Distributed Quantum Networks based on Trapped Ions

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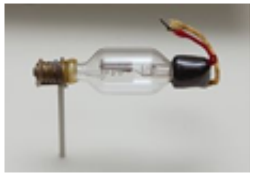
Outline

- Introduction:
  - Practical Framework for Quantum Networking
  - 3 Generation of Quantum Repeaters
- Trapped Ion Technology for Quantum Networking
- Towards a Demonstration of a Repeater Node
- Conclusions

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
(WDM systems, 5ESS switches) ~1980s

Data Dominates!

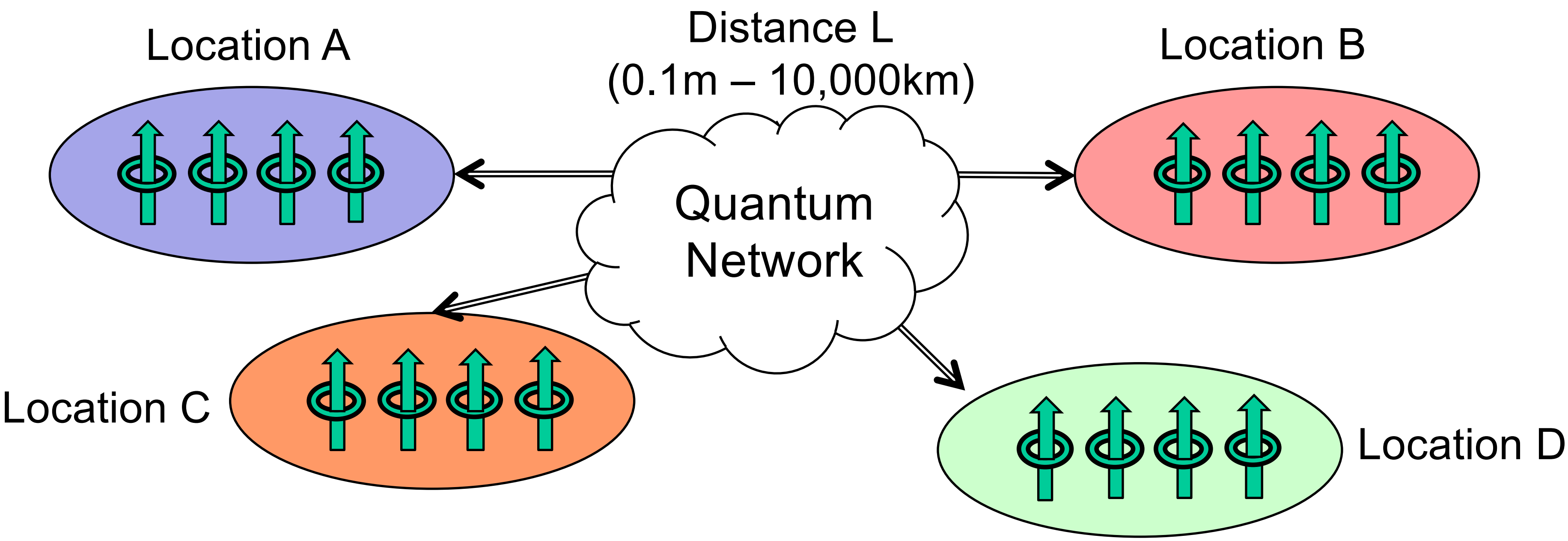
~Generic Q. Networks

Voice Dominates!

~QKD

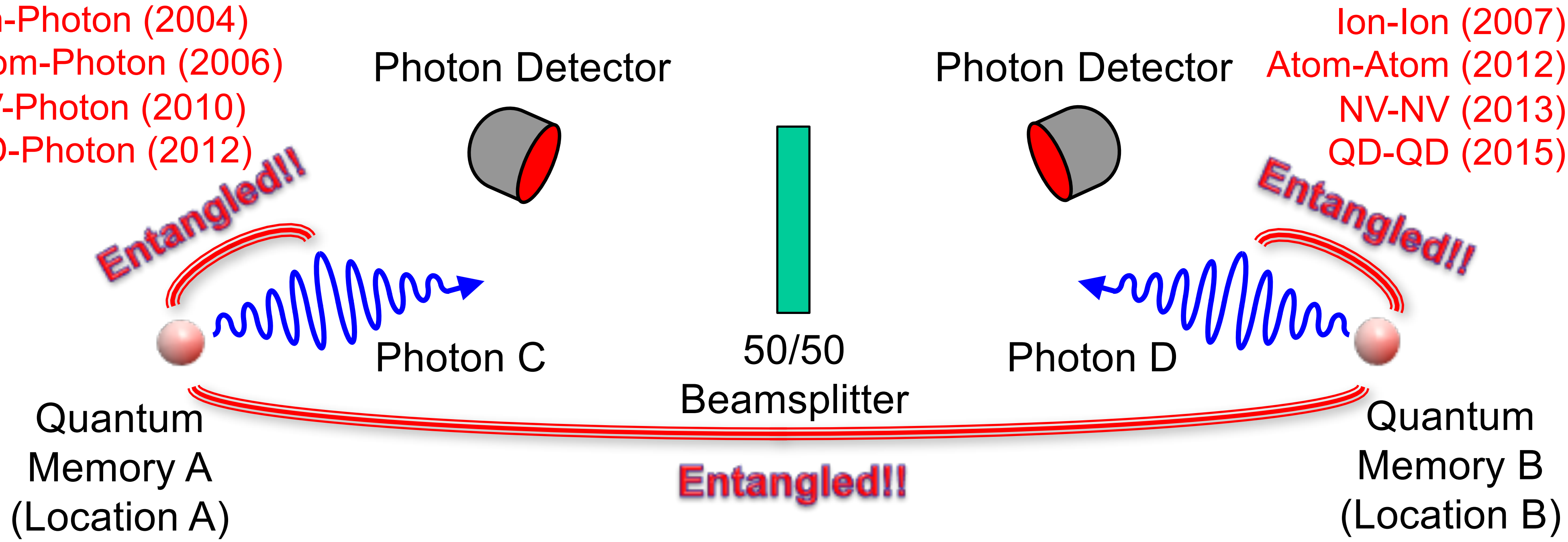
Tu Poster
Islam et al.

Key Attributes of Quantum Networks



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

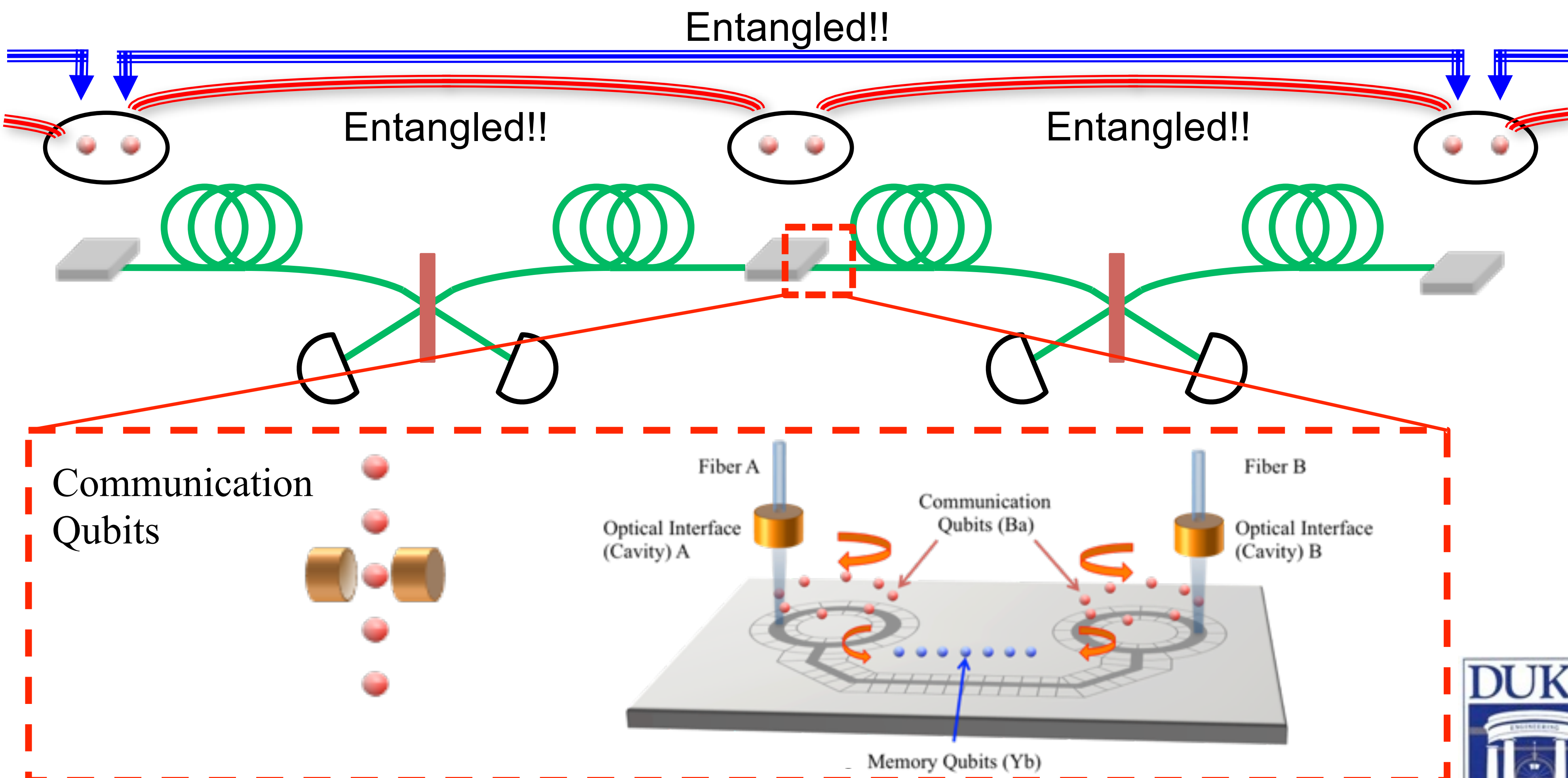
Generation of Remotely Entangled Memories



- 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.)

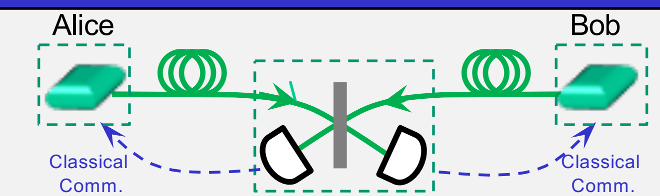
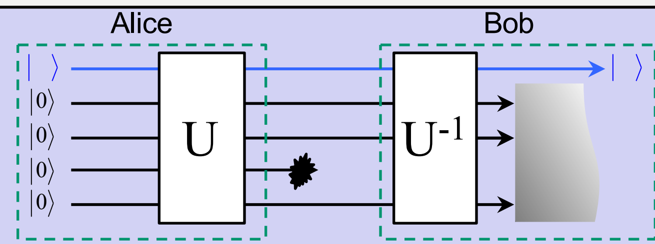
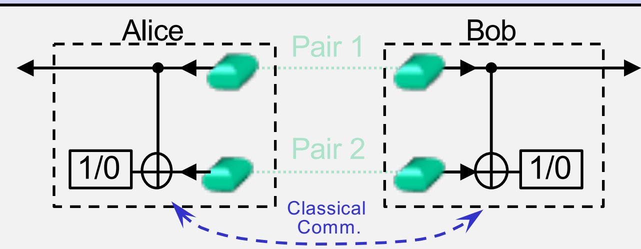
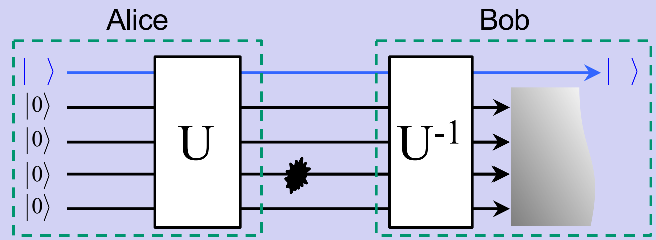
Quantum Repeater Platform

- 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)

Dealing with Photon Loss and Operation Errors

	Approaches	Example	Requirement
Loss Errors	**Heralded Generation (*)**		Prob. & Heralded, ***Two-Way*** Comm.
	Quantum Error Correction		Deterministic, ***One-Way*** Comm. Suppress $\varepsilon \to \varepsilon^{2t+1}$
Operation Errors	**Heralded Purification (**)**		Prob. & Heralded, ***Two-Way*** Comm.
	Quantum Error Correction		Deterministic, ***One-Way*** Comm. Suppress $\varepsilon \to \varepsilon^{t+1}$

(*) Experiments with ions, atoms, NVs, QDs, ensembles, … (**) Experiments with photons, ions, …

Three Generations of QRs

	Approaches	1st Generation	2nd Generation	3rd Generation
Loss Errors	Heralded Generation [*Two-Way* Comm.]	✓	✓	
	Quantum Error Correction [*One-Way* Comm.]			✓
Operation Errors	Heralded Purification [*Two-Way* Comm.]	✓		
	Quantum Error Correction [*One-Way* Comm]		✓	✓

Muralidharan et al., PRL 112, 250501 (2014); Sci. Rep. 6, (2016)

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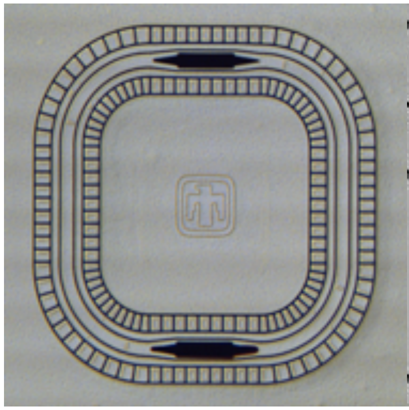
Advantages of Trapped Ion Systems

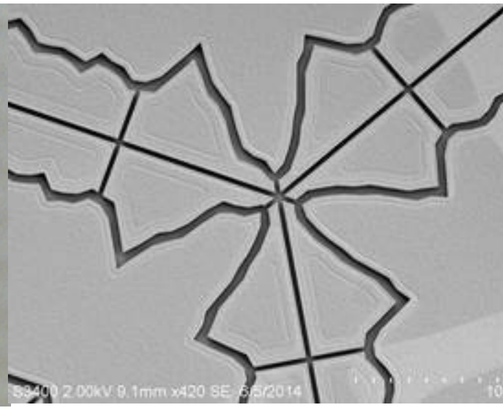
- "Best" Qubits and High Fidelity Operation
  - 1–1,000 sec coherence times routine in hyperfine qubits
  - State preparation and measurement (SPAM) errors in the 10^{-3}–10^{-4} range ($<10^{-5}$ possible)
  - Single-qubit gate errors in the 10^{-4}–10^{-6} range
  - Two-qubit gate errors in the 10^{-3} range ($<10^{-5}$ possible)
- Introduction of New Technologies

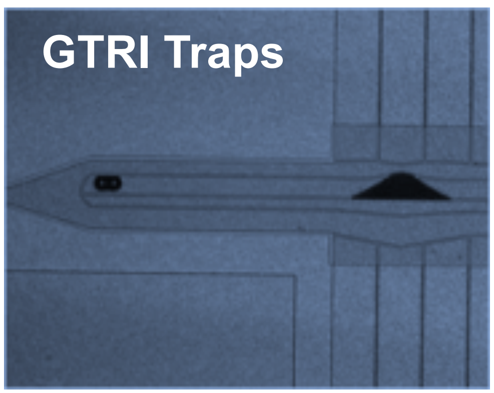
P. T. H. Fisk et al., IEEE T. Ultrason. Ferr. 44, 344 (1997)
C. Langer et al., PRL 95, 060502 (2005)
S. Olmschenk et al., PRA 76, 052314 (2007)
A. H. Myerson et al., PRL 100, 200502 (2008)
R. Noek et al., Opt. Lett. 38, 4735 (2013)
J. Benhelm et al, Nature Phys. **4** 463 (2008)
K. Brown et al, PRA **84** 030303 (2011)
T. Harty et al, PRL **113** 220501 (2014)
C. Ballance et al, arXiv:1512.04600 (2015)
J. Gaebler et al, arXiv:1604.00032 (2016)
R. Blume-Kohout et al, arXiv:1605.07674 (2016)

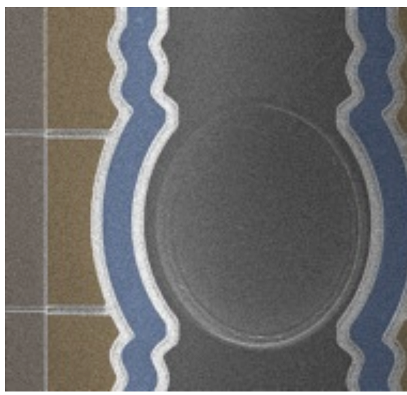
New Trapping Technology in MUSIQC

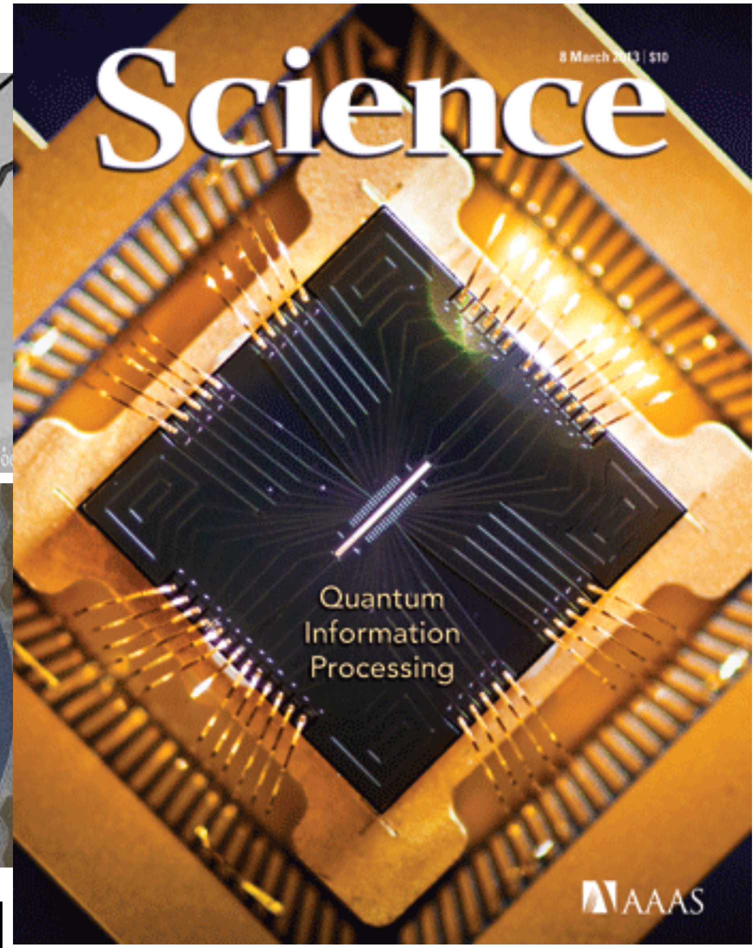
- Microfabricated Ion Traps











NJP 13, 075018 (2011)

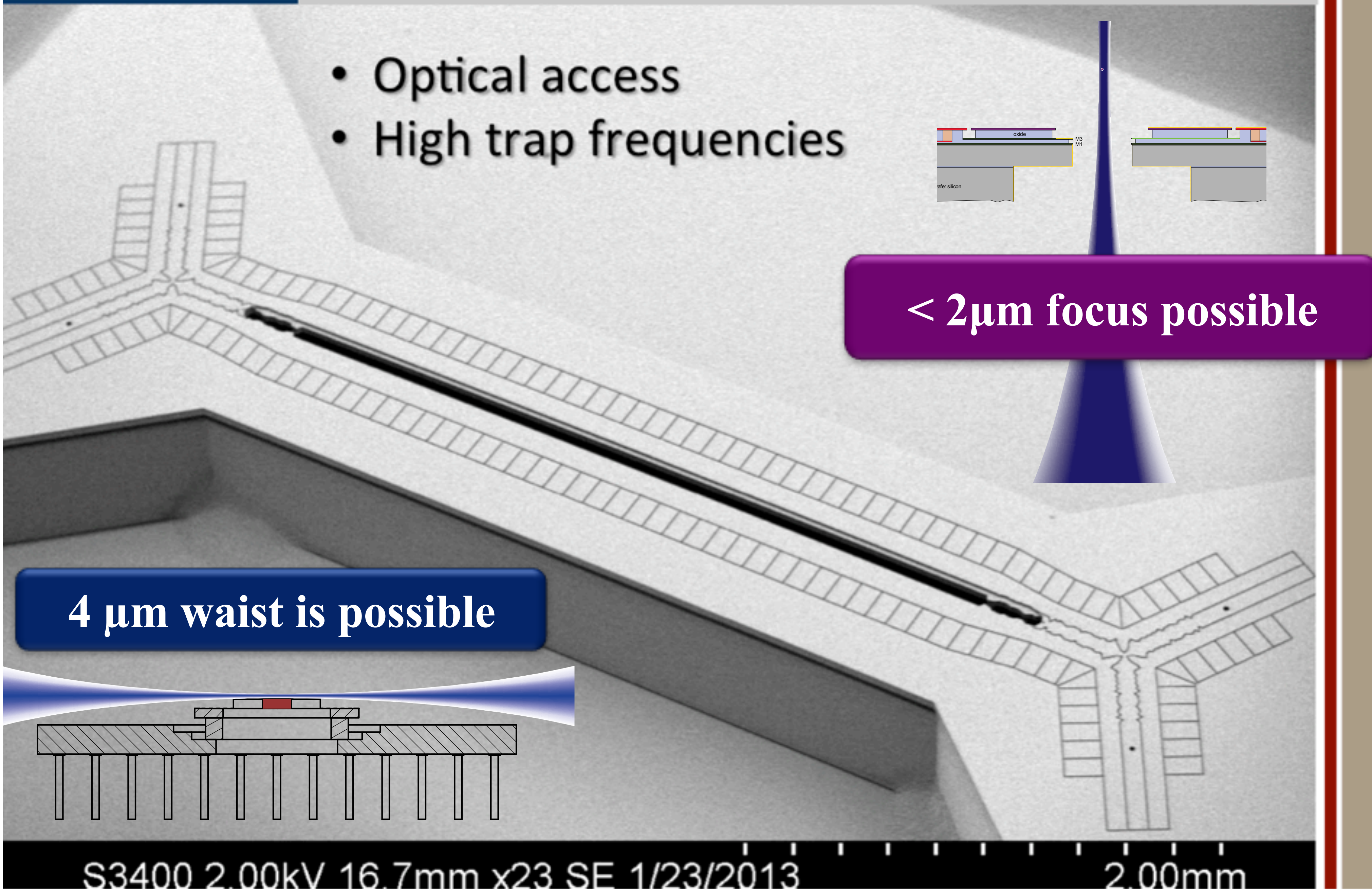
NJP 13, 103005 (2011)
NJP 14, 073012 (2012)
NJP 15, 033004 (2013)
NJP 15, 083053 (2013)

Advanced Trap Functionalities

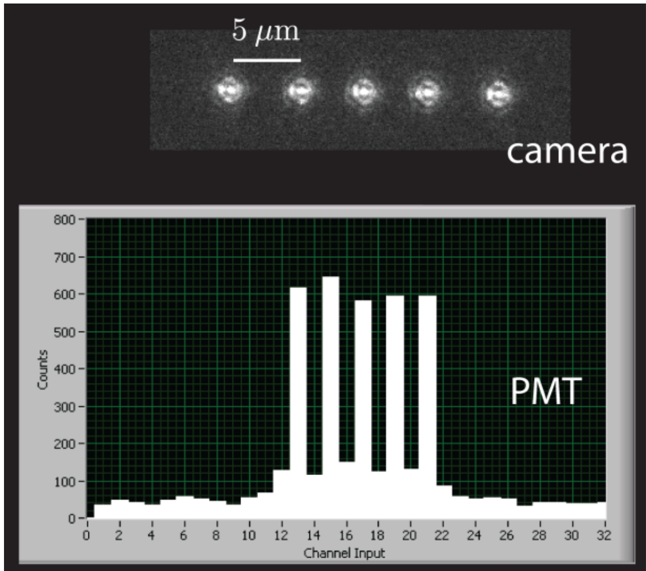
Jason Amini et al., GTRI (2011)

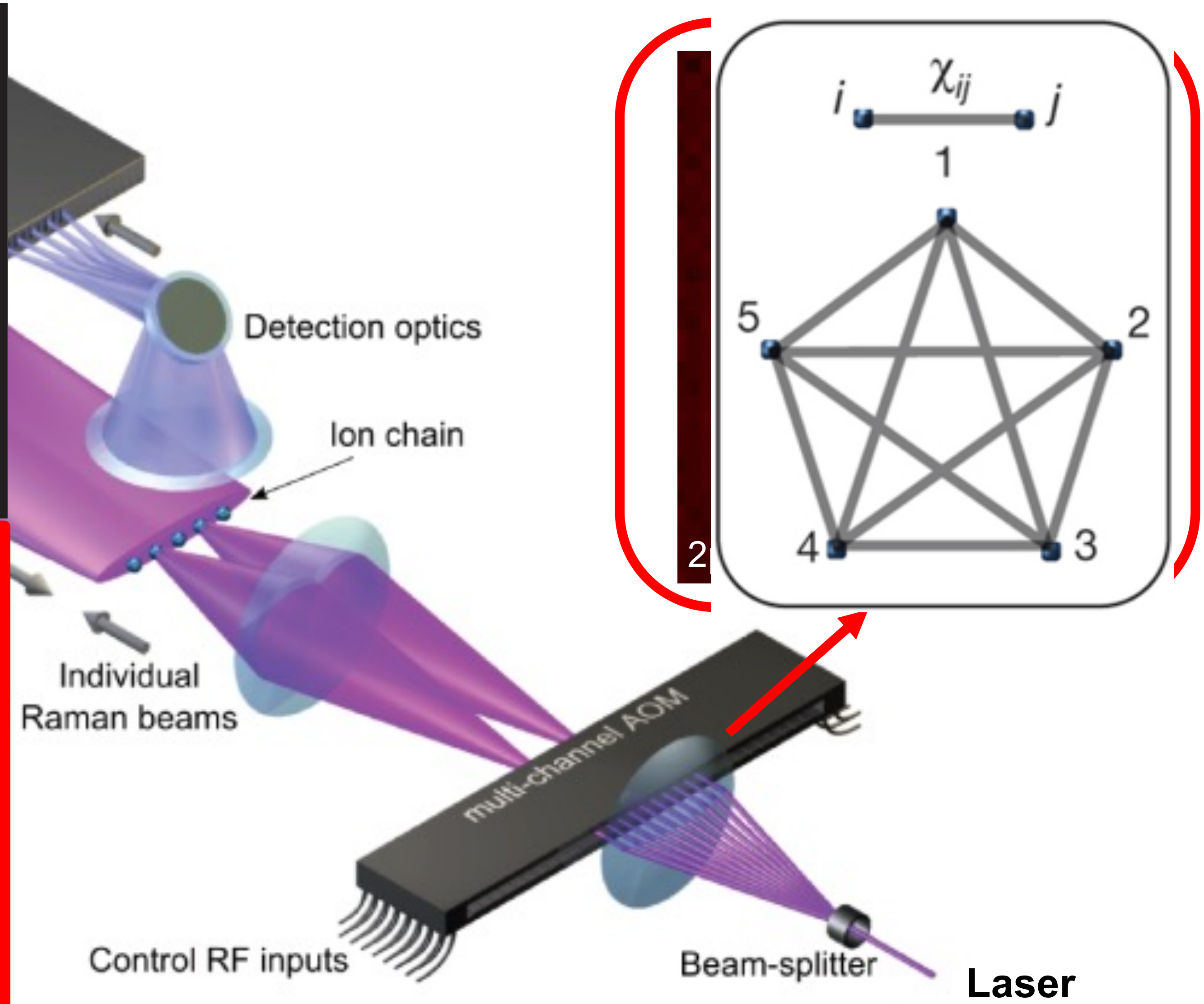
HOA 1

- Optical access
- High trap frequencies



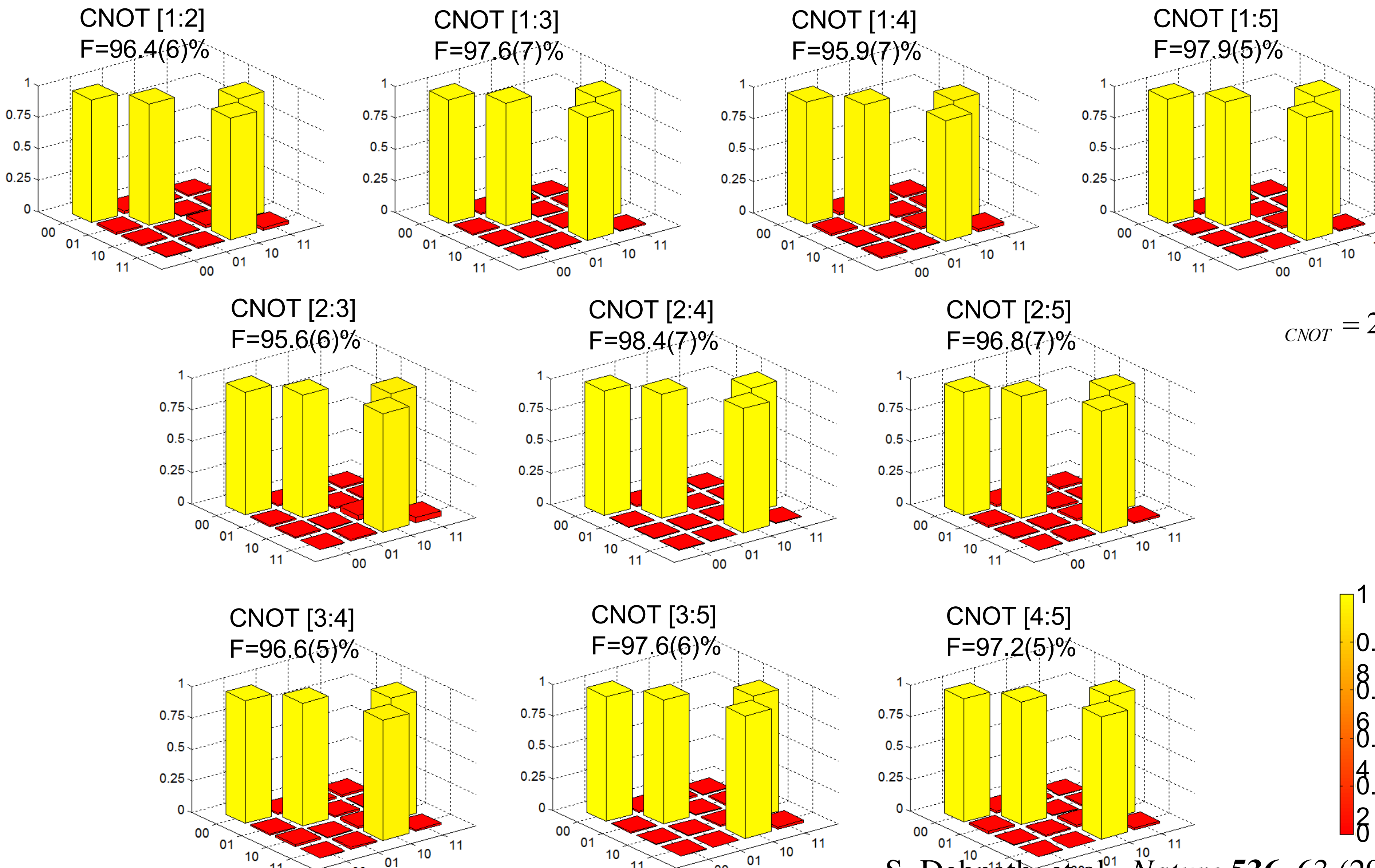
Physical Layer of a Fully Programmable QC





S. Debnath, et al., *Nature* **536**, 63 (2016)

5-Qubit QC with Full Connectivity



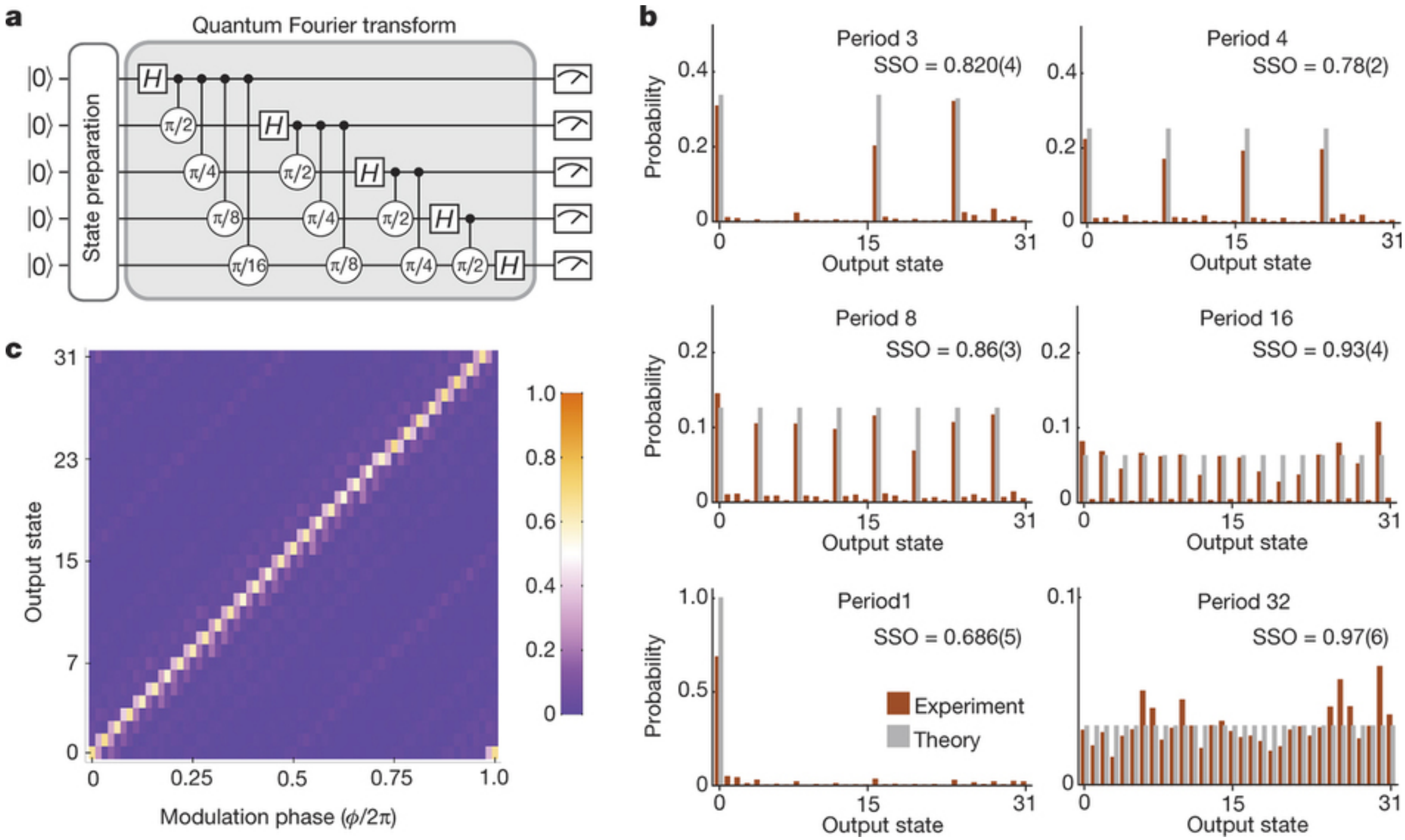
$_{CNOT} = 283\ s$

S. Debnath, et al., *Nature* **536**, 63 (2016)

SPAM errors reduce this by ~2%

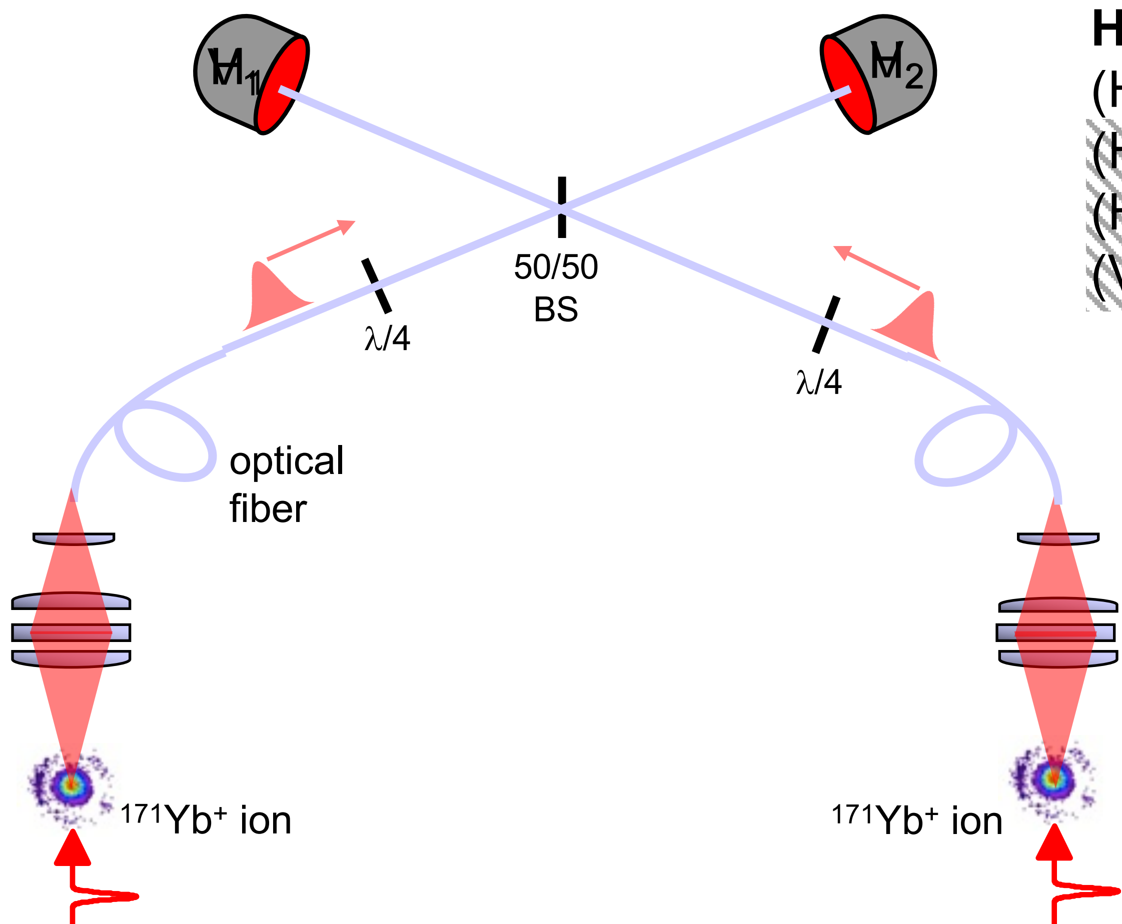
Operation of a Fully Programmable QC

- Deutsch-Jozsa Algorithm
- Quantum Fourier Transform Algorithm



S. Debnath, et al., *Nature* **536**, 63 (2016)

Remote Entanglement Generation via Photons



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)

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) $\rightarrow$ $|\uparrow\uparrow\rangle$

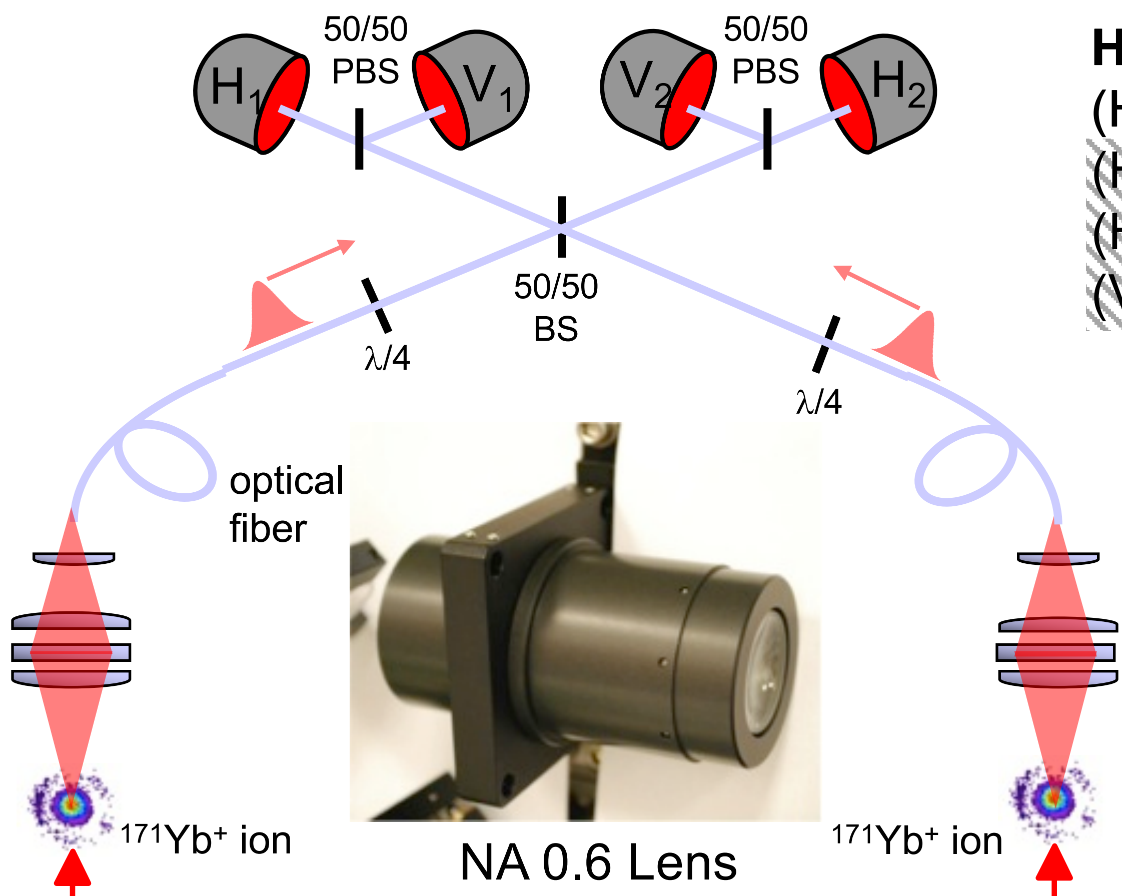
$$R_{ent} = \frac{1}{4} R \left(\eta_D \cdot F \cdot \frac{d\Omega}{4\pi} \right)^2$$

R: Repetition Rate
η_D: Detector Efficiency
$d\Omega$: Collection Solid Angle
F: Collection Efficiency

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

$$\tau_E / \tau_D = 27 - 670$$

Current Status on Entanglement Generation



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

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

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

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

$$R = 470kHz$$

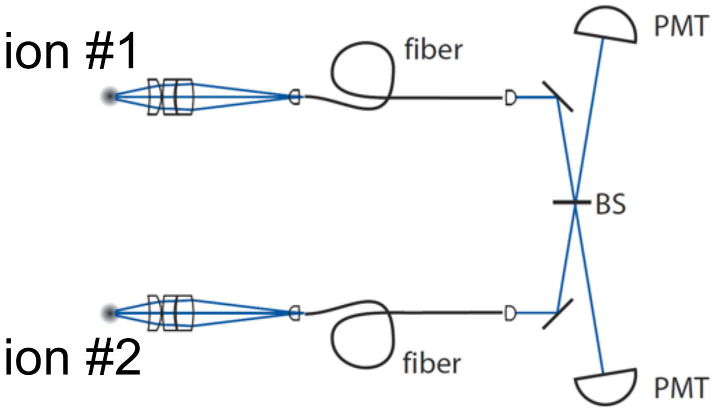
$$p = \eta_D \cdot F \cdot \frac{d\Omega}{4\pi} = (0.35)(0.14)(0.10)$$

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

$$\tau_E / \tau_D = 0.22s / 1.12s = 0.20$$

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

Fiber Coupling using High NA Optics



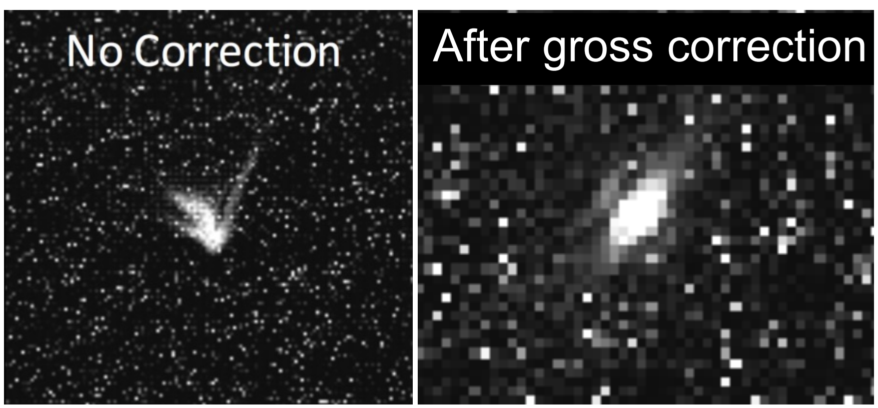
$$R_{ent} = \frac{1}{2} \quad p^2 = 4.5/\sec$$

D. Hucul, et al.,
Nature Physics 11, 37 (2015)

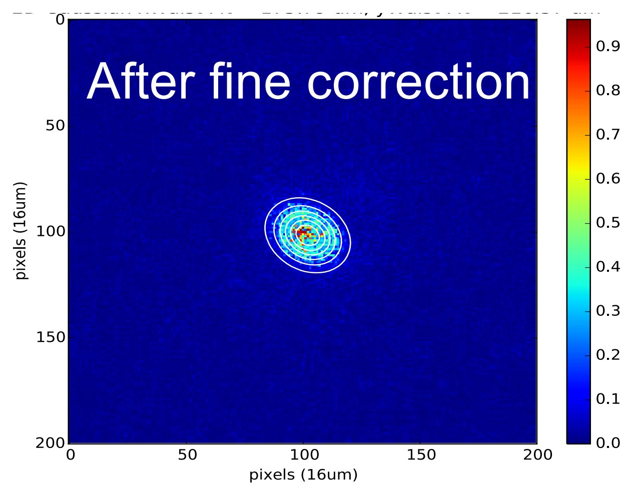
$$p = \eta_D F \frac{d\Omega}{4\pi} = 0.5\%$$ success prob. per ion

$$\Gamma = 600kHz$$ trial rate

Parameter	Jun 15
η_D	0.3
F	0.2
R_{ent} (per sec)	4.5



J. Wong-Campos et al., Nat. Phot. (2016)



Airy Radius 135μm (Diffraction Limit)
Waist in x: 176μm
Waist in y: 217μm

Cavity Integrated Trap at Duke

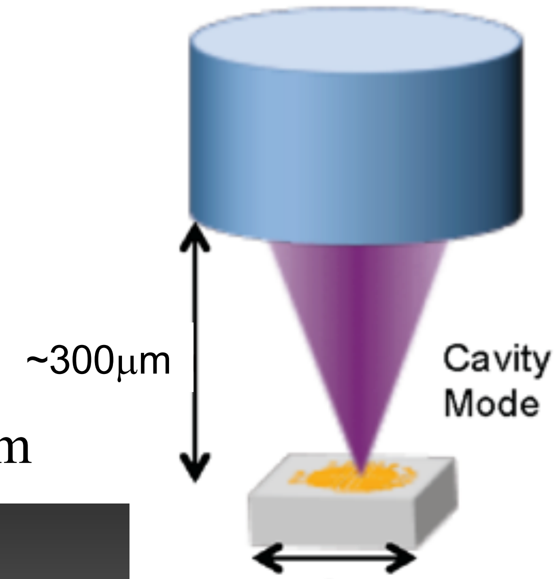
- Small waist, modest length leads to good coupling while lowering requirements for the mirror coatings

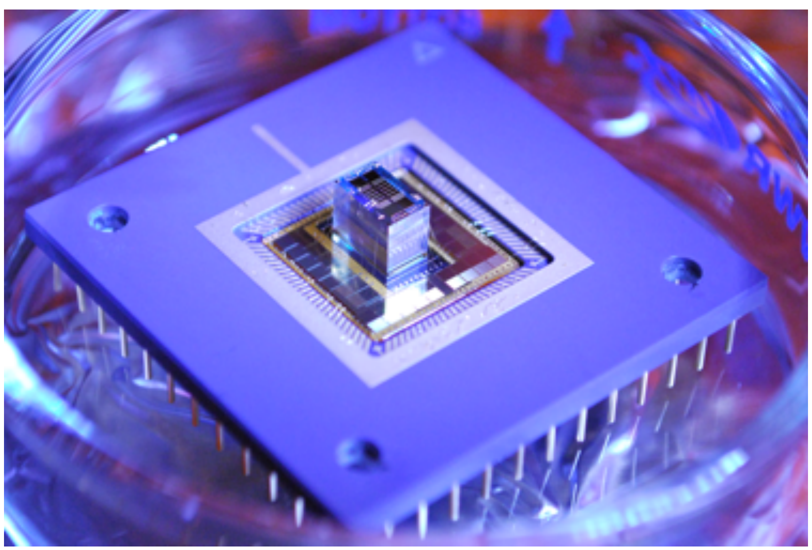
L_{cavity} = 300 μm
Z_{ion} = 50μm
W_{ion} = 4μm

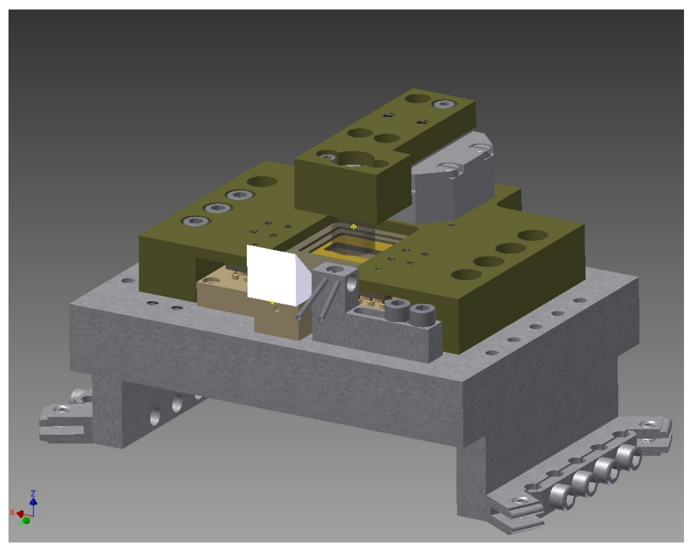
g = 60 MHz
κ = 160 MHz
γ_{Yb}=10 MHz

- Alignment is critical, mirror needs to be positioned to better than 1mm in all directions
- ≥70% collection efficiency expected in a practical system

Planar-concave cavity

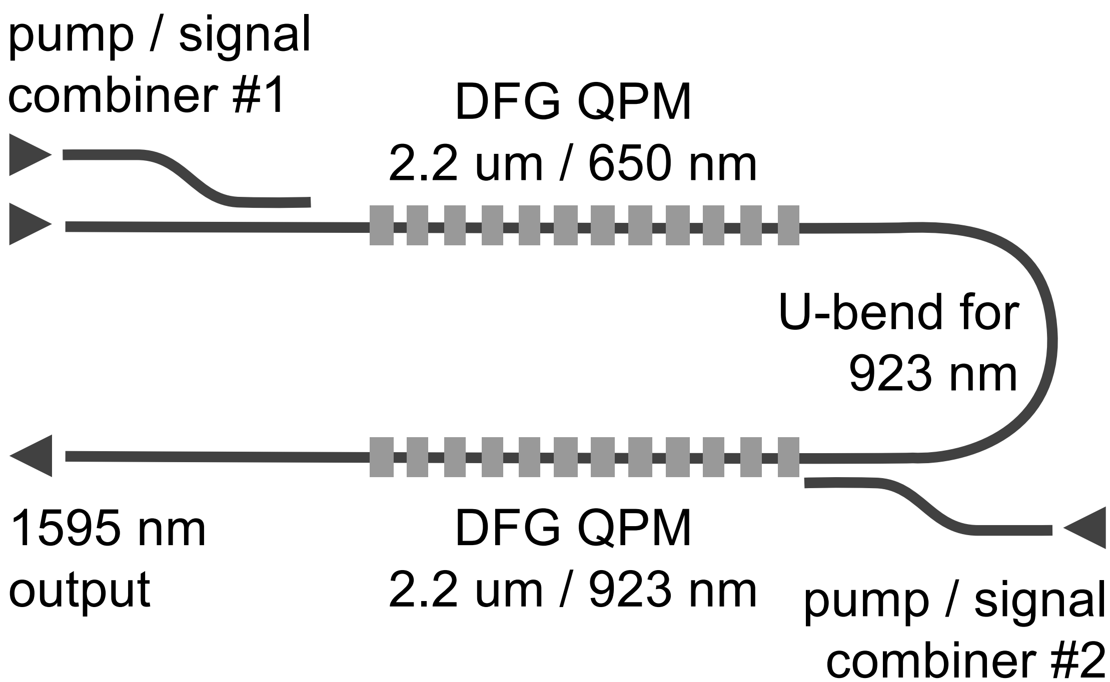






Fully Integrated Wavelength Conversion

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



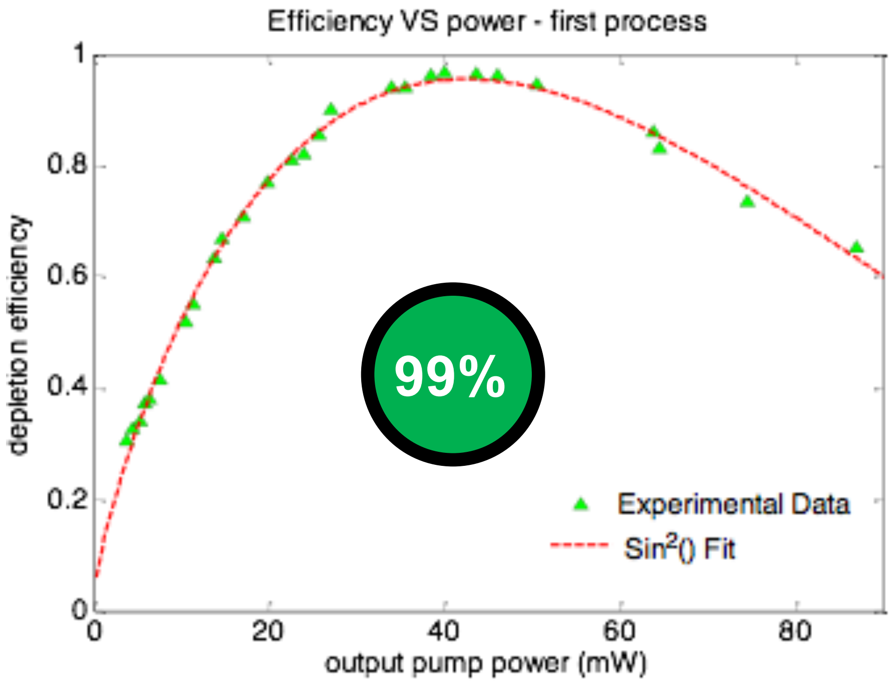
Double-pass configuration w/ integrated U-bend & WDMs

Fully Integrated Wavelength Conversion

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

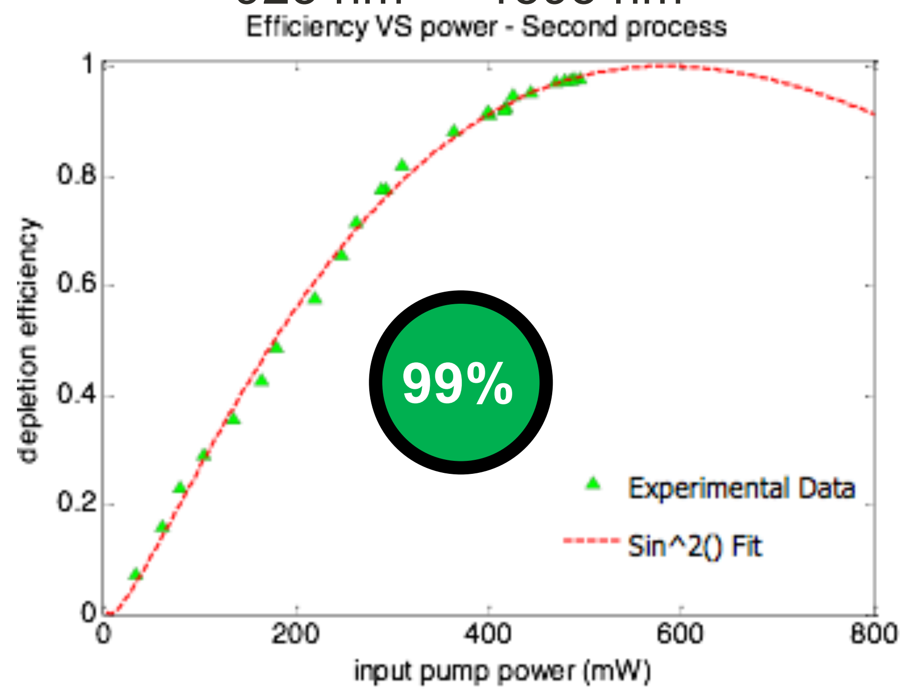
DFG-A

650 nm → 923 nm



DFG-B

923 nm → 1595 nm



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

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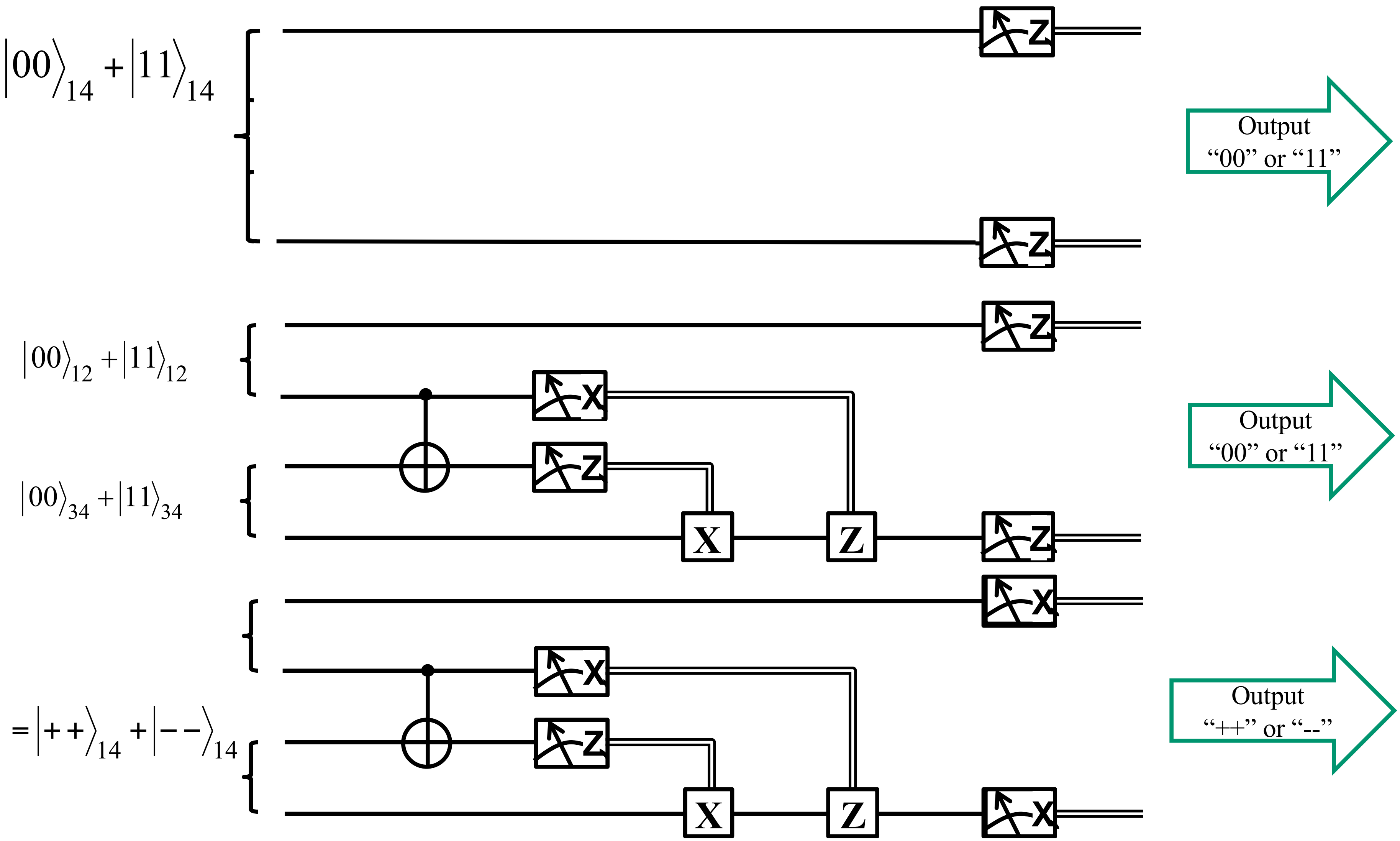
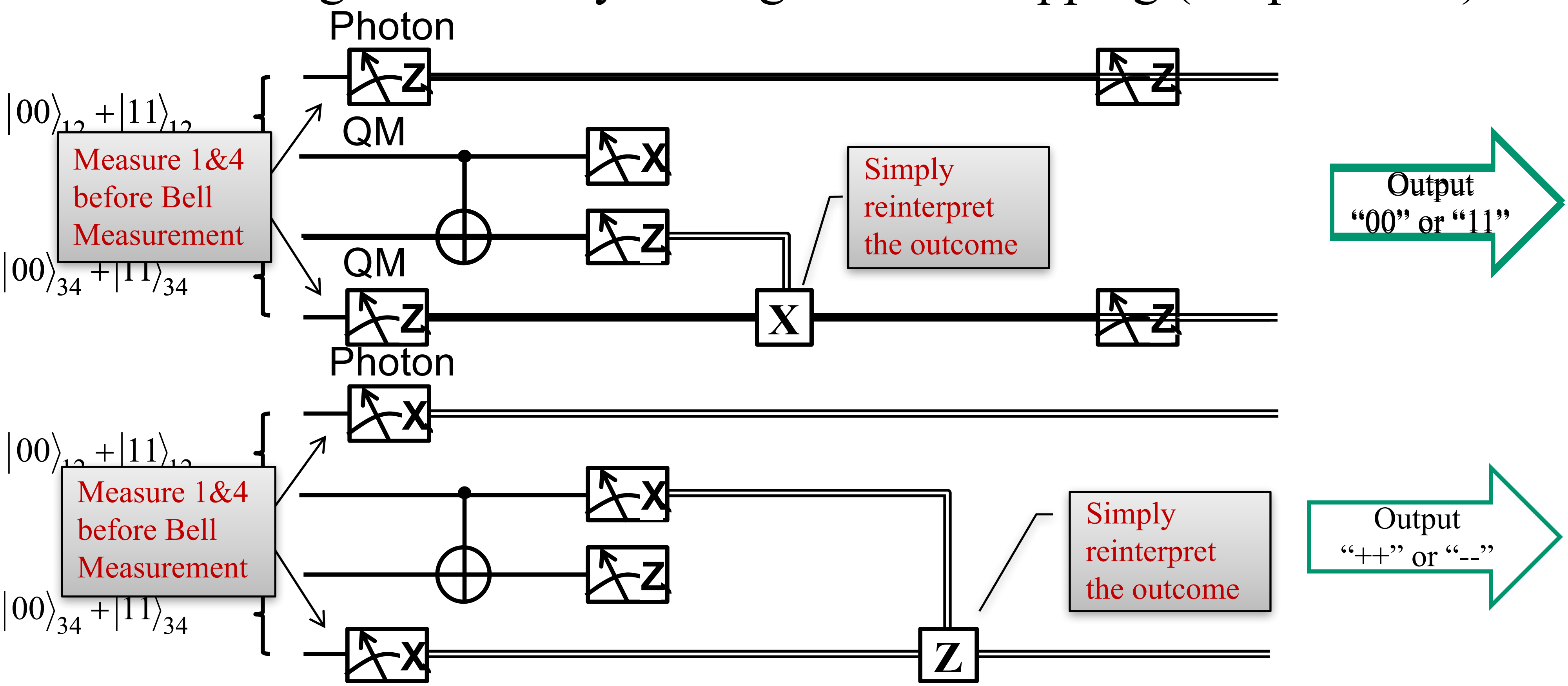
"Inverted" MA-MDI-QKD (Jiang, Lütkenhaus)

- Entanglement-based QKD (Ekert '92)



“Inverted” MA-MDI-QKD (Jiang, Lütkenhaus)

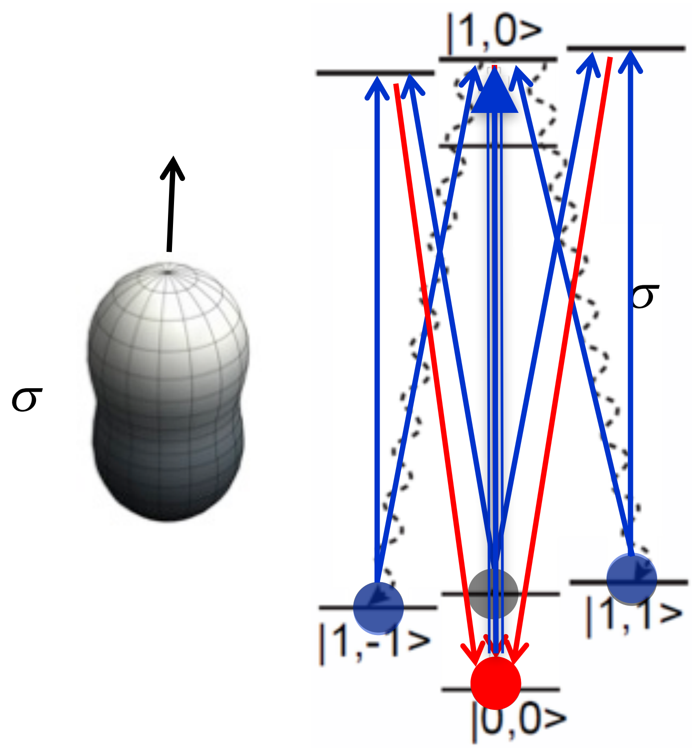
- Entanglement-based QKD (Ekert ’92)
- Extending the reach by Entanglement Swapping (teleportation)



- Initial photon from QM-photon entanglement measured right away!!
- QM-QM entanglement generation NOT required!!

Trapped Ion Implementation

- Qubit Choice
  - Photonic Qubit: polarization (easy analysis)
  - Atomic Qubit: Zeeman, converted to Clock-state

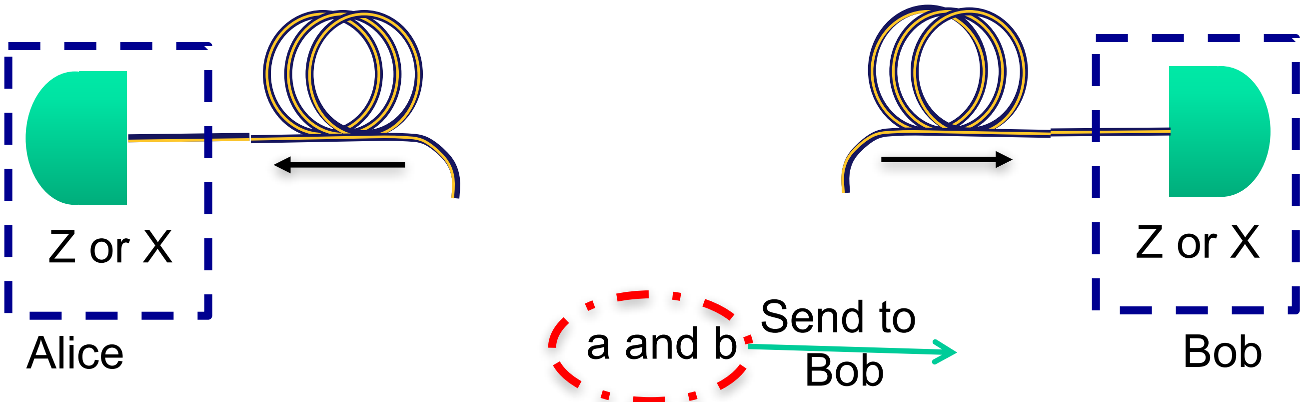


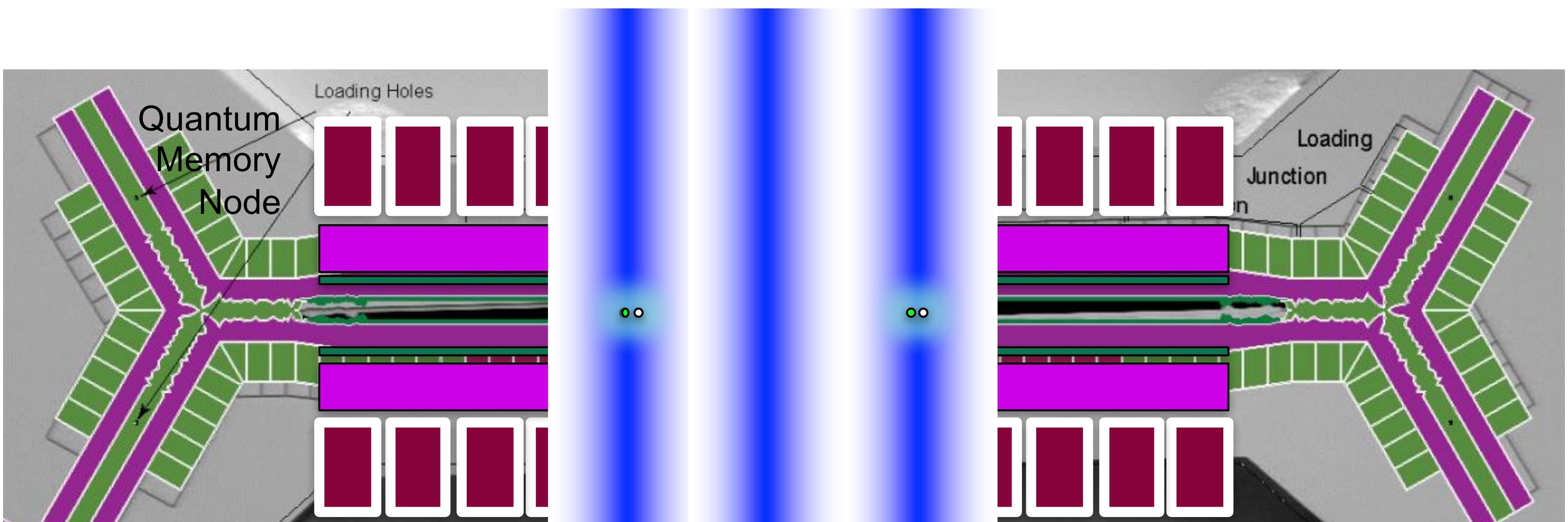
Polarization qubit

Experimental Order

1. Initialization (optical pumping)
2. Fast pump to excited state
3. Collect σ polarization light
4. Photon polarization-Zeeman state entanglement
5. Analyze photon polarization
6. Map Zeeman qubits to clock-state qubits (Individual ions)
7. Analyze atomic states

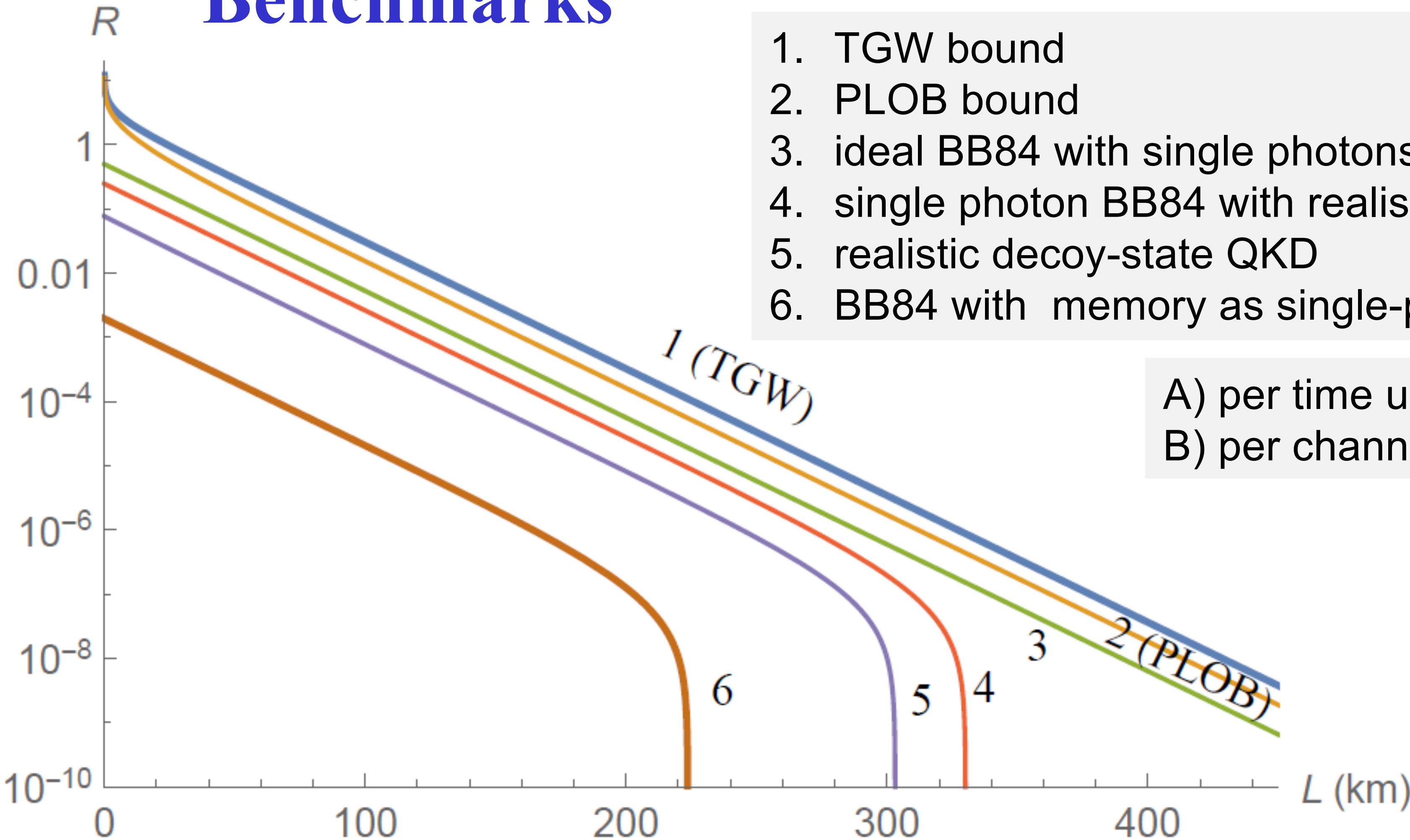
Experimental Procedure





Estimated Performance

Benchmarks



1. TGW bound
2. PLOB bound
3. ideal BB84 with single photons
4. single photon BB84 with realistic detectors
5. realistic decoy-state QKD
6. BB84 with memory as single-photon source.

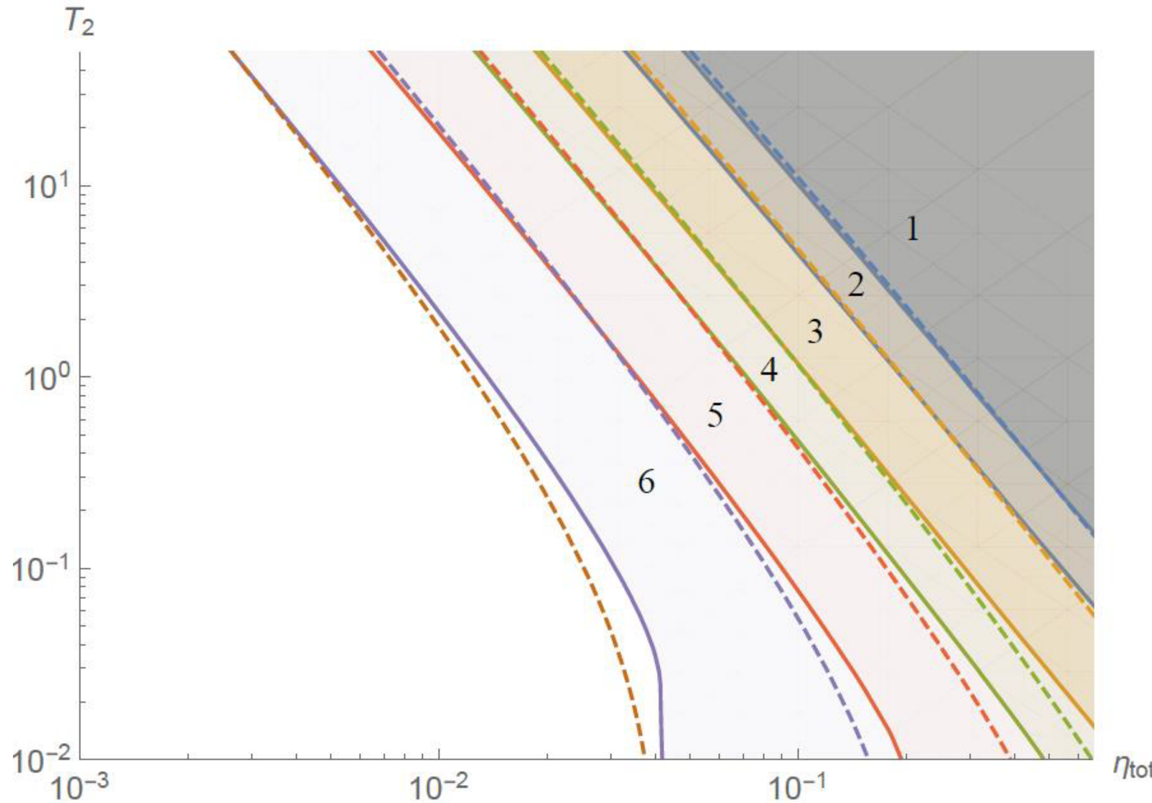
A) per time unit
B) per channel use

Luong, Jiang, Kim, Lütkenhaus, Appl. Phys B 122, 96 (2016)

Estimated Performance

Realistic Experimental Parameters

- η_p (preparation efficiency) $= 0.66$
- T_p (preparation time) $= 100\ \mu s$
- η_c (coupling efficiency) $= 0.04$
- T_2 (dephasing time) $= 1$ s
- c (speed of light in channel) $= 2 \times 10^5$ km/s
- L_{att} (attenuation length) $= 22$ km
- e_{mA} (misalignment error) $= e_{mB} = 0.01$
- p_d (dark count probability) $= 10^{-8}$
- η_d (detector efficiency) $= 0.3$
- p_{BSM} (BSM success probability) $= 1$
- λ_{BSM} (BSM noise parameter) $= 0.97$
- f (error correction inefficiency) $= 1.16$



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Conclusions

- Trapped ion platform is a compelling candidate for realizing quantum repeaters
  - Good memory-photon interface
  - "Full blown" quantum computer with deterministic gate operations is available
  - Performance enhancement efforts are on the way
- Demonstration of "useful" quantum repeater remains a challenge, yet within reach!!
  - Overall system efficiencies need dramatic improvements
  - Necessary technologies are under development
  - System integration will require substantial effort

Team and Collaboration

- Duke Team
  Peter Maunz
  Taehyun Kim
  So-Young Baek
  Kai Hudek
  Rachel Noek
  Emily Mount
  Daniel Gaultney
  Stephen Crain
  Caleb Knoernschild
  Andre van Rynbach
  Geert Vrijsen
  Yuhi Aikyo
  Clinton Cahall
  Chao Fang
  Robert "Tripp" Spivey
  George Schwartz
  Sarah Brandsen
  Seo Ho Youn
  Jinhyun Cho
  Kyle McKay
  Hui Son
  Ryan Clark
  Muhammed Ahsan
  John Montoya

- University of Maryland
  Chris Monroe
  Jonathan Mizrahi
  Marko Cetina
  Jason Amini
  Norbert Linke
  Ken Wright
  Shantanu Debnath
  Kale Johnson
  David Wong-Campos
  David Hucul
  Volkan Inlek
  Aaron Lee

- University of Waterloo
  Norbert Lütkenhaus
  David Luong
  Ryo Namiki
  Filippo Miato

- Yale University
  Liang Jiang
  Sre Muralidharan
  Linshu Li

- Stanford University
  Martin Fejer
  Carsten Langrock
  Vahid Esfandyarpour

- Sandia National Labs
  Peter Maunz
  Christian Arrington
  Drew Hollowell

- NIST
  Sae Woo Nam
  Varun Verma

- JPL
  Matthew Shaw
  Francesco Marsili
  Emma Wollman

Duke UNIVERSITY

The Laboratory for Physical Sciences

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