Quantum integrated photonics

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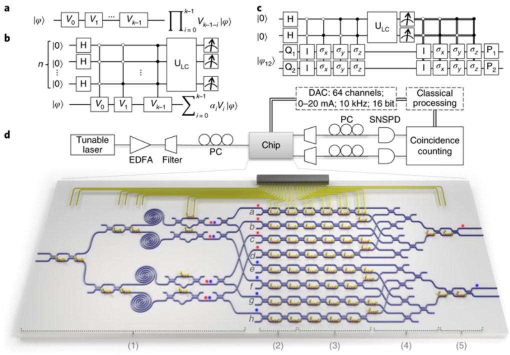
INSTITUTE

Photonics is a powerful tool for quantum information

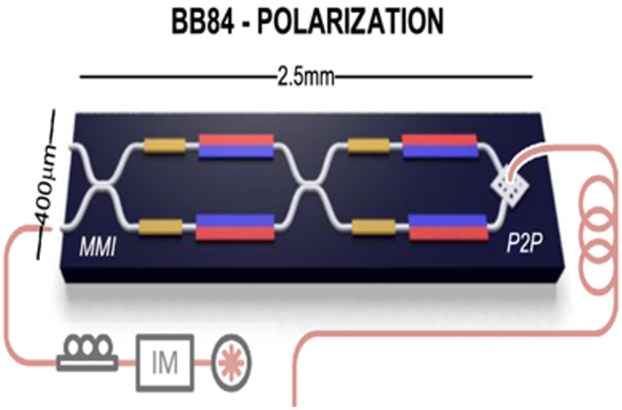
Quantum Computing

Quantum Networks

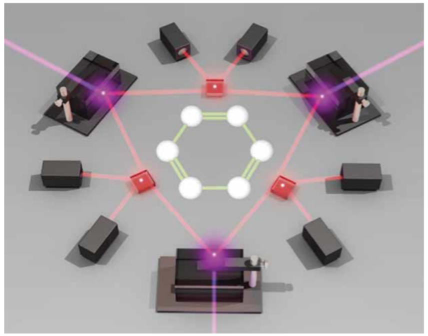
Quantum Simulation



Qiang, X. et al. Nat. Photonics 12, 534–539 (2018).

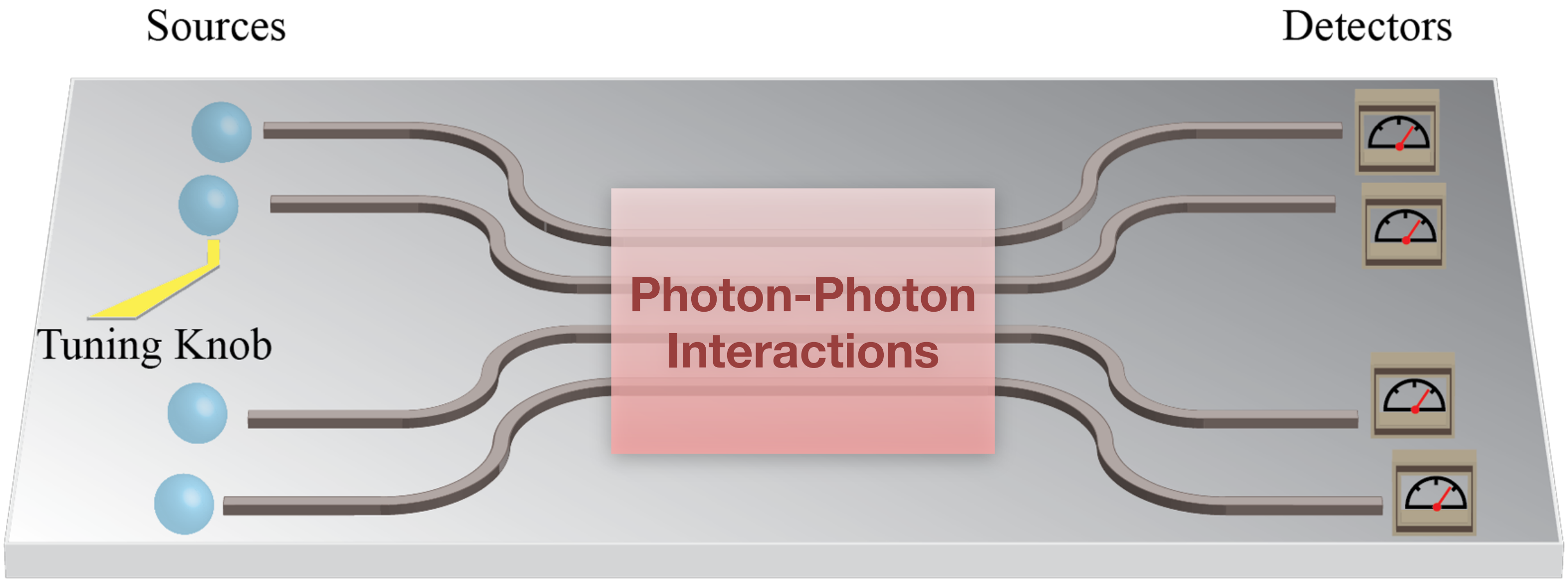


Sibson et al. *Optica* 4.2 (2017): 172-177.



Aspuru-Guzik and Walther, *Nature Physics* 8, 285 (2012)

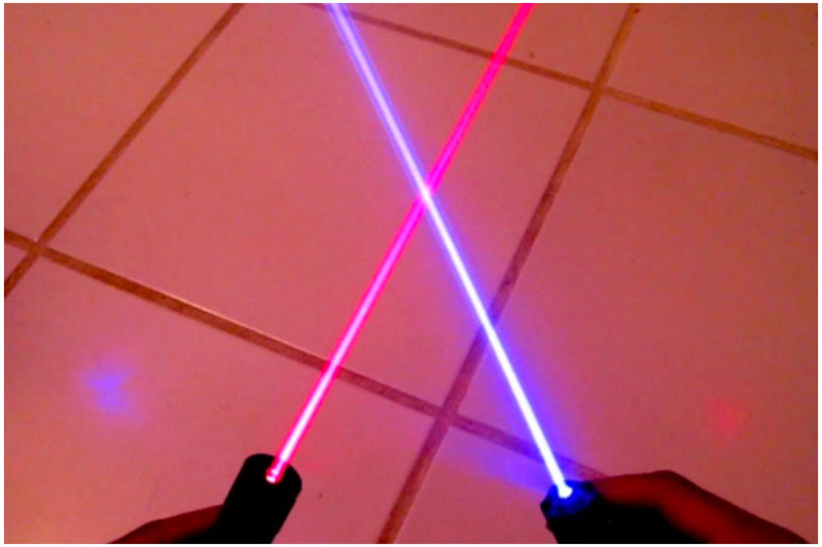
Scalability requires photonic integration



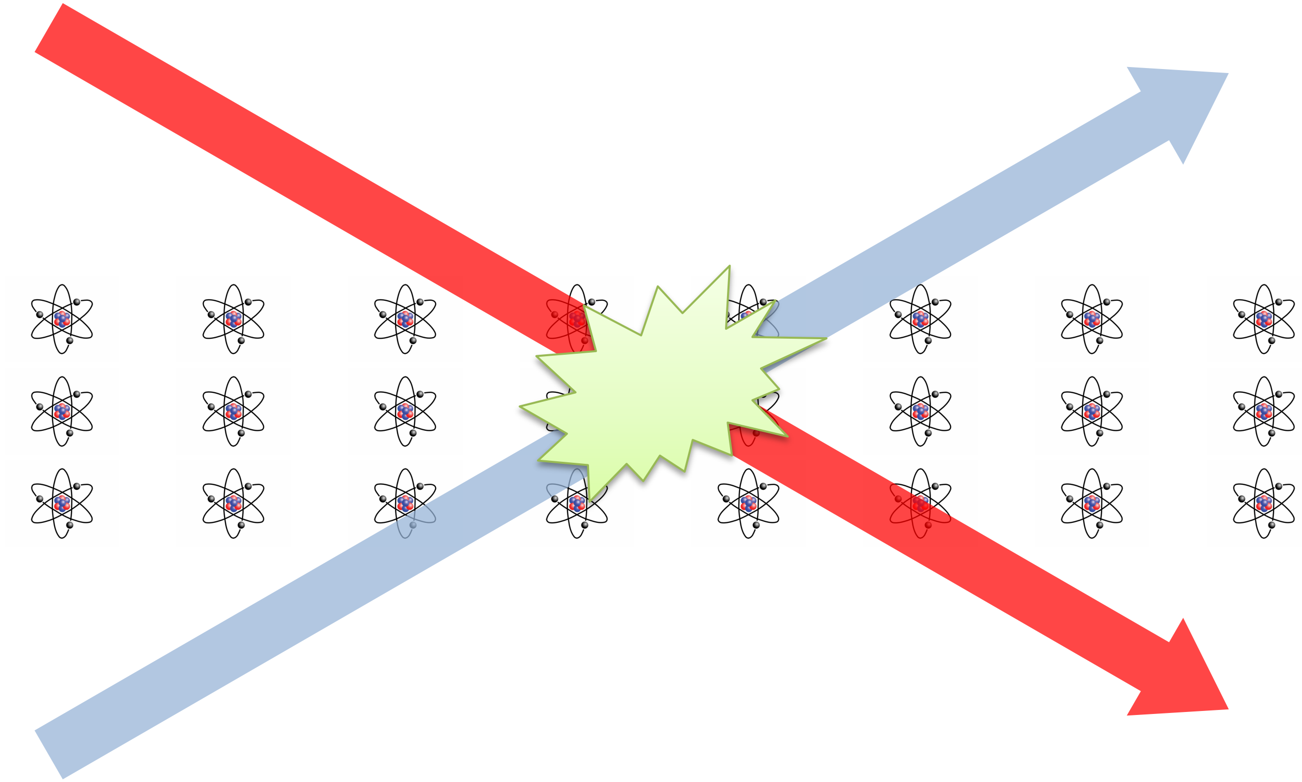
Politi, A., et al., *Science* 325, 1221 (2009)
O'Brien, J. L. *Science* 318, 1567 (2007)

Elshaariet al., *Nat. Comm.* 8, 379 (2017)
Wang, et al., *Nat. Photon* 11, 361 (2017)

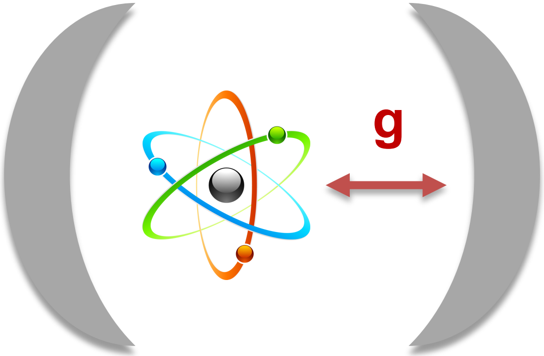
Light doesn’t naturally interact with light



Atoms mediate optical interactions



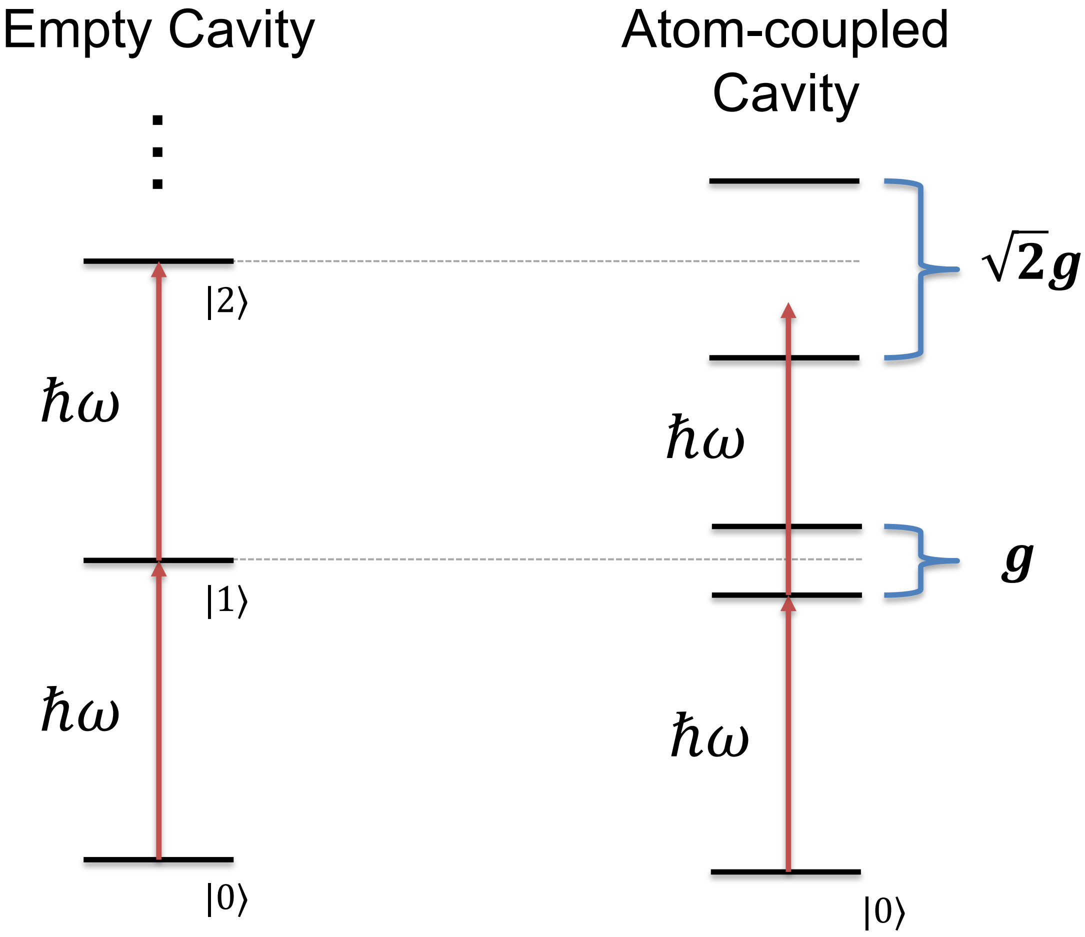
Quantum applications need single photon nonlinearity



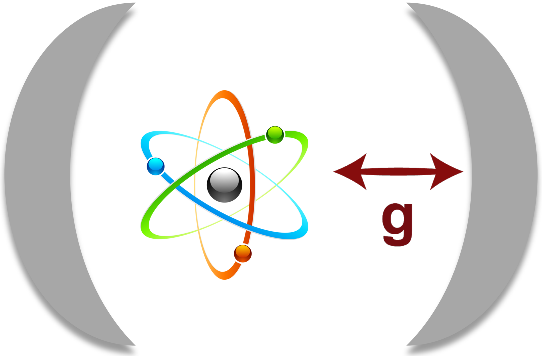
Interaction Hamiltonian

$$\mathbf{H} = \hbar g\left(a^{\dagger}\sigma_{-} + \sigma_{+}a\right)$$

Atom coupling generates an anharmonic spectrum



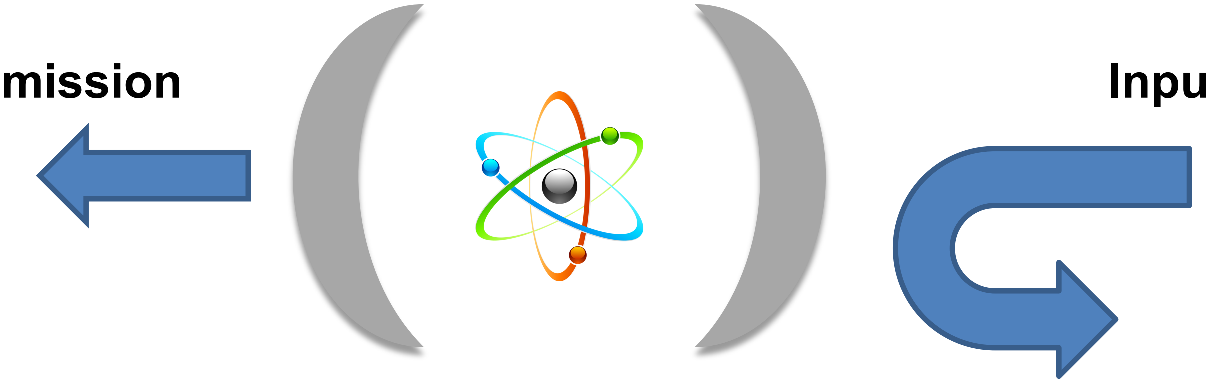
Real systems suffer from decoherence



Atomic Cooperativity

$$C = \frac{4g^2}{\gamma\kappa}$$

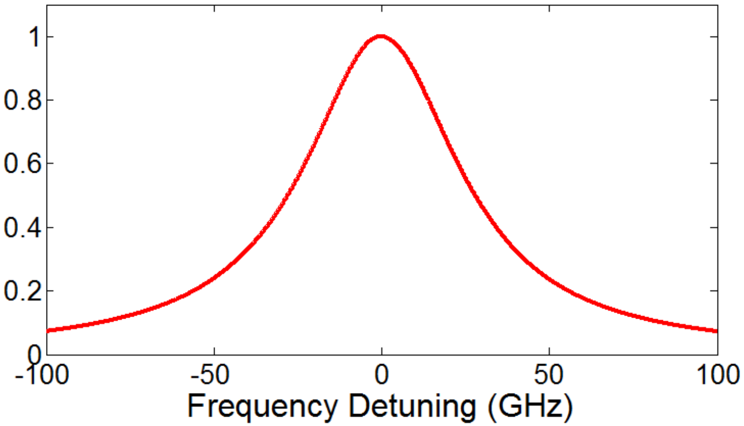
High cooperativity modifies the cavity spectrum



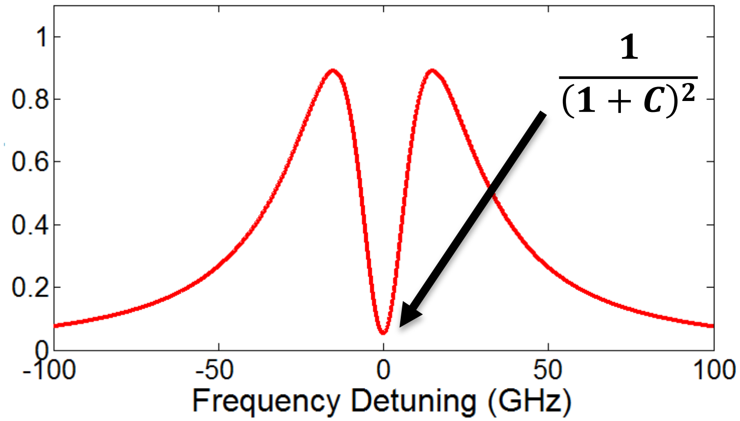
Transmission

Input

$C \ll 1$

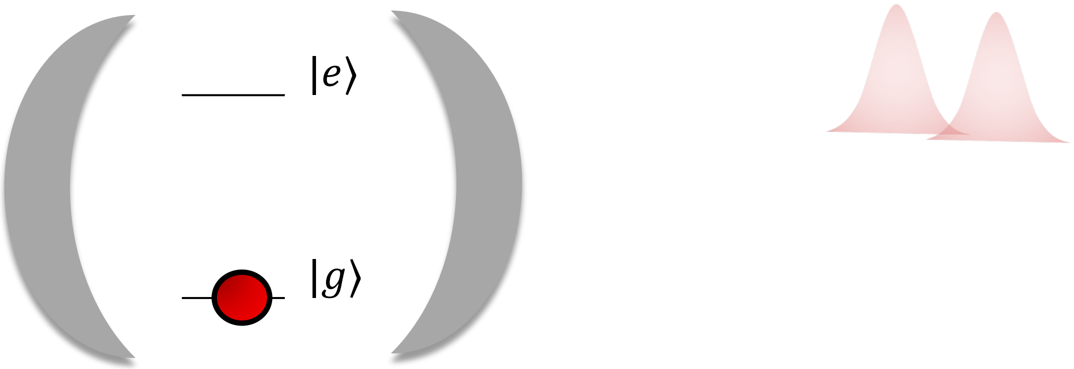


$C \gg 1$



E. Waks and J. Vuckovic, *PRL.* **96**, 153601 (2006)

High cooperativity generates strong photon-photon interactions



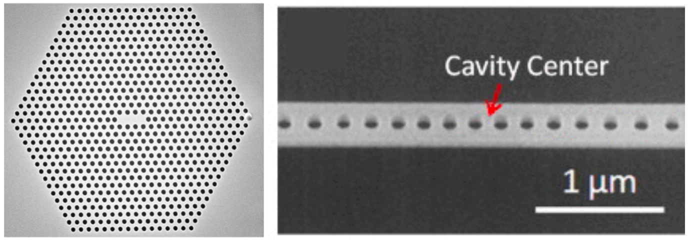
How do we reach high cooperativity?

$$C \propto \frac{Q}{V}$$

- **High quality factors**
- **Small mode volumes**

Quantum nanophotonic devices attain low photon number nonlinearities

Photonic crystals

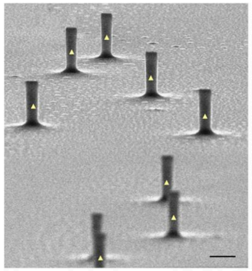


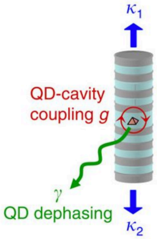
Faraon *et al.*, *Nature Physics* **4**, 859 (2008)

Reinhard *et al.*, *Nature Photonics* **6**, 93 (2012)

Bose *et al., PRL* 108, 227402 (2012)

Microposts

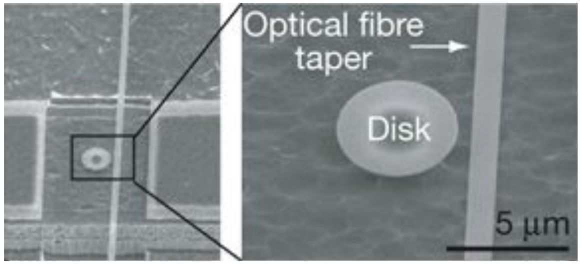




De Santis et al., *Nature Nanotechnology* 12, 663 (2017)

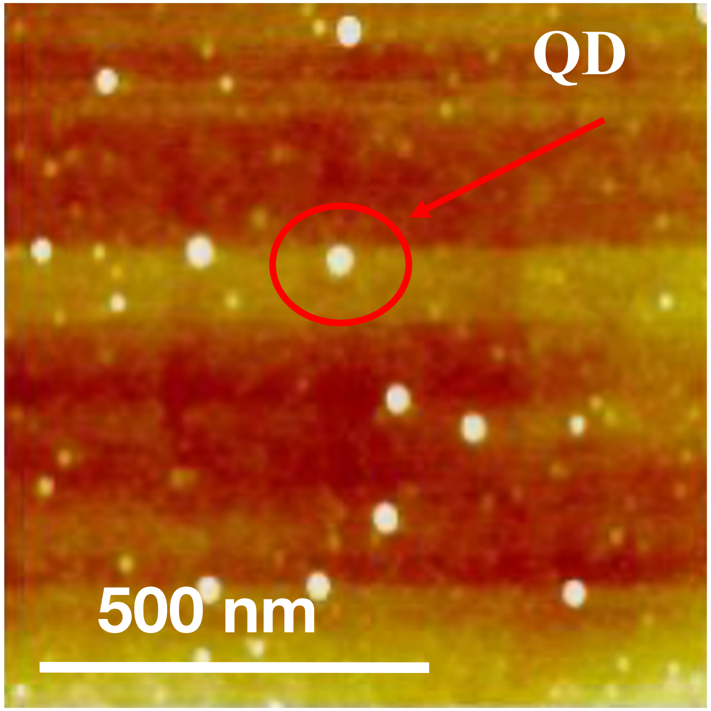
Snijders, et al., *Nature Communications* 7, 12578 (2016)

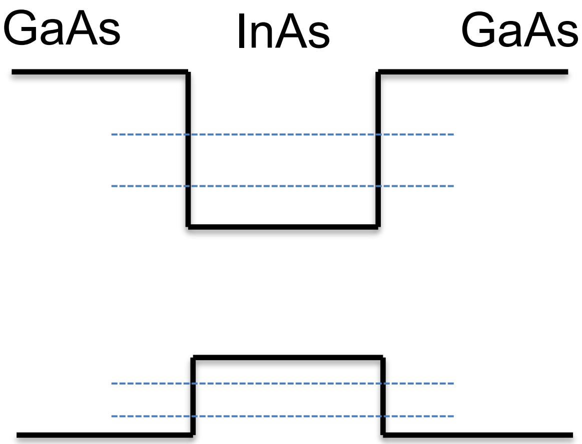
Microdisks



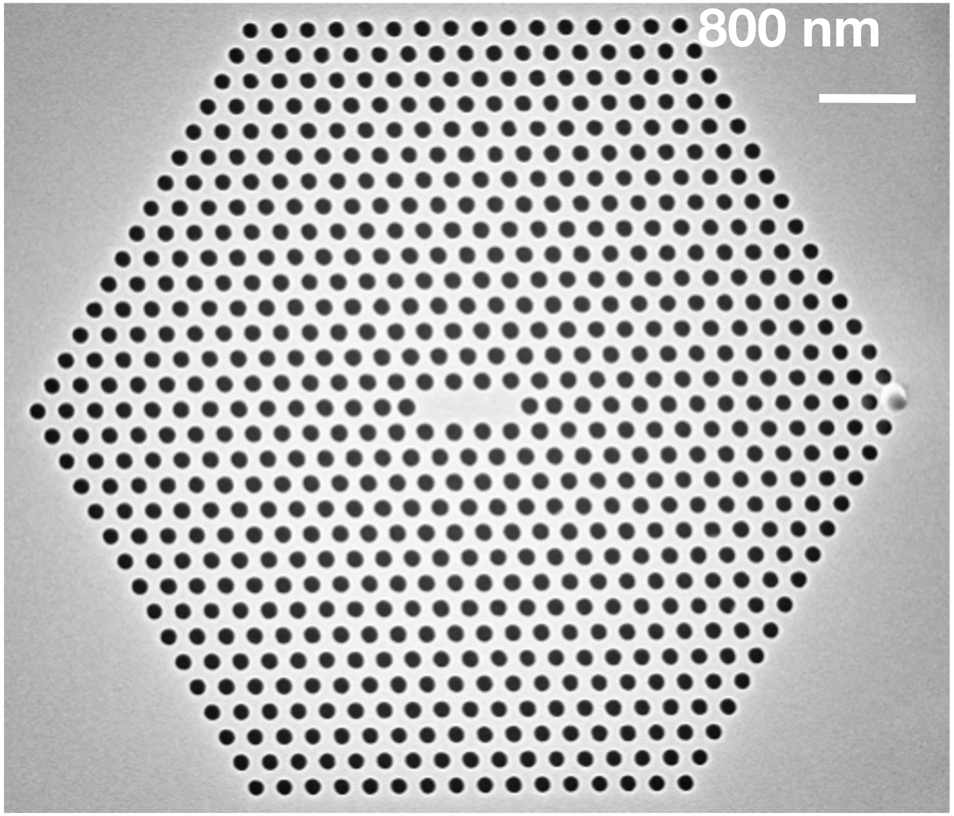
Srinivasan and Painter, *Nature* 450, 862 (2007)

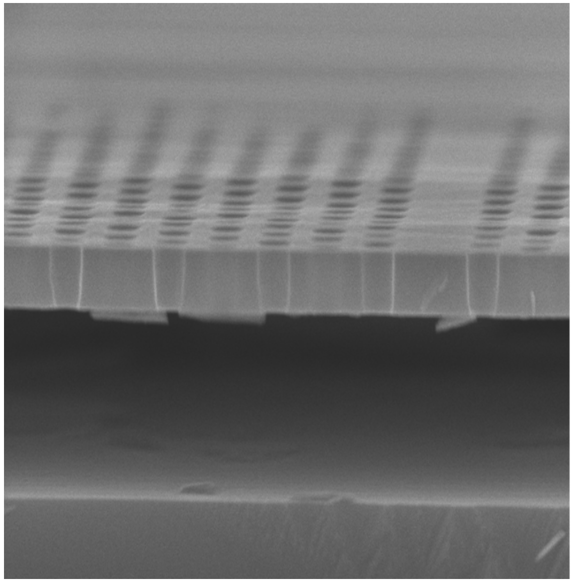
Quantum Dots: An "Artificial Atom"



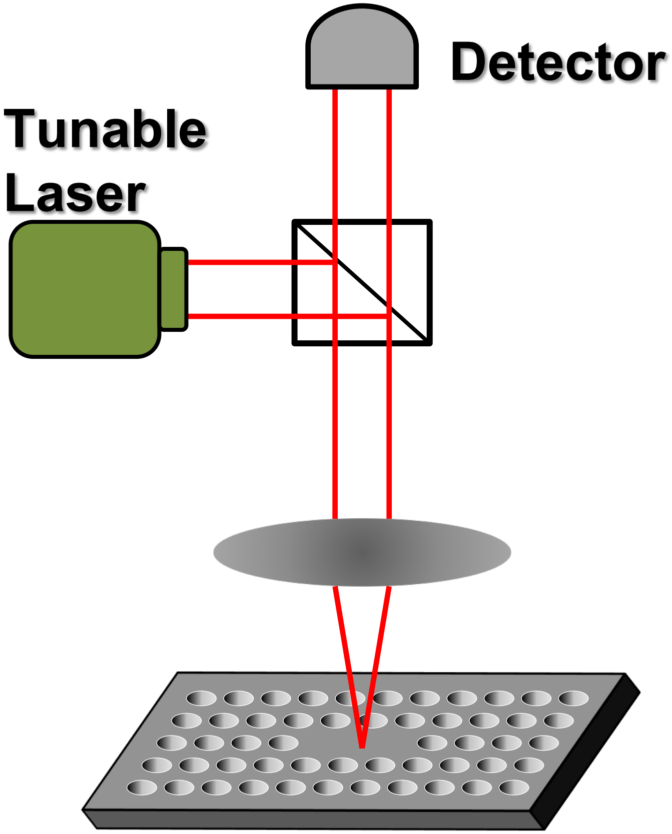


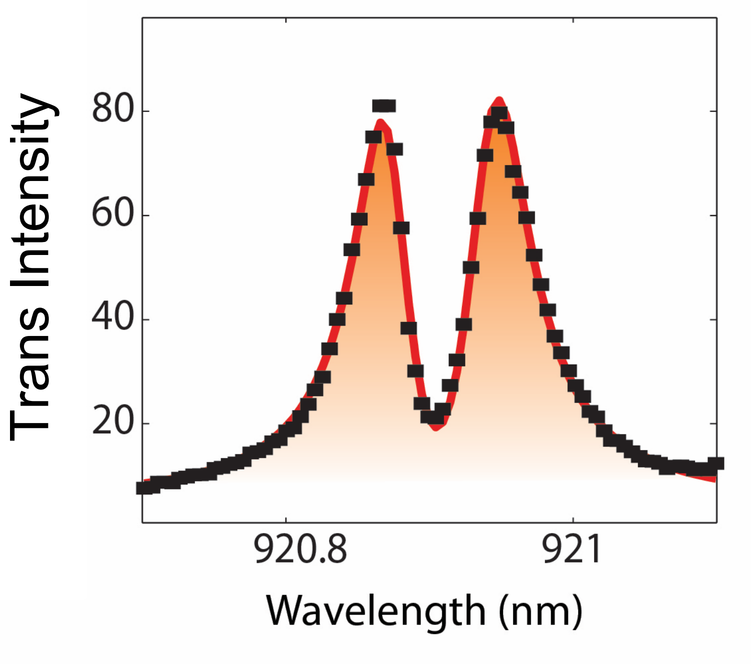
Photonic crystals reach high *Q* and small *V*





Photonic crystals generate low-photon-number nonlinearity





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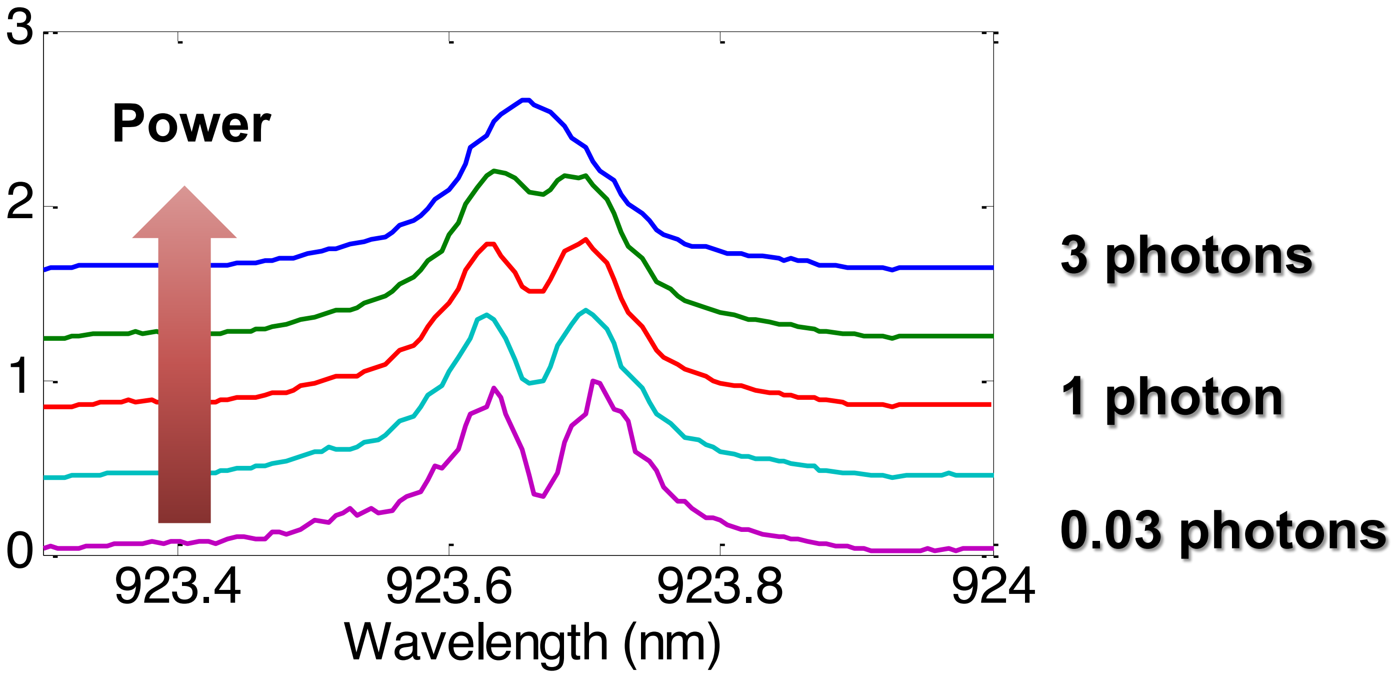
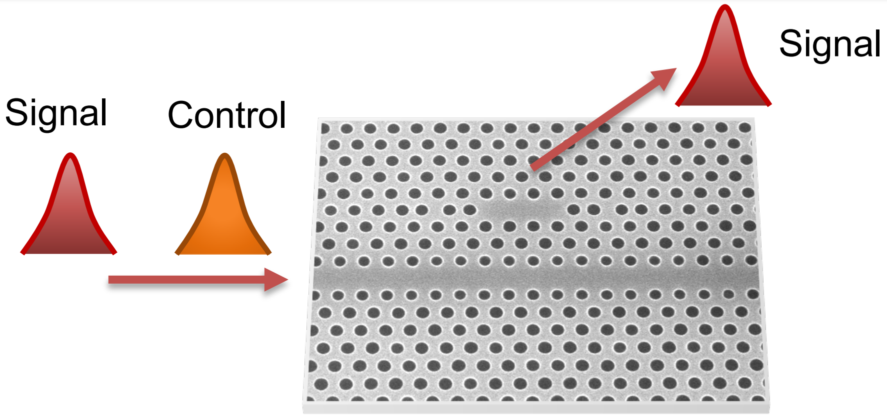
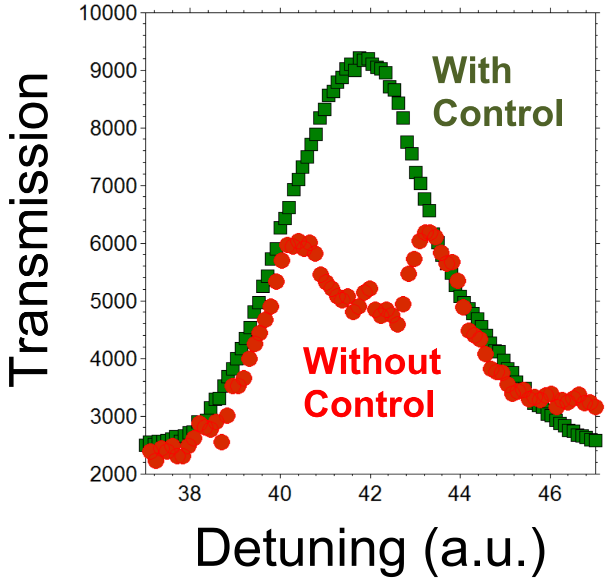


Photonic crystals generate low-photon-number nonlinearity

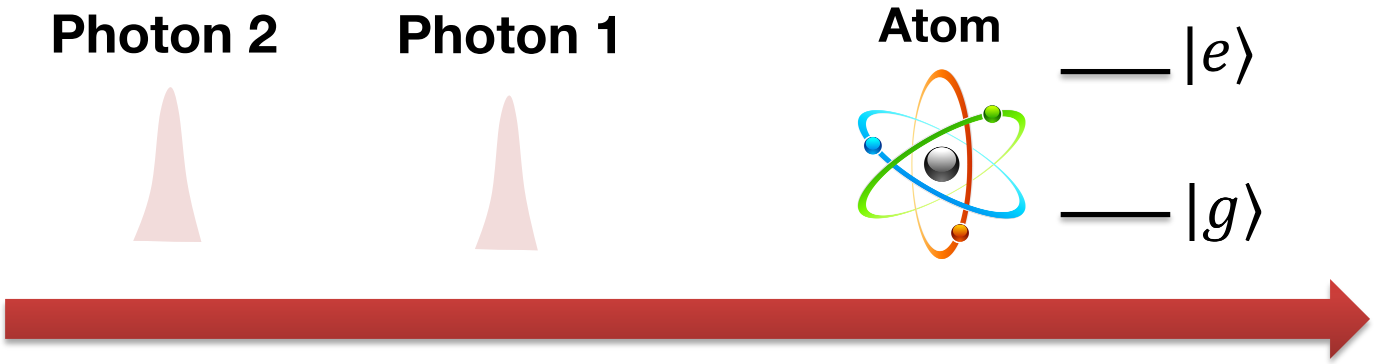




$$\langle n_c \rangle = 1.5$$

Bose et. al., *Phys. Rev. Lett.* **108**, 227402 (2012)

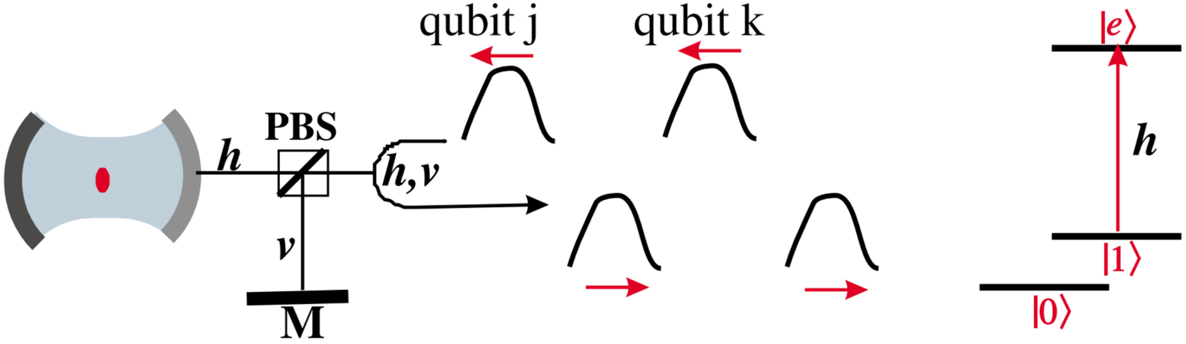
Two-level atoms cannot create single photon nonlinearities



Two-level atoms suffer from a time-bandwidth limit

Rosenblum, *Phys. Rev. A* 84, 033854 (2011).

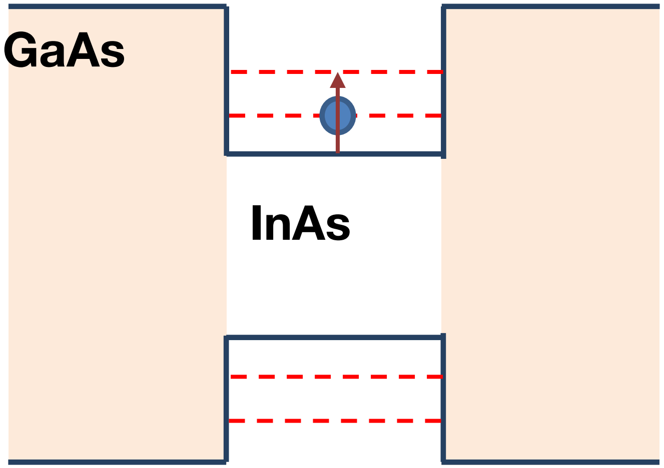
Atoms generate single photon interactions

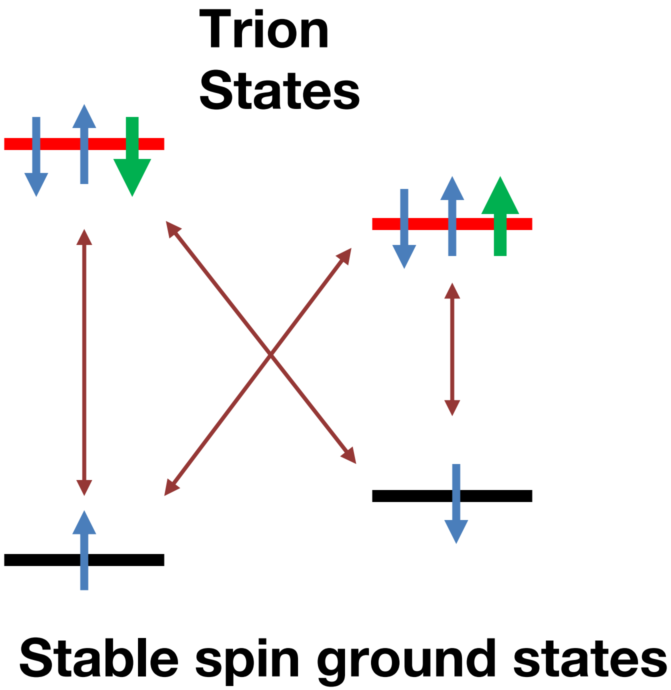


Duan & Kimble, *PRL* 92, 127902 (2004)

Quantum dots are qubits

Charged Quantum Dot





Gammon, D. *PRL* ***86***, 5176 (2001)
Bracker, *PRL*, ***94*** 047402 (2005)
Press et al., *Nature* 456, 218 (2008)
Berezonvsky et al., *Science* 320, 349 (2008)

Atoms modulate photon phase

Reflection coefficient

$$r = \frac{C-1}{C+1}$$

Low Cooperativity ($C \ll 1$)

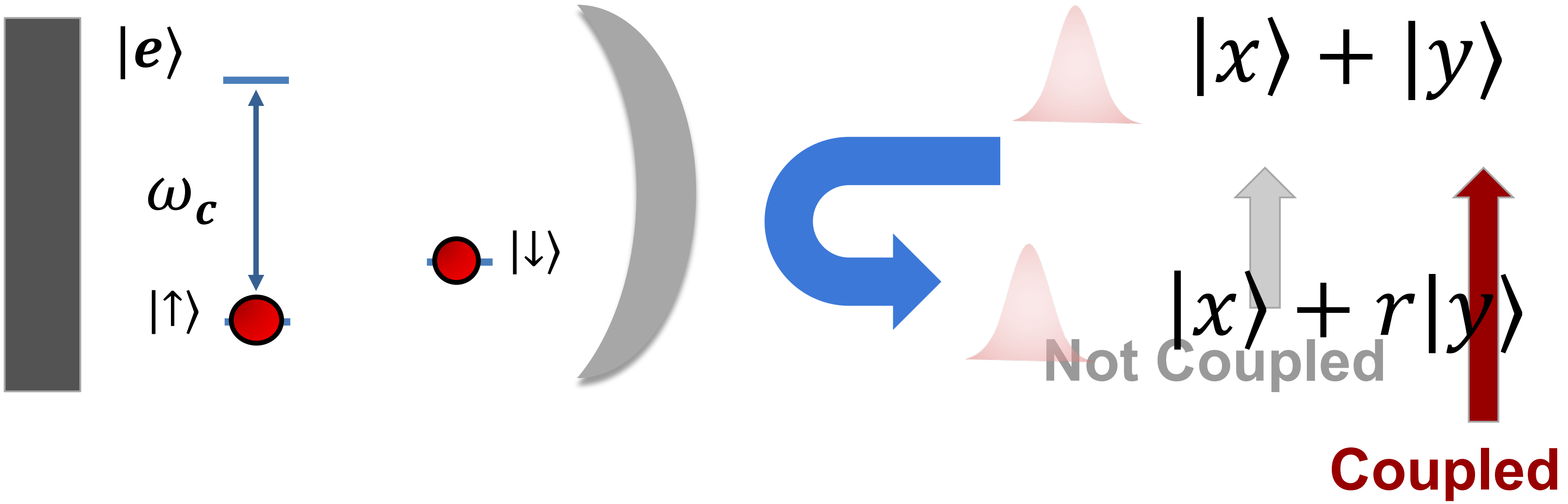
$$r = -1$$

High Cooperativity ($C \gg 1$)

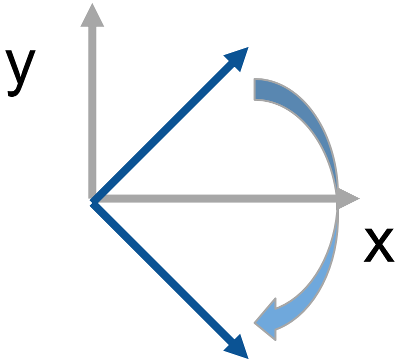
$$r = +1$$

E. Waks and J. Vuckovic, *PRL*. **96**, 153601 (2006)

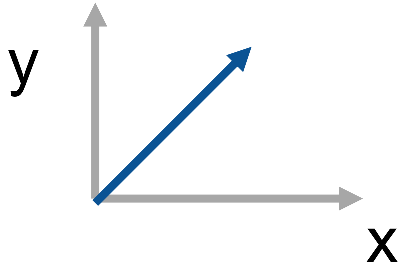
Spin controls photons



Spin down: $r = -1$

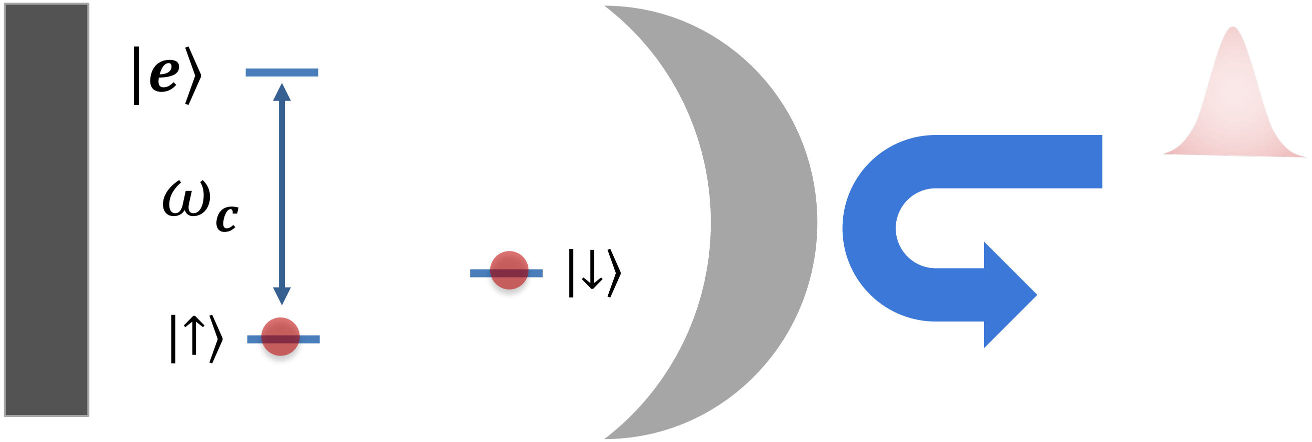


Spin up: $r = 1$



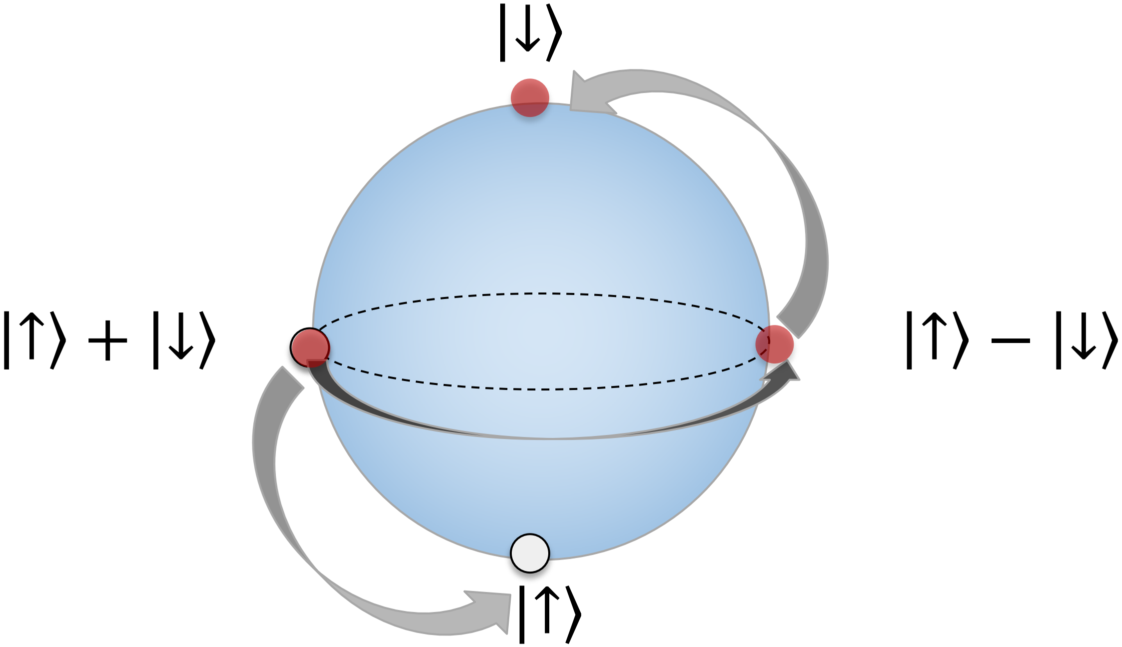
E. Waks and J. Vuckovic, *PRL*. **96**, 153601 (2006)

Photons control spin

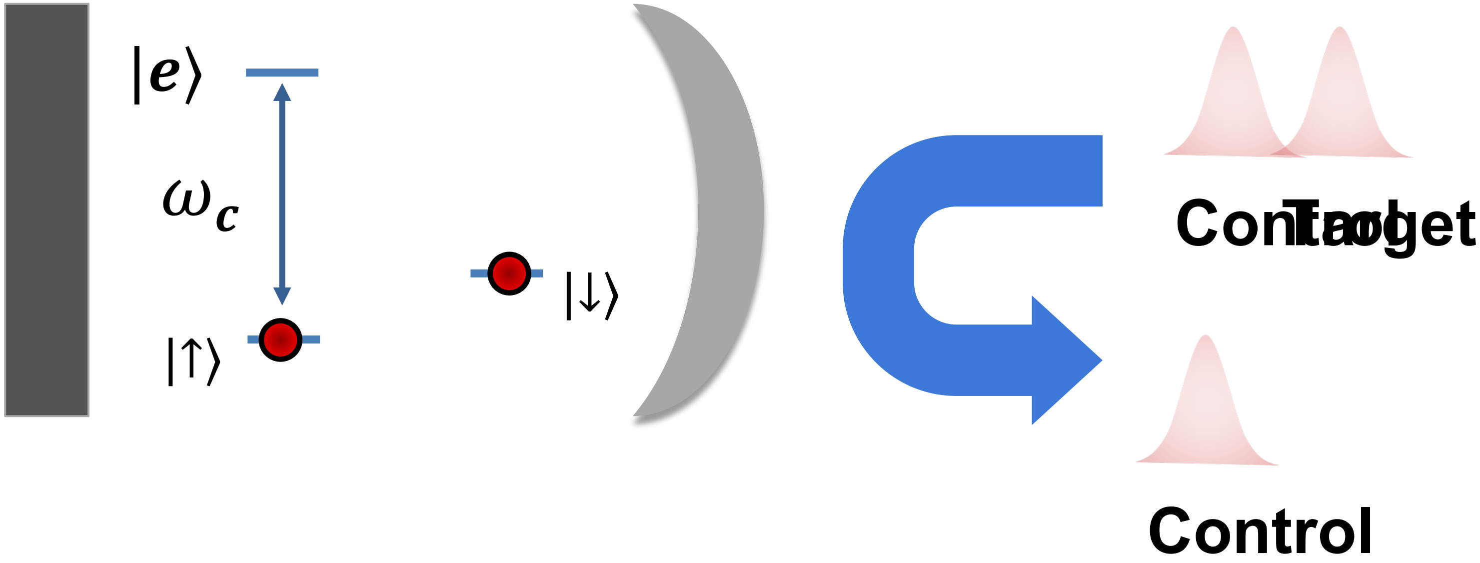


$$|\uparrow\rangle + |\downarrow\rangle \longrightarrow |\uparrow\rangle - |\downarrow\rangle$$

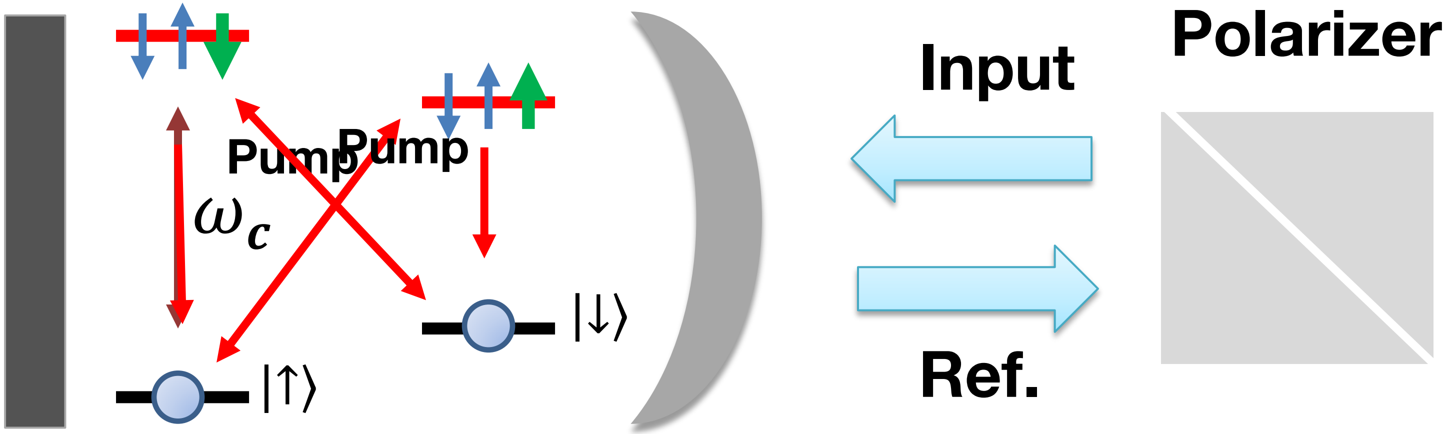
Photons control spin

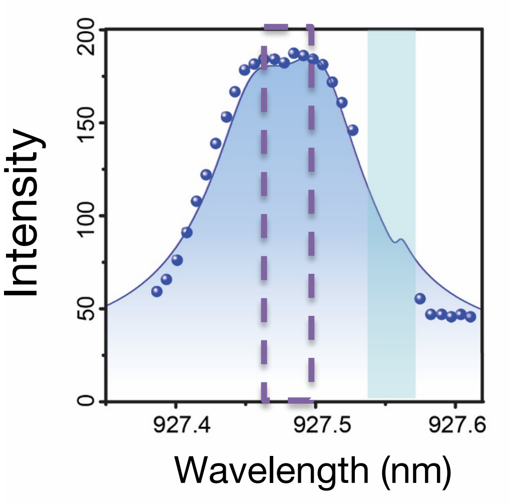


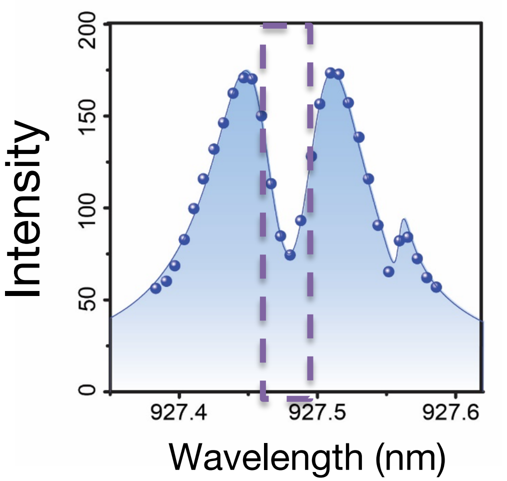
A photon controls a photon



Spin controls photon polarization

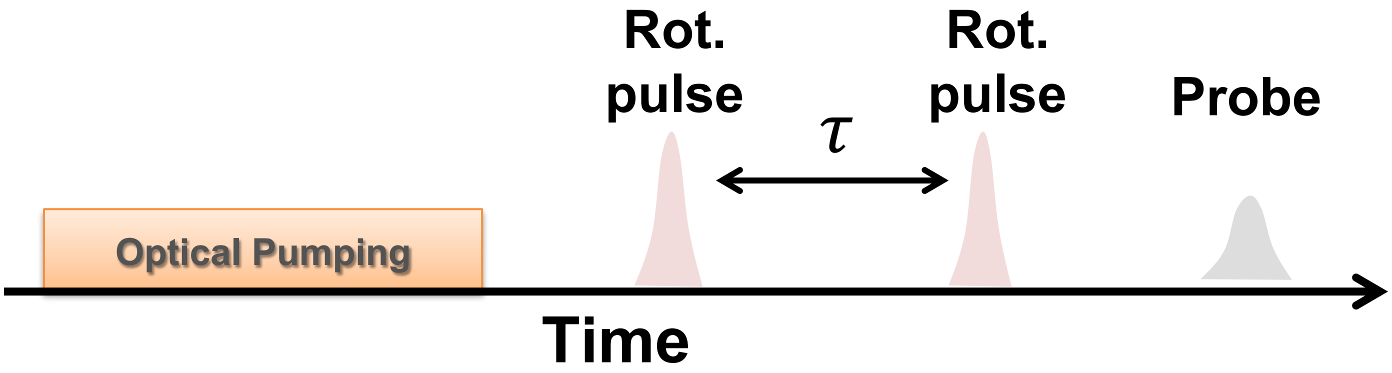


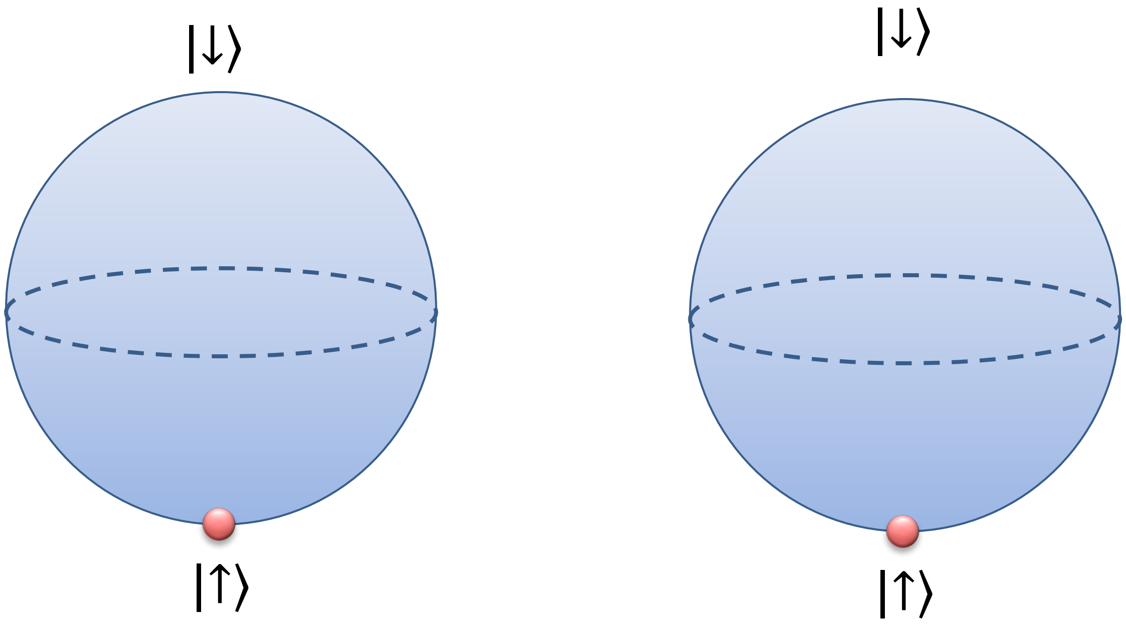




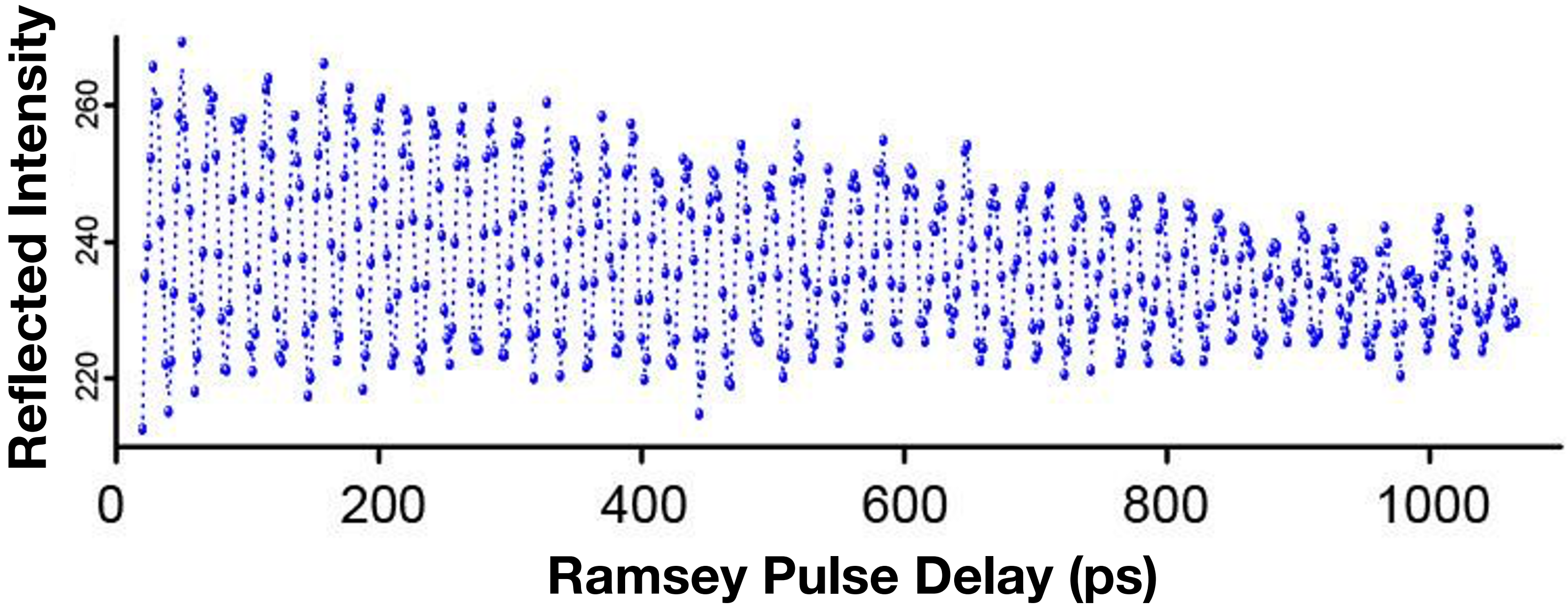
Sun et al., *Nature Nanotechnology* **11** 539 (2016)

Ramsey interferometry realizes complete coherent control



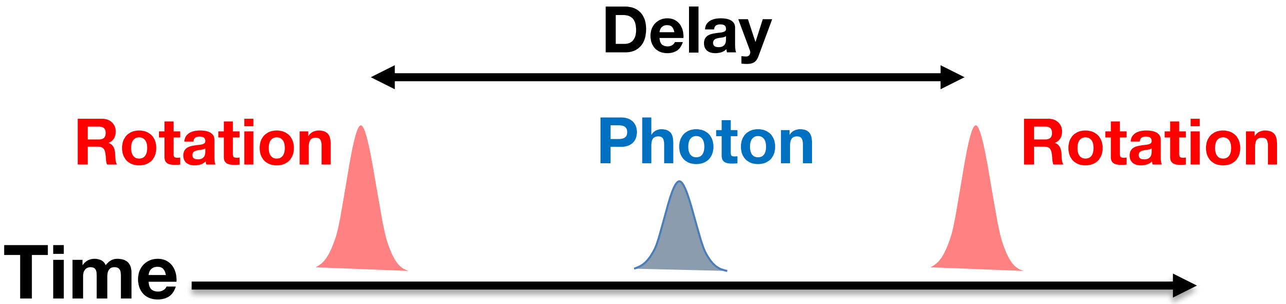


Cavity reflectivity exhibits electron spin resonance



Sun et al., *Nature Nanotechnology* **11** 539 (2016)

A single photon flips a spin

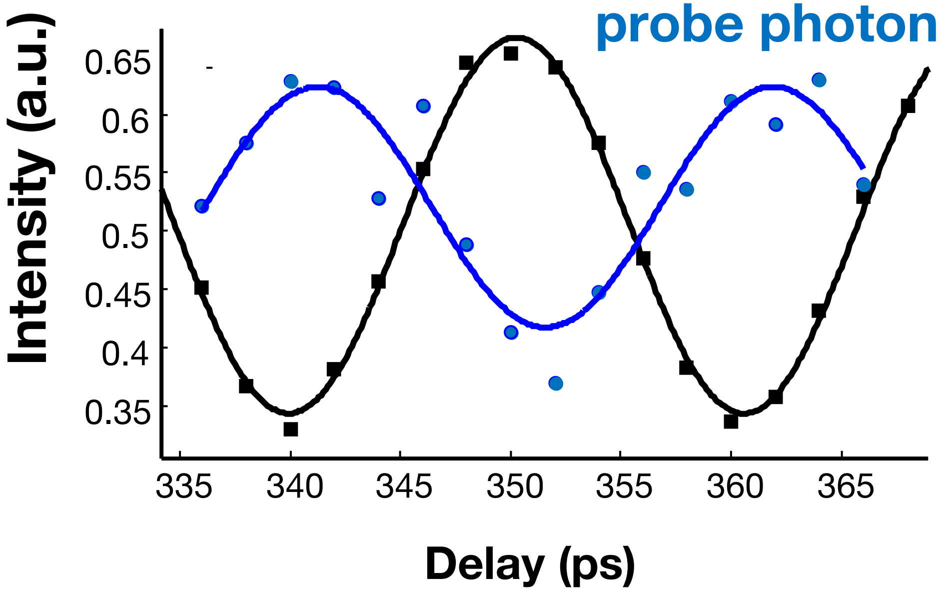


Delay

Rotation **Photon** **Rotation**

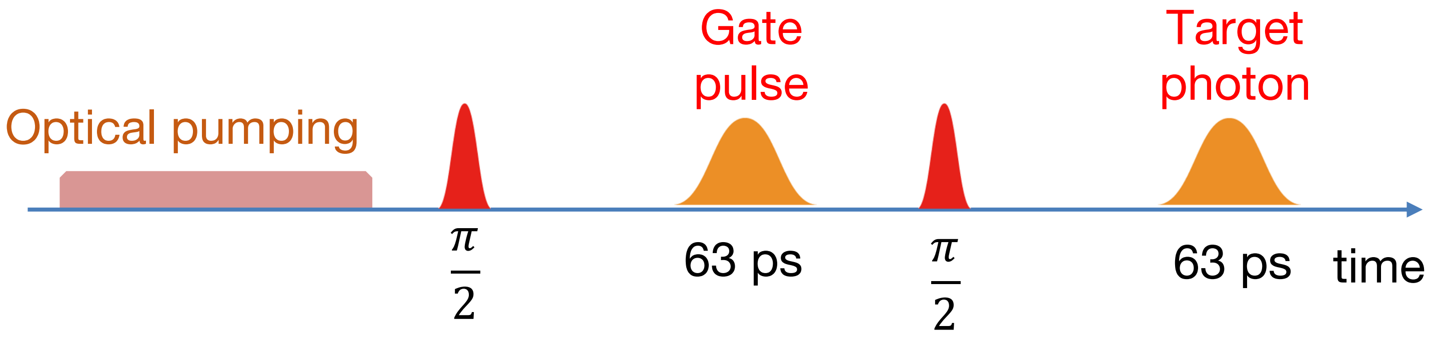
Time

Conditioned on probe photon



Sun et al., *Nature Nanotechnology* **11** 539 (2016)

A single photon controls a single photon



Optical pumping

$\frac{\pi}{2}$

Gate pulse

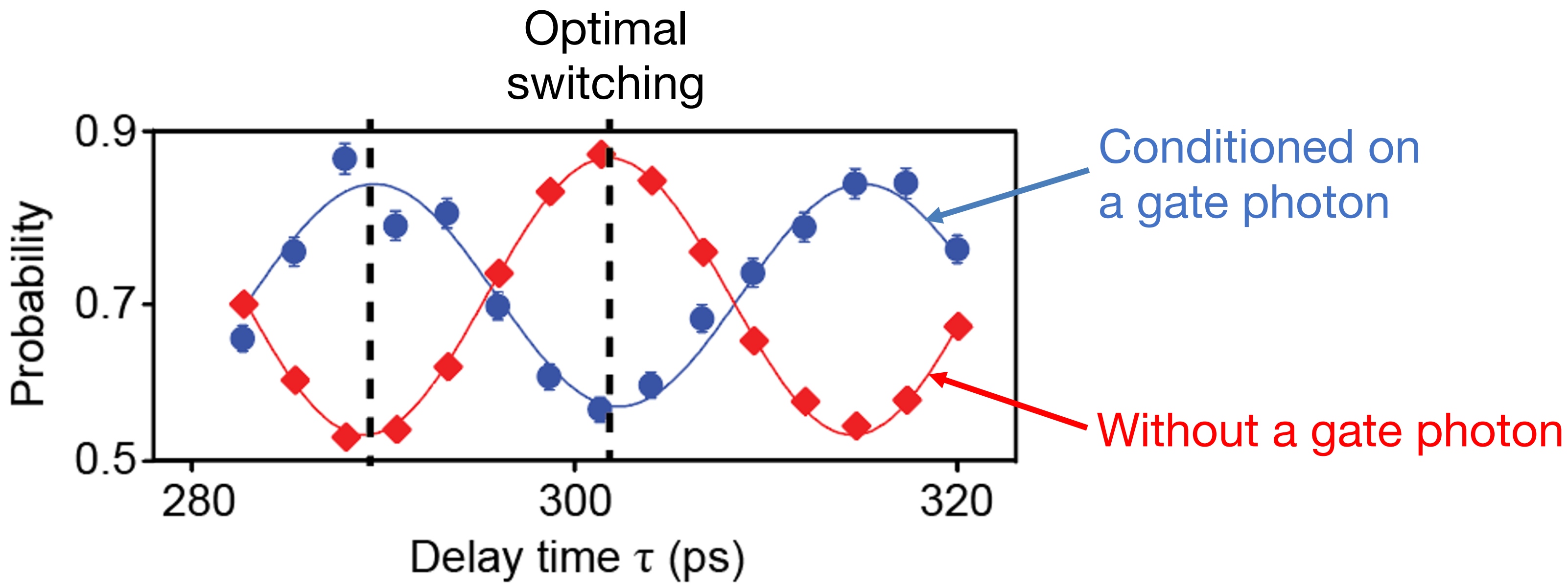
63 ps

$\frac{\pi}{2}$

Target photon

63 ps

time



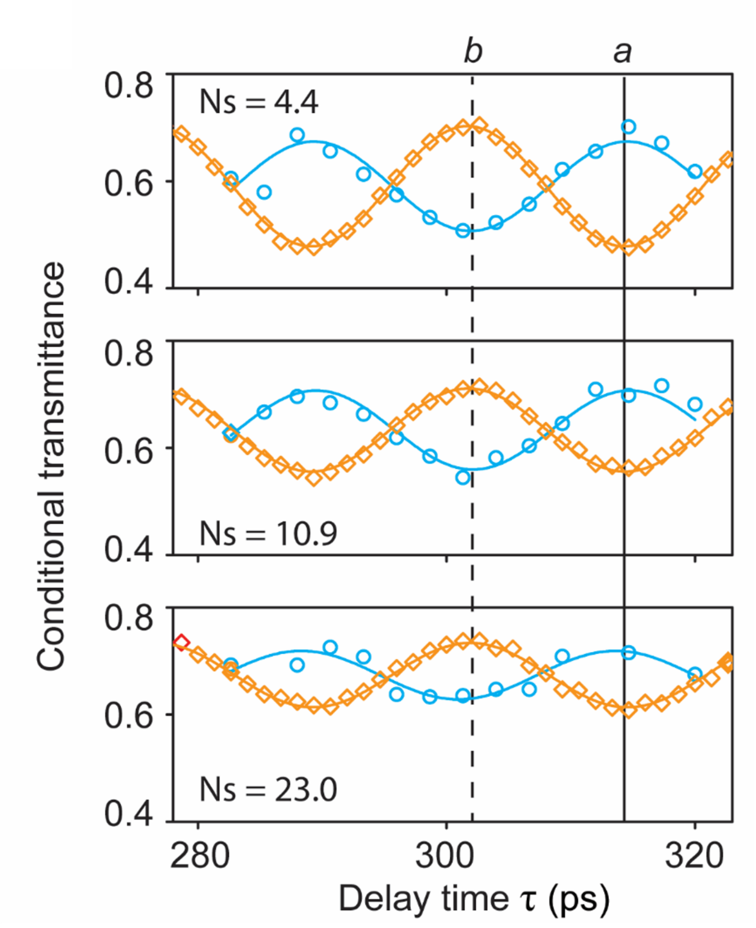
Optimal switching

Conditioned on a gate photon

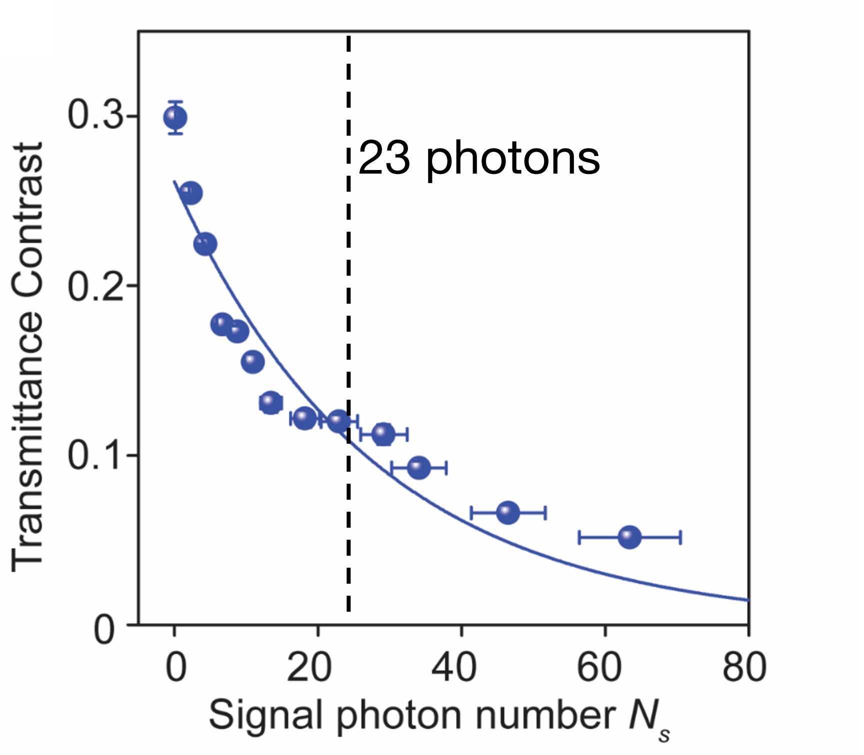
Without a gate photon

Sun et al., *Science* 361, 57 (2018)

A single photon controls many photons



Single photon transistor

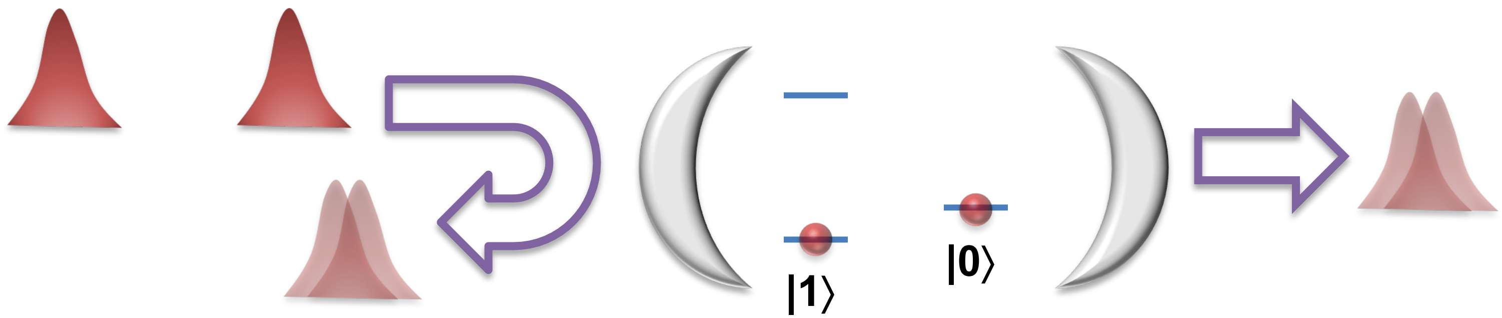


Sun et al., *Science* 361, 57 (2018)

Applications of quantum photonic circuits

Atoms mediate strong photon-photon interactions

Example: A deterministic photon entangler



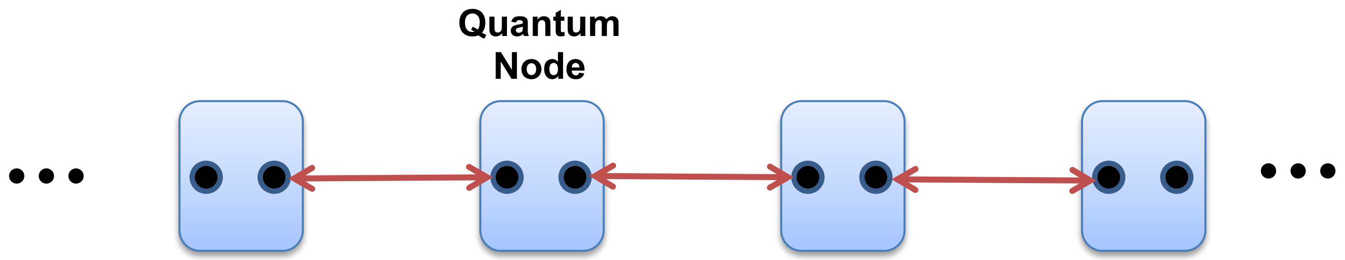
Entangled state: $\left|RR\right\rangle + \left|LL\right\rangle$

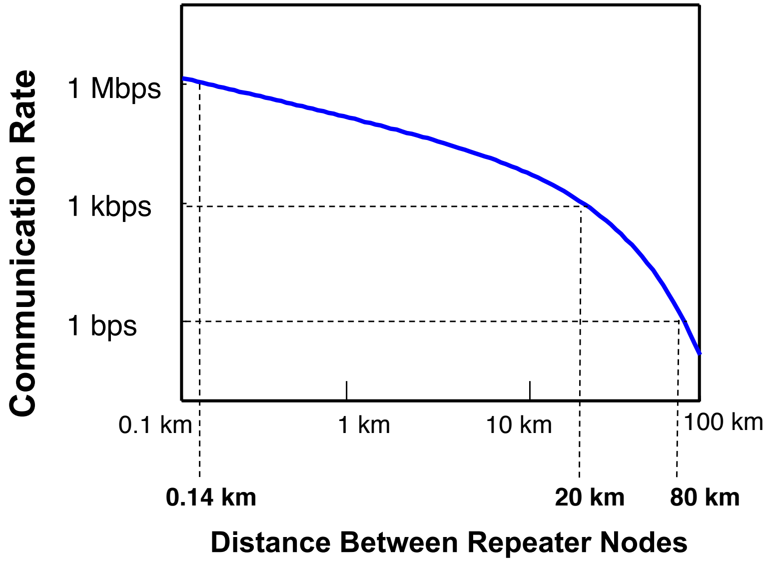
Scalable to many photons: $\left|RR\cdots R\right\rangle + \left|LL\cdots L\right\rangle$

Photonic cluster states:

Lindner and Rudolph, *Phys. Rev. Lett*. **103**, 113602 (2009)
Schwartz et. al, *Science* **354**, 434 (2016)
Pichler et al., PNAS **114**, 11362 (2017)

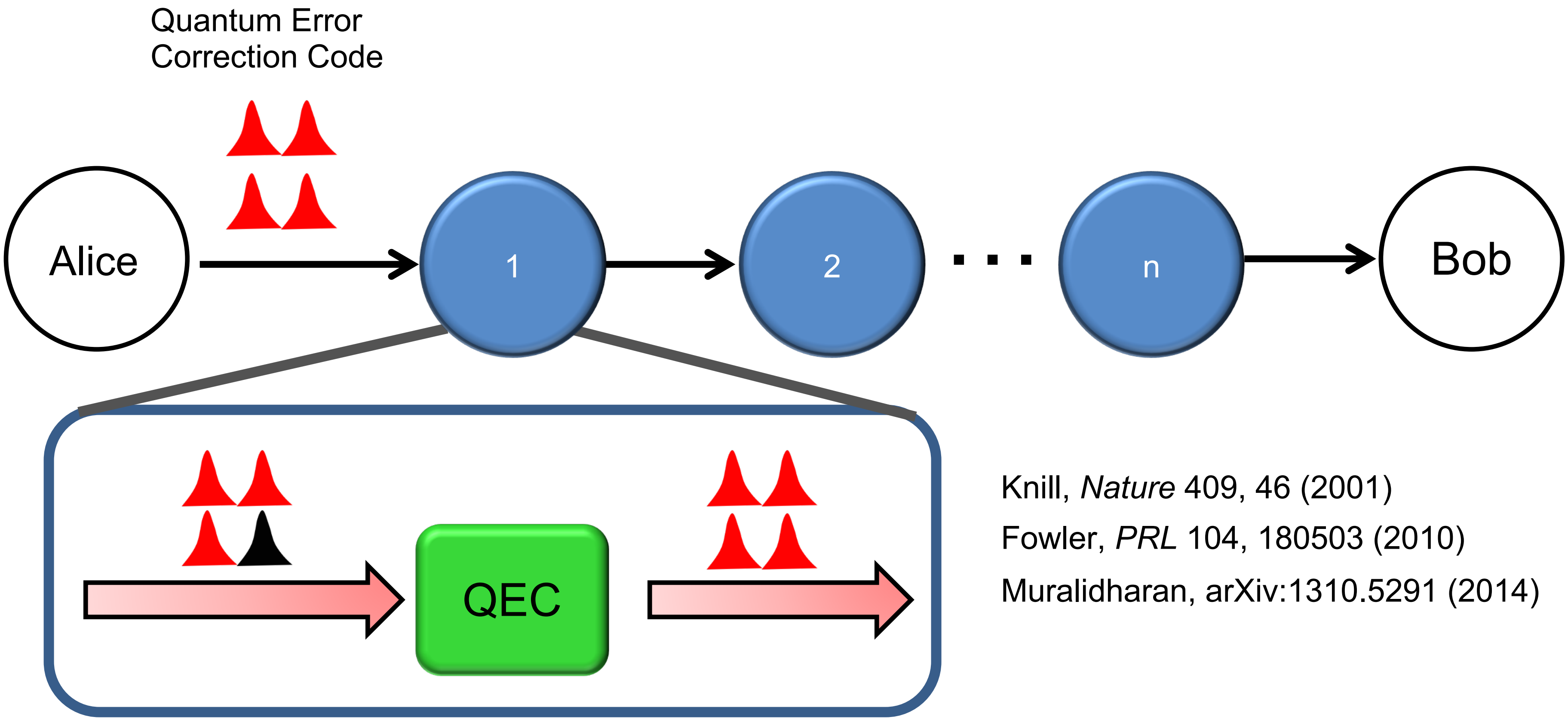
Memory-based quantum networks are slow





Munro *et al.*, *Nature Photonics* **6**, 777 (2012)

Quantum error correction eliminates latency

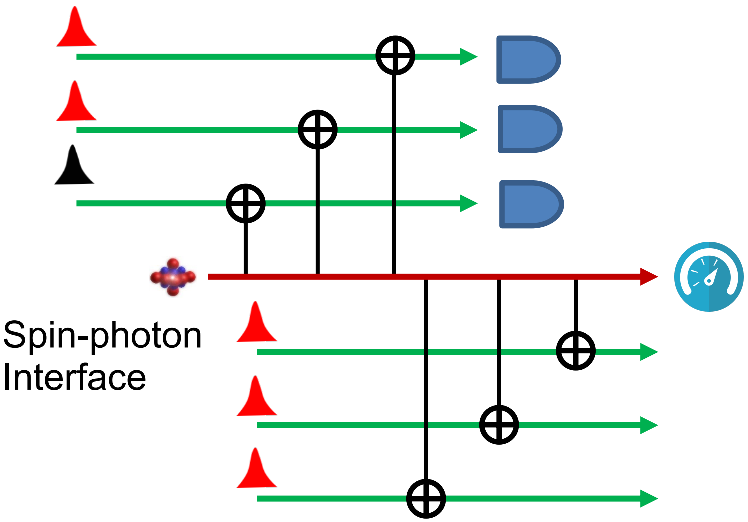


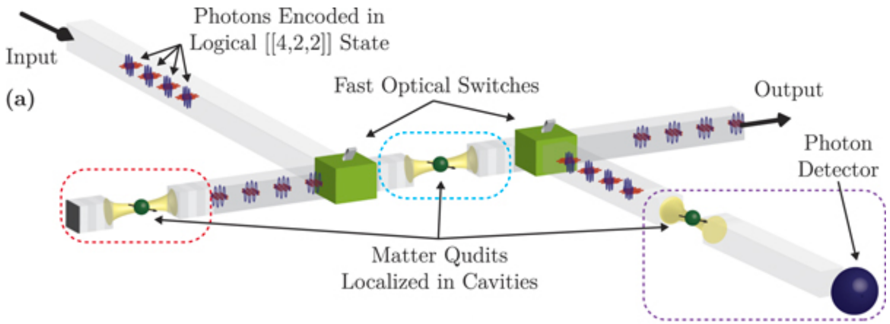
Knill, *Nature* 409, 46 (2001)

Fowler, *PRL* 104, 180503 (2010)

Muralidharan, arXiv:1310.5291 (2014)

A single spin qubit can implement error correction

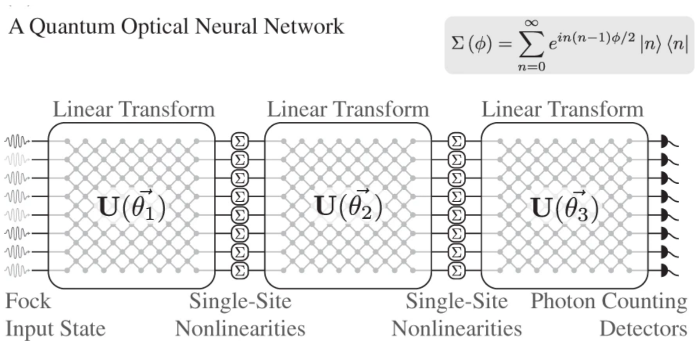




Glaudell, Waks, and Taylor, New J. Phys. 18 093008 (2016)

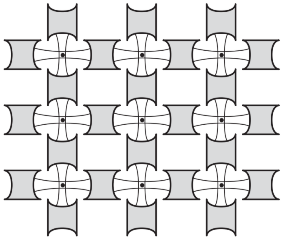
Single-photon nonlinearity opens an unexplored regime of photonics

Quantum Machine learning



Steinbrecher et al, *npj Quantum Information* **5**, 60 (2019)

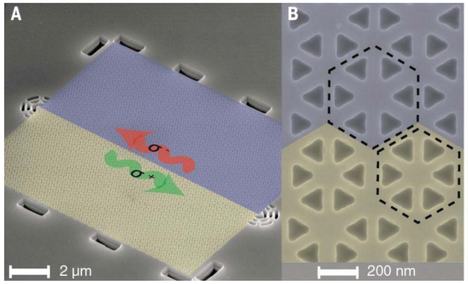
Quantum Simulations



Cho et al.,PRL 101, 246809 (2008)

Hafezi et al., NJP 15 (2013) 063001

Topological photonics



Barik et al., Science 359, 666 (2018)

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Mark Morris
Gerald Baumgartner

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