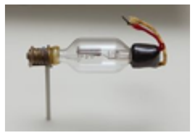
Distributing Quantum Entanglement over Communication Networks

Evolution of Communication Networks

1st phone call, 1876
NY-Chicago, 1892



Vacuum Tubes
(First triode, 1907)

PHONE TO PACIFIC FROM THE ATLANTIC

Perfect Test of Transcontinental Line Made by Inventors Bell and Watson.

4,750-MILE RECORD SET

Long-distance
communication, 1915

"Manual" switching
networks, ~1950s

Distributed Computing (Data Centers)

Global Internet Since 1990s

Modern telephone networks ~1980s

Data Dominates!

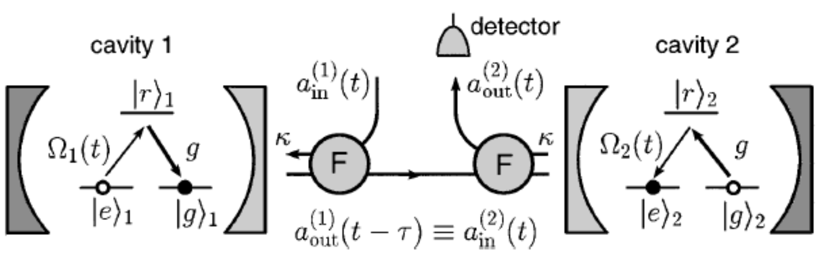
~Generic Q. Networks

Voice Dominates!

~QKD

Interface: Quantum Memories & Photons

- Early Ideas: State Transfer between Quantum Nodes
  - Memory-photon coupling enhanced by optical cavities
  - Experimental demonstration of atoms in cavities
  - Technical Challenges for "Pitch and Catch"
    - Precise pulse tailoring for efficient transfer
    - Photon loss leads to qubit losses
    - "Capturing" the photonic qubit by the memory qubit is challenging



Cirac, Zoller, Kimble and Mabuchi, PRL 78, 3221 (1997)

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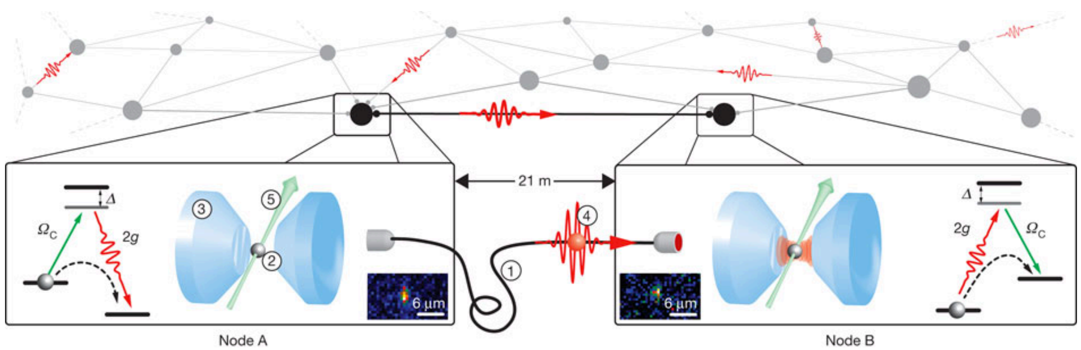
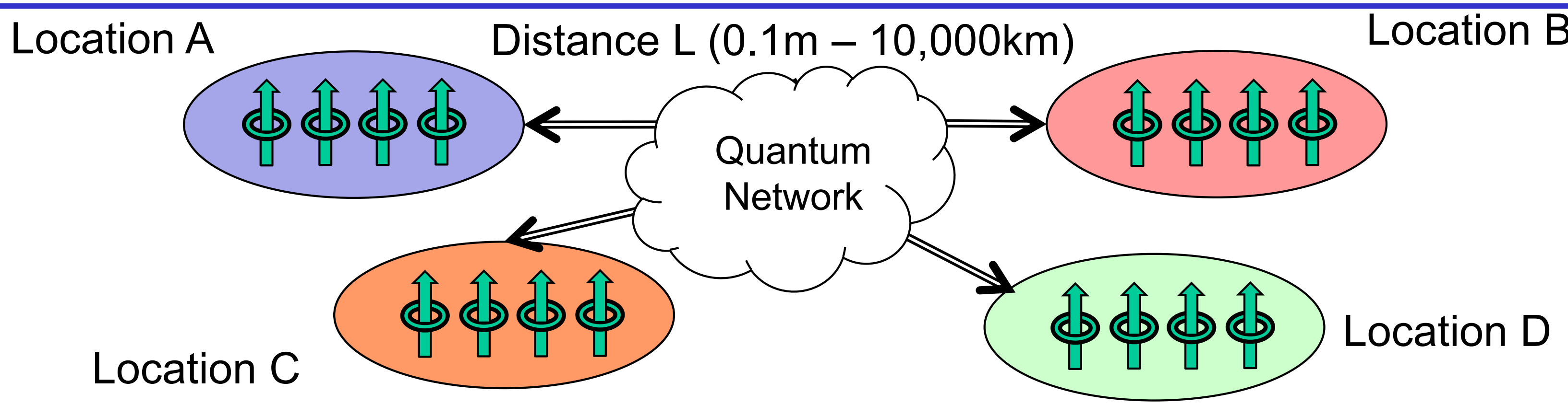


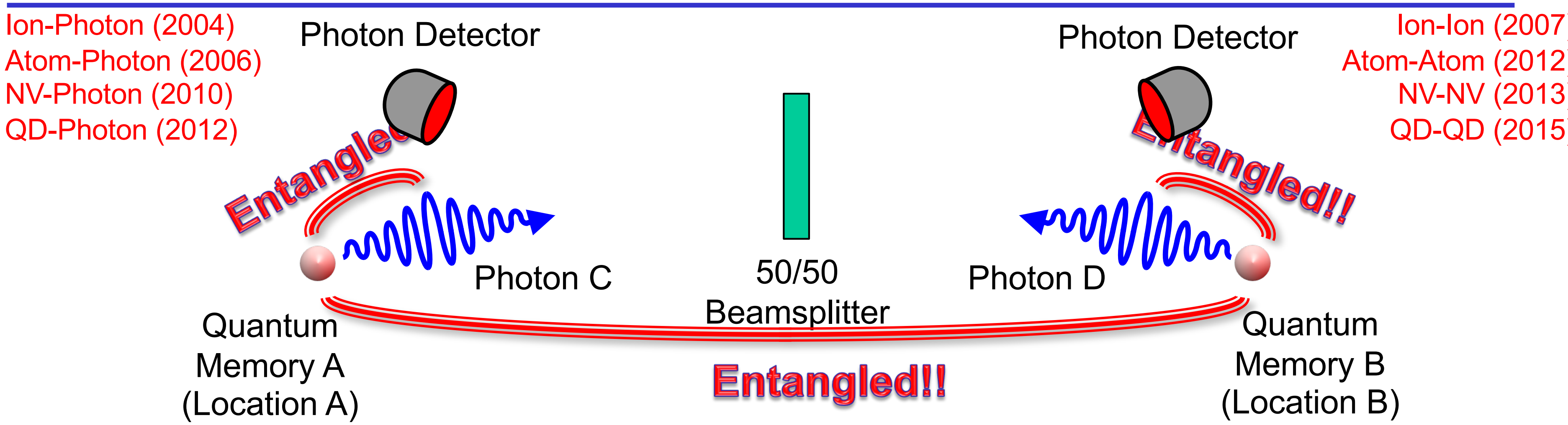
S. Ritter et al., Nature 484, 195 (2012)

Key Attributes of Quantum Networks



- Essence of "***(Quantum) Data Communication between Machines***"
  - Distance of Communications
    - Within a quantum processor node (~1 mm – 1 cm)
    - Between processor nodes (~10 cm – 10 m)
    - Long-distance nodes (~100 m – 10,000 km)
  - Types of Applications
    - Secret key generation (measurements on both ends: easy!!)
    - Quantum repeaters (entanglement swapping operation)
    - Generic quantum interconnects (remote quantum gates)

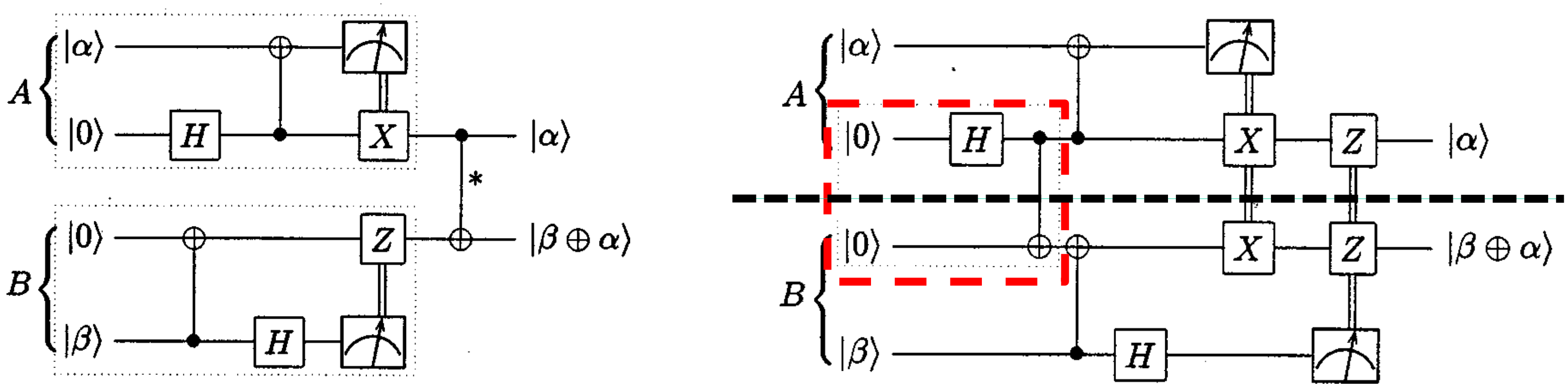
Generation of Remotely Entangled Memories



- When both photon detectors click, it signals successful entanglement between A&B
- With a good quantum memory, the generated entanglement can be stored and used for deterministic quantum logic operation
- Opportunities for photonics technology
  - Optical networking to construct quantum networks
  - Manipulation of photonic qubits (frequency conversion, etc.)

Remote CNOT Gate Construction

- Logic gates between two qubits can be realized without direct interaction, if entanglement is used

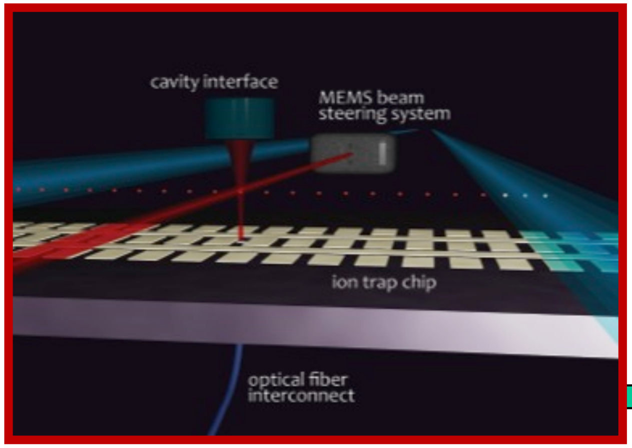


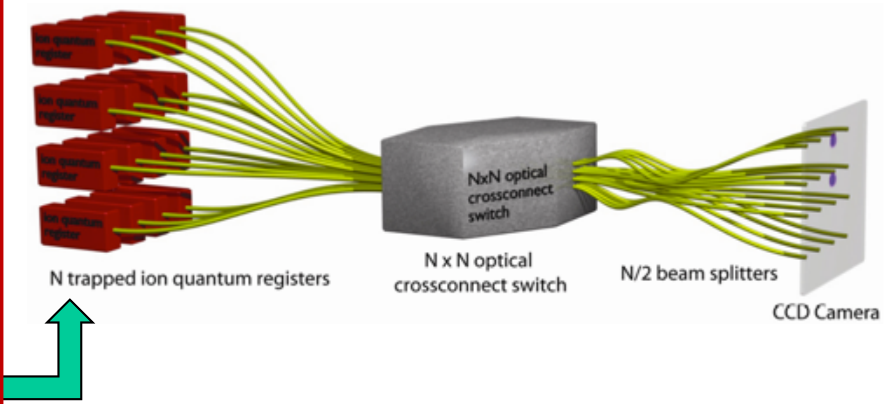
- Extremely useful for scalable distributed quantum multi-computer!!

Gottesman and Chuang, Nature 402, 390 (1999)
Zhou, Leung and Chuang, PRA 62, 052316 (2000)

MUSIQC: Multi-Tier Approach to Scalability

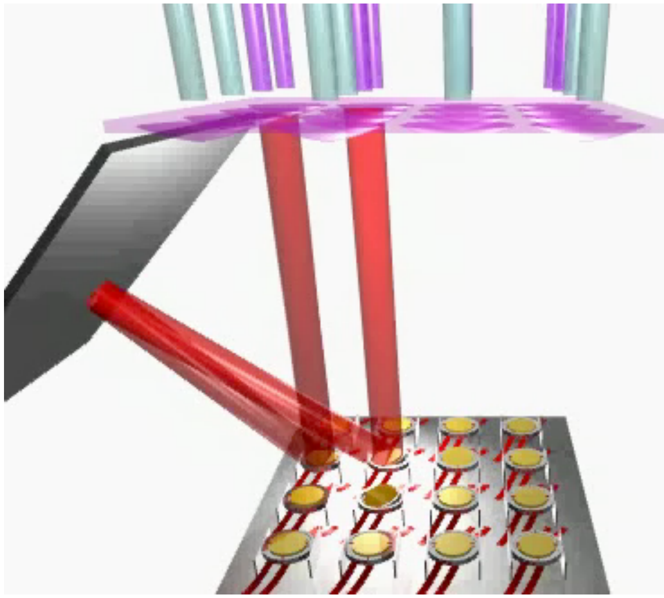
- Quantum Computation in Small Coulomb Crystals
  - Linear ion chain with 20-100 ions (Elementary Logic Unit, or ELU)
  - Arbitrary quantum logic operation among the qubits in the chain
- Interconnect of Multiple Coulomb Crystals via Photonic Channel
  - Reconfigurable interconnect using optical crossconnect (OXC) switches
  - Efficient optical interface for remote entanglement generation





Beam Steering Optical Switches

Reflector



I/O Single-mode Fibers

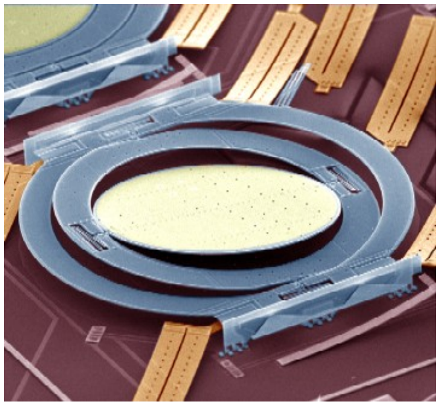
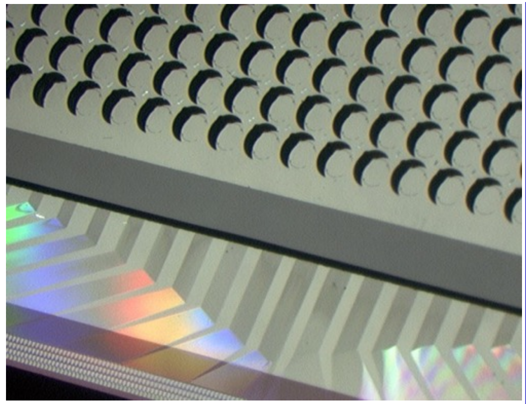
Imaging Lenses

MEMS 2-axis Tilt Mirrors

- Only feasible Technology to scale to Large Portcount
- Proper design eliminates path length-dependent loss

Optical switches developed in early 2000s, deployed in datacenters today

World’s Largest Optical Switch

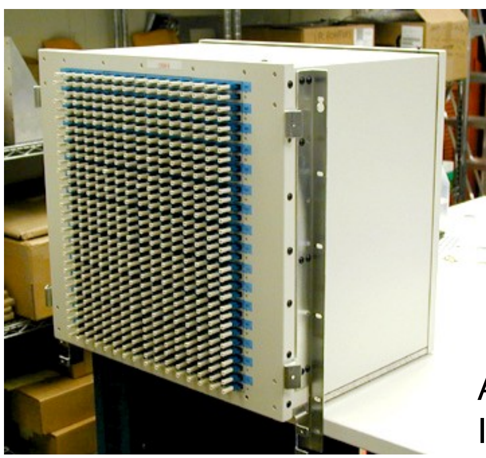
Surface Micromachined Mirror

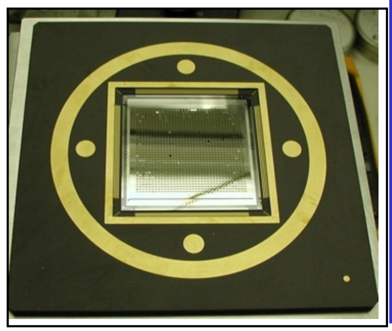
Bulk Micromachined Mirror

1296 x 1296 Optical Switch

J. Kim et al., IEEE PTL 15, 1537 (2003)

256 x 256 Optical Switch

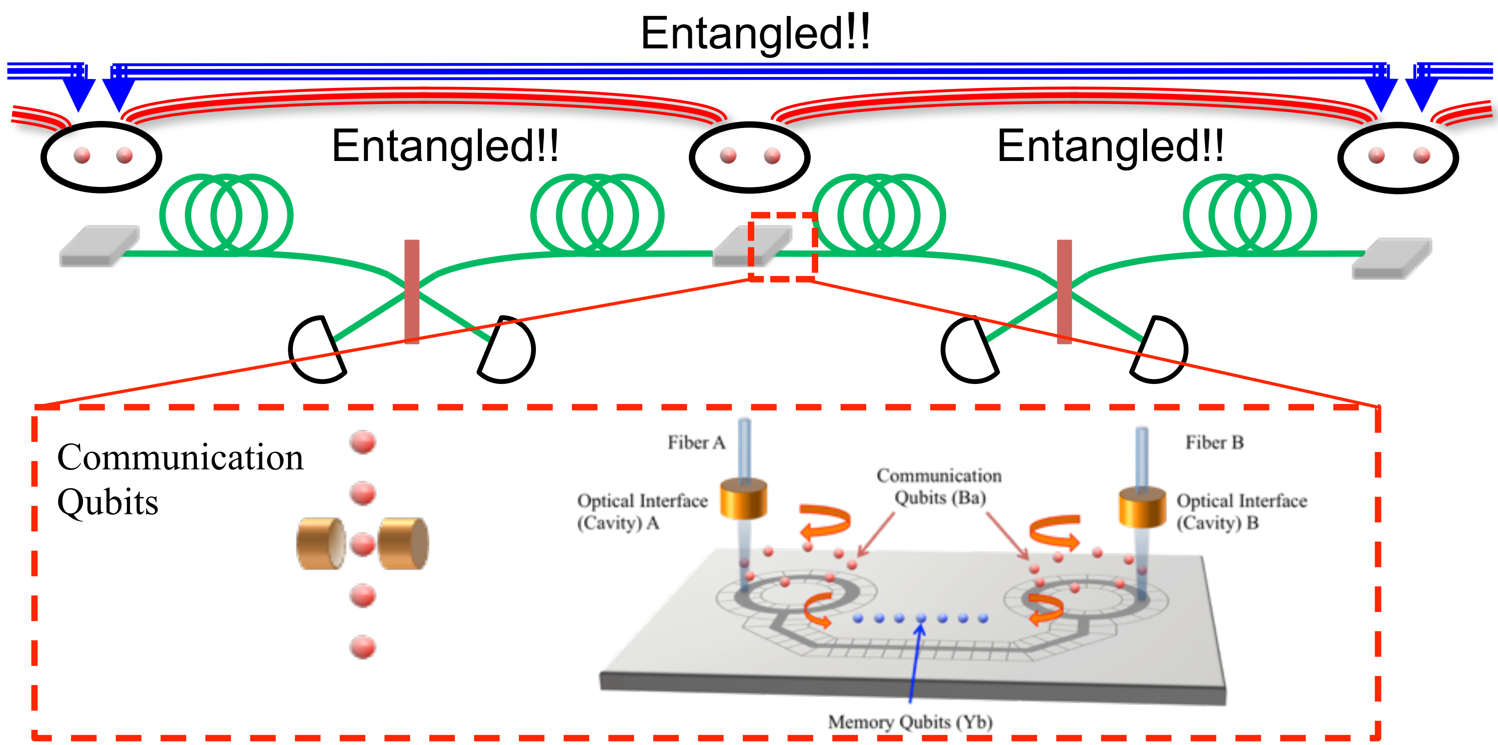




Aksyuk et al.,
IEEE PTL 15, 587 (2003)

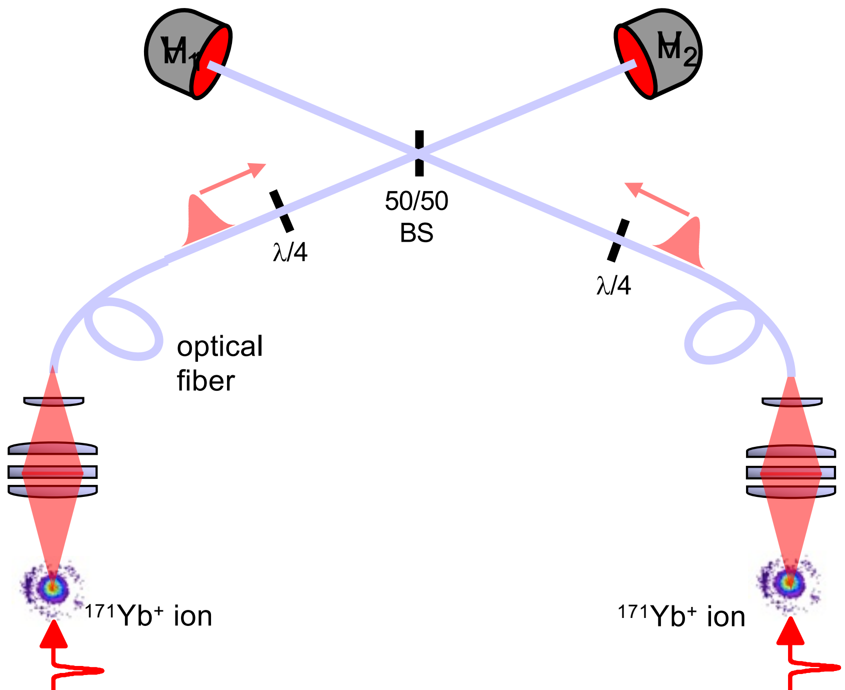
Quantum Repeater Platform

- Quantum Repeater for Long-Distance Quantum Communication
  - Small quantum computer with two optical ports function as a quantum repeater



Monroe and Kim, Science 339, 1164 (2013)

The Protocol: Ion-Photon Entanglement



Heralded coincident events (p_{suc}=1/4):

(H_1 & V_2) or (V_1 & H_2) $\rightarrow$ $|\downarrow\uparrow\rangle - |\downarrow\uparrow\rangle$

(H_1 & V_1) or (V_2 & H_2) $\rightarrow$ $|\downarrow\uparrow\rangle + |\downarrow\uparrow\rangle$

(H_1 & H_1) or (H_2 & H_2) $\rightarrow$ $|\downarrow\downarrow\rangle$

(V_1 & V_1) or (V_2 & V_2) $\rightarrow$ $|\uparrow\uparrow\rangle$

$$R_{ent} = \frac{1}{4} R \left(\eta_D \cdot F \cdot \frac{d\Omega}{4\pi} \right)^2$$

R: Repetition Rate

η_D: Detector Efficiency

$d\Omega$: Collection Solid Angle

F: Collection Efficiency

$$R_{ent} = 0.001 - 0.025 s^{-1}$$

Simon & Irvine, PRL **91**, 110405 (2003)
L.-M. Duan, et. al., QIC **4**, 165 (2004)
Y. L. Lim, et al., PRL **95**, 030505 (2005)
D. Moehring et al., *Nature* **449**, 68 (2007)

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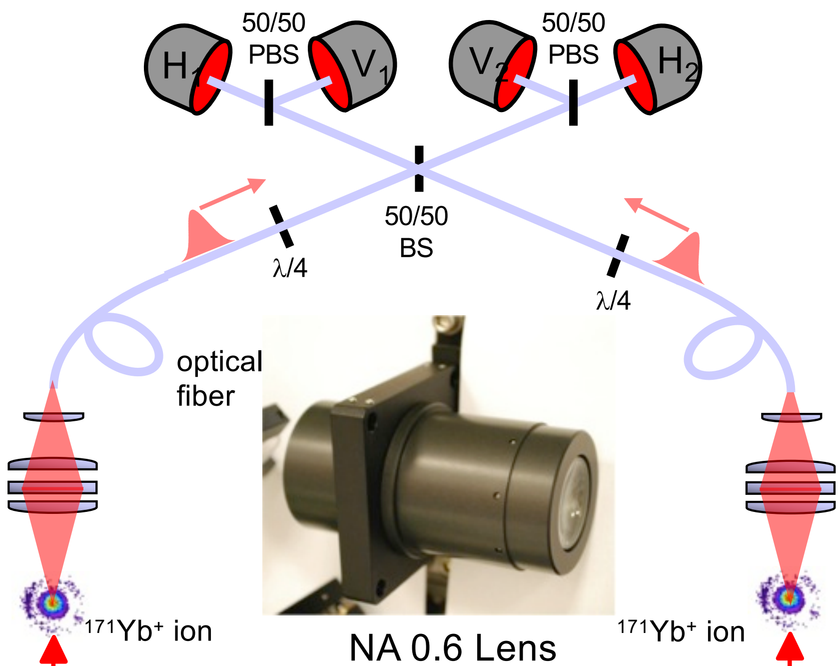

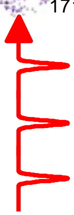

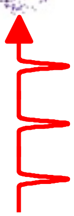

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Kim, Maunz & Kim, PRA **84**, 063423 (2011)

Heralded coincident events (p_{suc}=1/2):

$(H_1\ \&\ V_2)$ or $(V_1\ \&\ H_2)$ $\rightarrow$ $|\downarrow\uparrow\rangle - |\downarrow\uparrow\rangle$

$(H_1\ \&\ V_1)$ or $(V_2\ \&\ H_2)$ $\rightarrow$ $|\downarrow\uparrow\rangle + |\downarrow\uparrow\rangle$

$(H_1\ \&\ H_1)$ or $(H_2\ \&\ H_2)$ $\rightarrow$ $|\downarrow\downarrow\rangle$

$(V_1\ \&\ V_1)$ or $(V_2\ \&\ V_2)$ $\rightarrow$ $|\uparrow\uparrow\rangle$

$$R_{ent} = \frac{1}{2} R \left(\eta_D \cdot F \cdot \frac{d\Omega}{4\pi}\right)^2$$

$$R = 470kHz$$

$$p = \eta_D \cdot F \cdot \frac{d\Omega}{4\pi} = (0.35)(0.14)(0.10)$$

$$R_{ent} = 4.5 s^{-1}$$

Hucul et al, (UMD) Nature Phys. 11, 37 (2015)

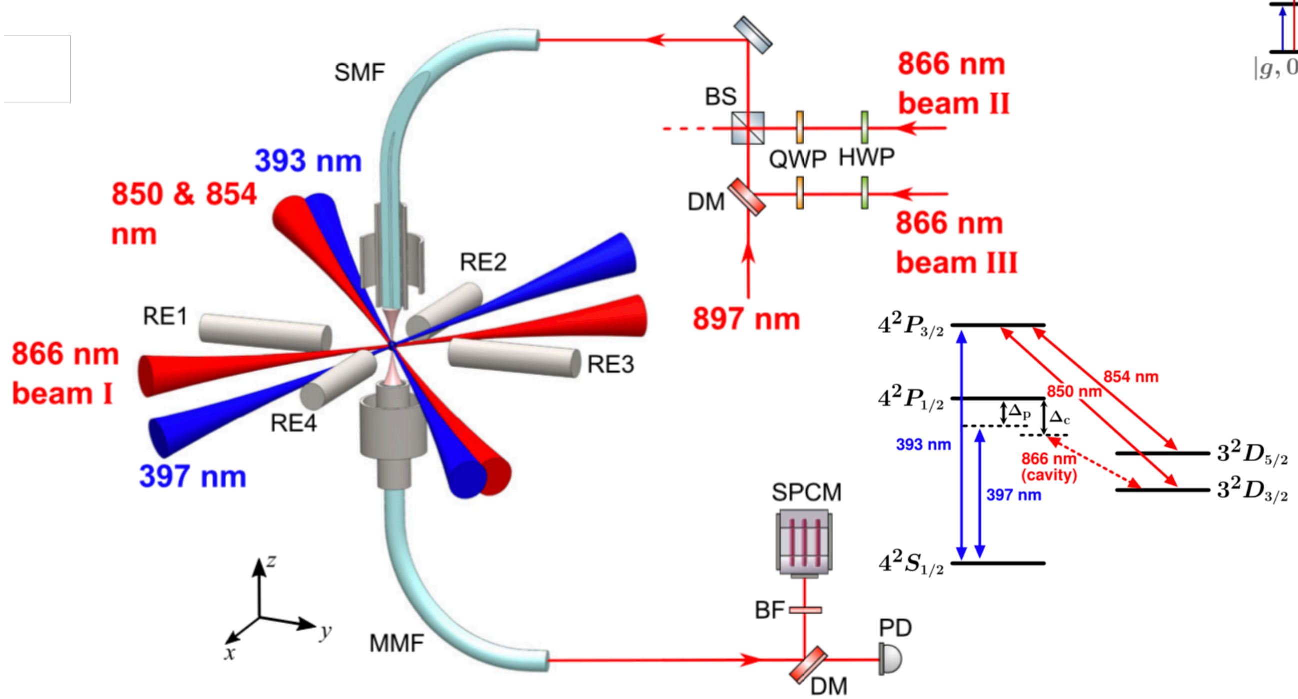
Oxford Result: 180 s^{-1} with Sr^+ ions

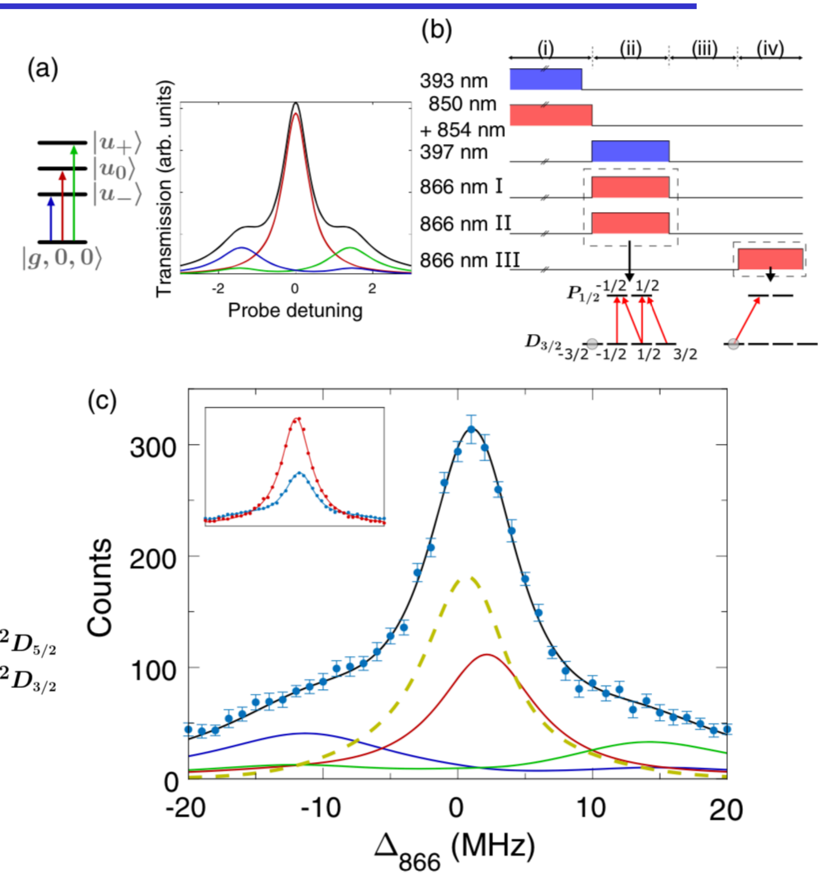
Stephenson et al., arXiv:1911.10841 (2019)

~10,000 s^{-1} is feasible

Small-Volume Optical Cavities

- Achieve stronger coupling with ions
- UV cavity is more difficult than IR cavities!!

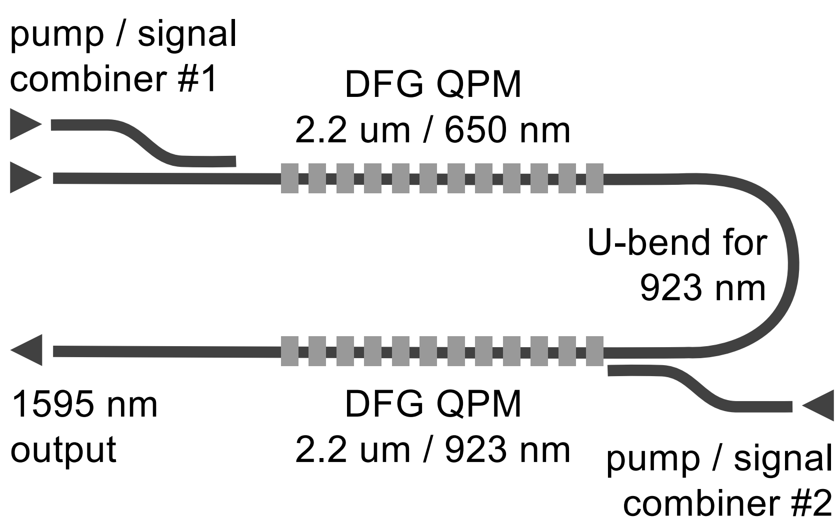




Takahashi et al., Phys. Rev. Lett. 124, 013602 (2020)

Fully Integrated Wavelength Conversion

- Fully integrated device to convert 650nm photon to 1595nm
- Two-step conversion to eliminate spontaneous parametric down-conversion (SPDC) and Stokes-Raman noise



Double-pass configuration w/ integrated U-bend & WDMs

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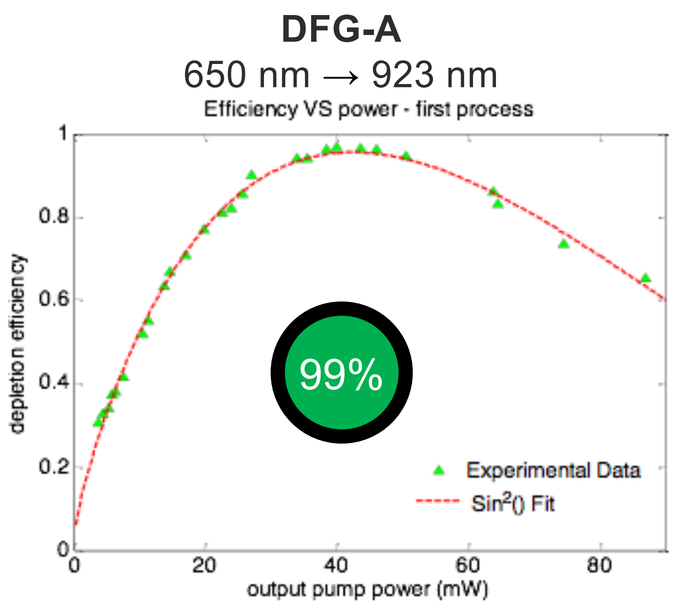
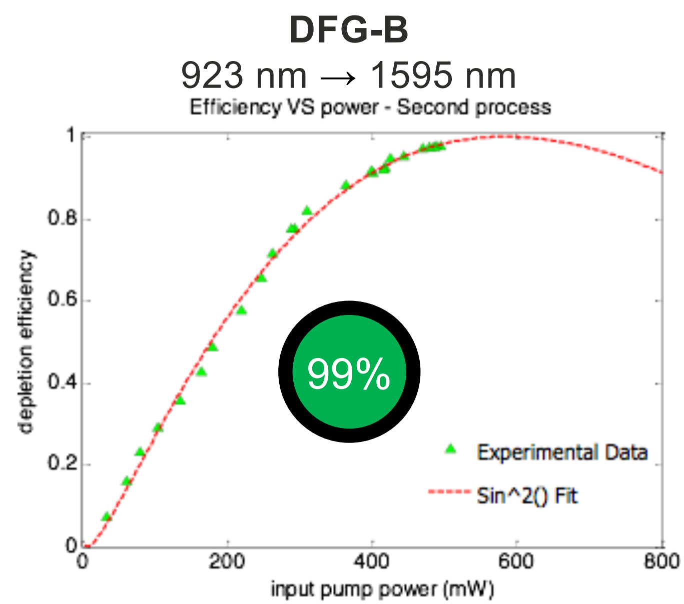
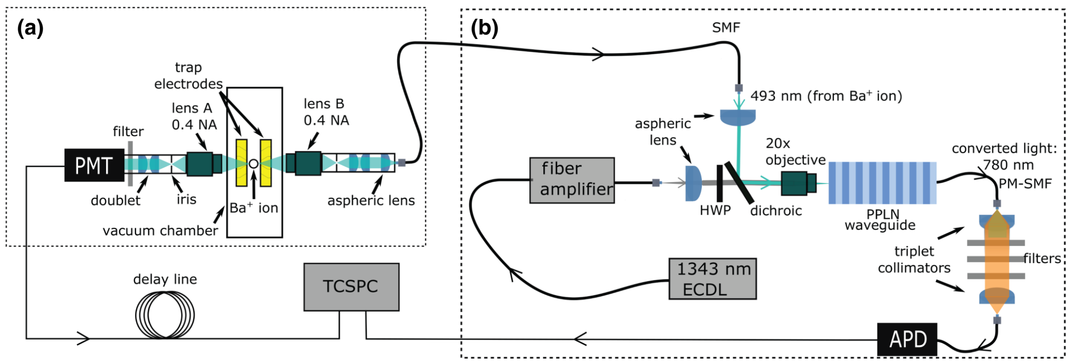




Both processes can be driven to **near unity conversion**
Both processes operate at identical pump wavelength and temperature

Wavelength Conversion from Ions

- Converting emitted photons from an ion
  - 493nm photon from Ba^+ ion converted to 780nm



Siverns et al.,
Phys. Rev. Appl. 11, 014044 (2019)