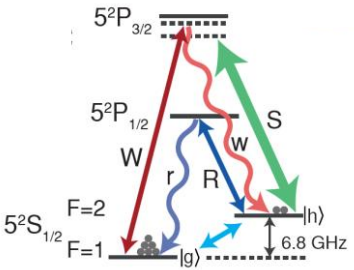
$$\hat{S}^{\dagger}(\mathbf{K}) = N^{-1/2}\sum_{n}^{N}\exp(i\mathbf{K}\cdot\mathbf{r}_n)|h_n\rangle\langle g_n|$$

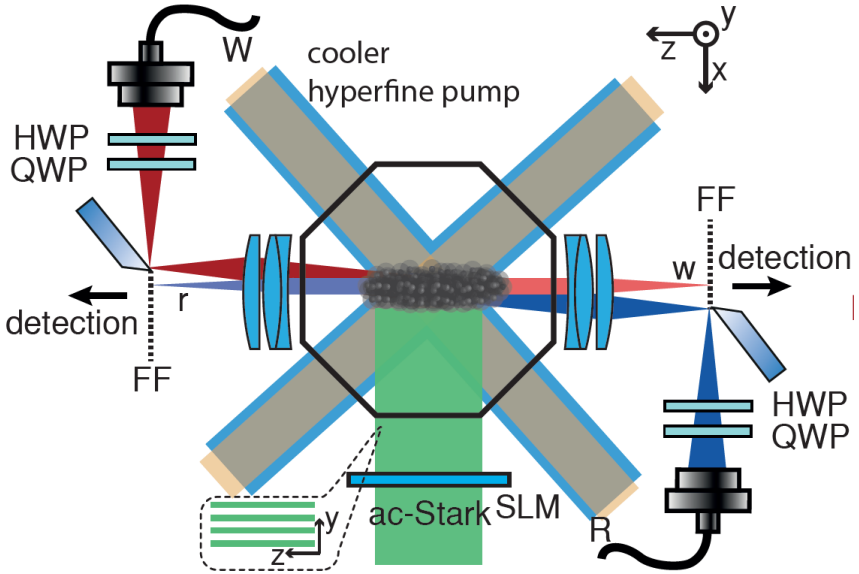
Phase accumulated due to ac-Stark shift

$$\hat{S}_S^{\dagger}(\mathbf{K}) = N^{-1/2}\sum_{n}^{N}\exp(i(\mathbf{K}\cdot\mathbf{r}_n+\varphi_S(\mathbf{r}_n))|h_n\rangle\langle g_n|$$

$$= \int \mathscr{F}[\exp(i\varphi_S(\mathbf{r}))](\mathbf{k})\hat{S}^{\dagger}(\mathbf{K}+\mathbf{k})\mathrm{d}\mathbf{k},$$

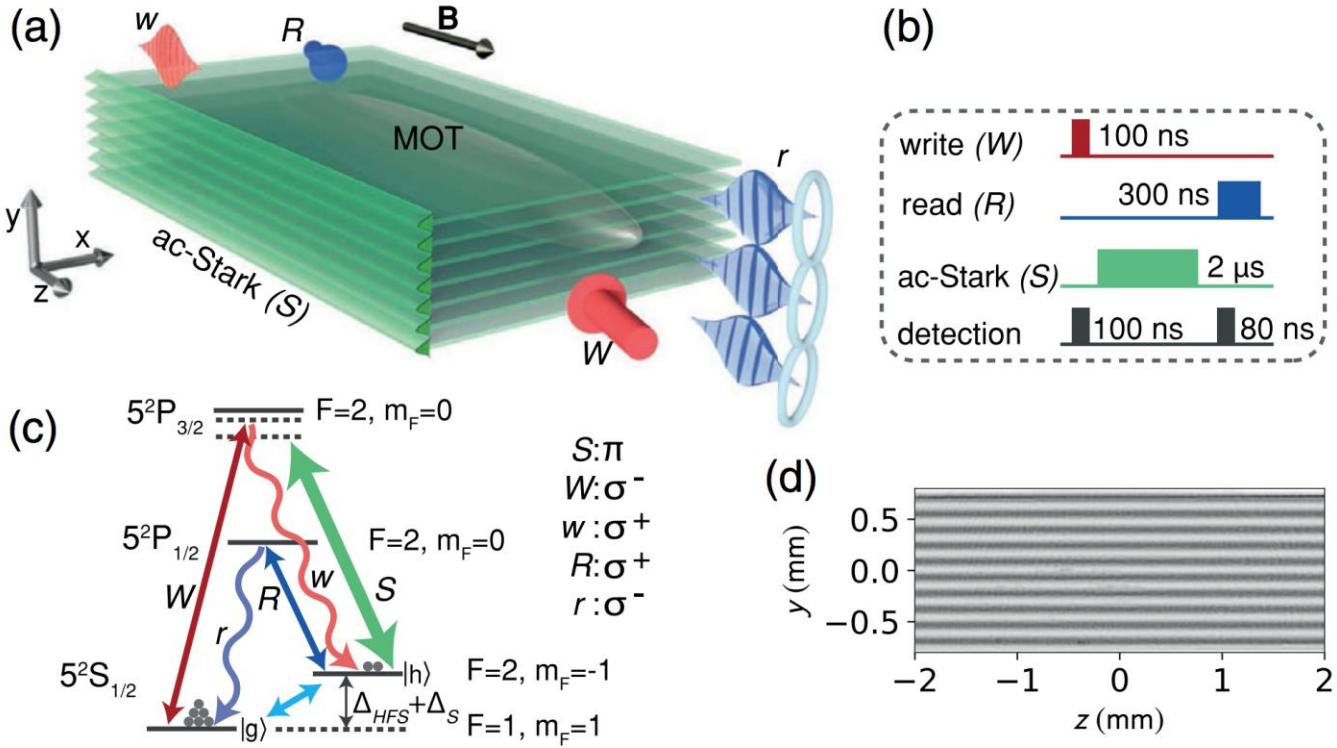
$$\hat{S}_S^{\dagger}(K_y) = \sum_{n=-\infty}^{\infty} J_n(\chi)\exp(in\vartheta)\hat{S}^{\dagger}(K_y+nk_g).$$





Spin wave reshaping

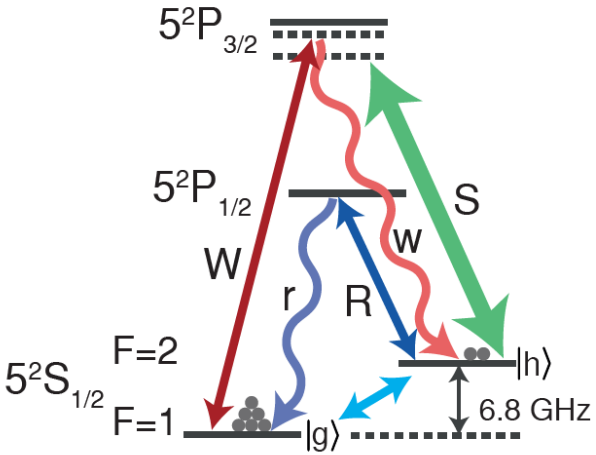
cf. Gradient Echo Memory: Nature **461**, 241 (2009), Phys. Rev. A **82**, 043847 (2010).

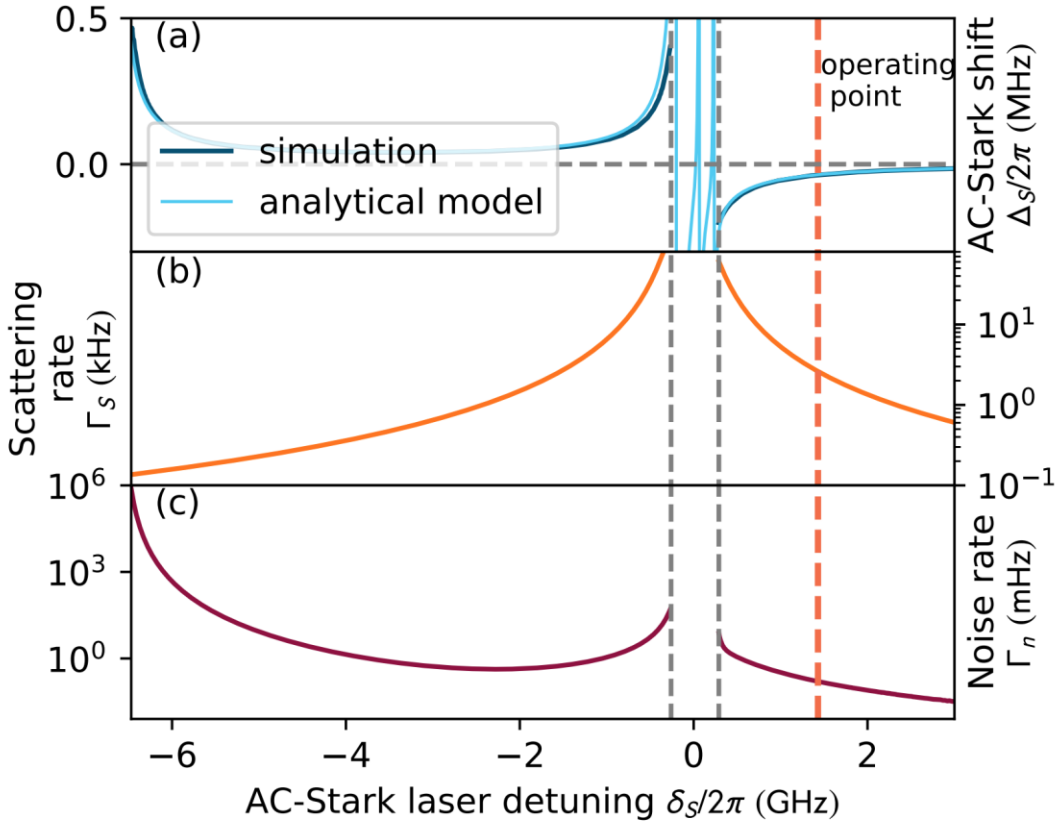


MP, M. Mazelanik, A. Leszczyński, M. Lipka, M. Dąbrowski, W. Wasilewski, Phys. Rev. Lett. **122**, 063604 (2019)

See also: effect on collective classical spins: Opt. Lett. **43**, 1147 (2018)

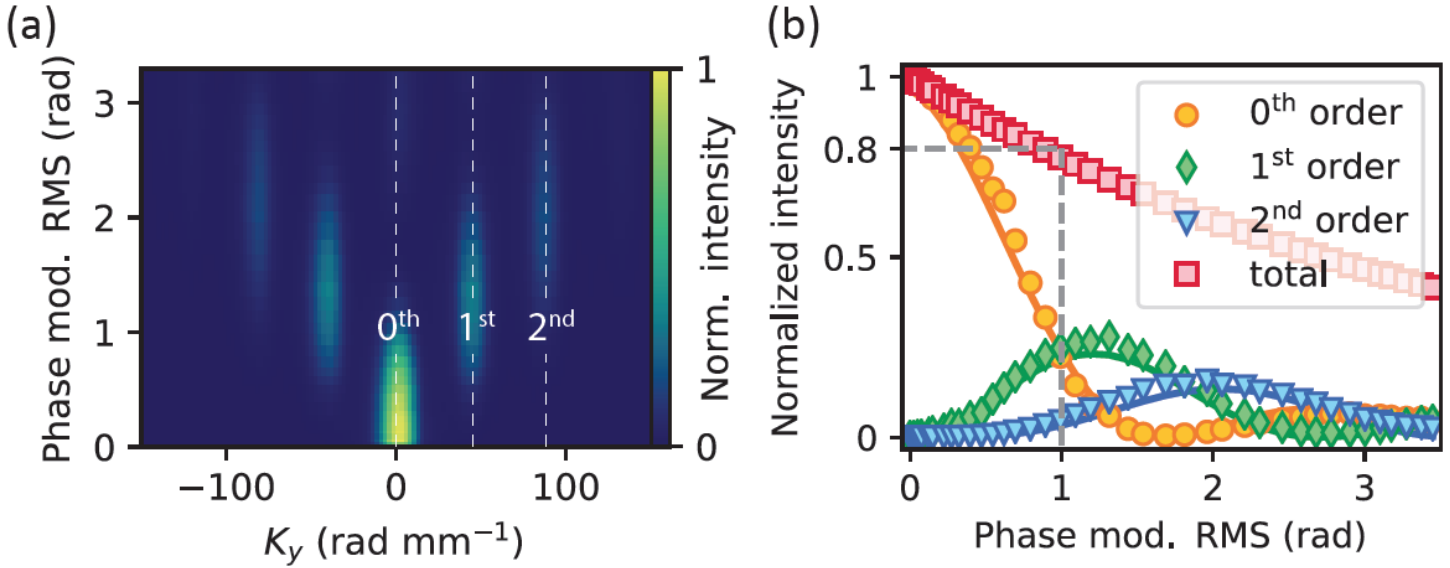
Ac-Stark configuration





Efficient modulation with small loss and noise addition

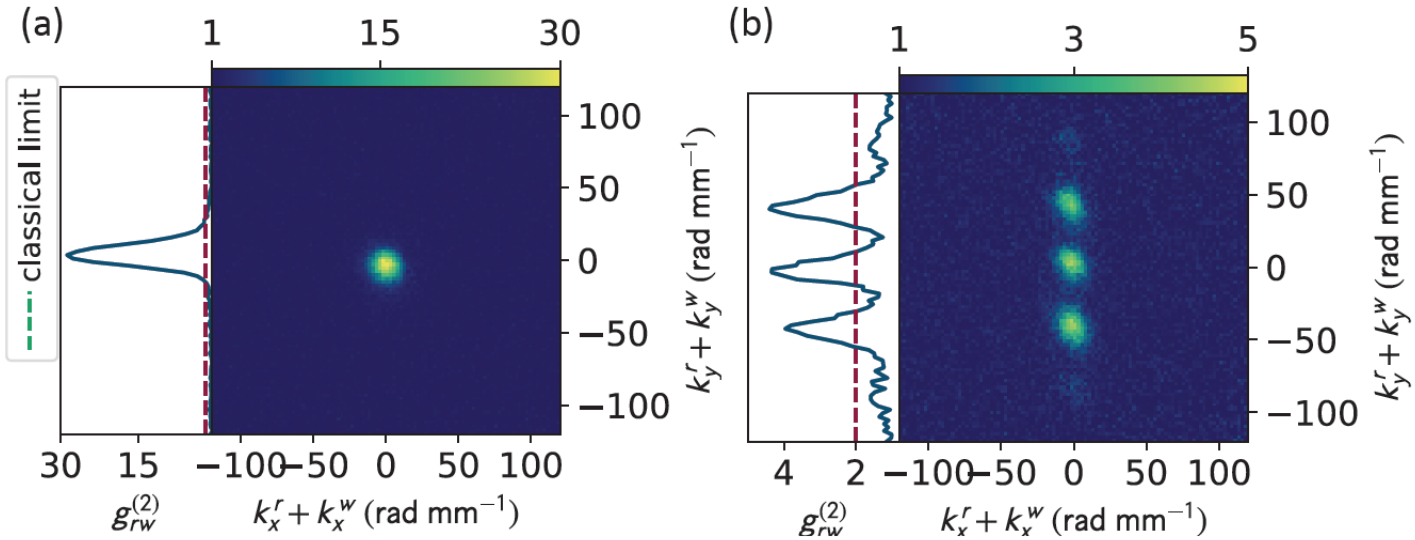
Spin-wave phase modulator



Directing spin waves into selected diffraction orders

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

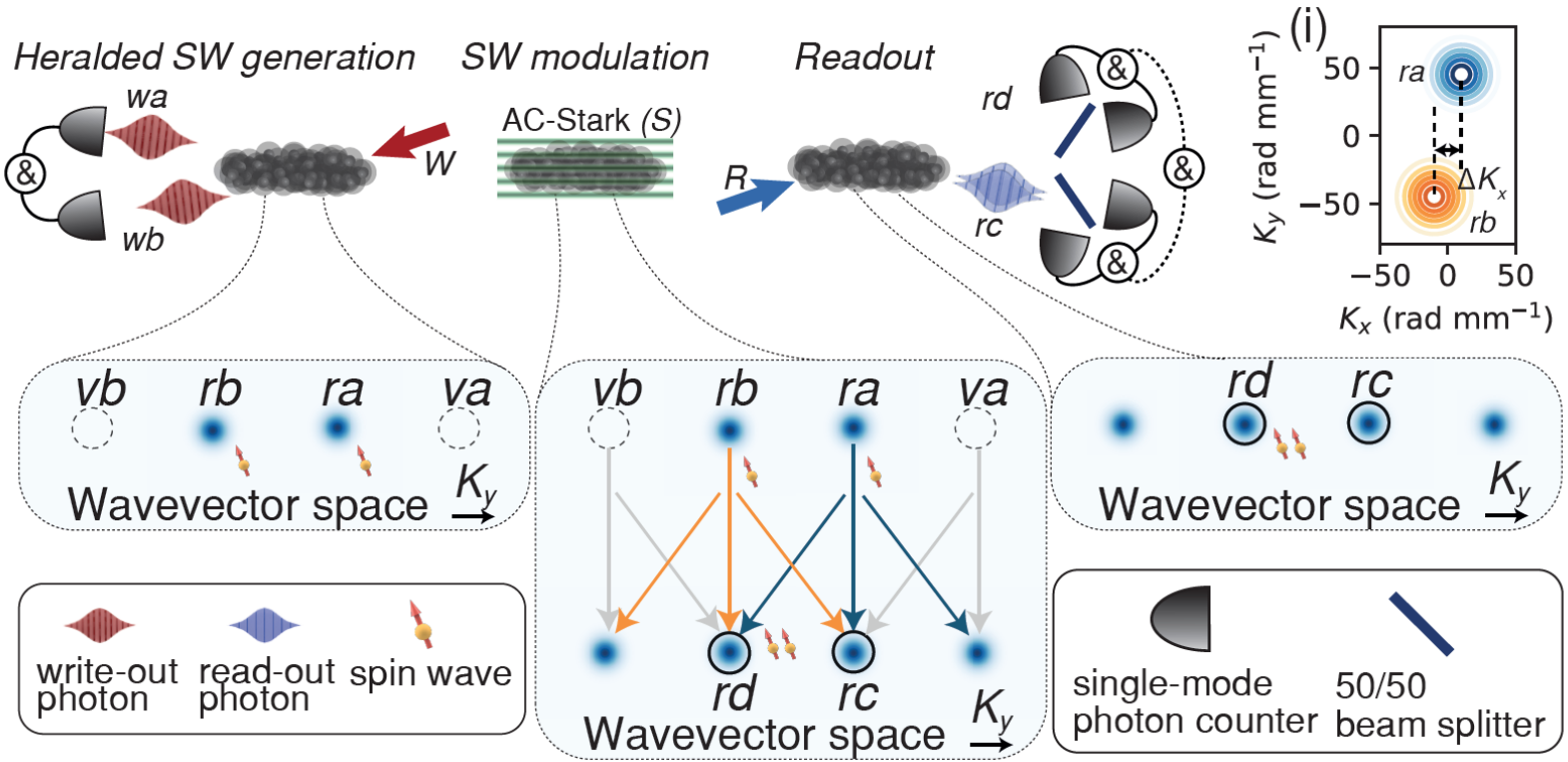
Operation for single photons



Diffraction observed in correlation functions as splitting of the central peak

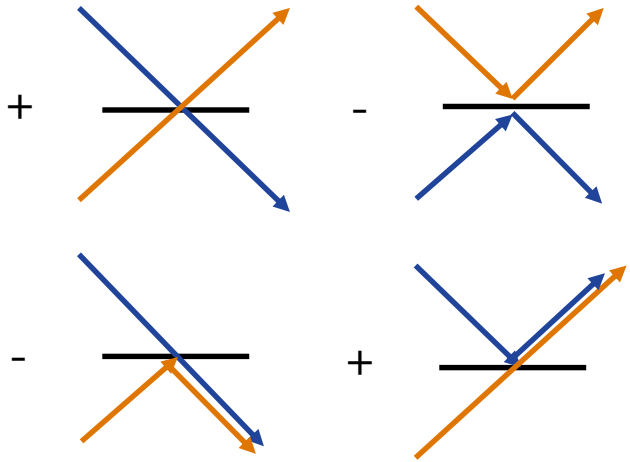
Phys. Rev. Lett. **122**, 063604 (2019)

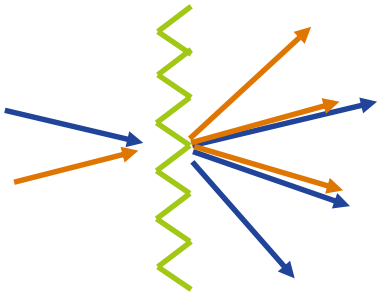
The three-way splitter

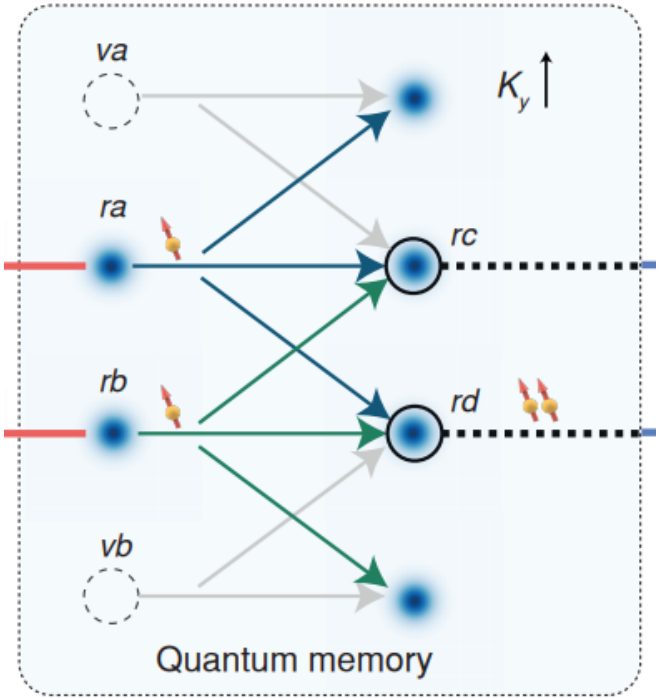


Phys. Rev. Lett. **122**, 063604 (2019)

Splitting spin waves

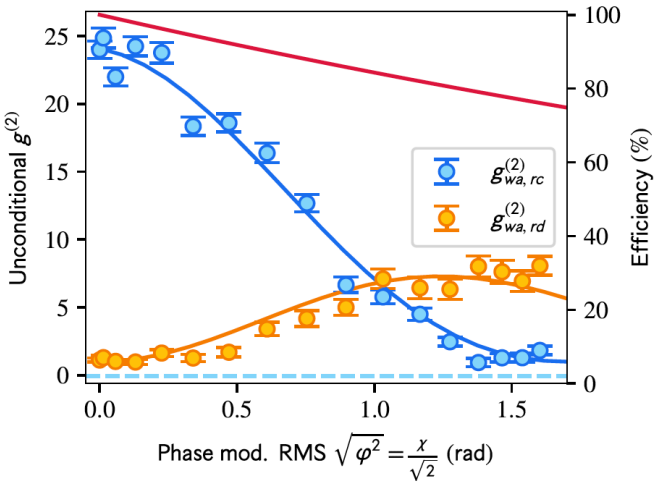




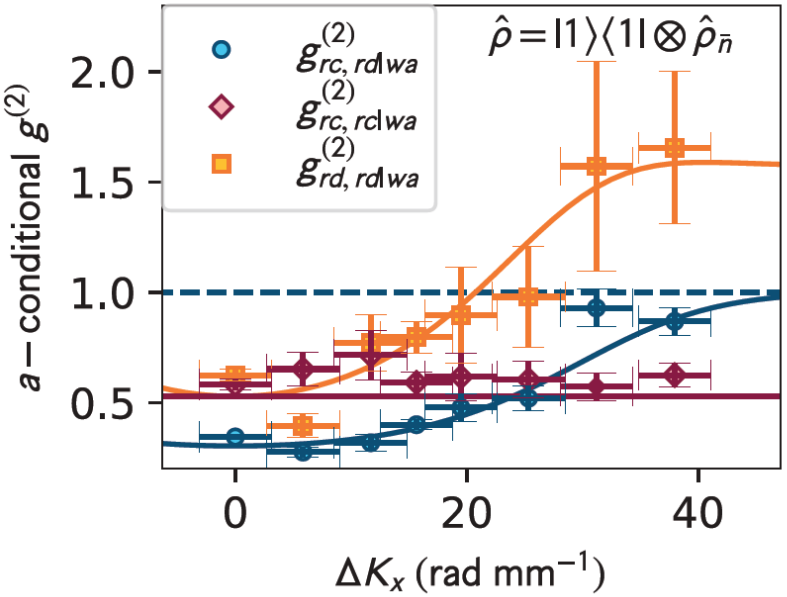


Handburry Brown-Twiss measurement

Demonstration of nonclassical statistics (heralded $g^{(2)}<0.3$) of spin wave through beamsplitting performed in the spin-wave domain

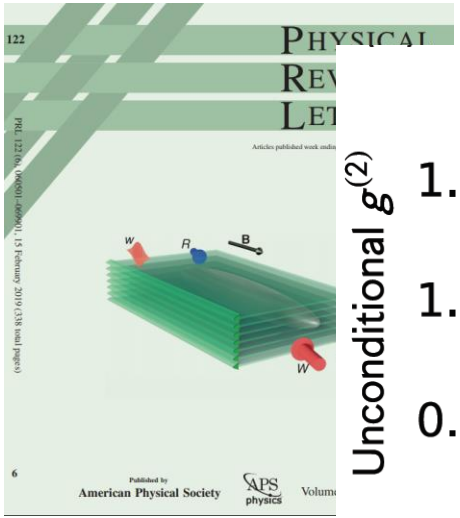


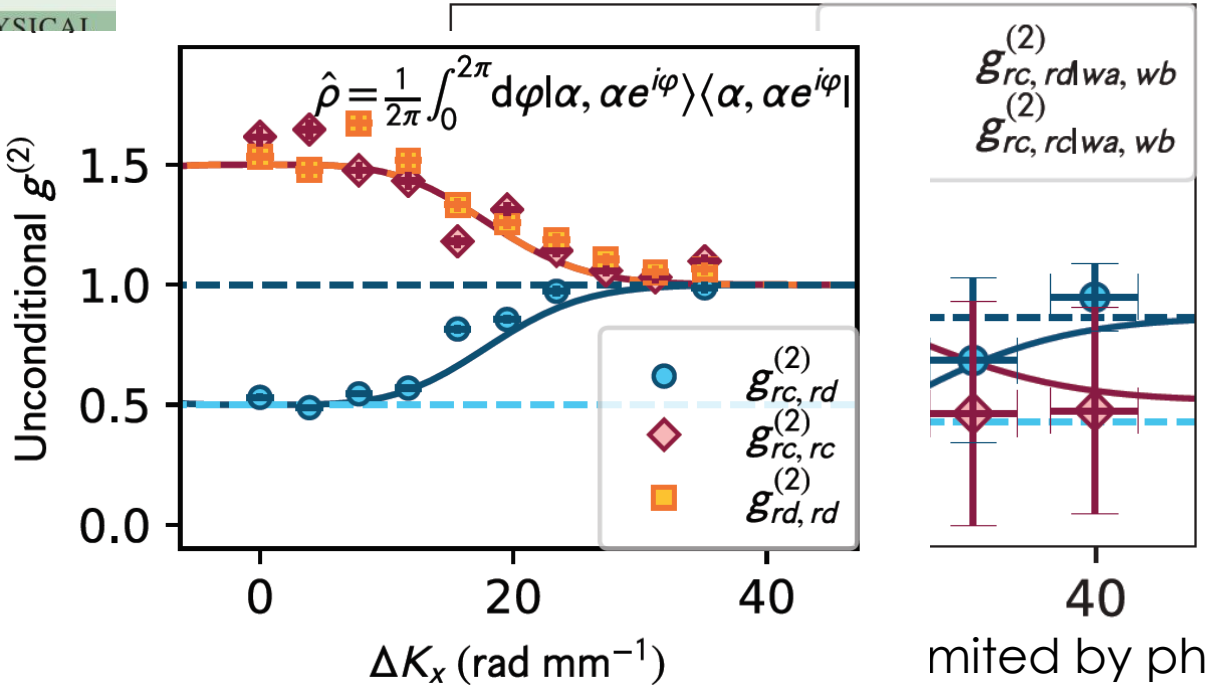
A weak thermal state as noise model

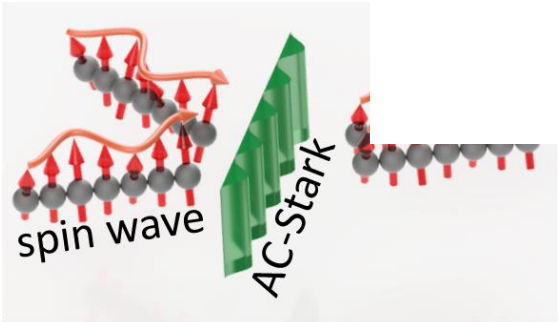


Phys. Rev. Lett. **122**, 063604 (2019)

Hong-Ou-Mandel interference





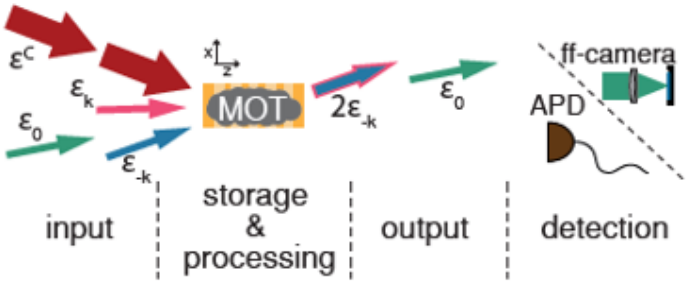


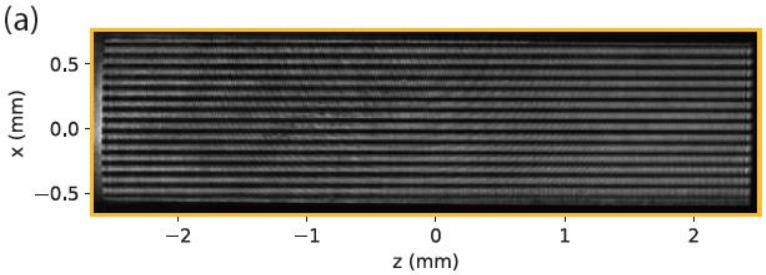
mited by photon purity: with weak coherent states we observed interferometric visibility of >95%

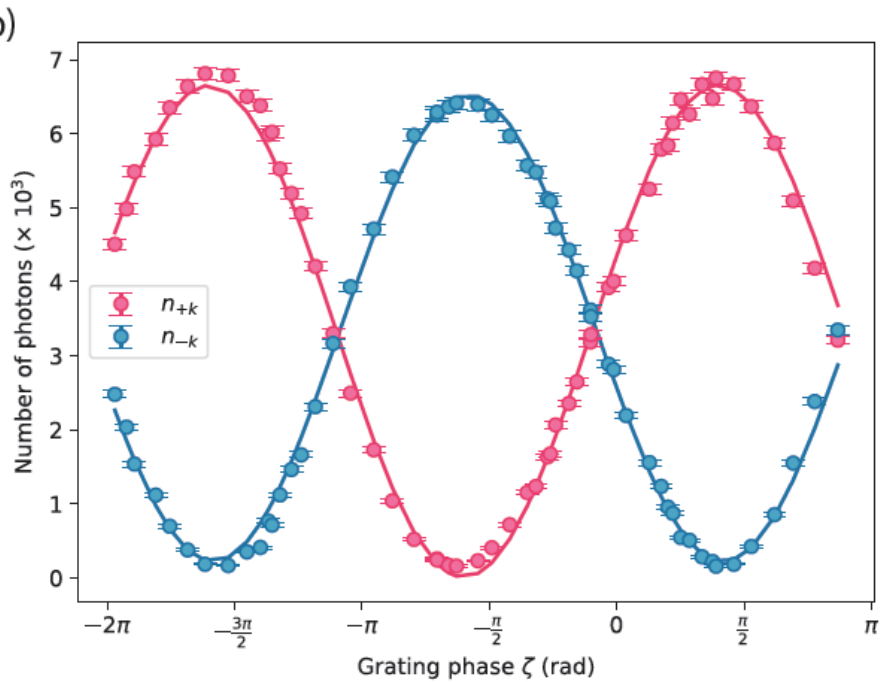
Phys. Rev. Lett. **122**, 063604 (2019)

Classical spin wave interference

Memory for coherent light

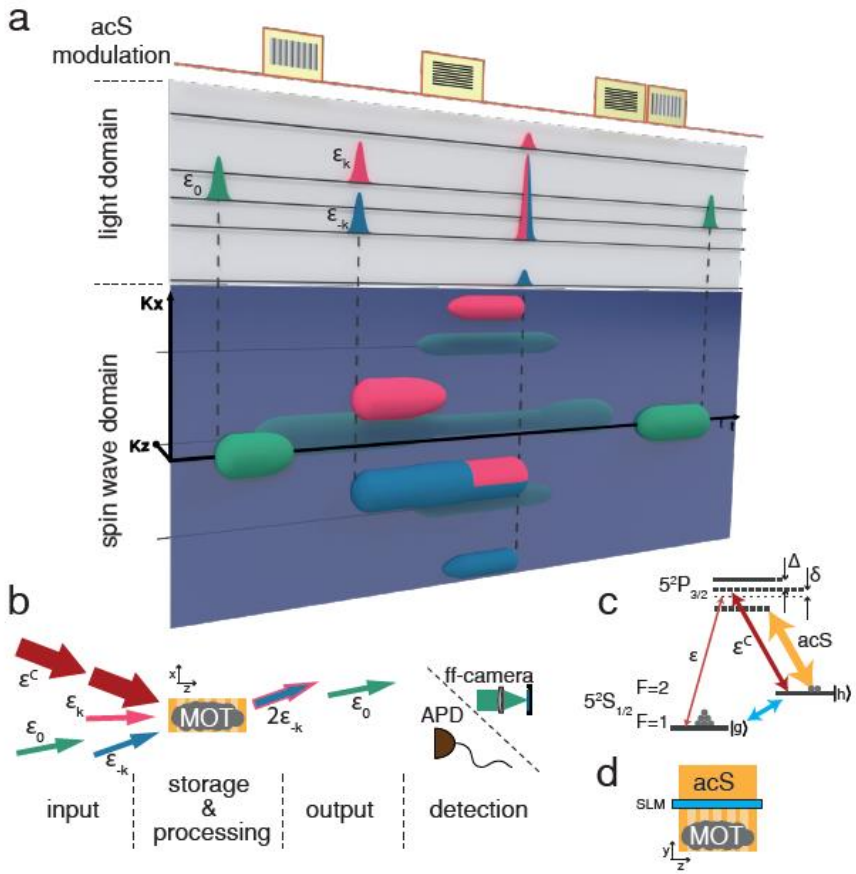


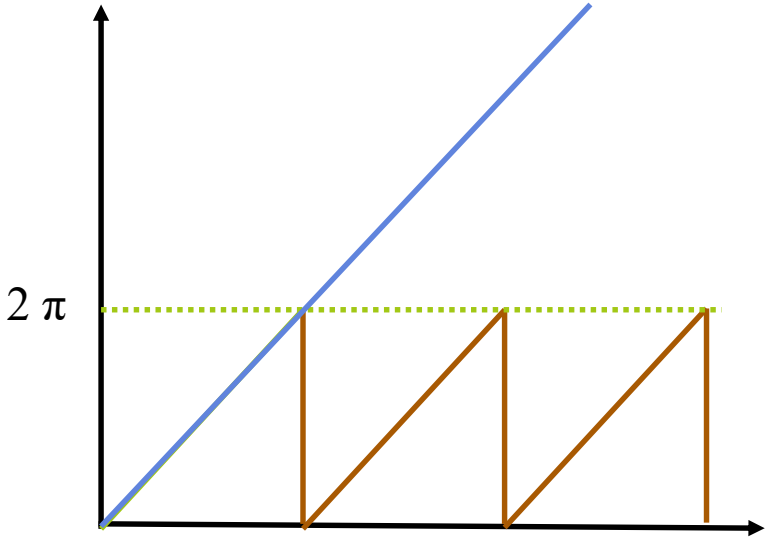




M. Mazelanik, **MP**, A. Leszczyński, M. Lipka, W. Wasilewski, npj Quantum Information **5**, 22 (2019)

Going to many dimensions



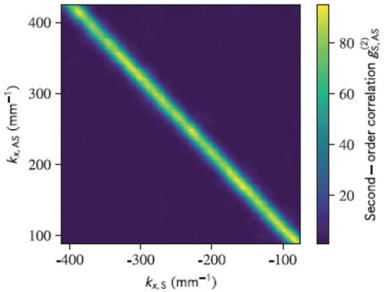


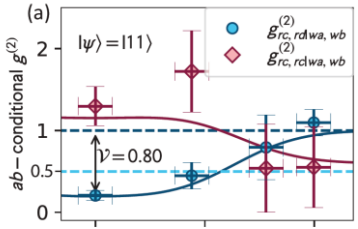
$$c_n = \frac{1}{2\pi}\int_0^{2\pi} \exp(i\varphi_{\mathrm{acS}}^{\mathrm{periodic}}(\xi) - in\xi)\mathrm{d}\xi$$

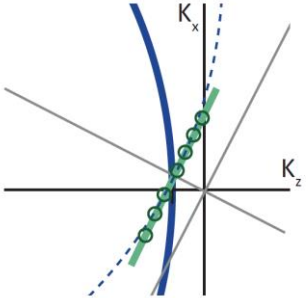
npj Quantum Information **5**, 22 (2019)

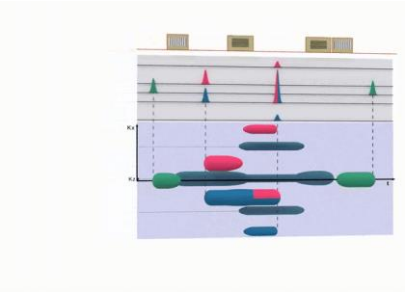
Maniuplating photons, spin waves and phonons

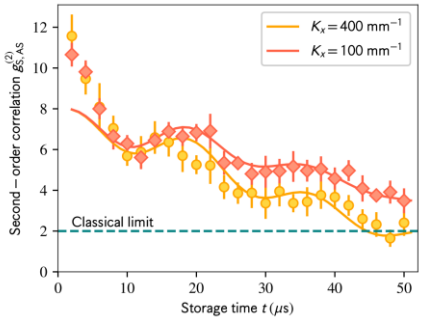
- Wavevector-multiplexed quantum memory
- Quasi-deterministic generation of single photons
- Photonic-like maniupulation of material quasi-particles
- Spin-wave-based interferometric processor for stored light
- Heralded phononic Fock states

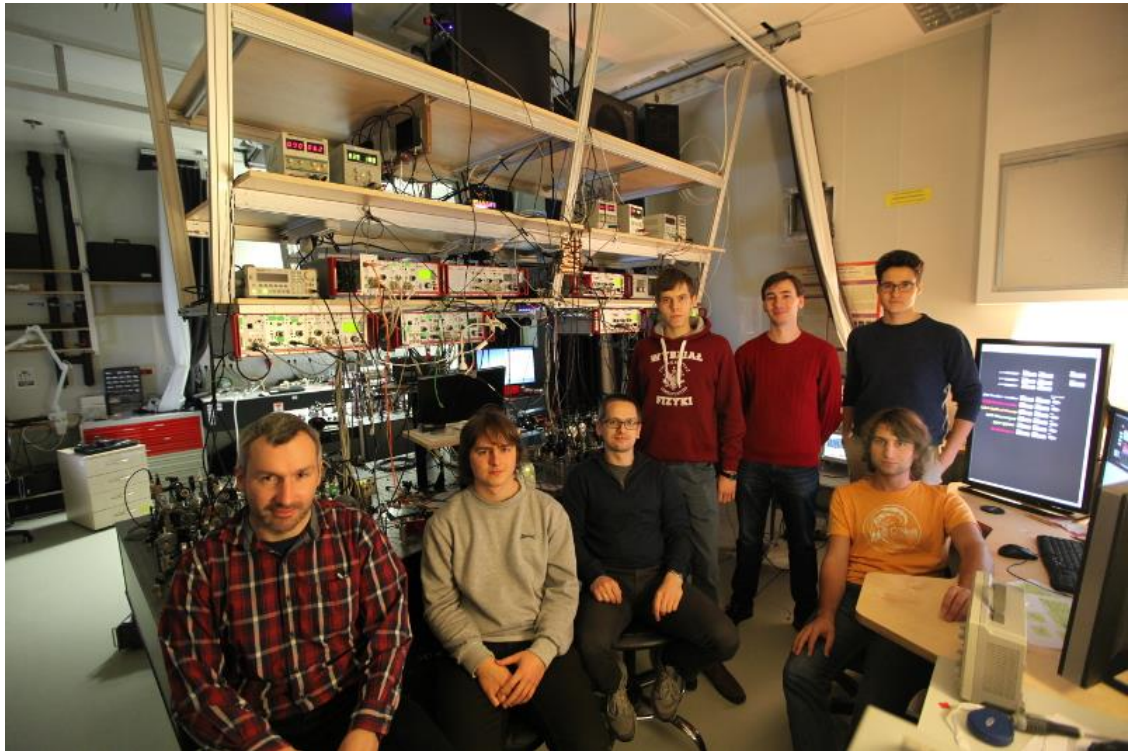












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Adam Leszczyński – quantum memory
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Krzysztof Zdanowski
Andrzej Ostasiuk
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