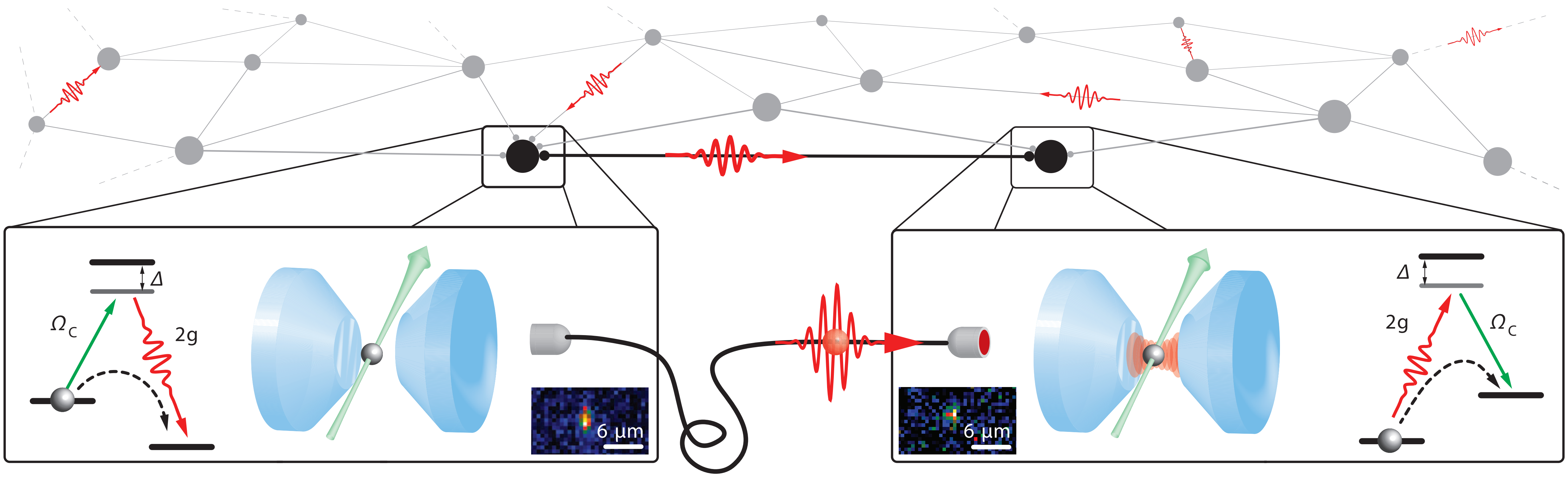


Ritter et al., *Nature* 484, 195 (2012)

Trapped Ions/Atoms: Quantum Networks

Christian Vázquez, David Nadlinger

This Talk

- Quantum Networks: Why? How?
- Two Entanglement Generation Experiments:
  Moehring et al., “Entanglement of single-atom quantum bits at a distance”, *Nature* 449, 68 (2007)

  Ritter et al., “An elementary quantum network of single atoms in optical cavities”, *Nature* 484, 195 (2012)
- Results/Comparison
- Perspectives

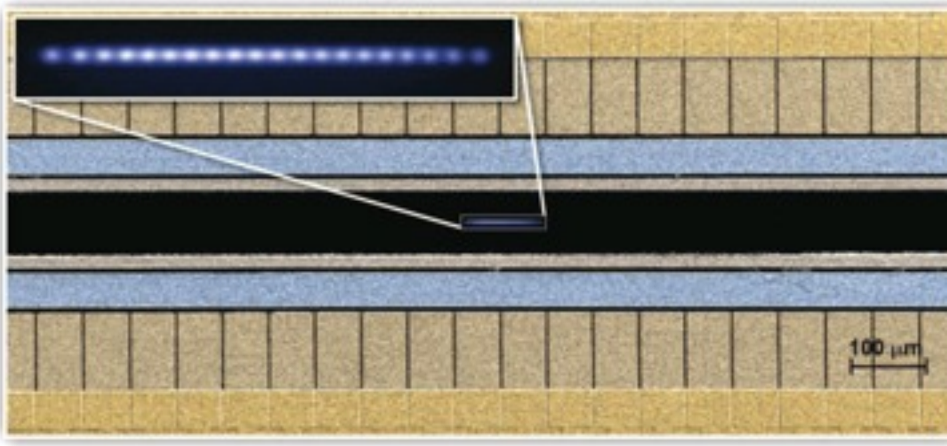
Why Quantum Networks?

Large number of ions in one trap is not feasible:

- 1D string -> requirements on trap potential
- Heating rate increases linearly
- Mechanical mode density increases

State of the art: ~15 qubits

- Entanglement of 14 ions
  Monz et al., *Phys. Rev. Lett.* 106, 130506 (2011)
- Simulations using long chains (~20 ions)

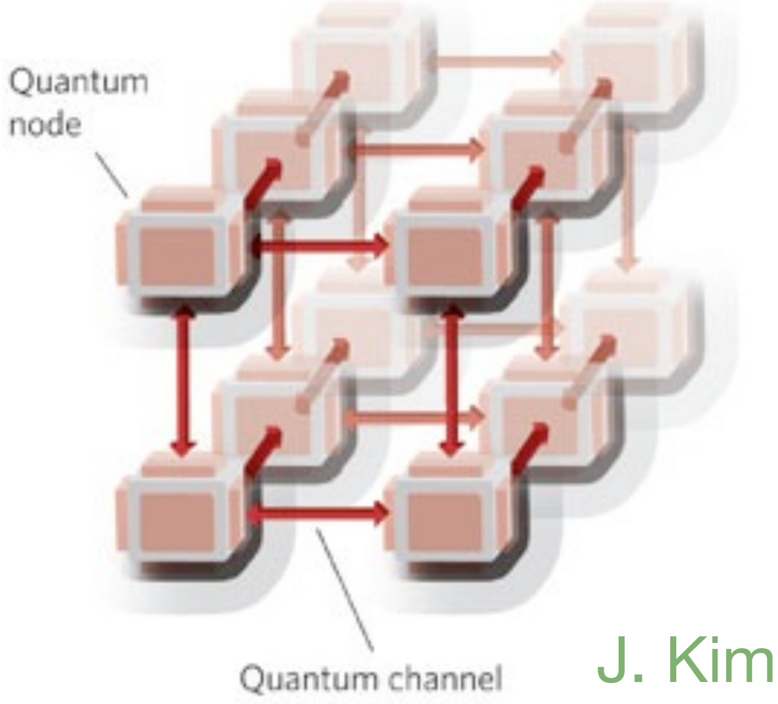


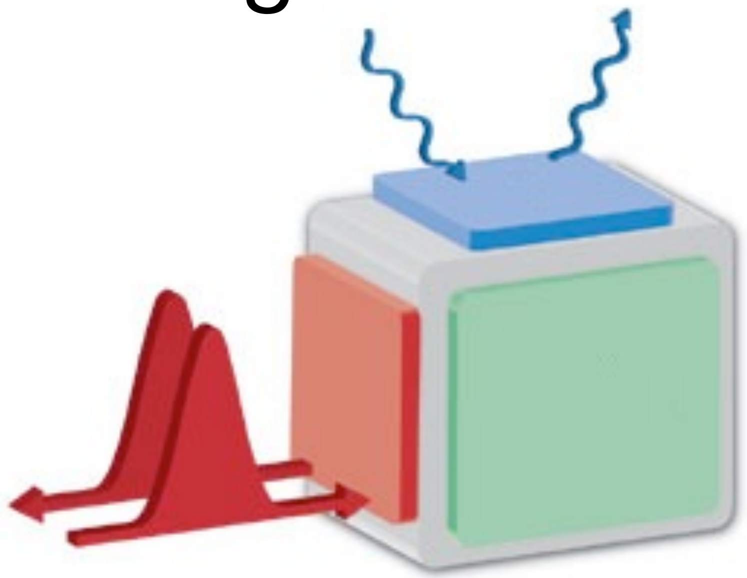
C. Monroe and J. Kim, *Science* 339, 1164 (2013)

Why Quantum Networks?

k systems of *n* qubits:

- With classical links: d = $k2^n$ (dim. of state space)
  With quantum links: d = 2^{nk}
- Multiple qubit entanglement
  -> State transfer, information sharing





J. Kimble, *Nature* 453, 1023 (2008)

Requirements for Quantum Networks

We infer the following requirements.

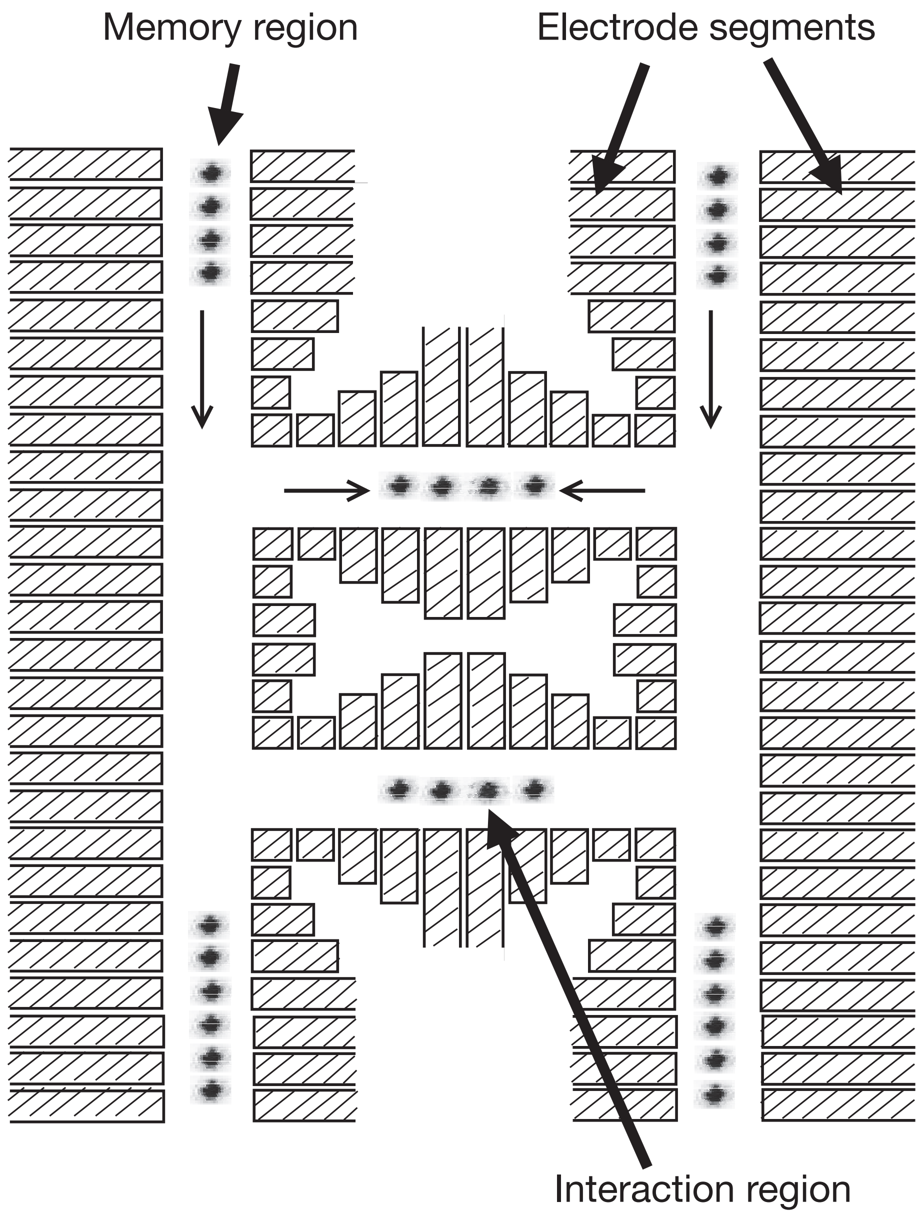
For Nodes:

- Receiving, storing, releasing quantum information

For Channels:

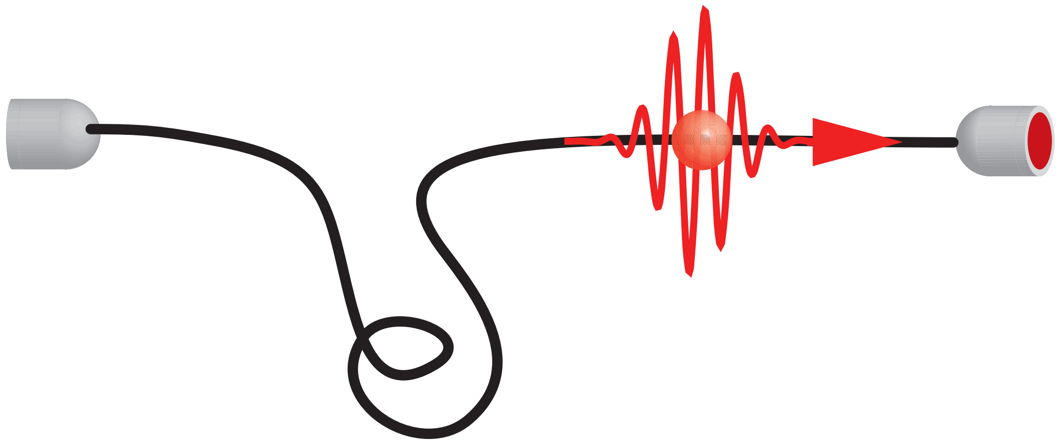
- Faithfully transmit quantum state between nodes

Linking Ion Traps



“Quantum CCD”

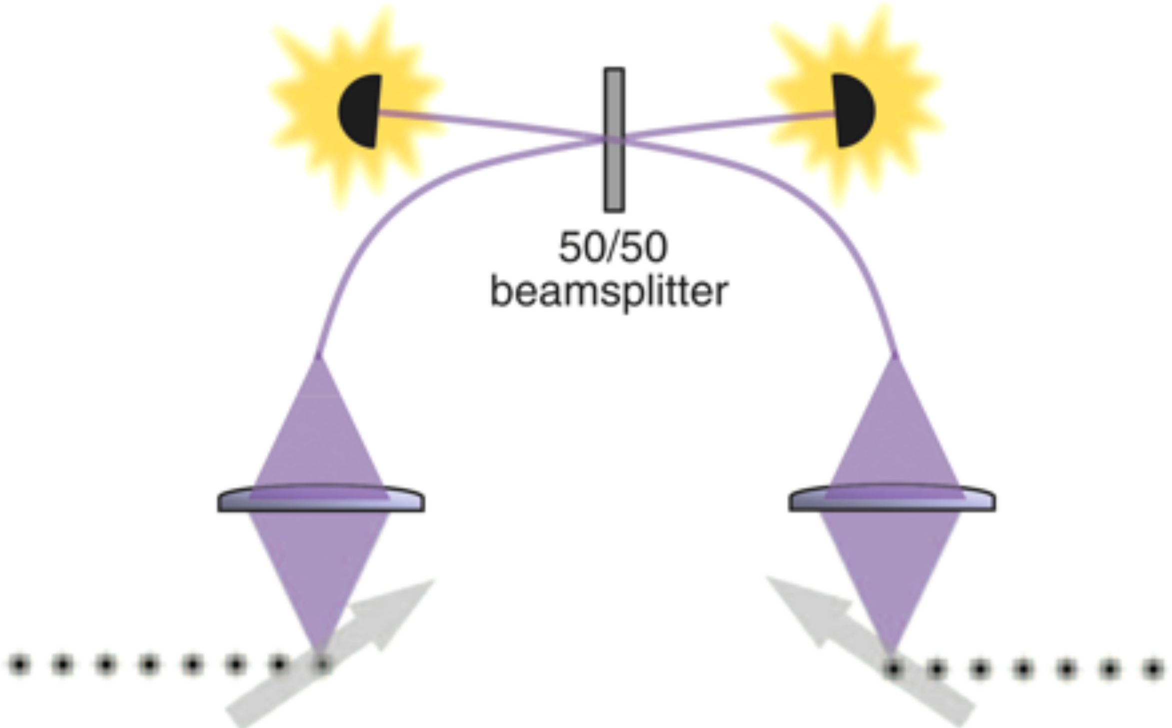
Kiepinski, Monroe, Wineland, *Nature* 417, 709 (2002)



Photons

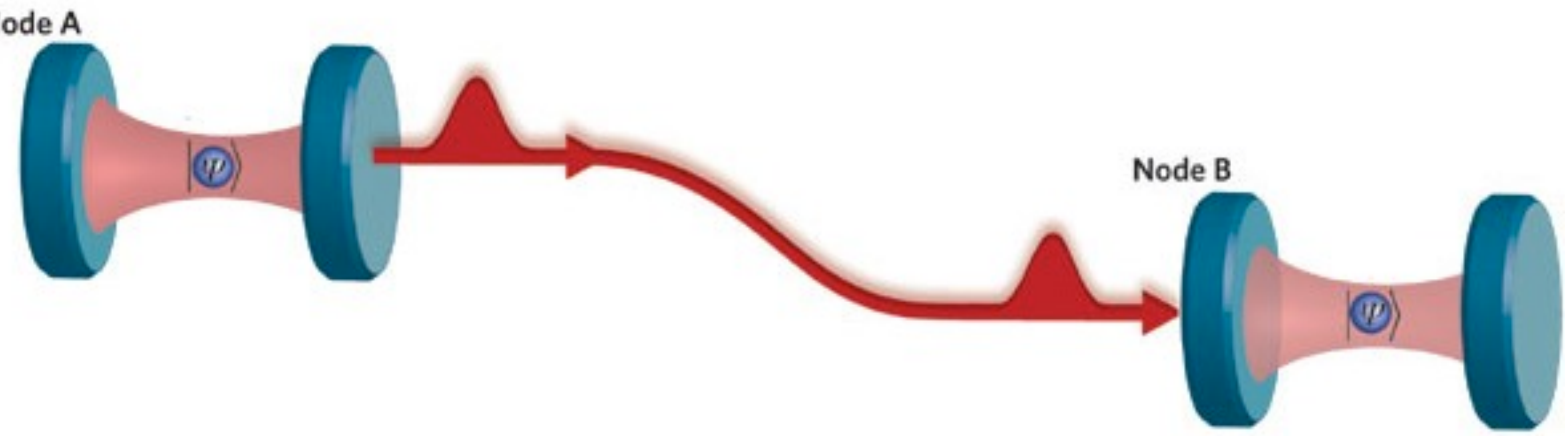
Entangling Atoms using Photons

Heralded entanglement gen. using beamsplitter: Moehring et al. (2007)



C. Monroe and J. Kim, *Science* 339, 1164 (2013)

Cavity QED:
Ritter et al. (2012)



H. Kimble, *Nature* 453, 1023 (2008)

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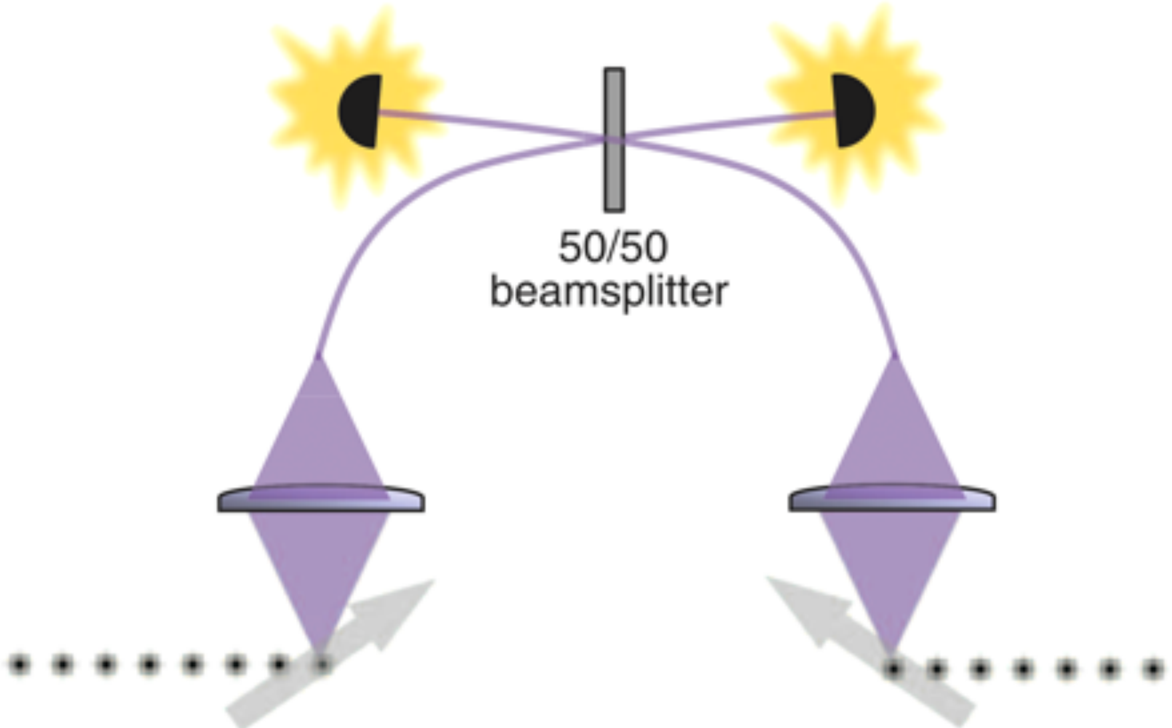

C. Monroe and J. Kim, *Science* 339, 1164 (2013)

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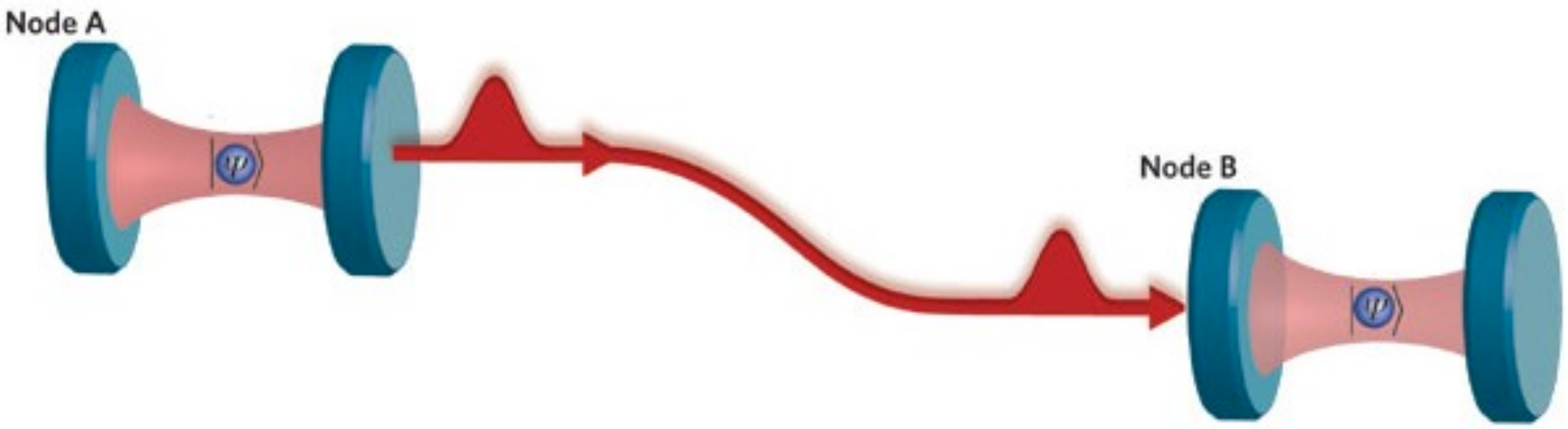
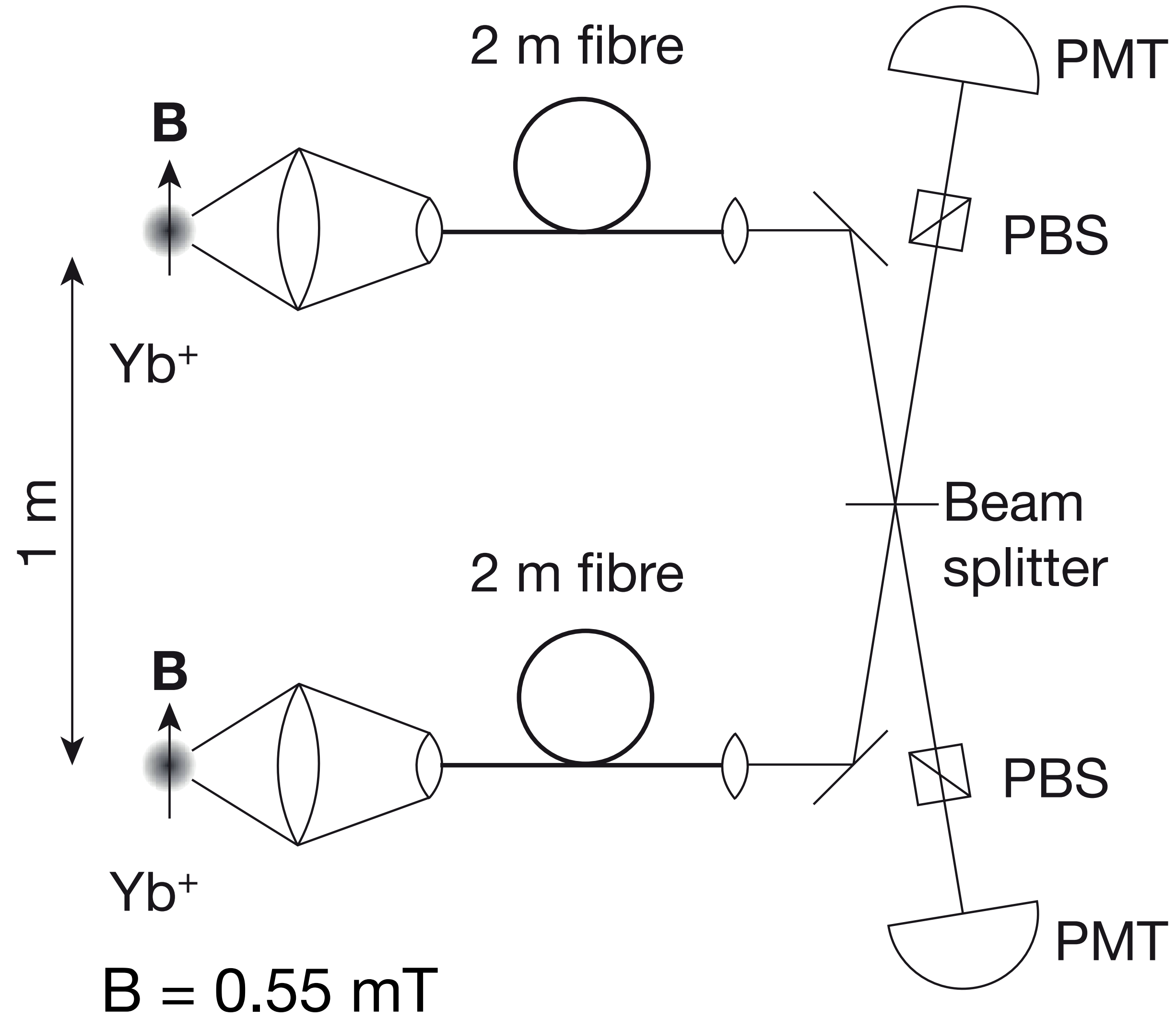
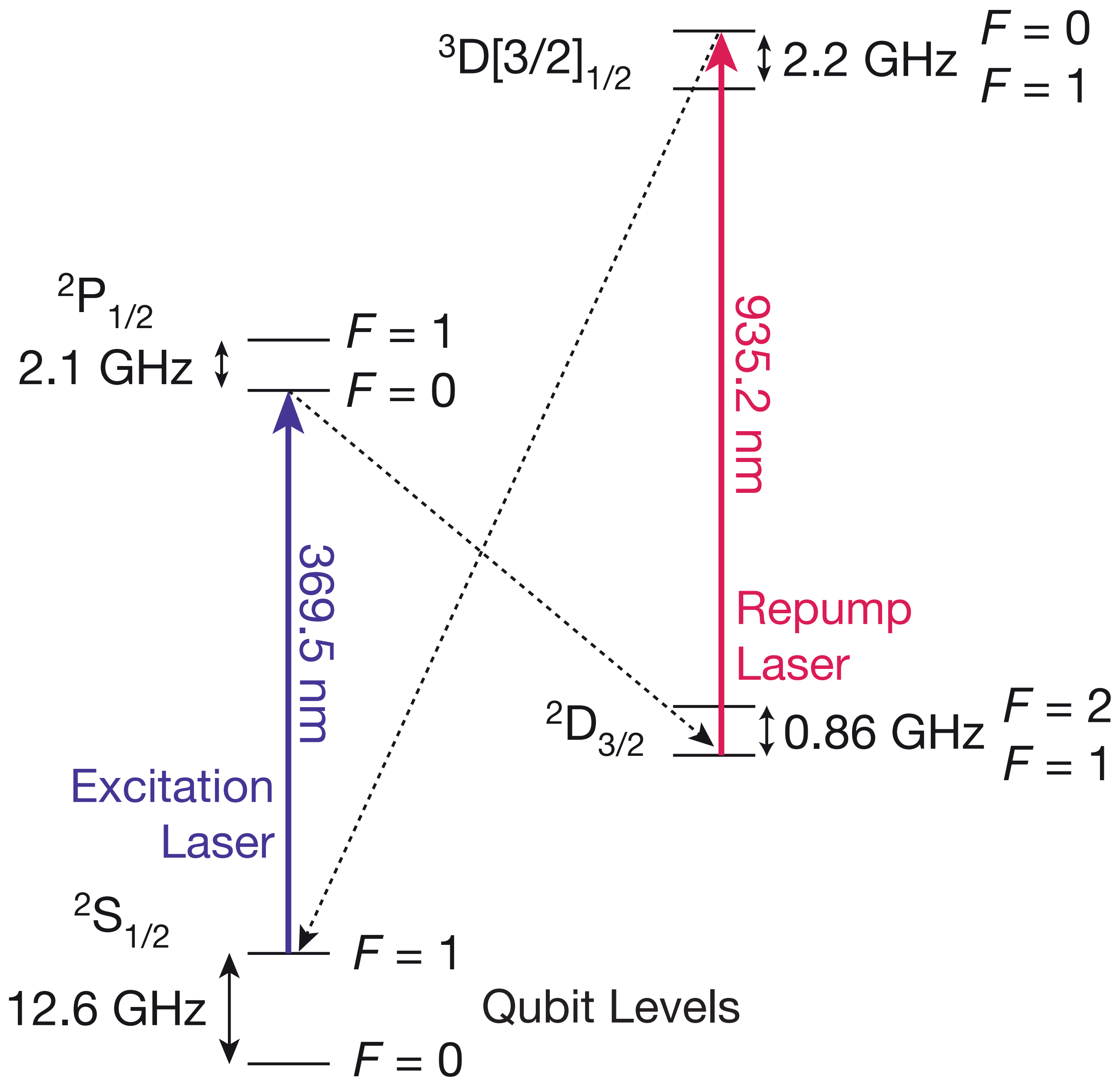
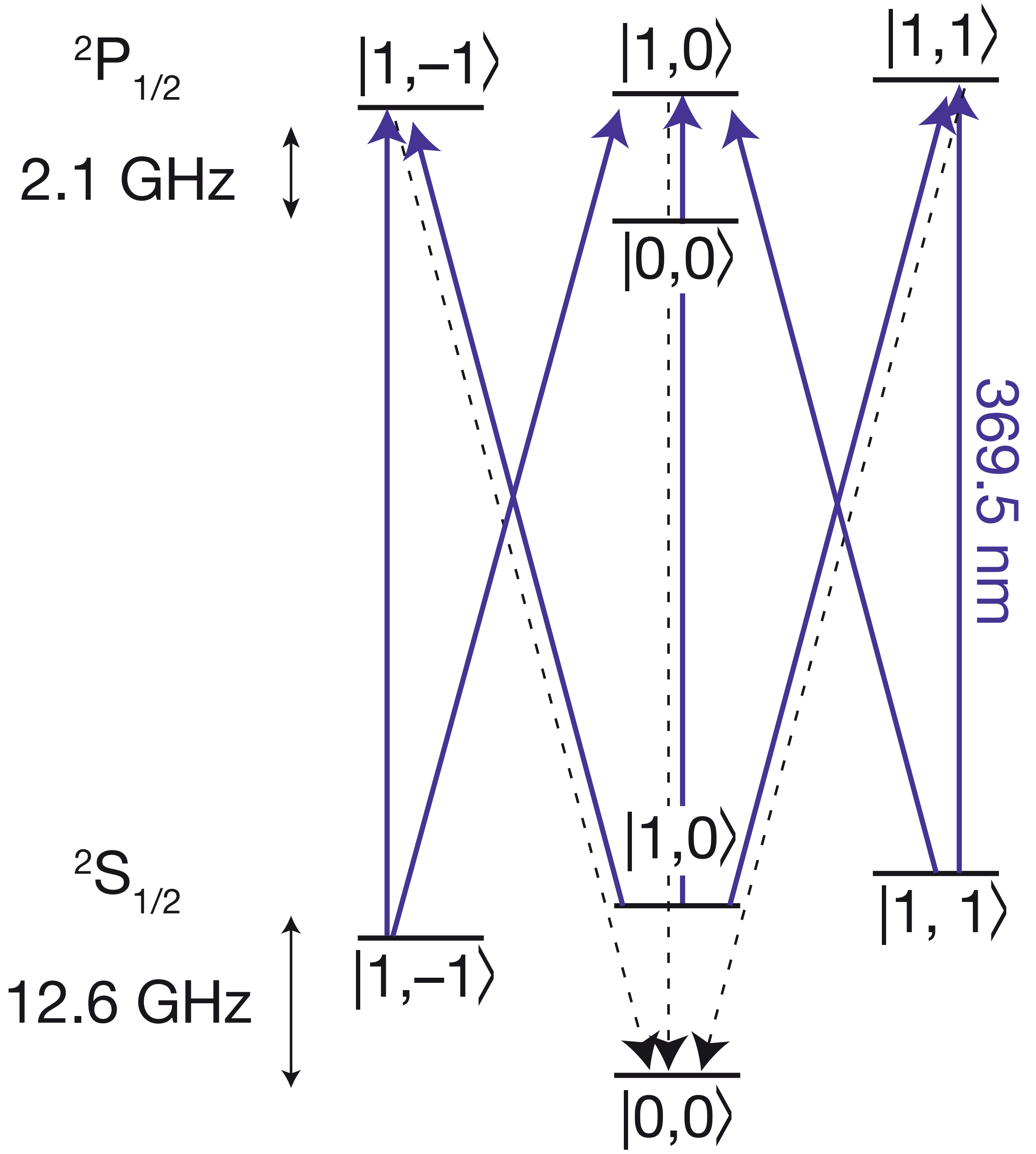


H. Kimble, *Nature* 453, 1023 (2008)

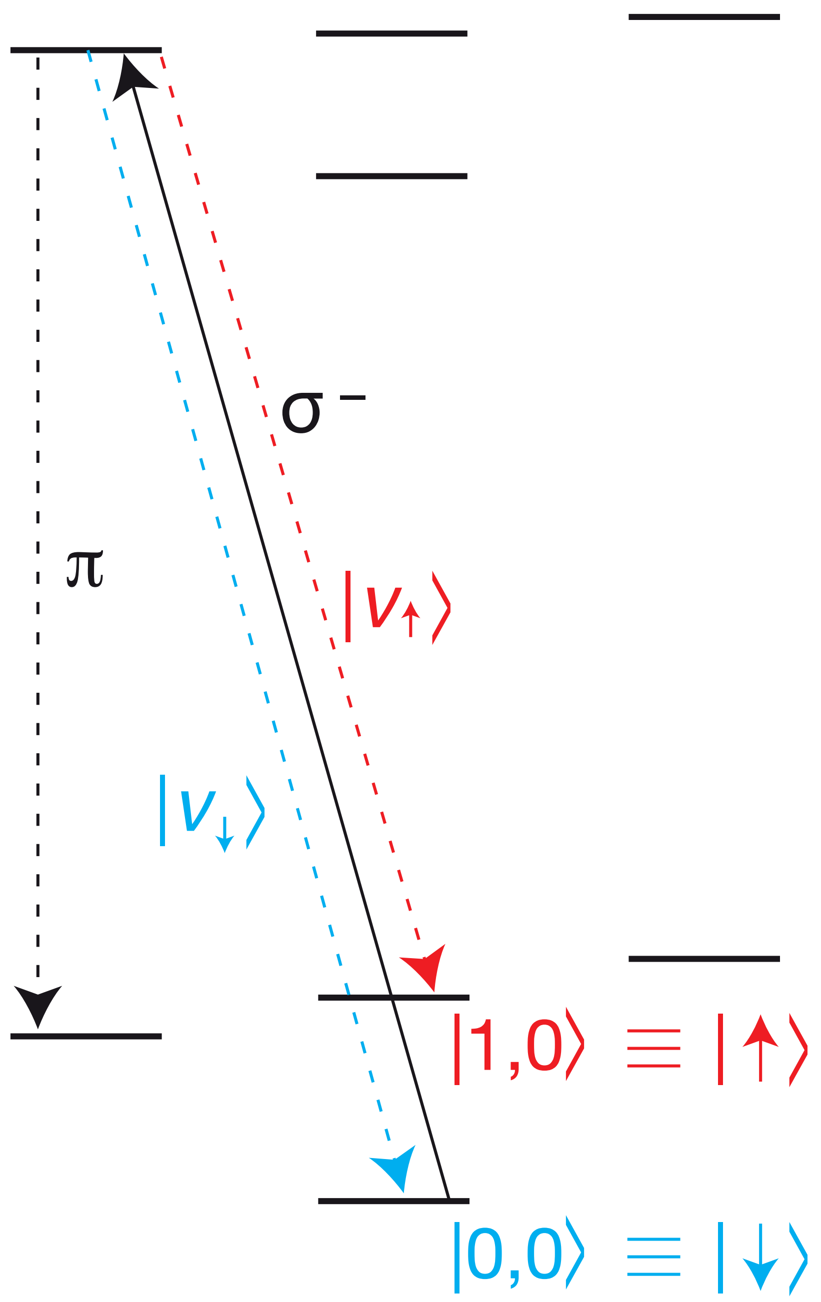
Moehring (2007): Exp. Setup





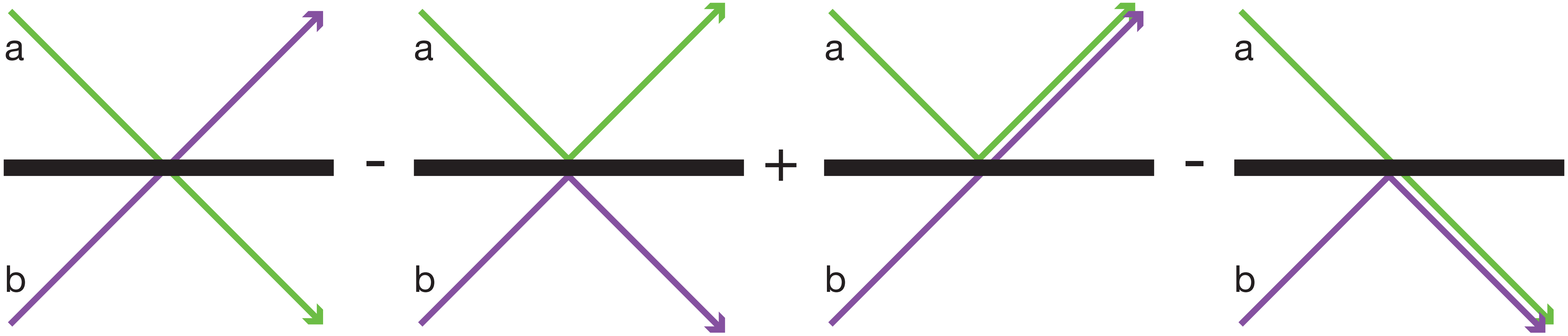


Initialization:
Pump $^2S_{1/2}|F=1\rangle \leftrightarrow {}^2P_{1/2}|F=1\rangle$



Discard π photons:
$(|\uparrow\rangle|\nu_\uparrow\rangle - |\downarrow\rangle|\nu_\downarrow\rangle)/\sqrt{2}$

50/50 (non-polarizing) beam splitter:



Consider input state $\frac{1}{2}\left[\left(\overset{\text{atom}}{|\uparrow\rangle_a}\,\overset{\text{photon}}{|\nu_\uparrow\rangle_a} - |\downarrow\rangle_a\,|\nu_\downarrow\rangle_a\right) \otimes \left(|\uparrow\rangle_b\,|\nu_\uparrow\rangle_b - |\downarrow\rangle_b\,|\nu_\downarrow\rangle_b\right)\right] =$

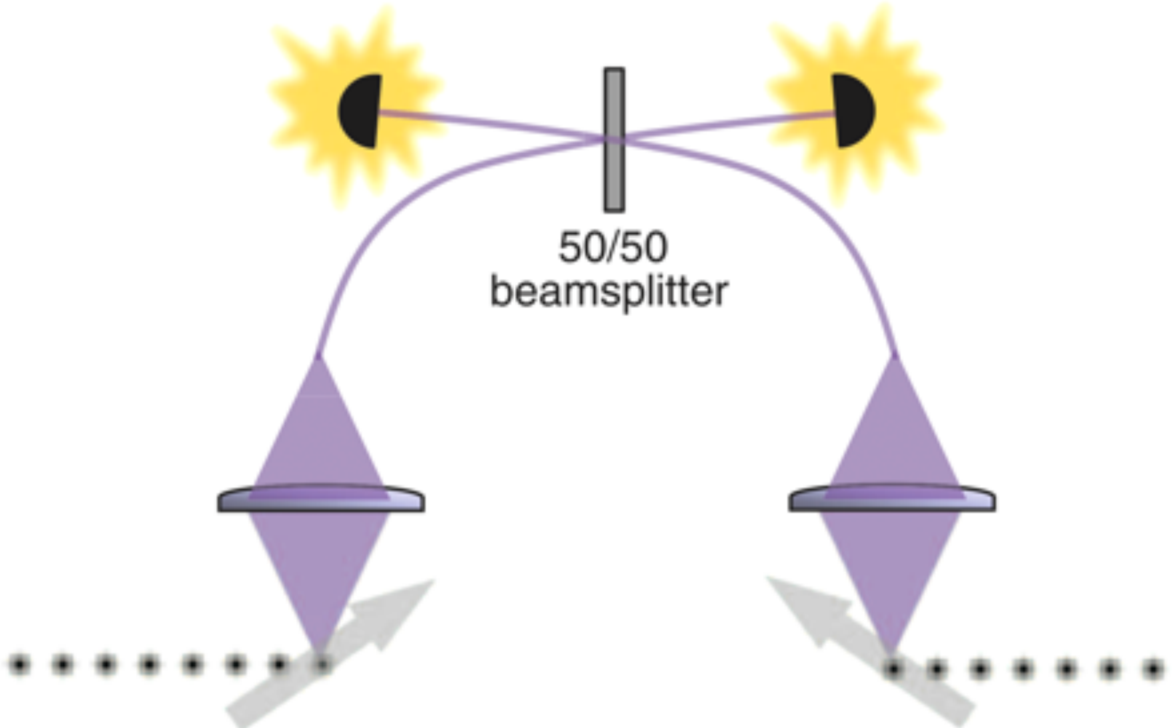
$$\frac{1}{2}\Big(\underbrace{|\Phi^+\rangle_{\text{atom}}\,|\Phi^+\rangle_{\text{photon}}}_{\text{symmetric}} + \underbrace{|\Phi^-\rangle_{\text{atom}}\,|\Phi^-\rangle_{\text{photon}}}_{\text{symmetric}} - \underbrace{|\Psi^+\rangle_{\text{atom}}\,|\Psi^+\rangle_{\text{photon}}}_{\text{symmetric}} - \boxed{\underbrace{|\Psi^-\rangle_{\text{atom}}\,|\Psi^-\rangle_{\text{photon}}}_{\text{antisymmetric}}}\Big)$$

where $\left|\Phi^\pm_{\text{photon}}\right\rangle = \frac{1}{\sqrt{2}}\left(|\nu_\uparrow\rangle_a\,|\nu_\uparrow\rangle_b \pm |\nu_\downarrow\rangle_a\,|\nu_\downarrow\rangle_b\right)$ $\quad\left|\Psi^\pm_{\text{photon}}\right\rangle = \frac{1}{\sqrt{2}}\left(|\nu_\uparrow\rangle_a\,|\nu_\downarrow\rangle_b \pm |\nu_\downarrow\rangle_a\,|\nu_\uparrow\rangle_b\right)$

Detecting 2 coincident photons projects atoms into $|\Psi^-\rangle_{\text{atom}}$,
coincident photons “herald” entanglement creation!

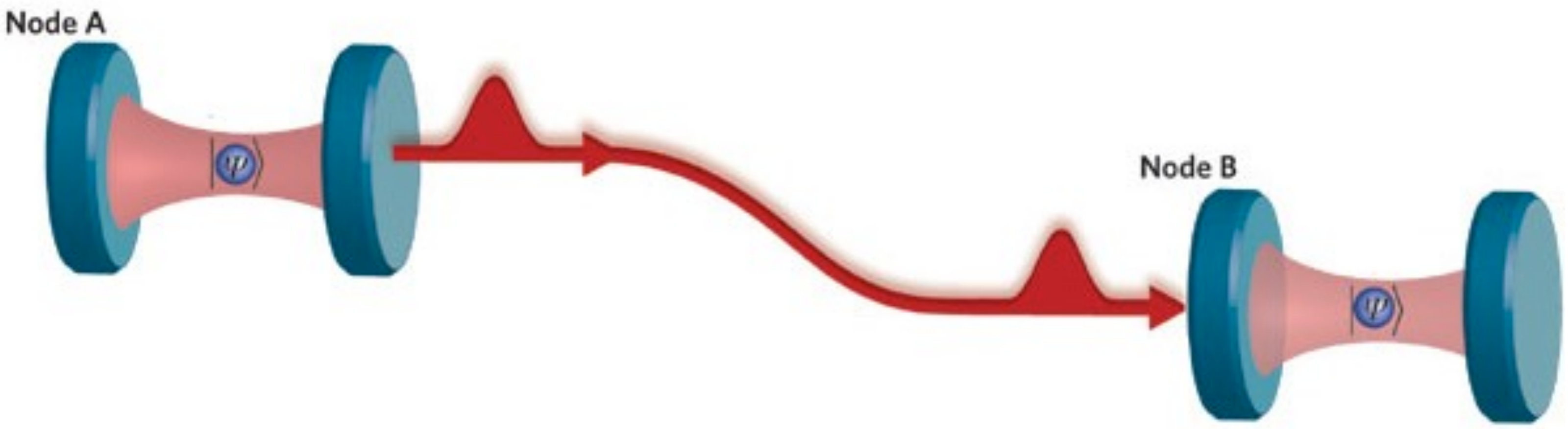
Entangling Atoms using Photons

Heralded entanglement gen. using beamsplitter: Moehring et al. (2007)



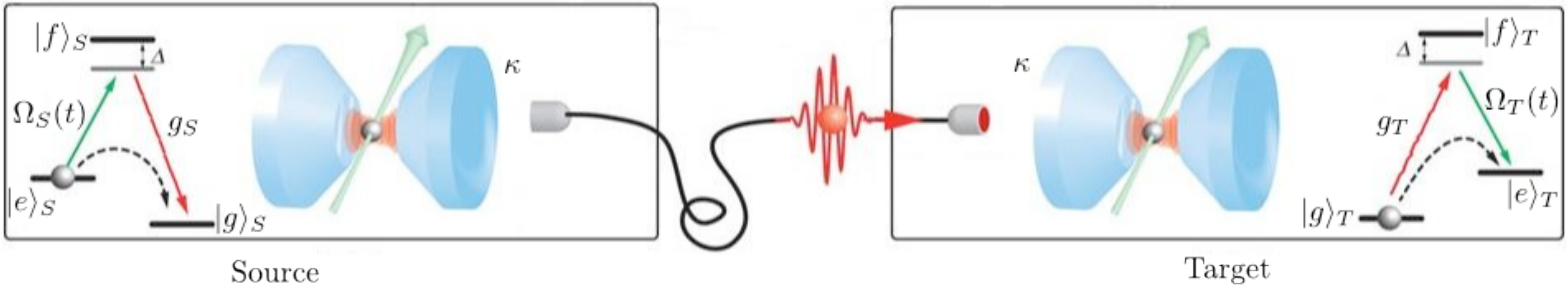
C. Monroe and J. Kim, *Science* 339, 1164 (2013)

Cavity QED:
Ritter et al. (2012)



H. Kimble, *Nature* 453, 1023 (2008)

State Transfer, Entangl. Creation

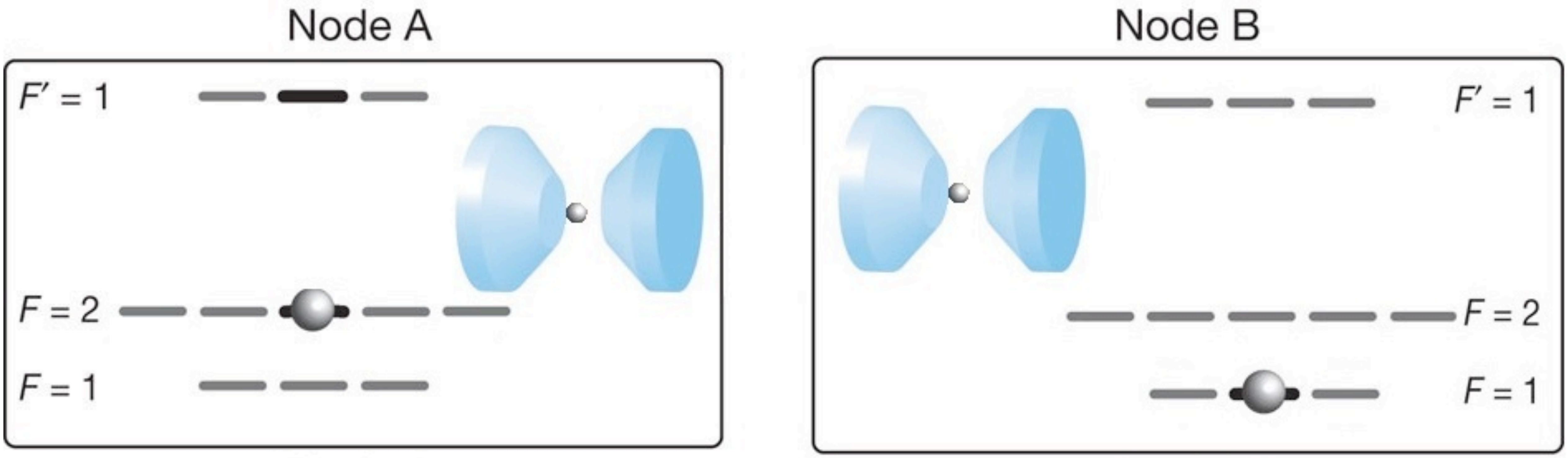


Ideal state transfer follows from adequate Raman pulses: photonic wave packet determined by $\Omega_i(t)$

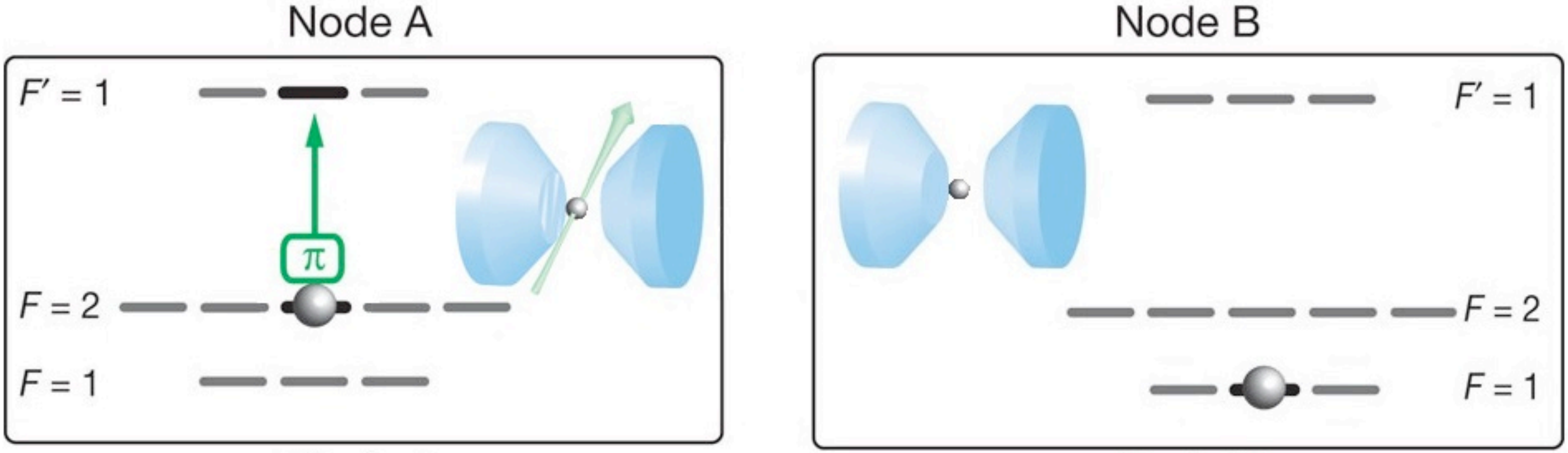
$$
\begin{aligned}
&(c_g|g\rangle_1 + c_e|e\rangle_1)\,|g\rangle_2 \otimes |0\rangle_1|0\rangle_2|\mathrm{vac}\rangle \\
&\qquad \to |g\rangle_1(c_g|g\rangle_2 + c_e|e\rangle_2) \otimes |0\rangle_1|0\rangle_2|\mathrm{vac}\rangle
\end{aligned}
$$

Cirac, Zøller, Kimble, Mabuchi, *Phys. Rev. Lett*. 78, 3221 (1997)

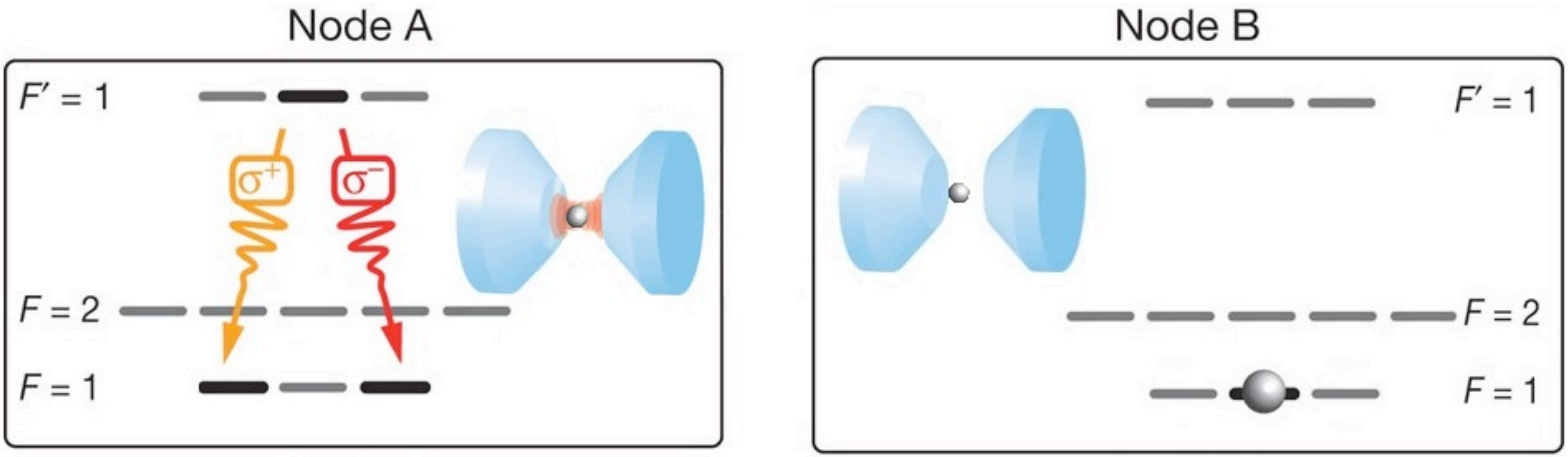
Ritter (2012): Entangl. Sequence



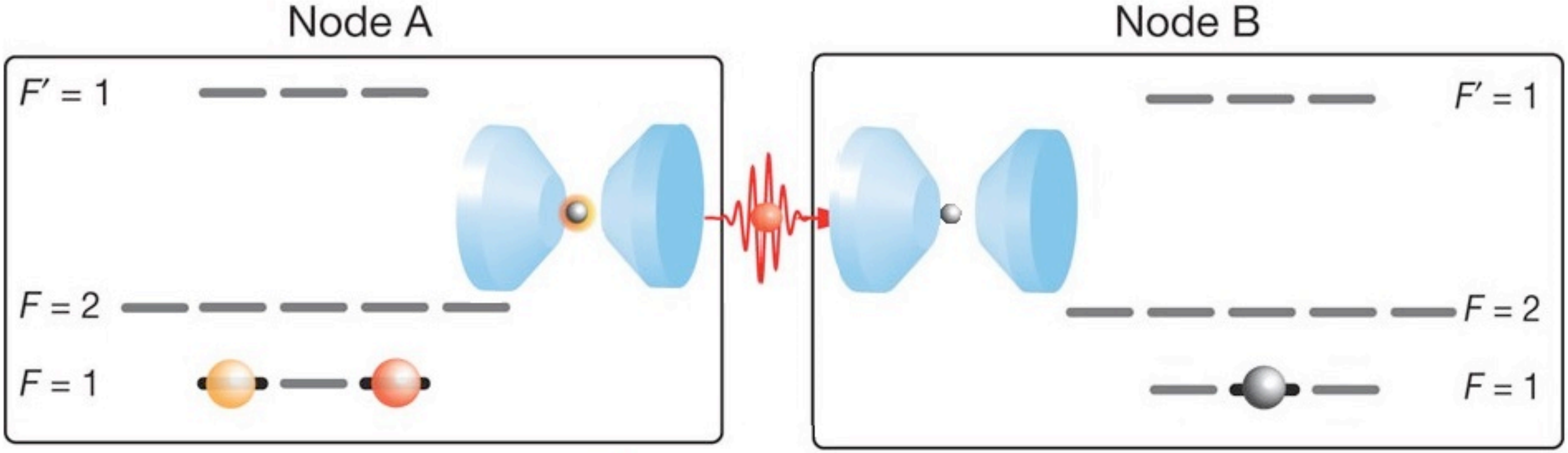
Ritter (2012): Entangl. Sequence



Ritter (2012): Entangl. Sequence

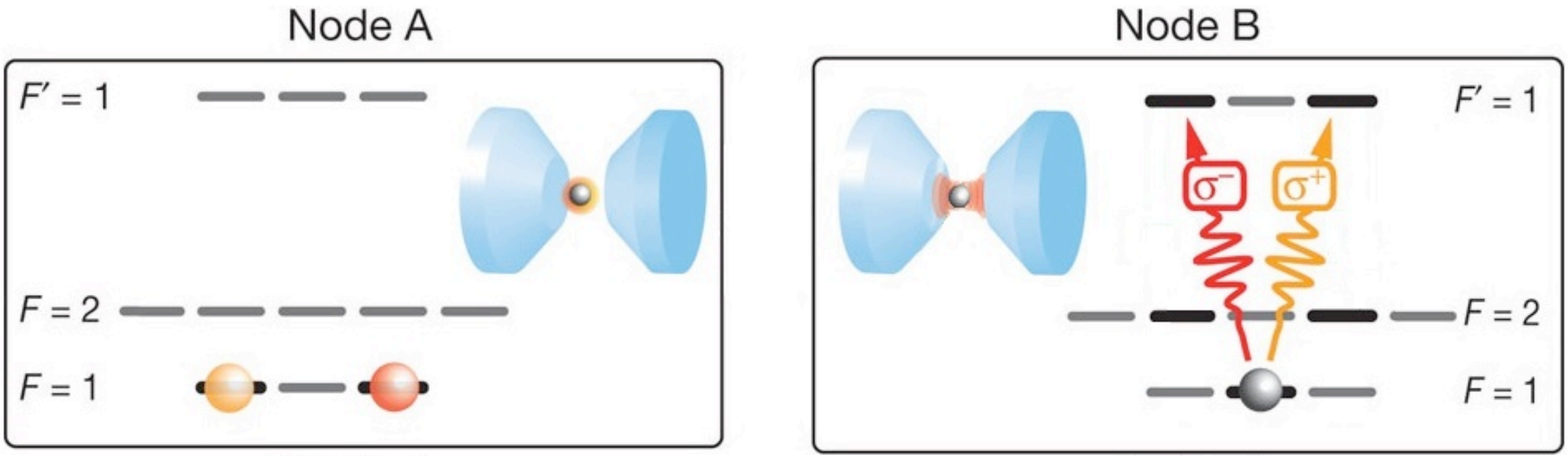


Ritter (2012): Entangl. Sequence

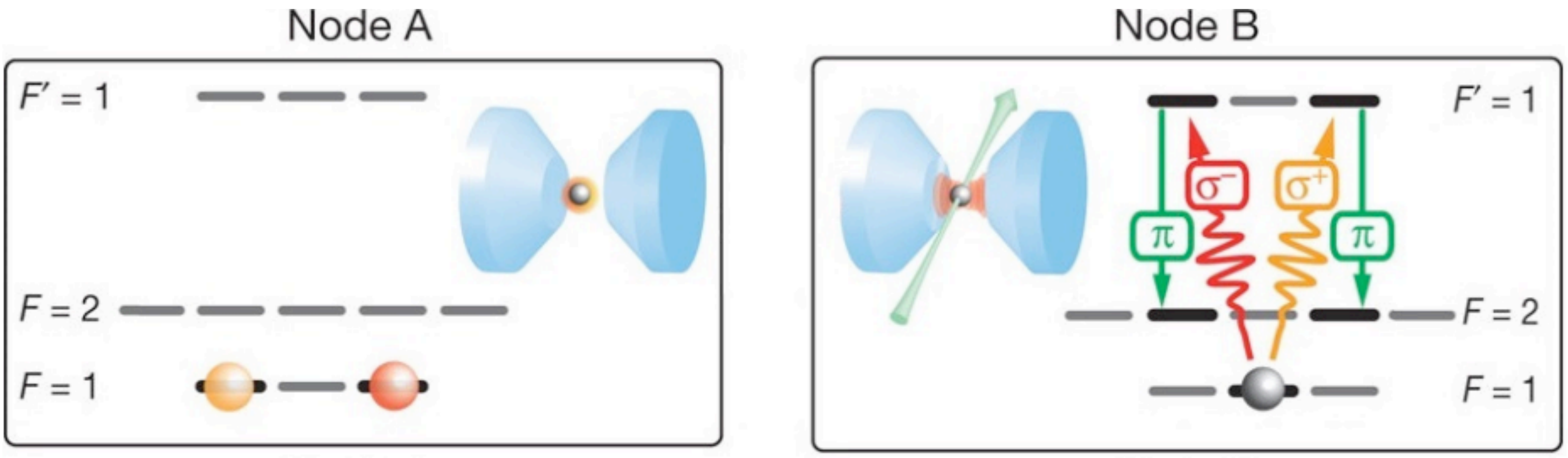


$$\left|\psi^{-}_{\mathrm{A}\otimes\mathrm{photon}}\right\rangle = \frac{1}{\sqrt{2}}\left(|1,-1\rangle\otimes|R\rangle - |1,1\rangle\otimes|L\rangle\right)$$

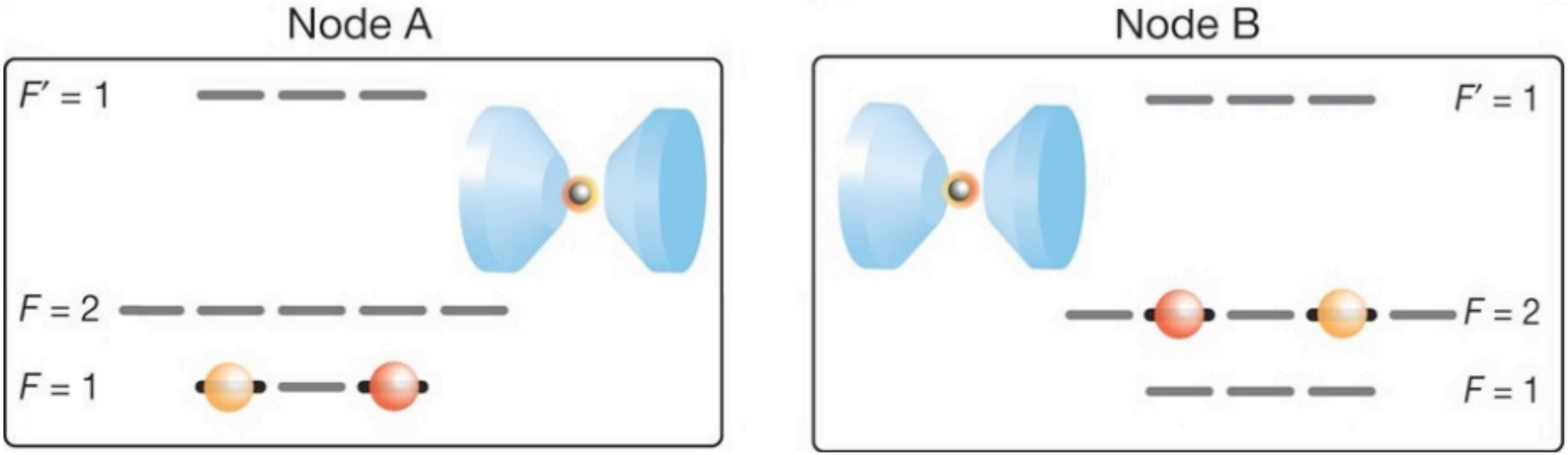
Ritter (2012): Entangl. Sequence



Ritter (2012): Entangl. Sequence



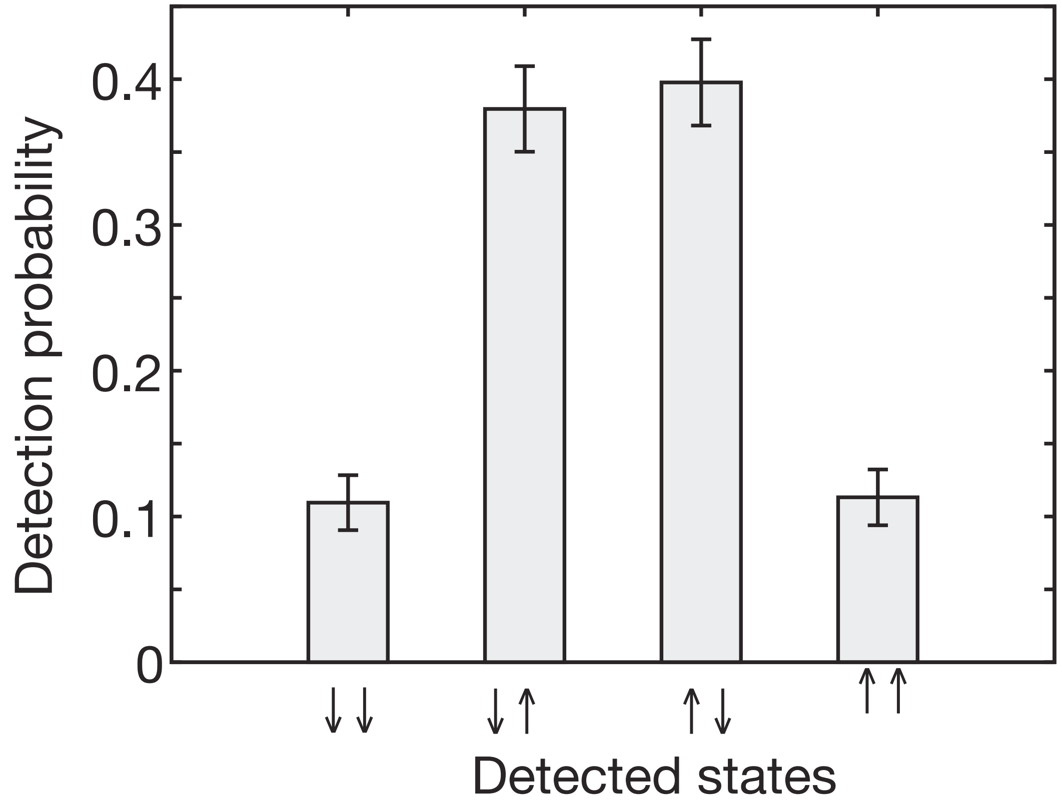
Ritter (2012): Entangl. Sequence

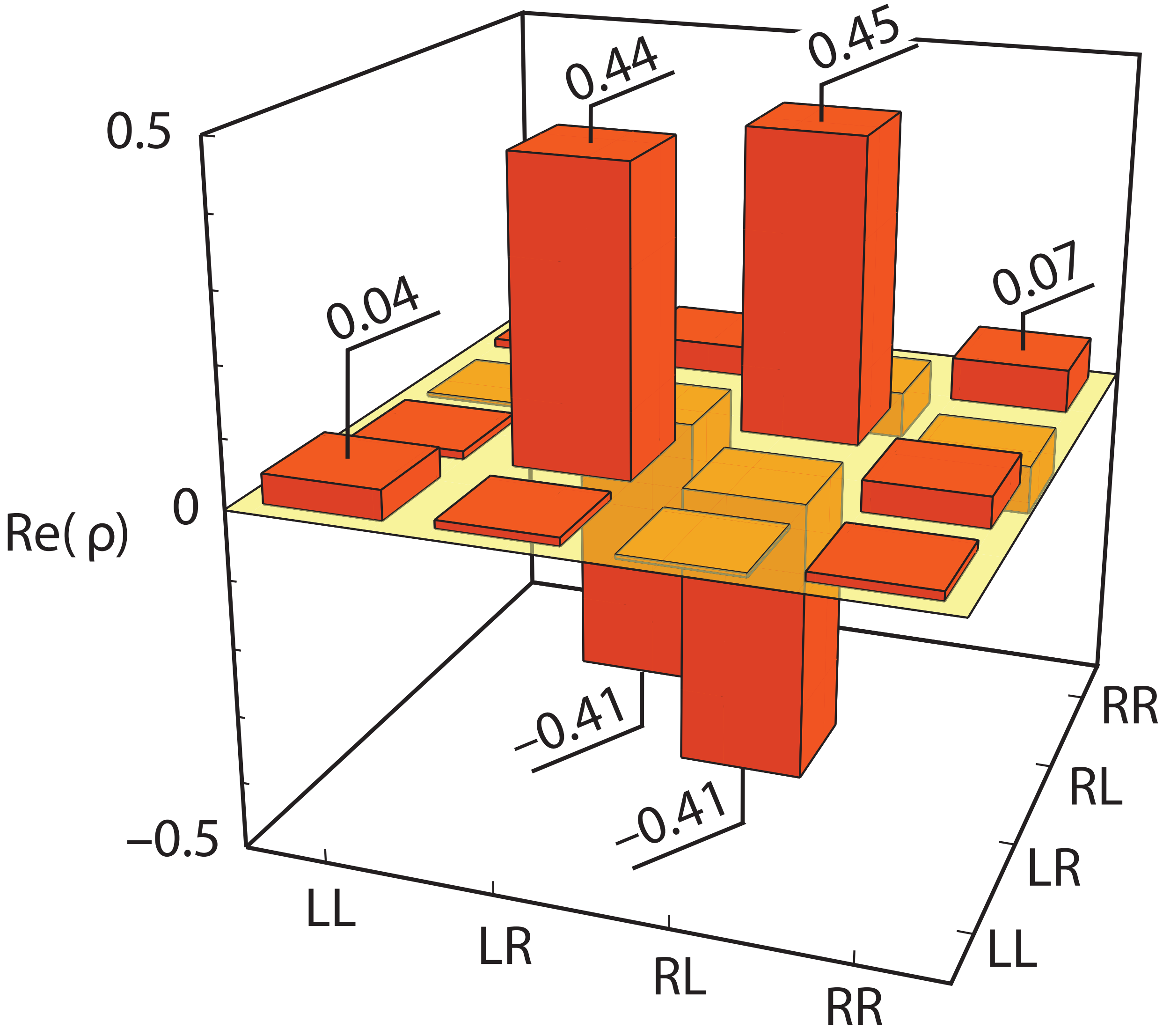


$$\left|\psi^{-}_{A\otimes B}\right\rangle = \frac{1}{\sqrt{2}}\left(|1,-1\rangle\otimes|2,1\rangle - |1,1\rangle\otimes|2,-1\rangle\right)$$

State Tomography

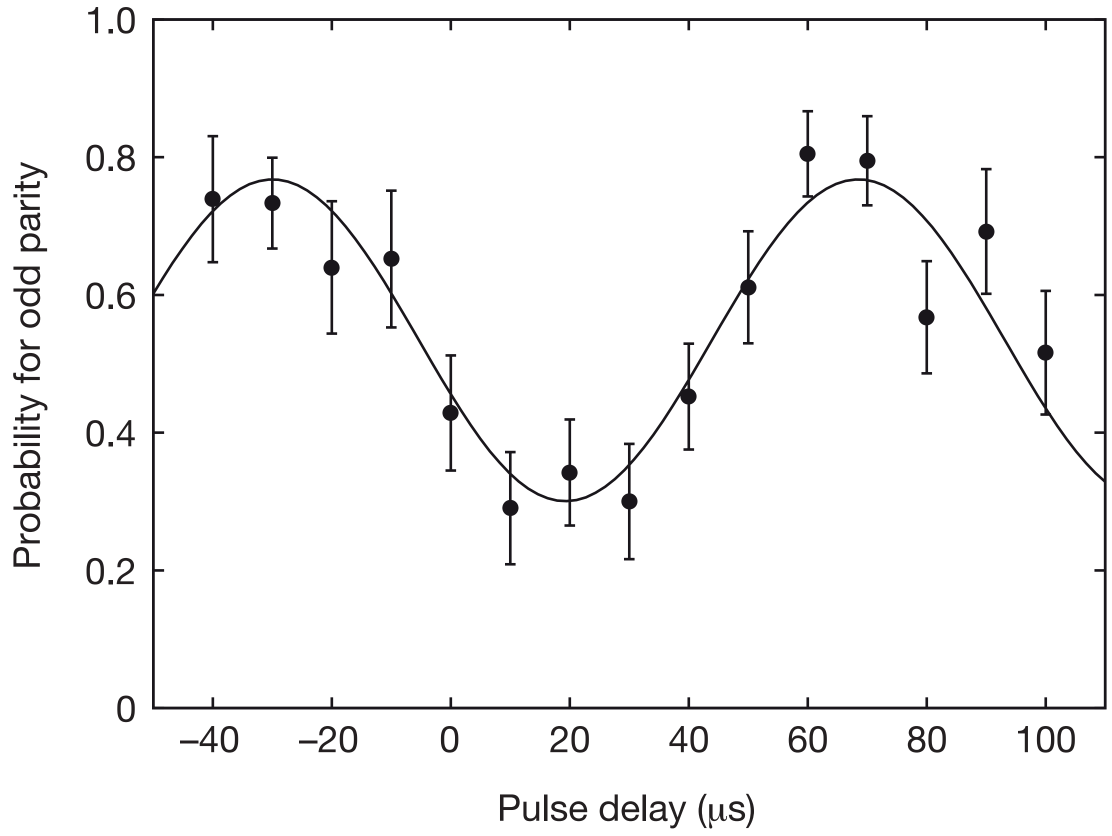
- Moehring (2007): Only correlations in unrotated basis
- Ritter (2012): Full state tomography

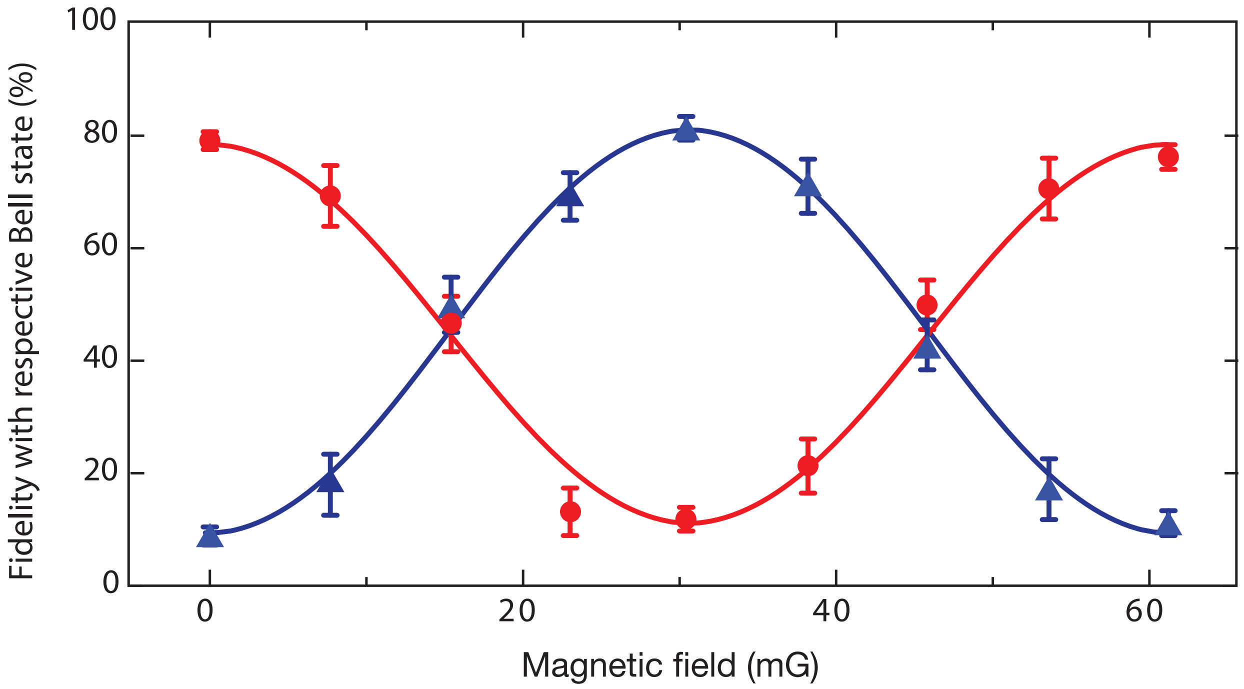




Local rotations: fidelity oscillates

- Moehring (2007): Microwave pulses, different phase
- Ritter (2012): Extra B field applied for 12.5 µs



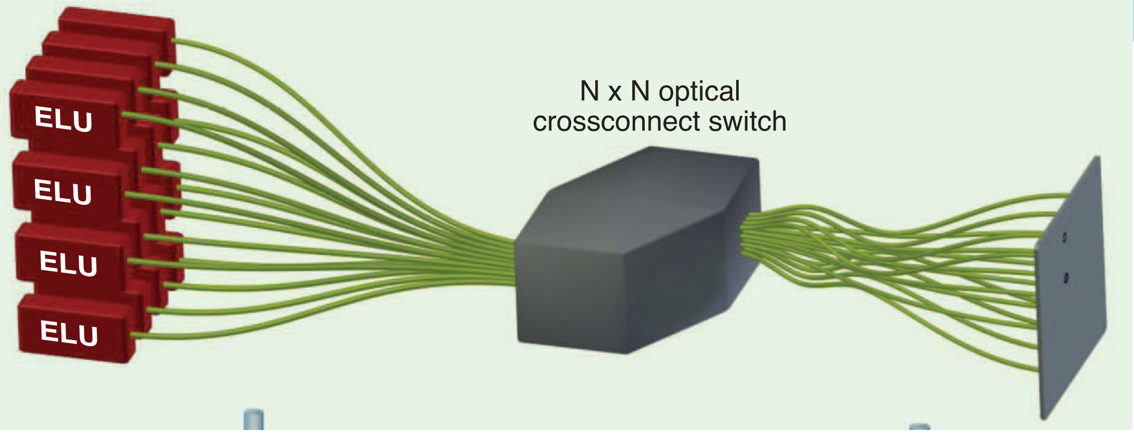


$$|\Psi^+\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A \otimes |1\rangle_B + |1\rangle_A \otimes |0\rangle_B) \qquad |\Psi^-\rangle = \frac{1}{\sqrt{2}}(|0\rangle_A \otimes |1\rangle_B - |1\rangle_A \otimes |0\rangle_B).$$

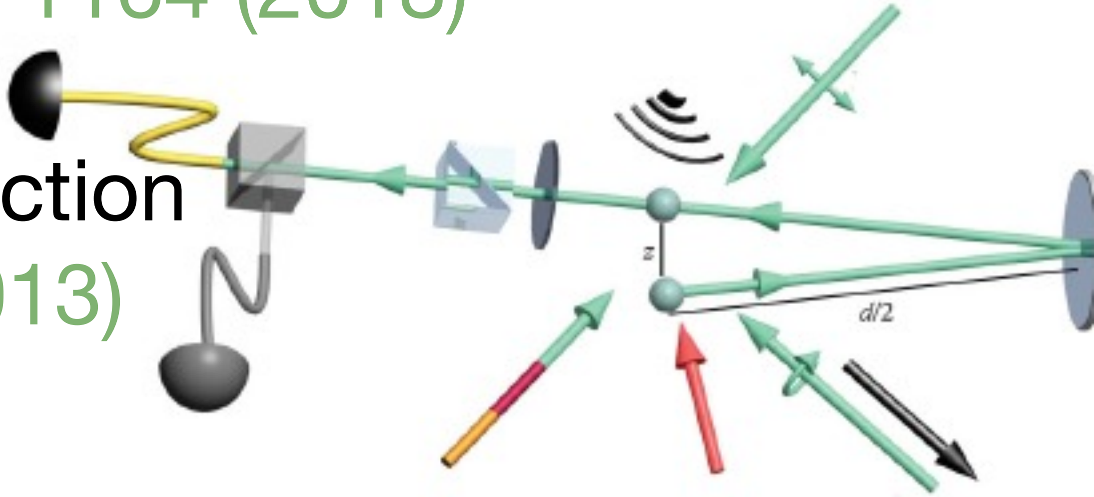
Comparison

Moehring (2008)		Ritter (2012)
Excitation to upper state with short pulse	**Photon creation**	Stimulated Raman process (STIRAP)
Interference at 50/50 beam splitter	**Photon use**	Raman process at target atom
$F = 65 \pm 3\%$	**Fidelity to target state**	$F = 85 \pm 1.3\ \%$
$p = 3.6 \cdot 10^{-9}$	**Success probability of entanglement scheme**	$p = 0.02$
$R = 0.118\ \mathrm{min}^{-1}$	**Rate of entanglement creation**	$R = 1800\ \mathrm{min}^{-1}$
Coincidence detection	**Entanglement heralding**	None

Perspectives

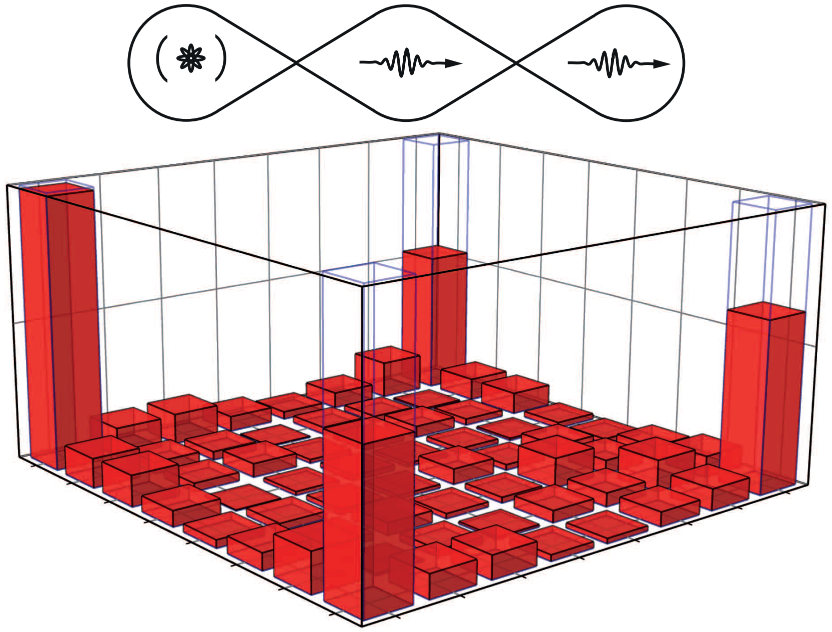


- Review:
  C. Monroe and J. Kim, *Science* 339, 1164 (2013)



- Entanglement by single photon detection
  Slodička et al., *PRL* 110, 083603 (2013)

- Atom/photon quantum gates
  Reiserer et al., *Nature* 508, 237 (2014)
  Tiecke et al., *Nature* 508, 241 (2014)



Conclusion

- To build large-scale quantum systems, we need to create entanglement between distant nodes
- Two approaches for entangling atoms/ions discussed:
    - Heralded entanglement creation using beam splitter (probabilistic)
    - Atom-cavity nodes allowing deterministic interaction with photons