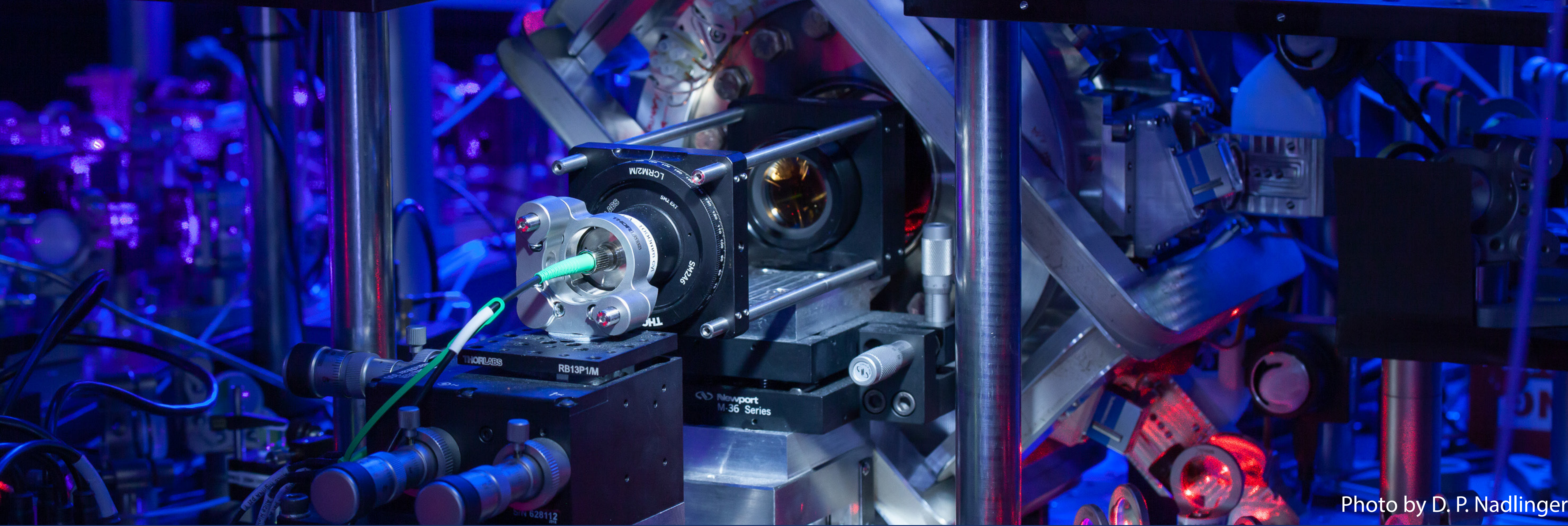
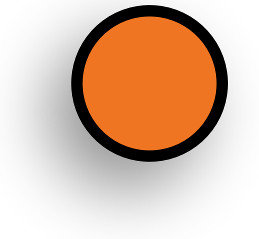


Photo by D. P. Nadlinger

Distributed Quantum Computing across an Optical Network Link

Dougal Main
University of Oxford
Oxford Ion Trap Group

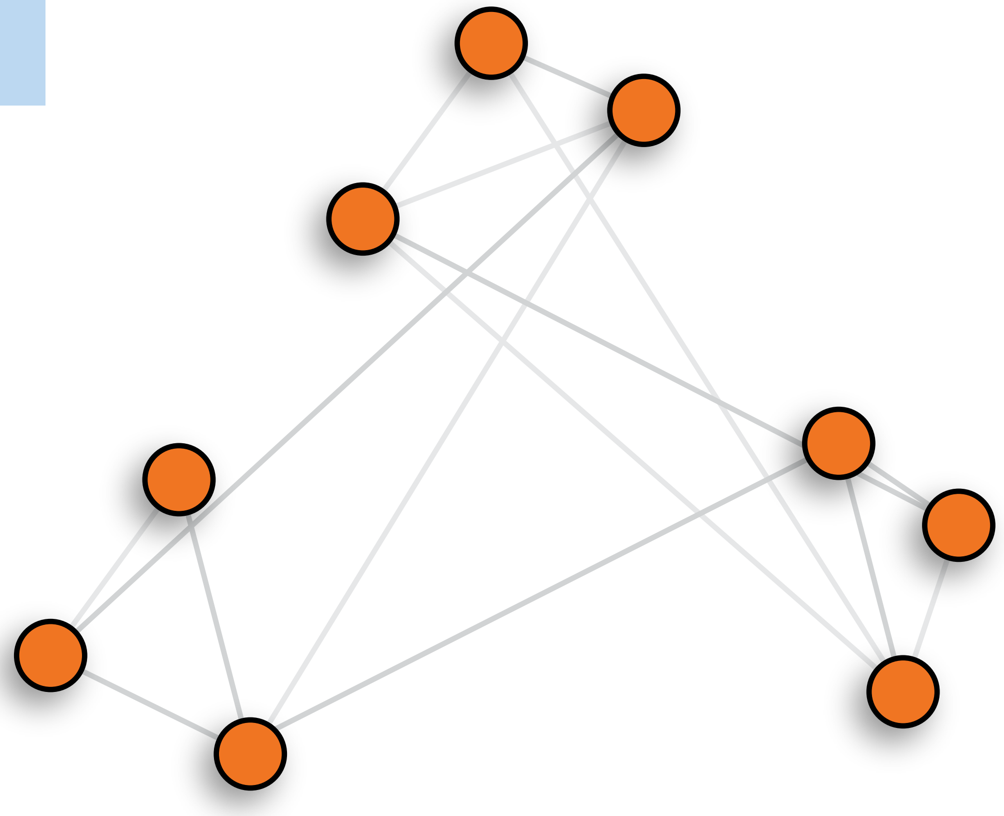
Distributed Quantum Computing



Distributed Quantum Computing

Distributed Quantum Computing

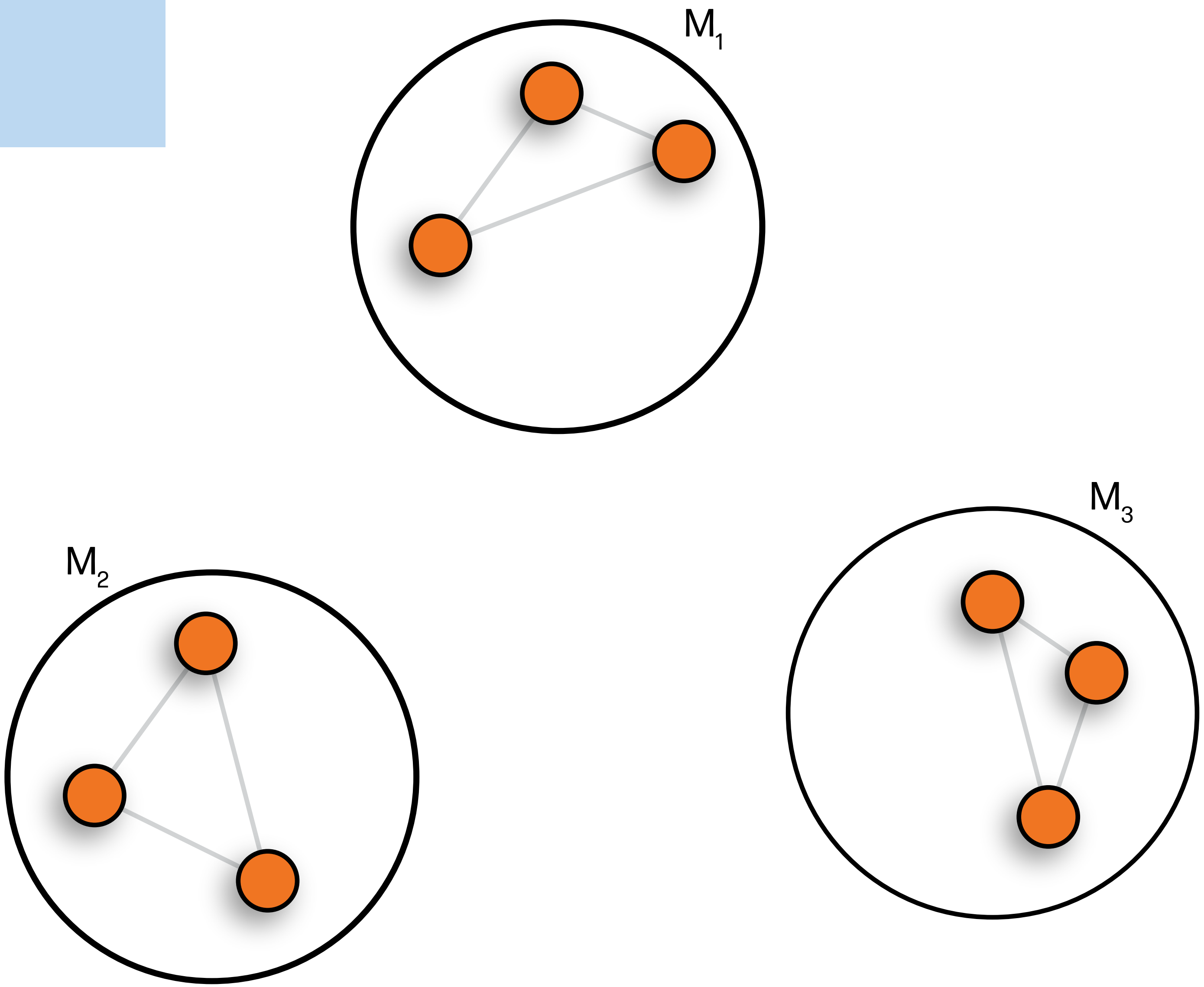
Problem: Scaling up comes with major technical challenges



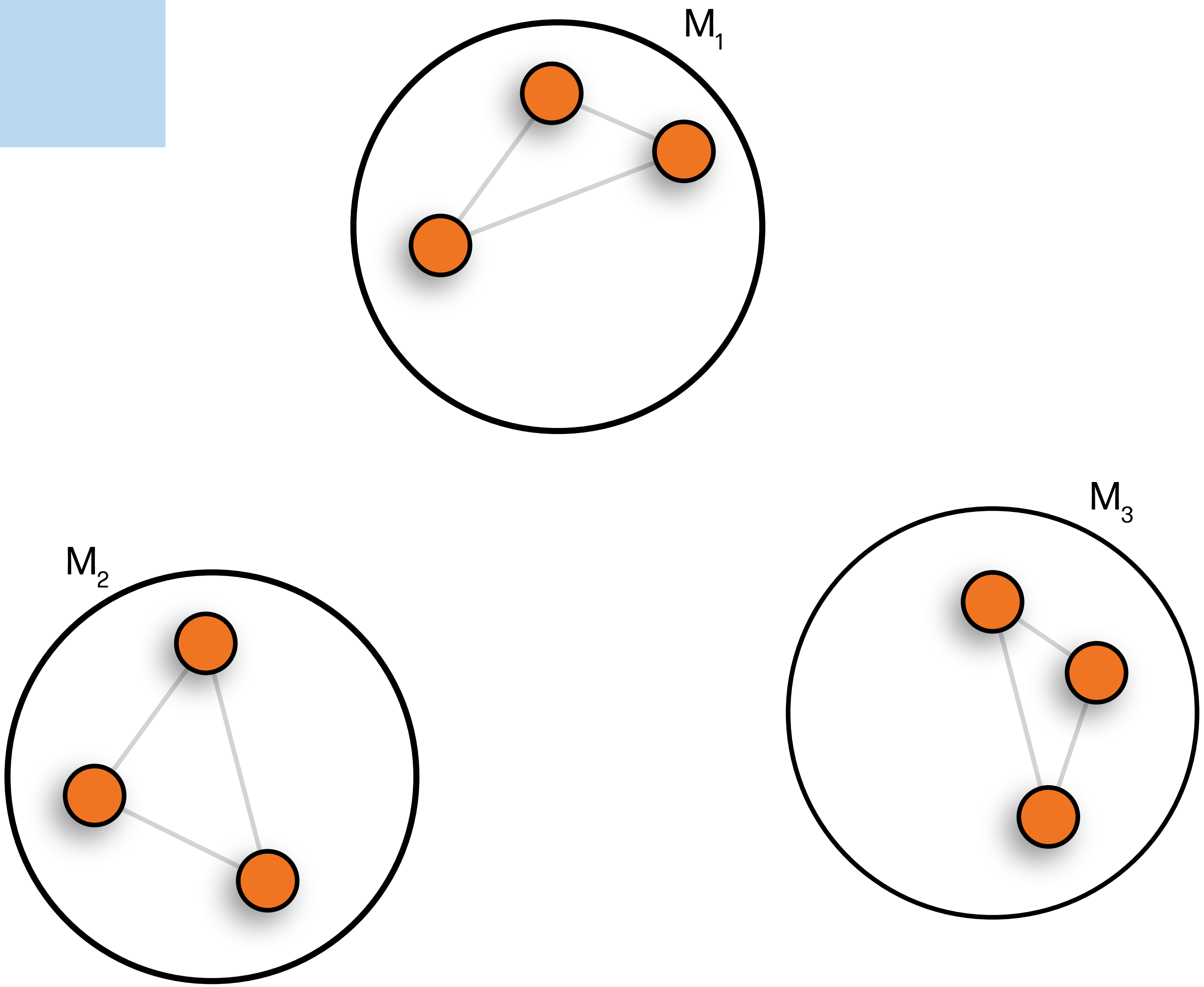
Distributed Quantum Computing

Problem: Scaling up comes with major technical challenges

Solution: Distributed quantum computing architecture



Interfacing Modules



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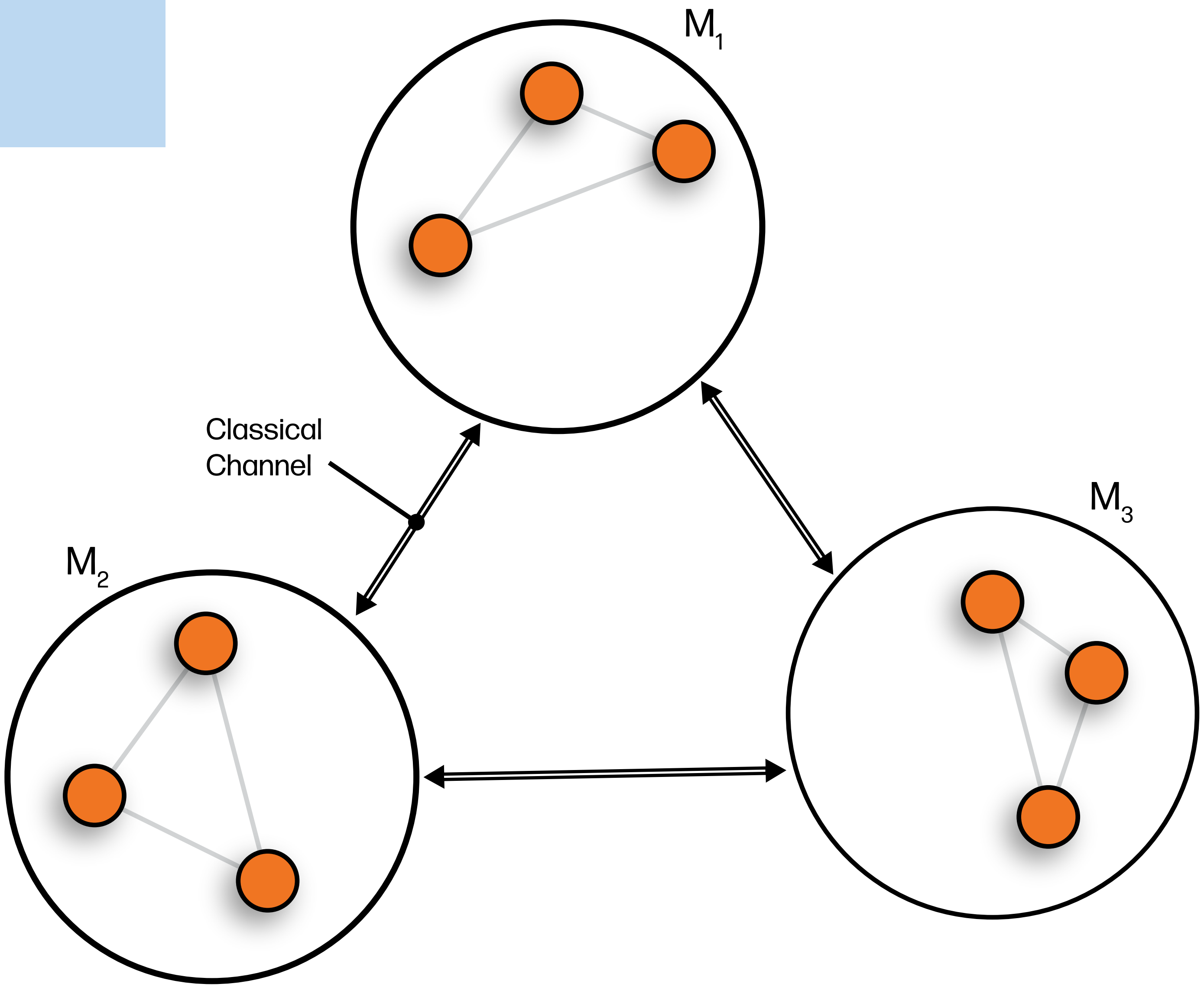

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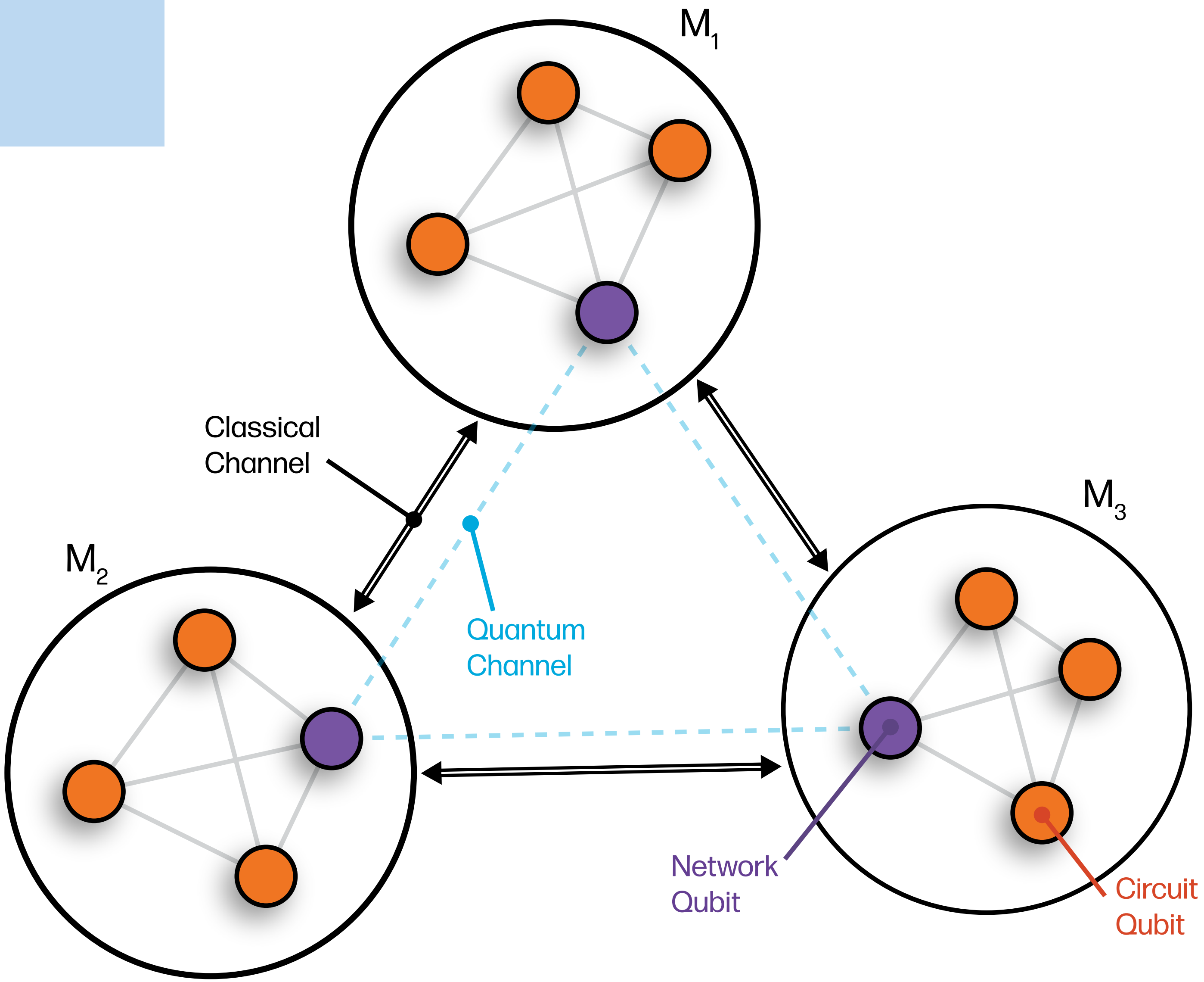
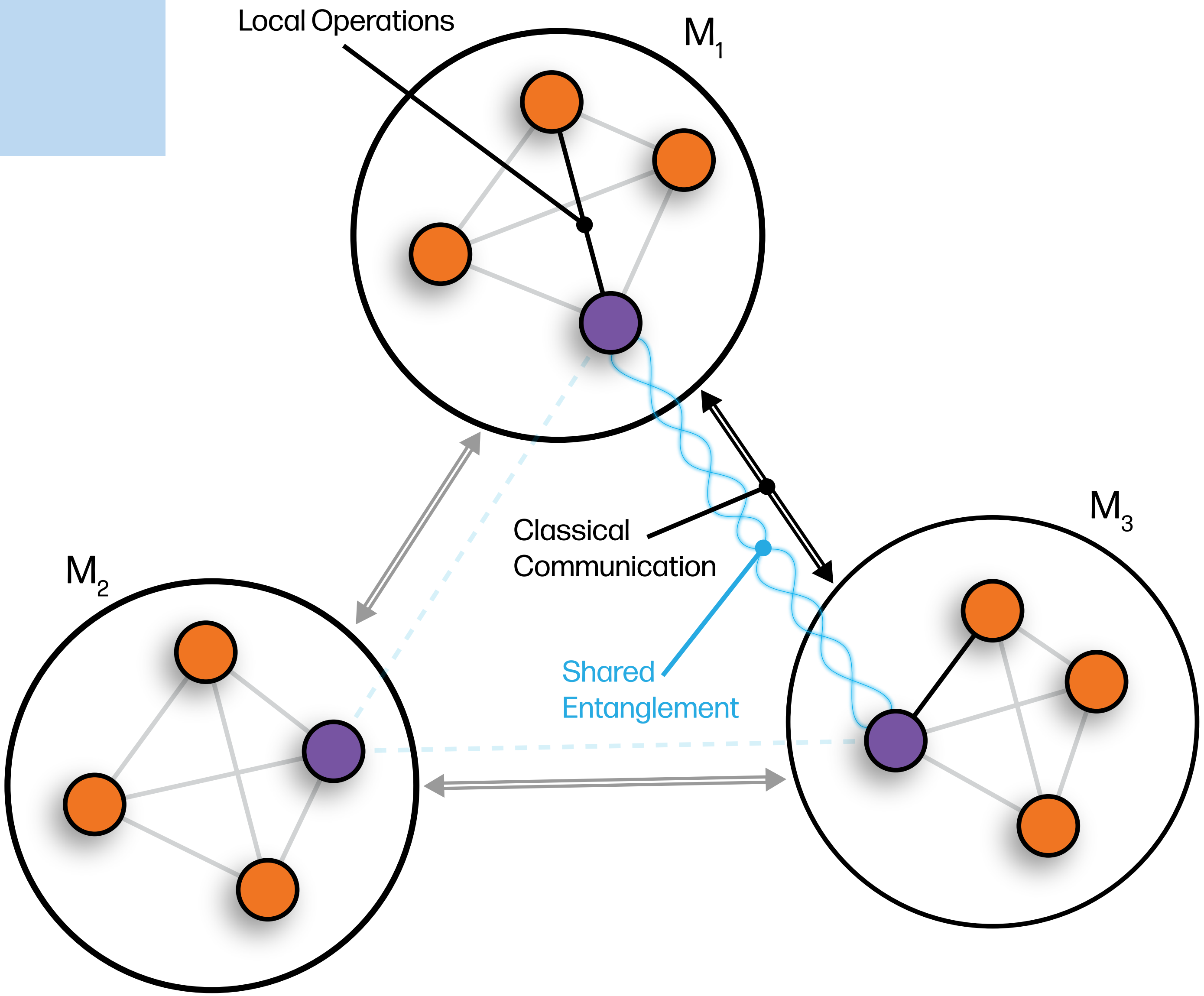


Interfacing Modules

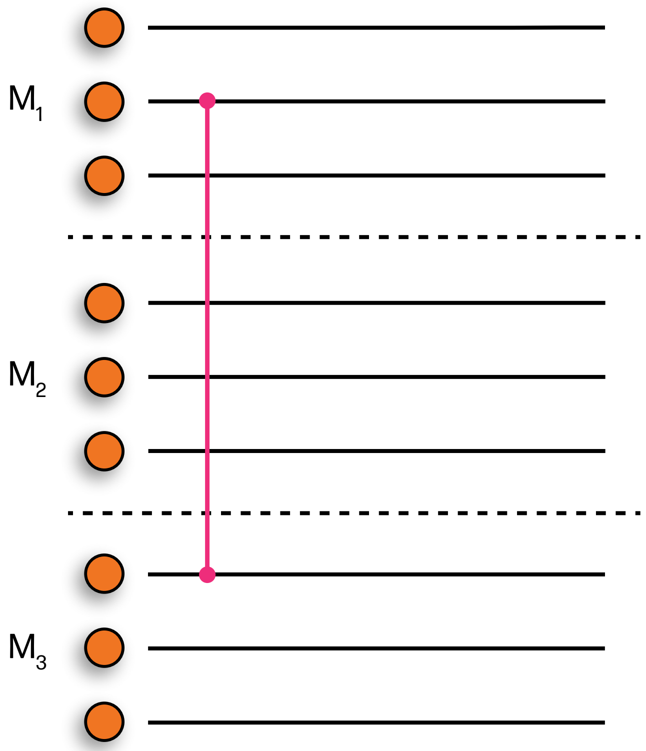
Quantum teleportation protocols are characterised by the resources:

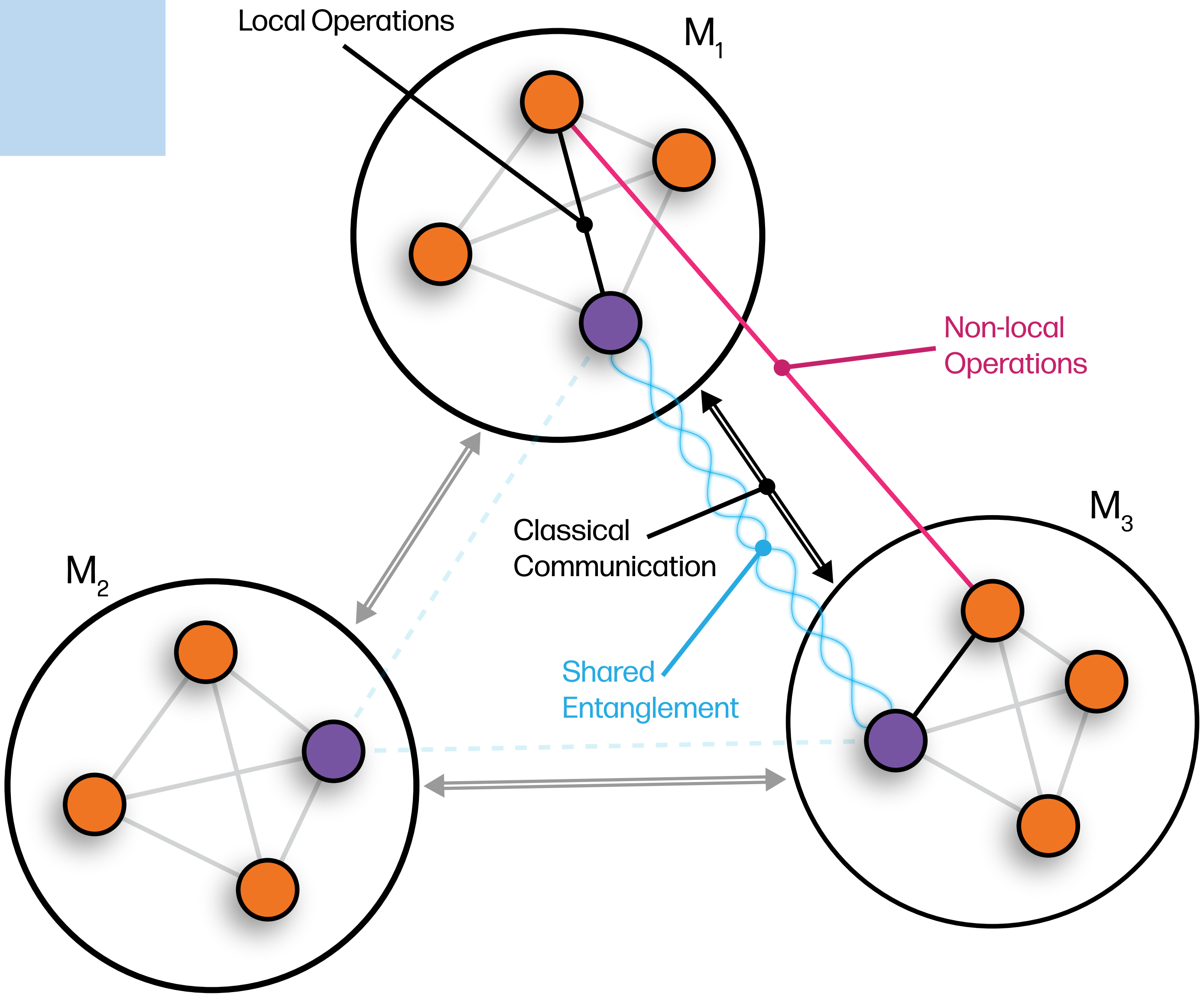
- **shared entanglement**
- **local operations** and **classical communication** (LOCC)



Quantum Gate Teleportation

Quantum gate teleportation enables the mediation of **logical gates** between qubits that **cannot directly interact**





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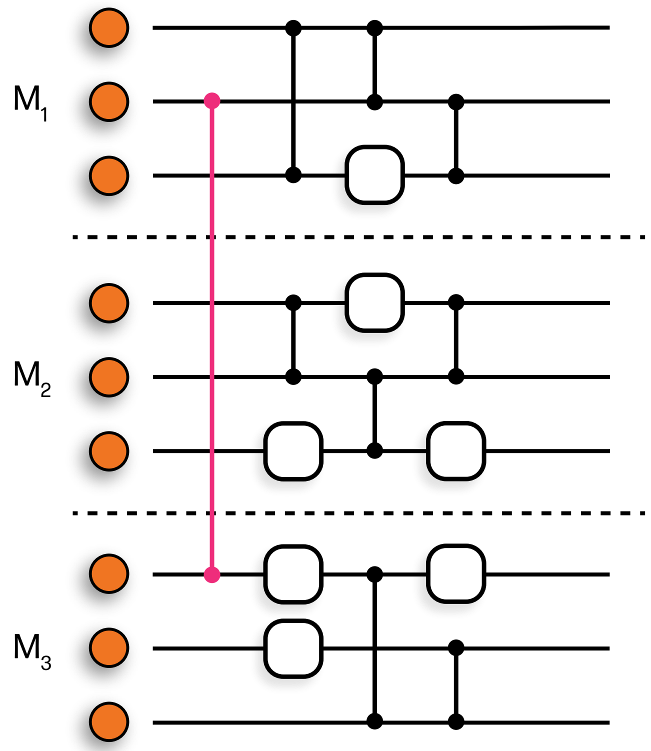

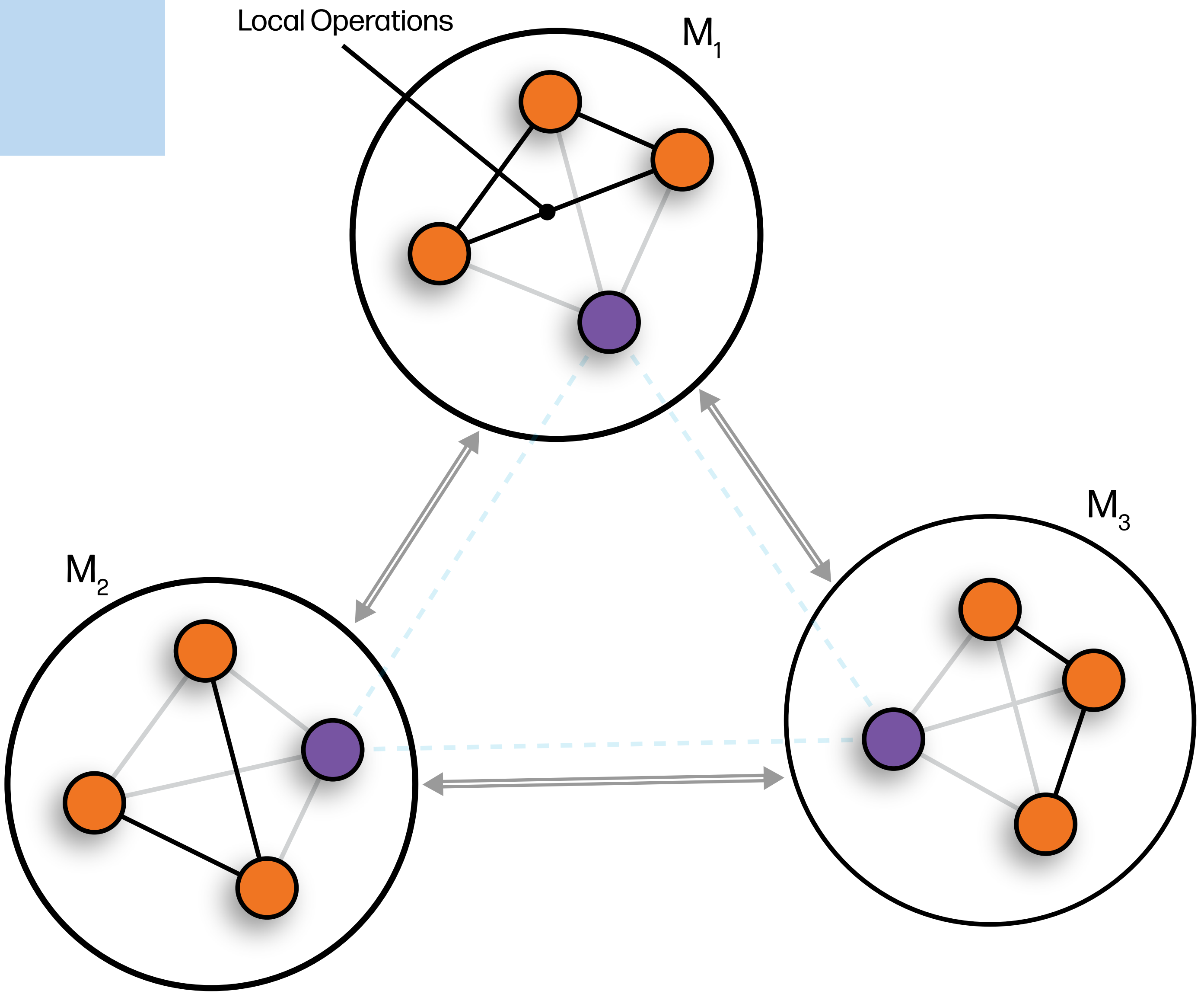

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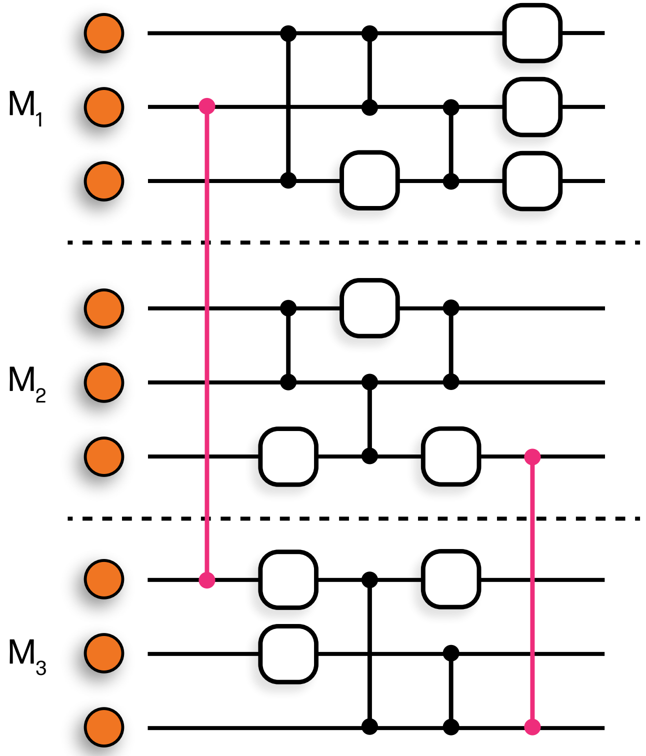

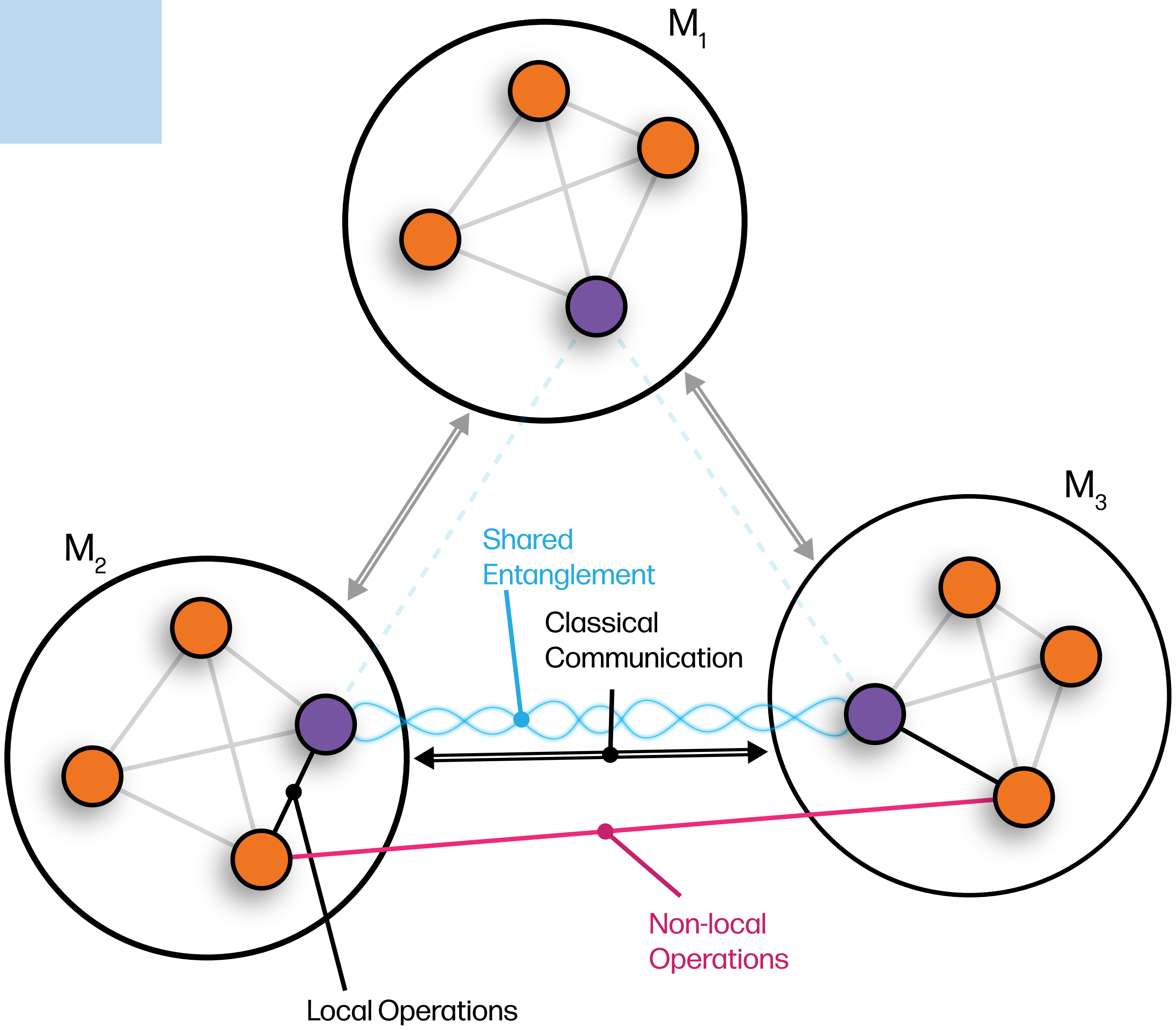

Experimental Demonstrations of QGT

Experimental Demonstrations of QGT

Purely photonic demonstrations

Fidelity: 84%

Experimental Teleportation of a Quantum Controlled-NOT Gate

Yun-Feng Huang,[1] Xi-Feng Ren,[1] Yong-Sheng Zhang,[1] Lu-Ming Duan,[2,1] and Guang-Can Guo[1]
[1]*Laboratory of Quantum Information, University of Science and Technology of China, Hefei, Anhui 230026, Peoples Republic of China*
[2]*Department of Physics and FOCUS Center, University of Michigan, Ann Arbor, Michigan 48109, USA*
(Received 2 August 2004; published 6 December 2004)

Teleportation-based realization of an optical quantum two-qubit entangling gate

Wei-Bo Gao[a,1], Alexander M. Goebel[b,1], Chao-Yang Lu[a,1], Han-Ning Dai[a], Claudia Wagenknecht[b], Qiang Zhang[a], Bo Zhao[a], Cheng-Zhi Peng[a], Zeng-Bing Chen[a], Yu-Ao Chen[a,2], and Jian-Wei Pan[a,b,2]

Experimental Demonstrations of QGT

Purely photonic demonstrations

Fidelity: 84%

Non-deterministic ✗

No memory for output states ✗

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Experimental Demonstrations of QGT

Superconducting cavities

Fidelity: 79(2)%

Circuit qubit separation: ~ 2 cm

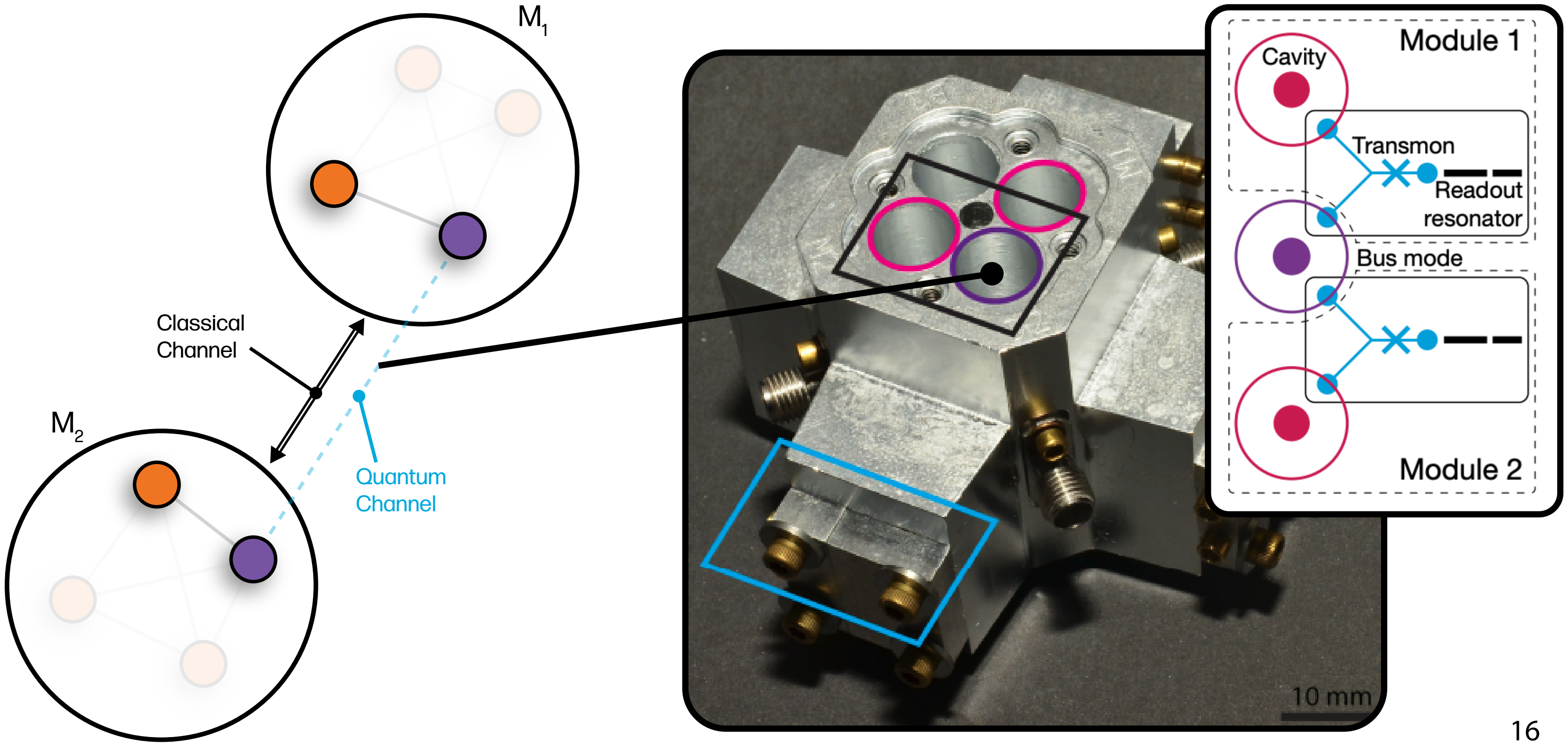
Circuit qubits within the **same device**

Deterministic ✓

Limited to a **single** teleported gate ✗

Deterministic teleportation of a quantum gate between two logical qubits

Kevin S. Chou[1,2]*, Jacob Z. Blumoff[1,2,3], Christopher S. Wang[1,2], Philip C. Reinhold[1,2], Christopher J. Axline[1,2], Yvonne Y. Gao[1,2], L. Frunzio[1,2], M. H. Devoret[1,2], Liang Jiang[1,2] & R. J. Schoelkopf[1,2]*



Experimental Demonstrations of QGT

Quantum gate teleportation between separated qubits in a trapped-ion processor

YONG WAN, DANIEL KIENZLER, STEPHEN D. ERICKSON, KARL H. MAYER, TING REI TAN, JENNY J. WU, HILMA M. VASCONCELOS, SCOTT GLANCY, EMANUEL KNILL, DAVID J. WINELAND, ANDREW C. WILSON, AND DIETRICH LEIBFRIED fewer Authors Info & Affiliations

Trapped-ion QCCD

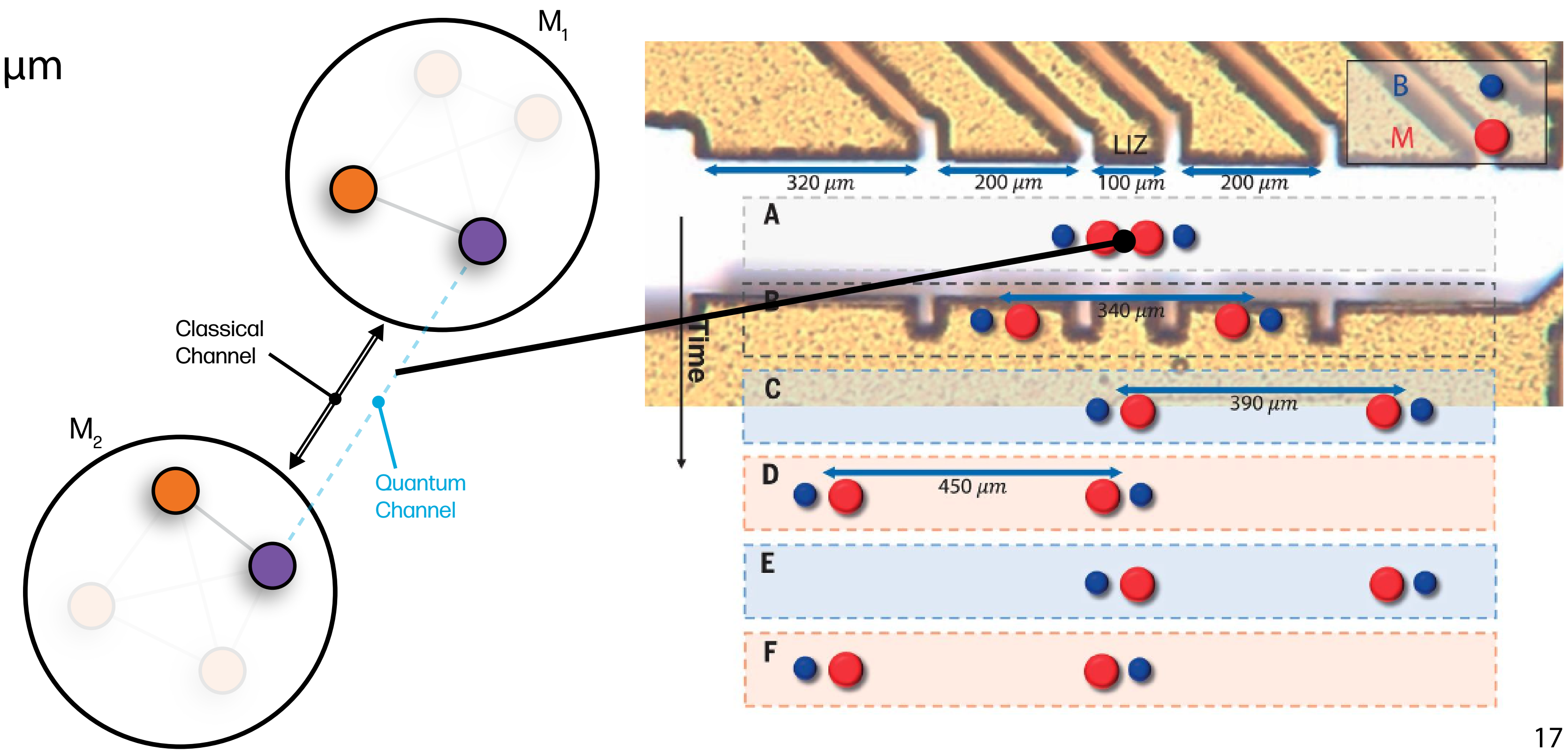
Fidelity: (0.845, 0.872)

Circuit qubit separation: ~ 340 μm

Circuit qubits within the **same device**

Deterministic ✓

Limited to a **single** teleported gate ✗



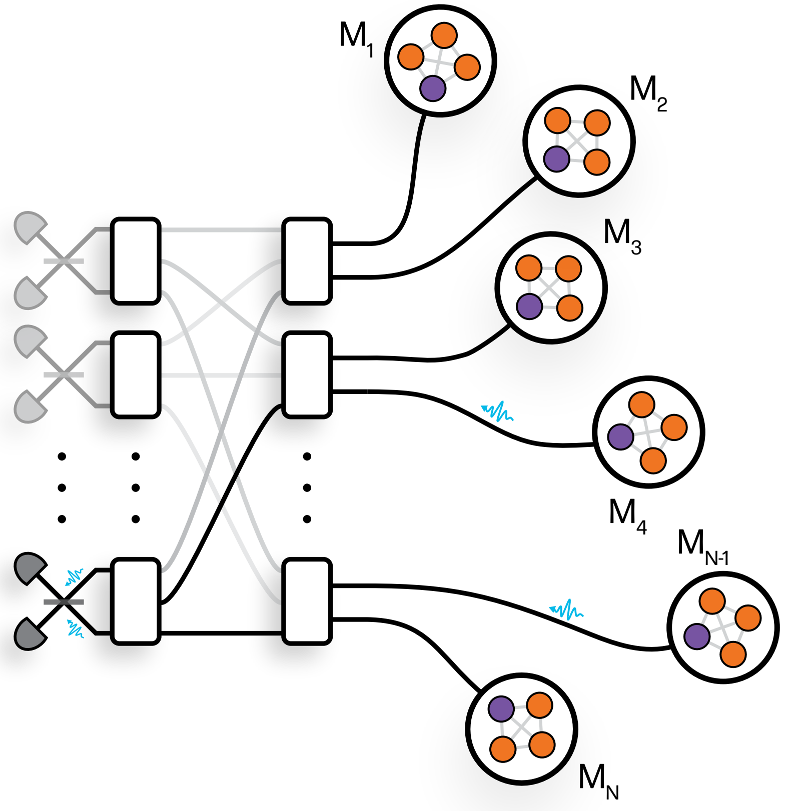
Photonic Quantum Networks

Photons make **natural carriers** of quantum information

Photonic Quantum Networks

Photons make **natural carriers** of quantum information

Photonic networks provide a **versatile** and **reconfigurable** interconnect layer for DQC



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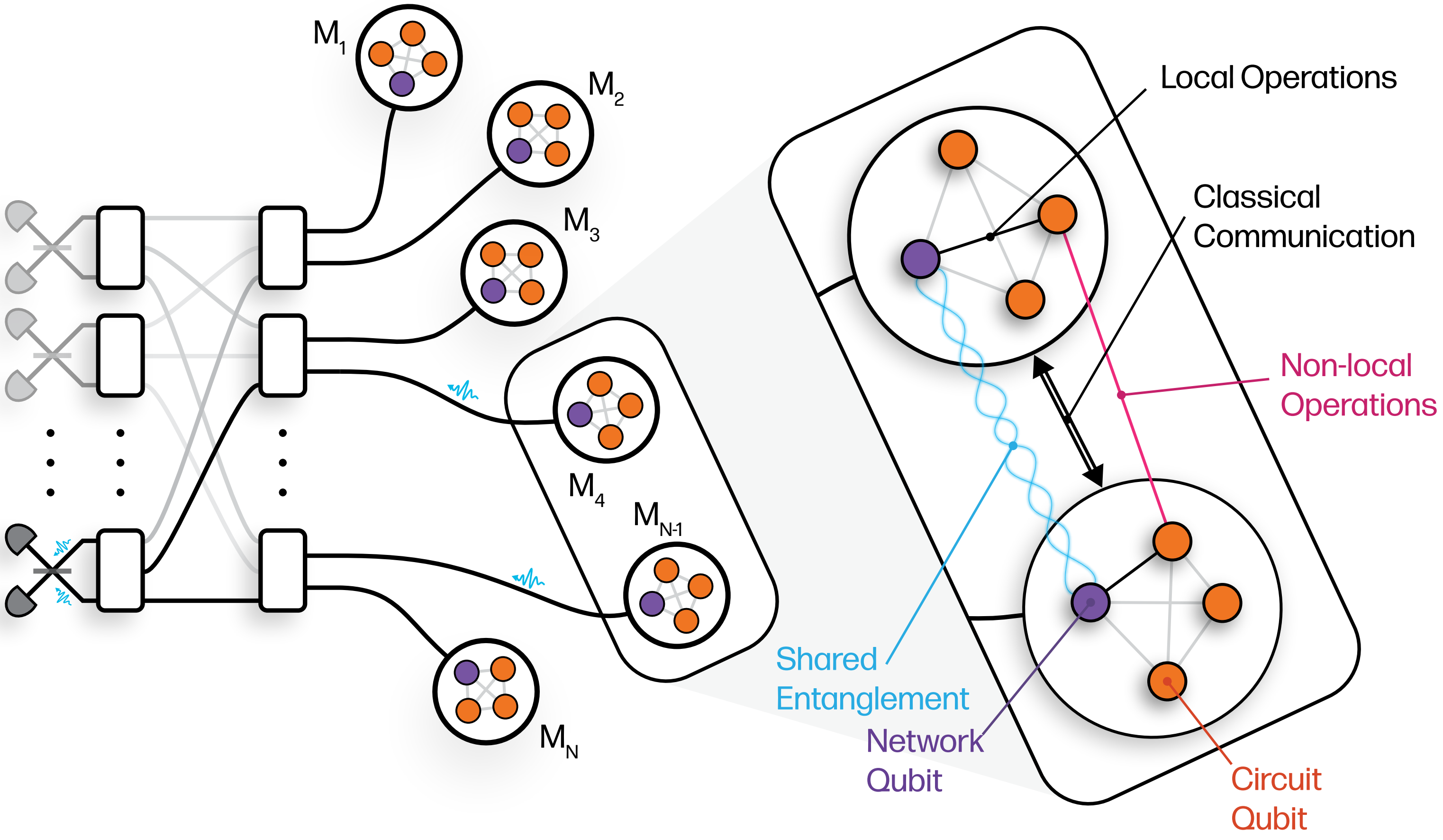

Our Work

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State-of-the-art quantum network

Experimental quantum key distribution certified by Bell's theorem

https://doi.org/10.1038/s41586-
Received: 29 September 2021
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An elementary quantum network of entangled optical atomic clocks

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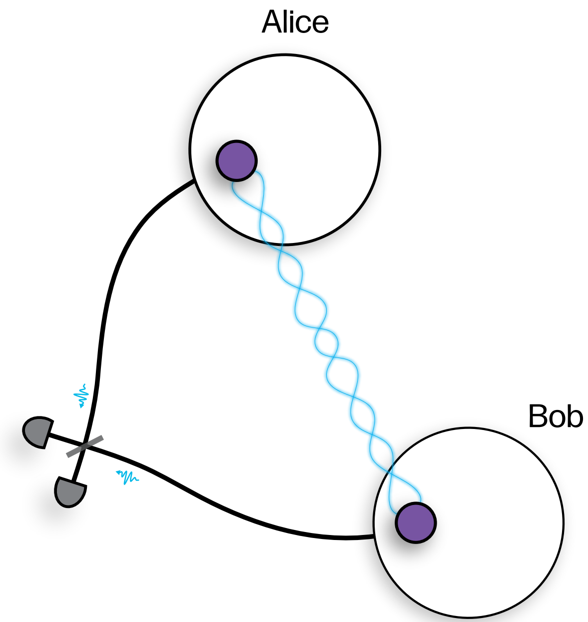
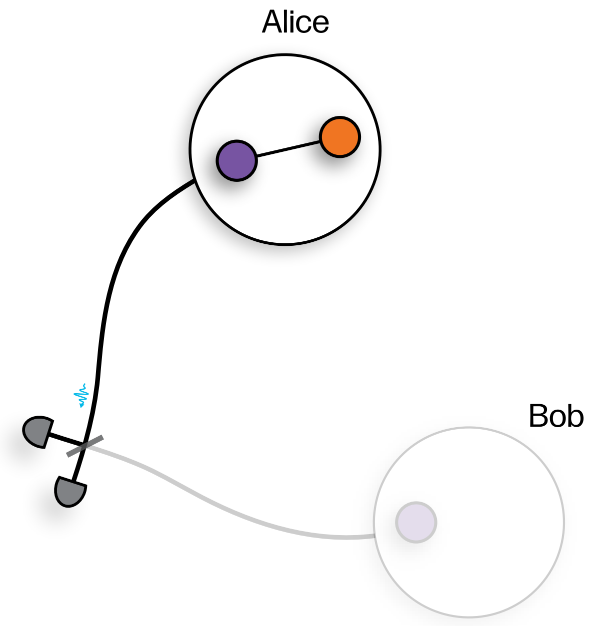


Our Work



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Robust quantum memory

Robust Quantum Memory in a Trapped-Ion Quantum Network Node

P. Drmota,* D. Main, D. P. Nadlinger, B. C. Nichol, M. A. Weber, E. M. Ainley, A. Agrawal,
R. Srini
Department of Physics, University

Verifiable blind quantum computing with trapped ions and single photons

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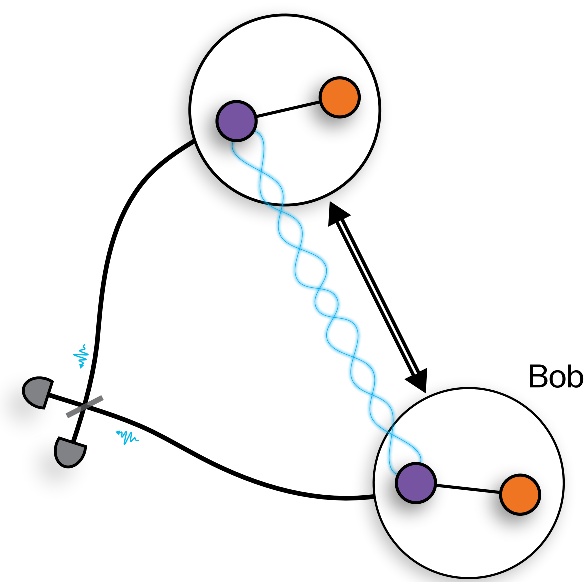

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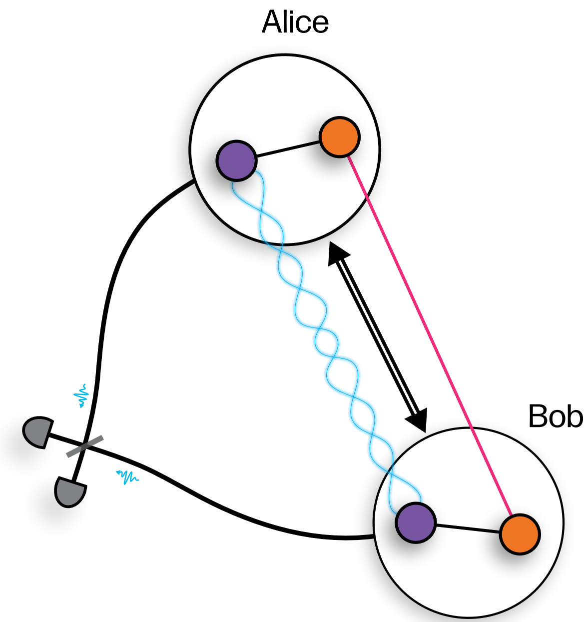
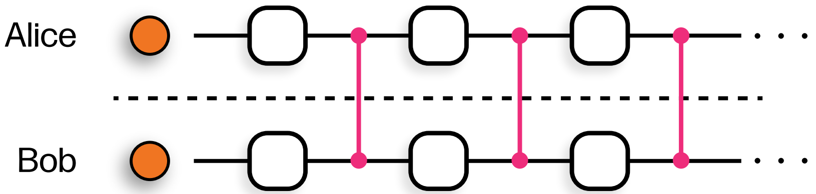
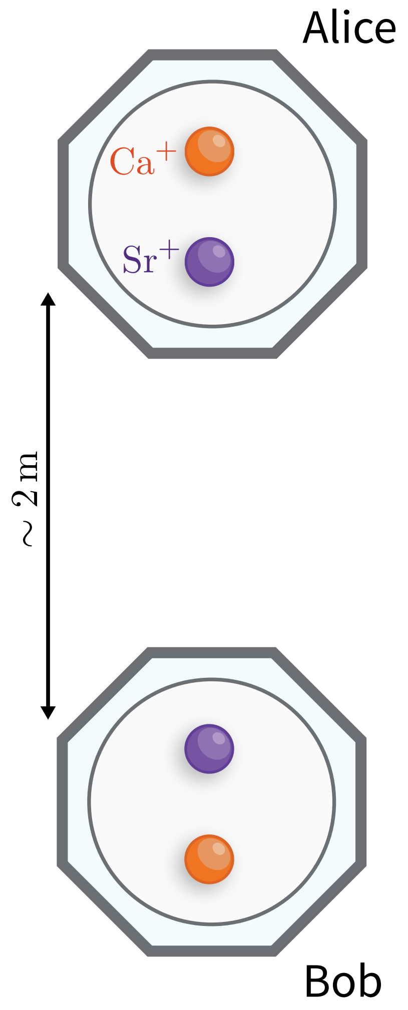
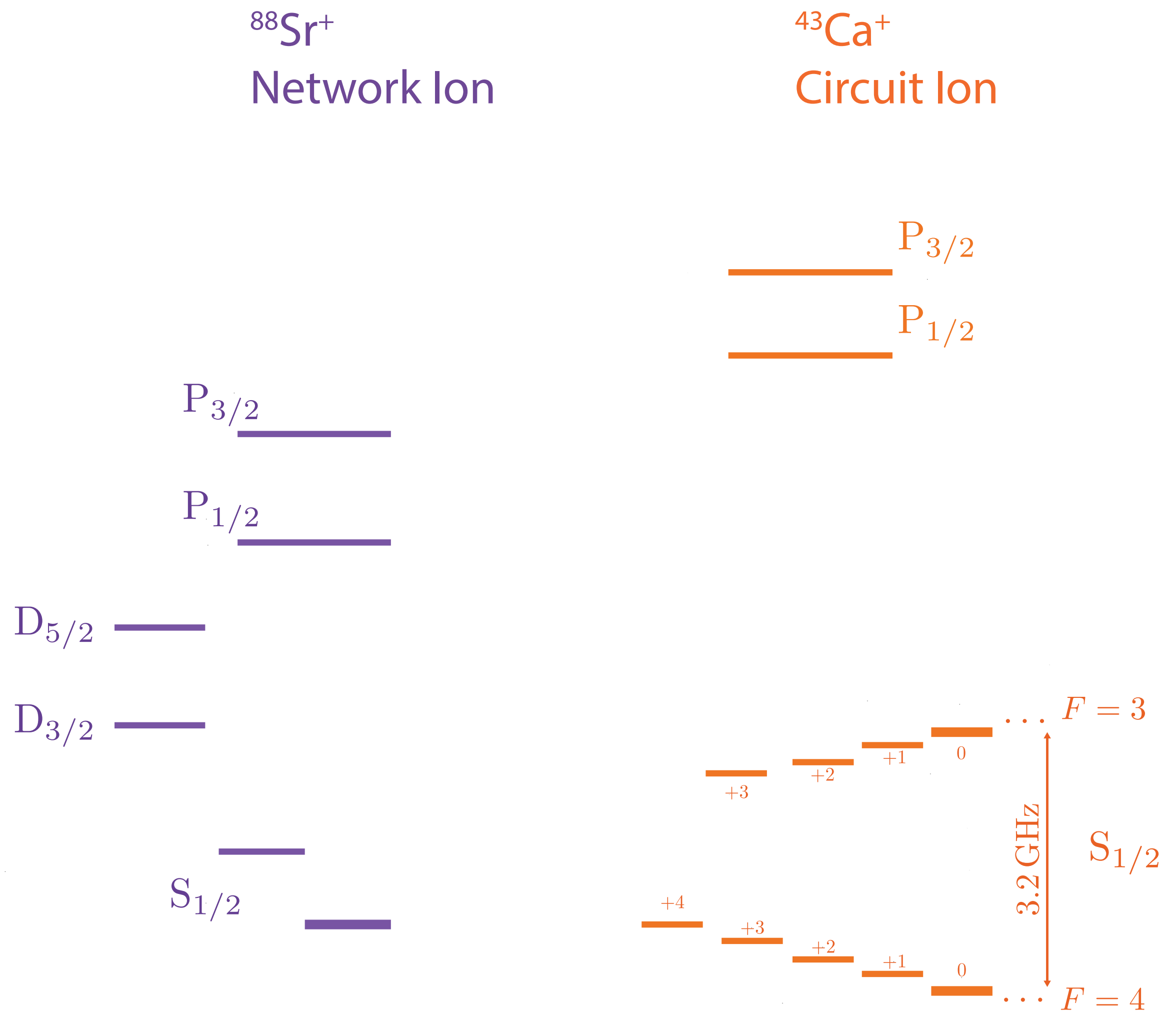




Quantum Gate Teleportation: Protocol





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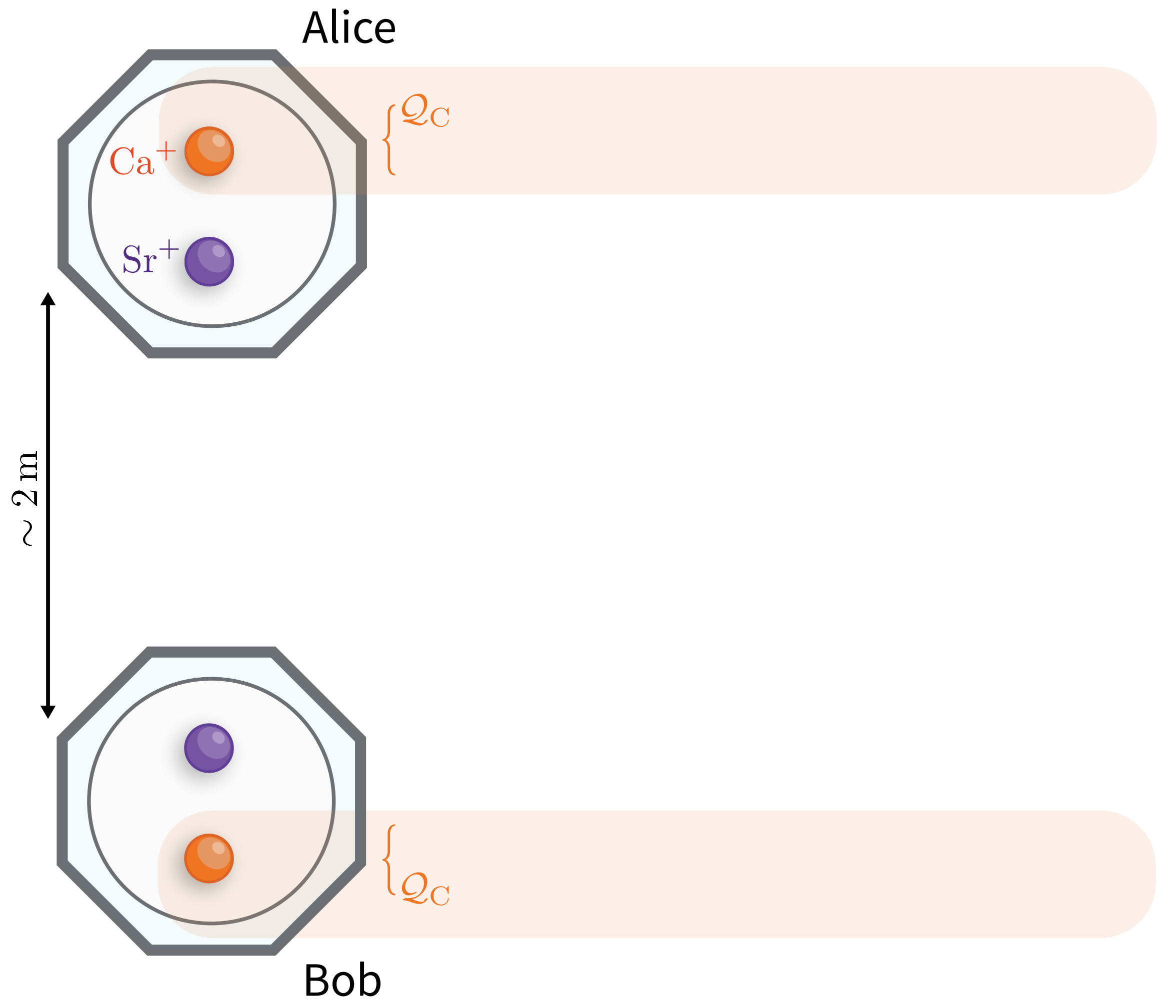

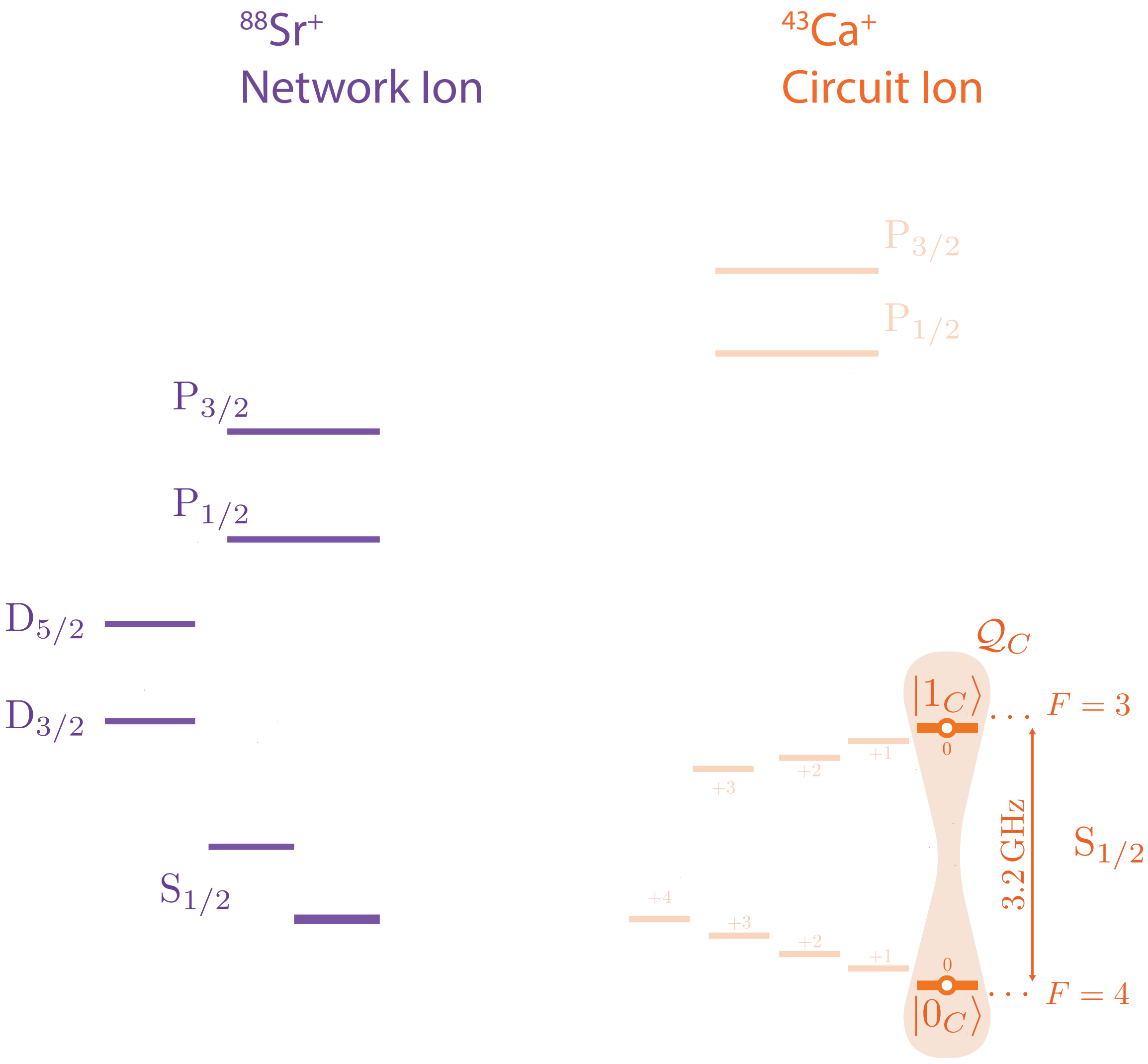

Input: $|\psi_C^{AB}\rangle \in \mathcal{Q}_C^{\otimes 2}$

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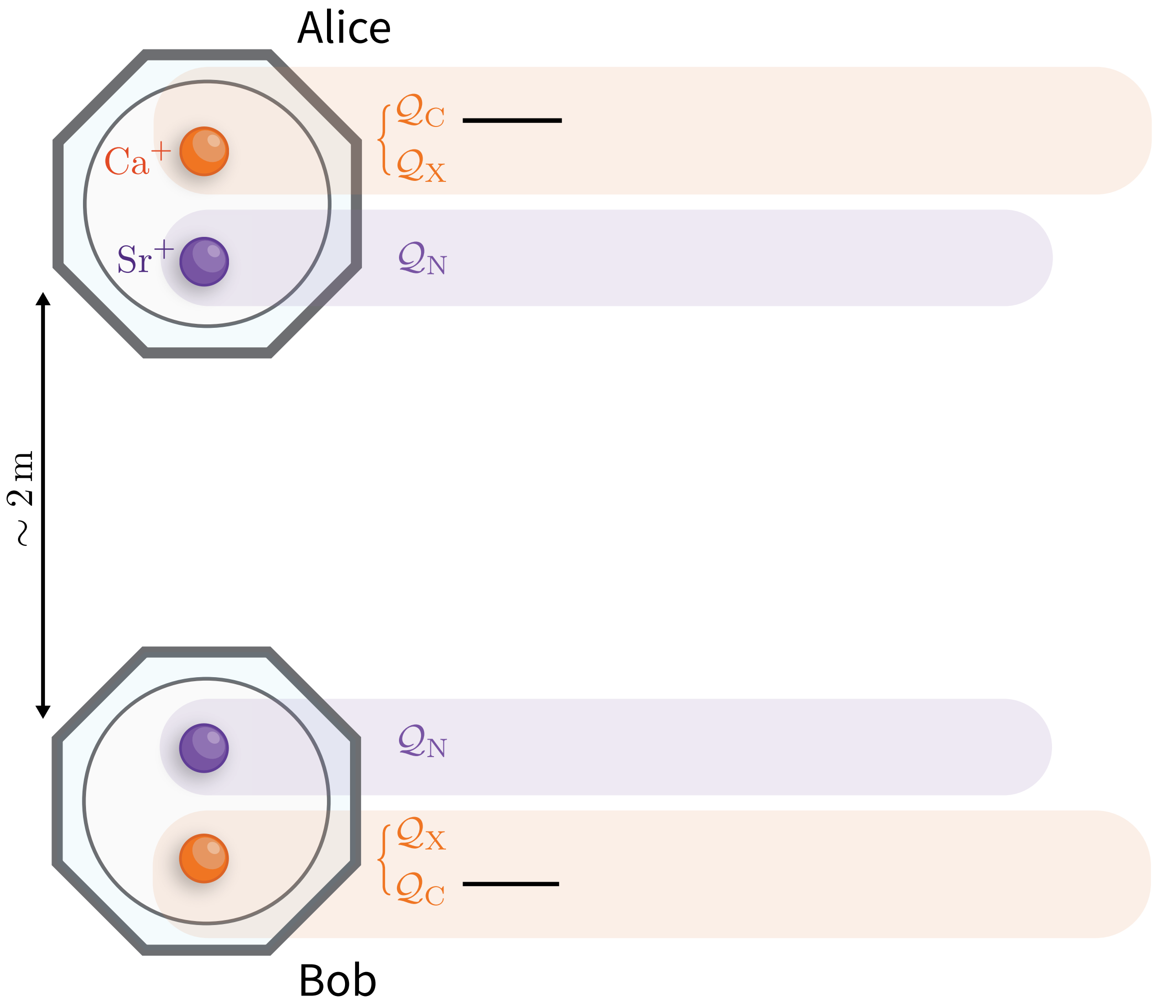

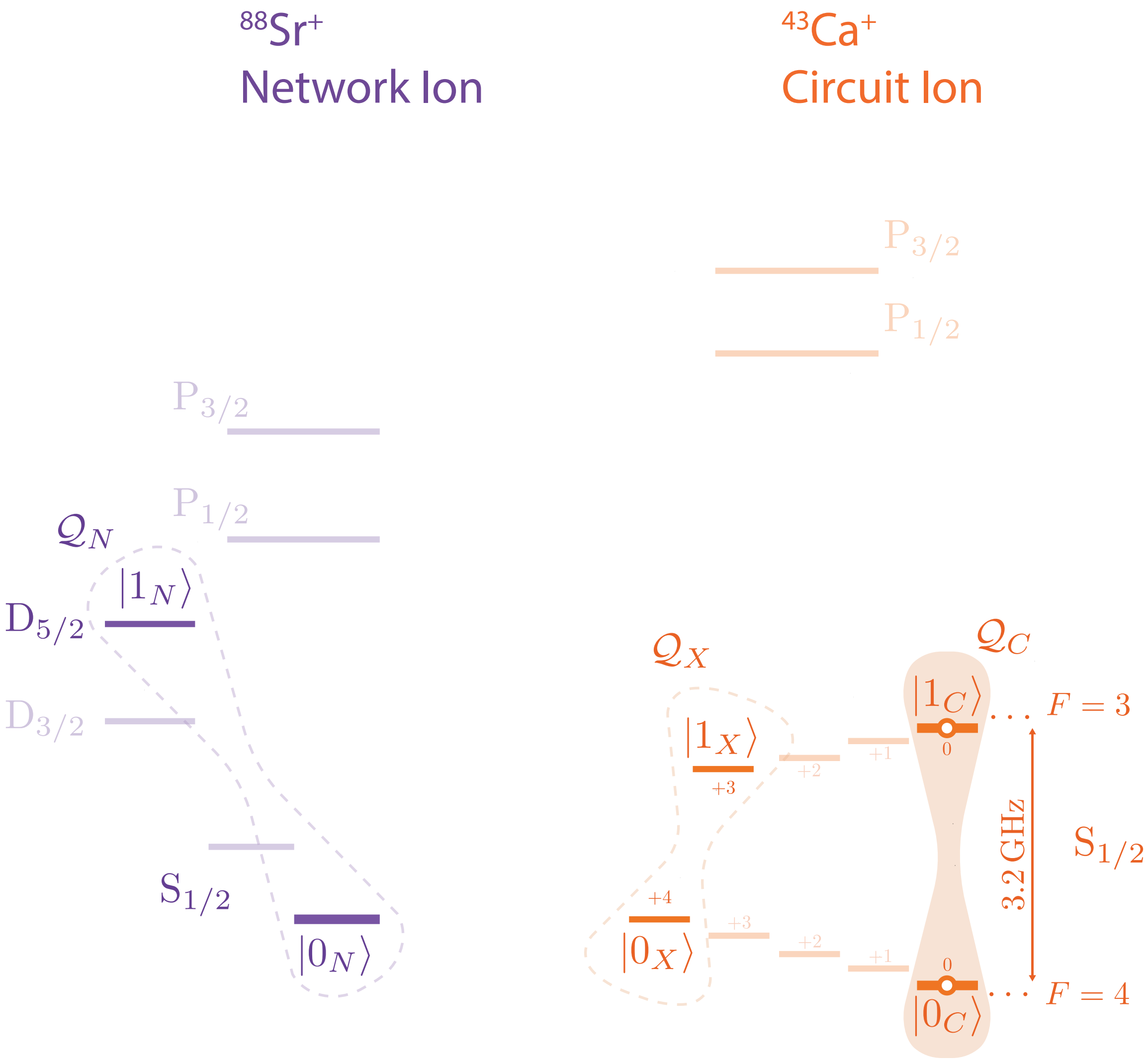

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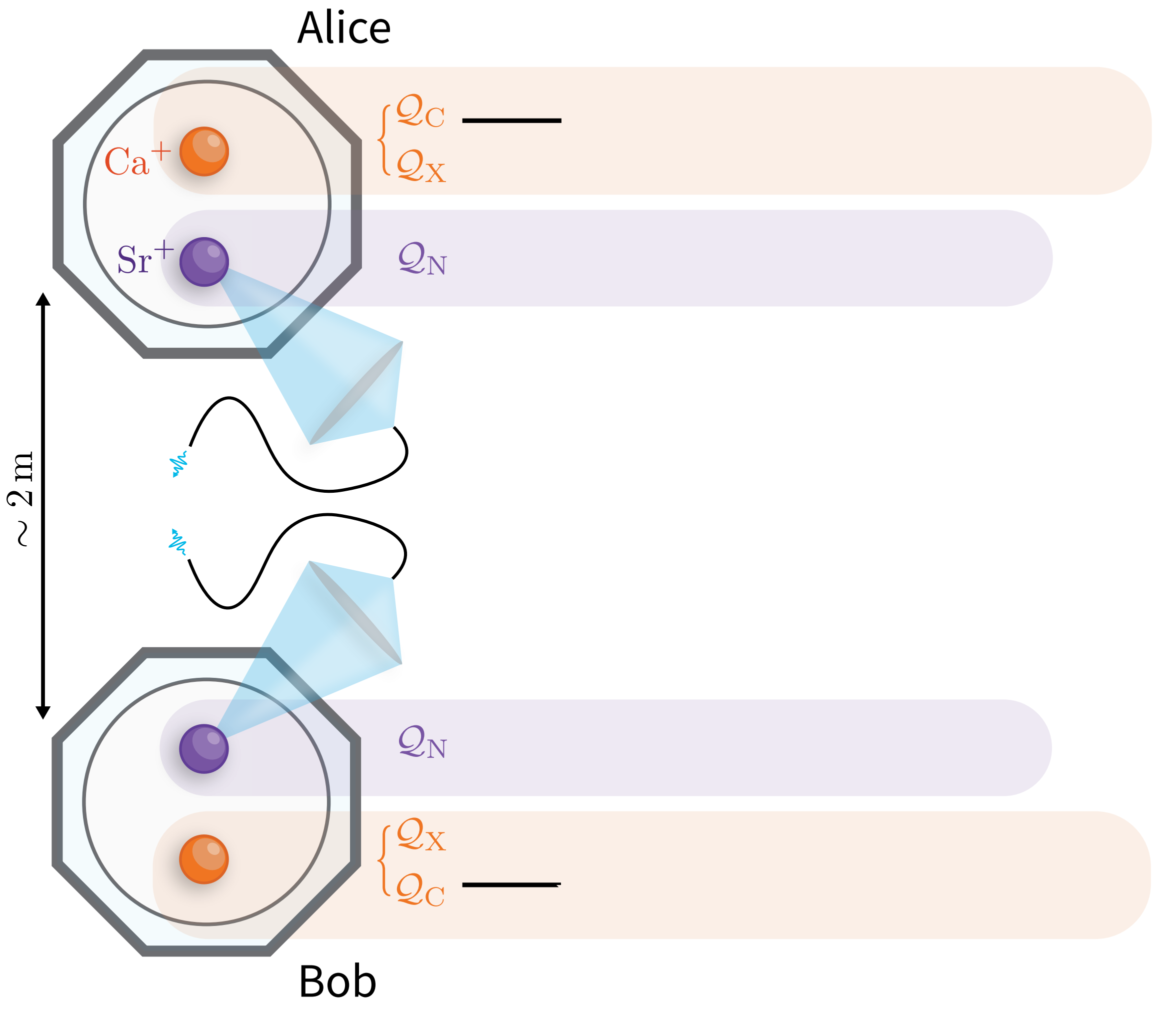

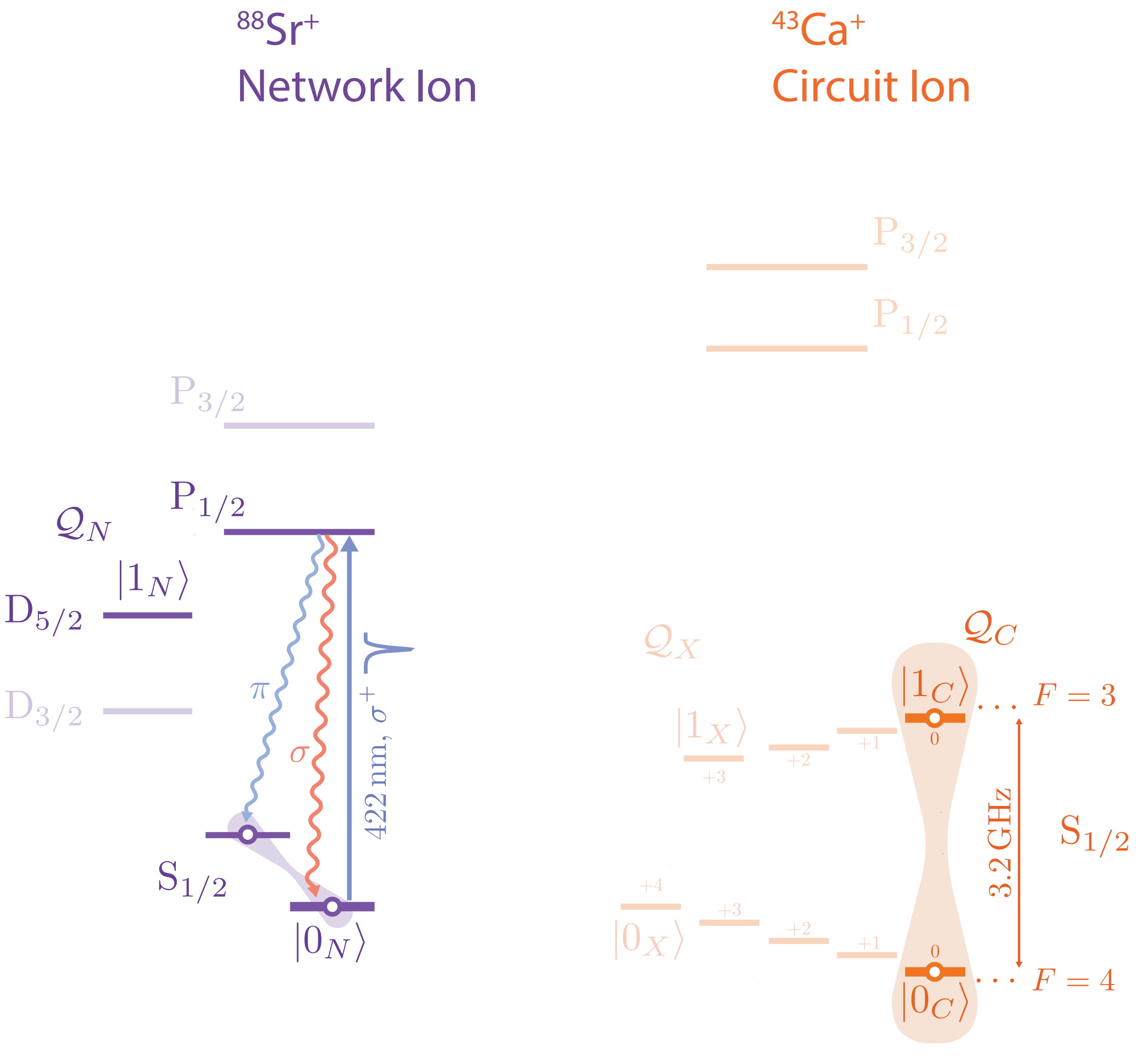

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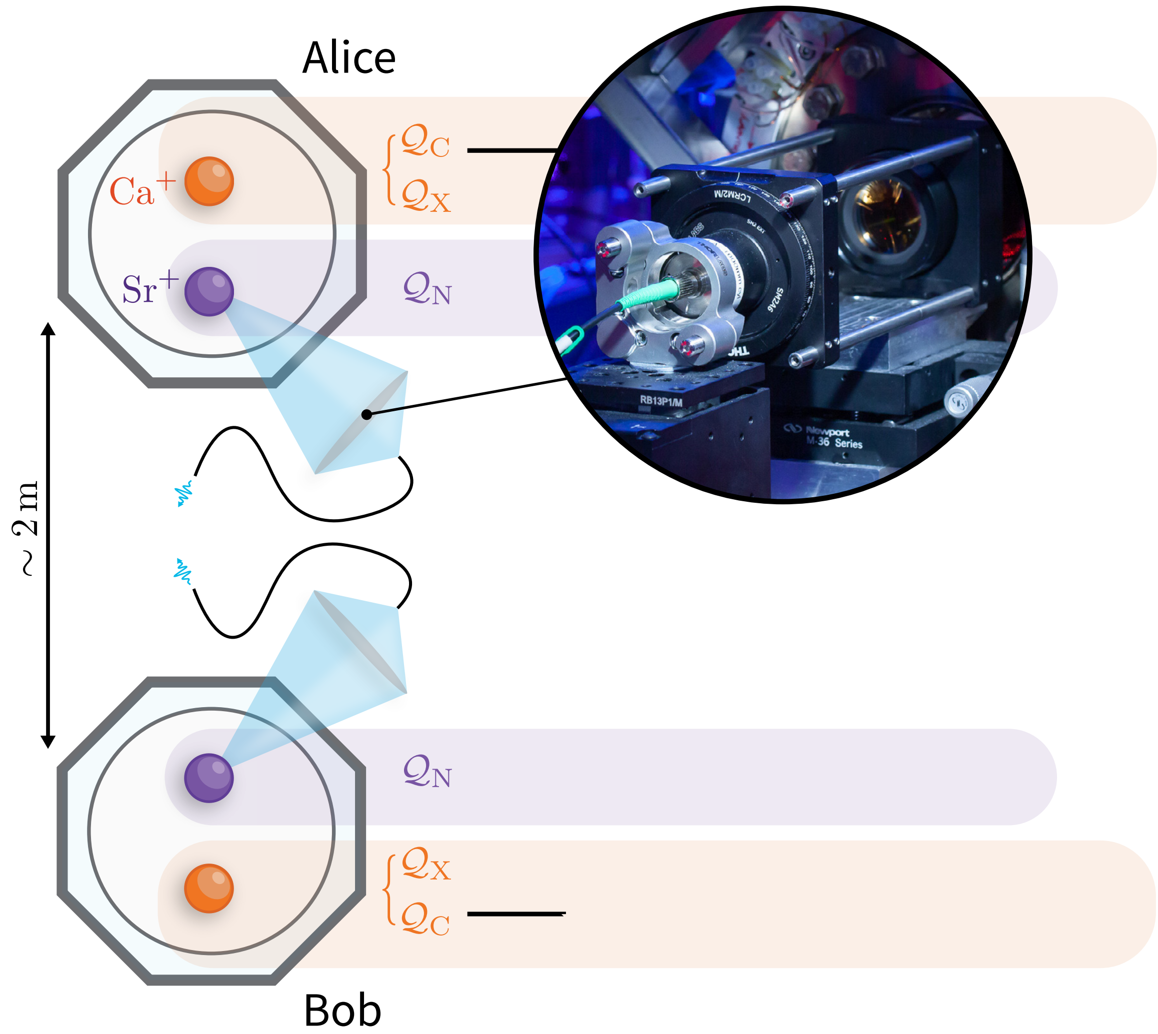
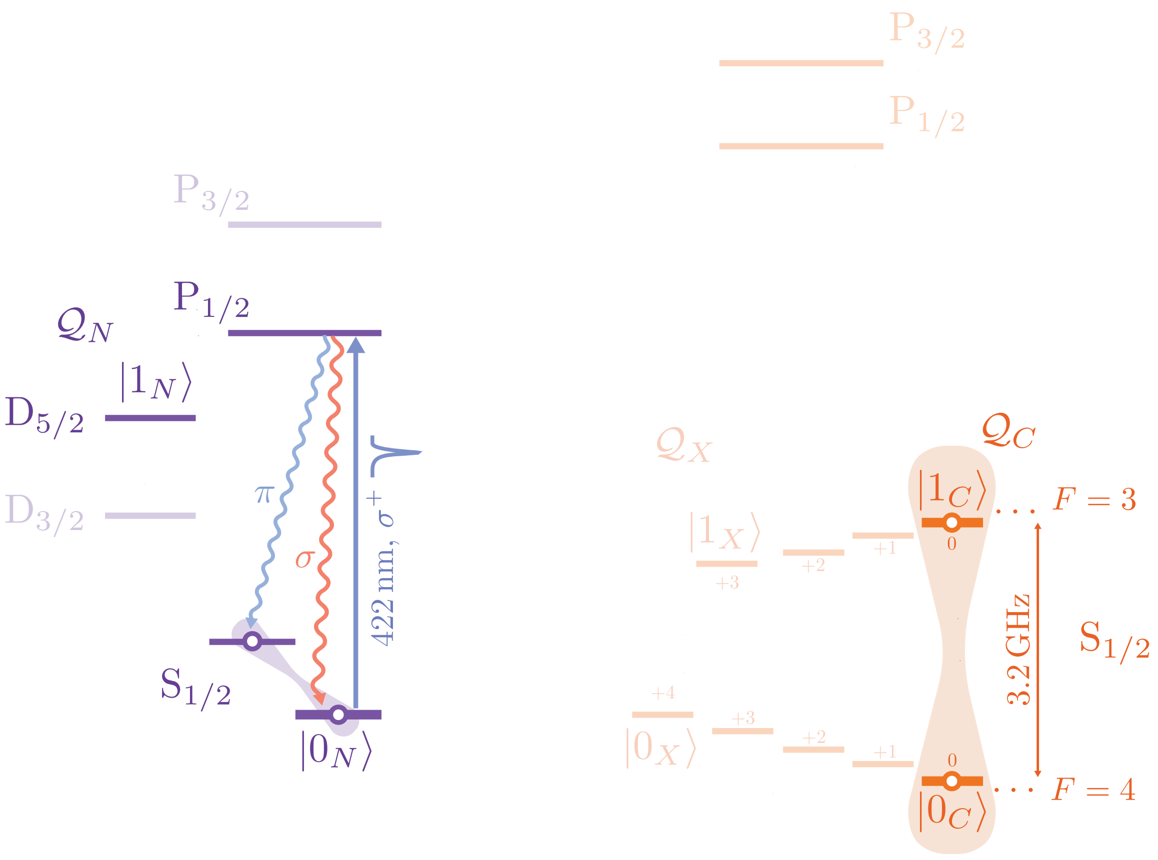


^{88}Sr$^+$
Network Ion

^{43}Ca$^+$
Circuit Ion



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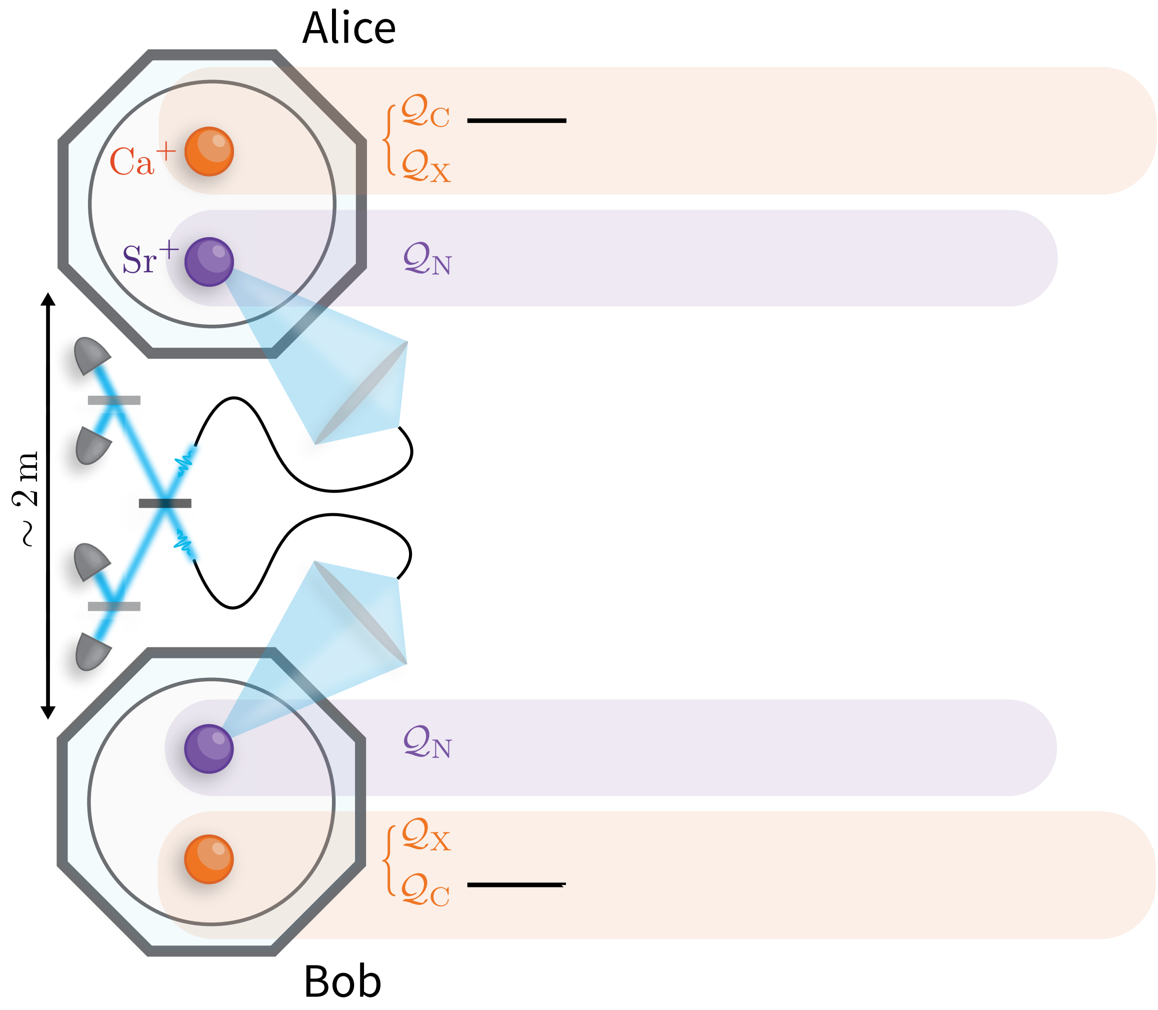

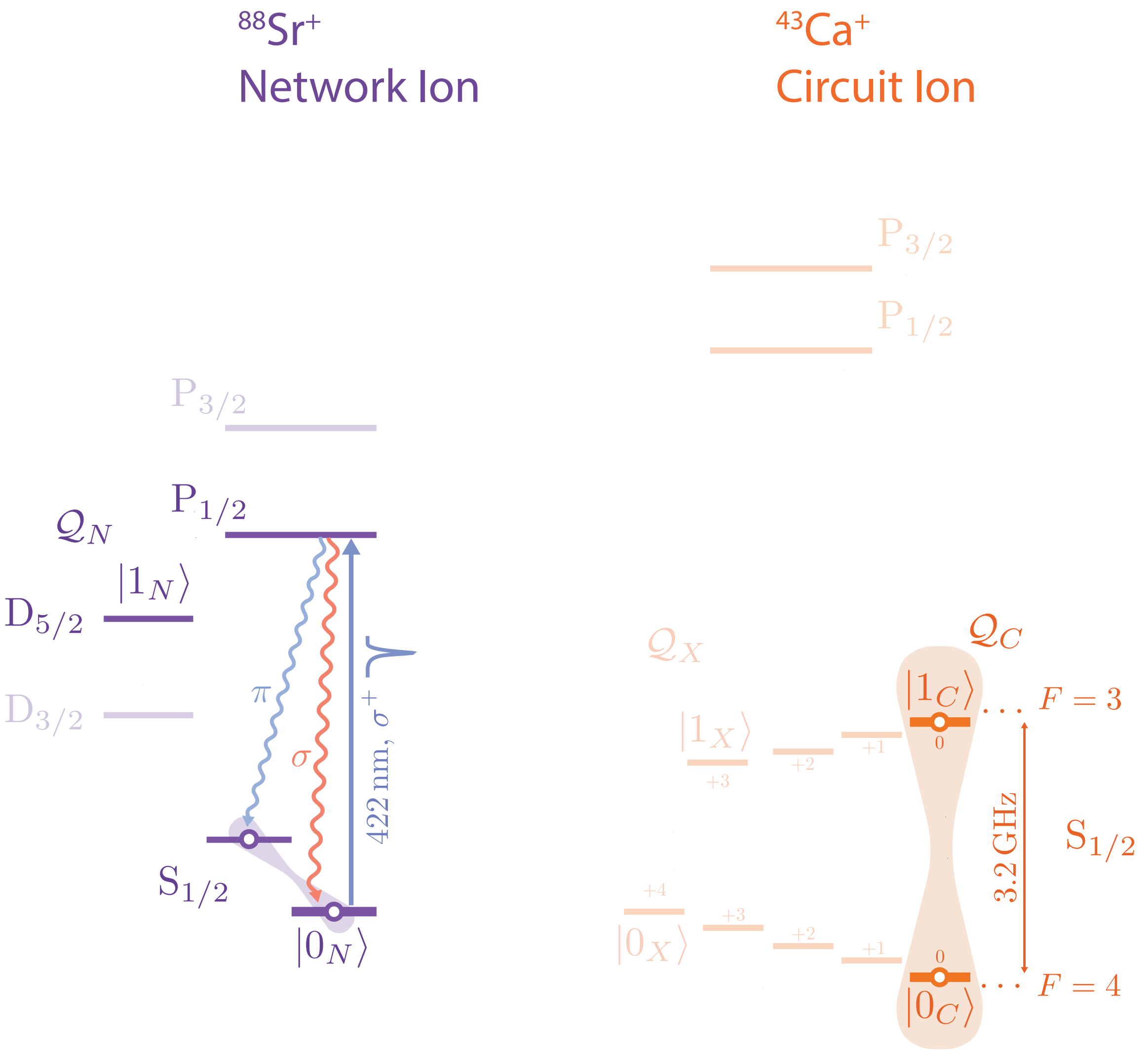

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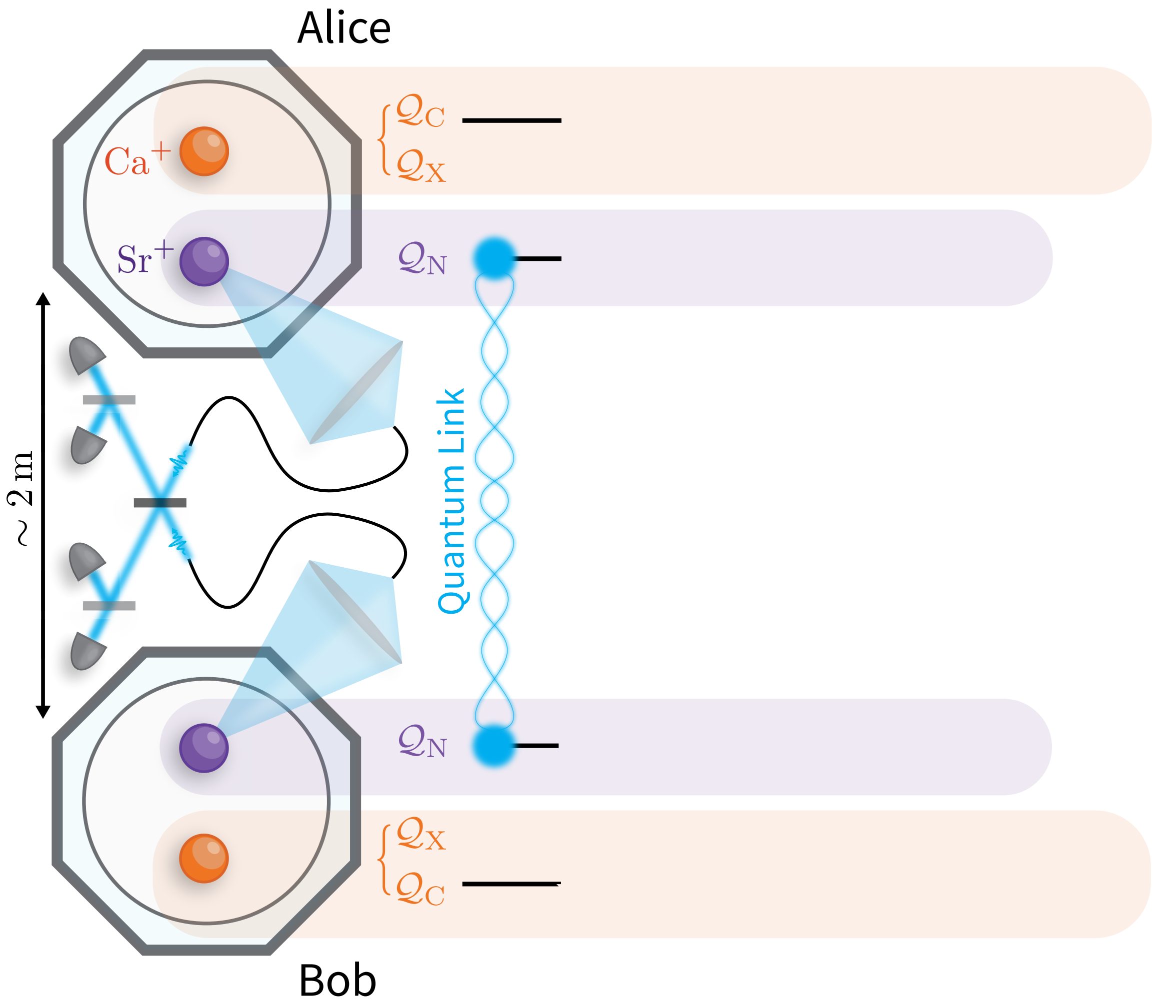

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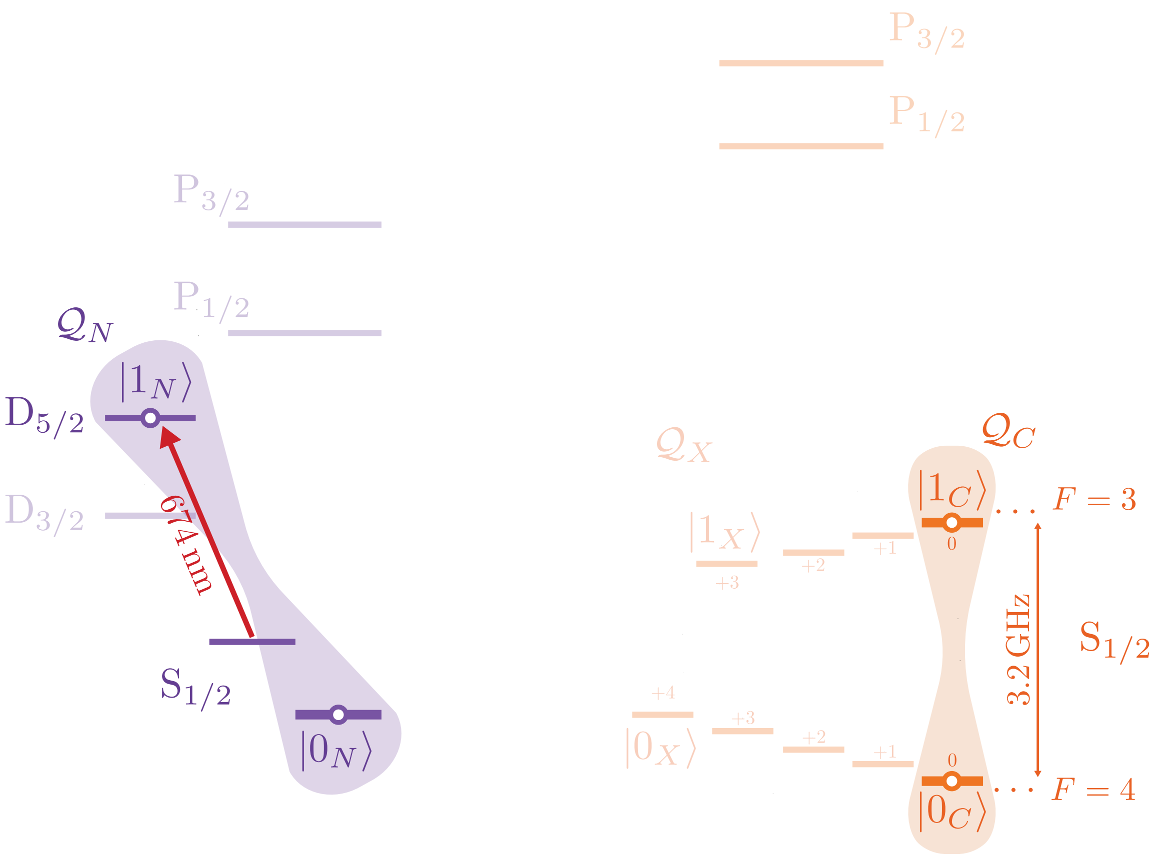

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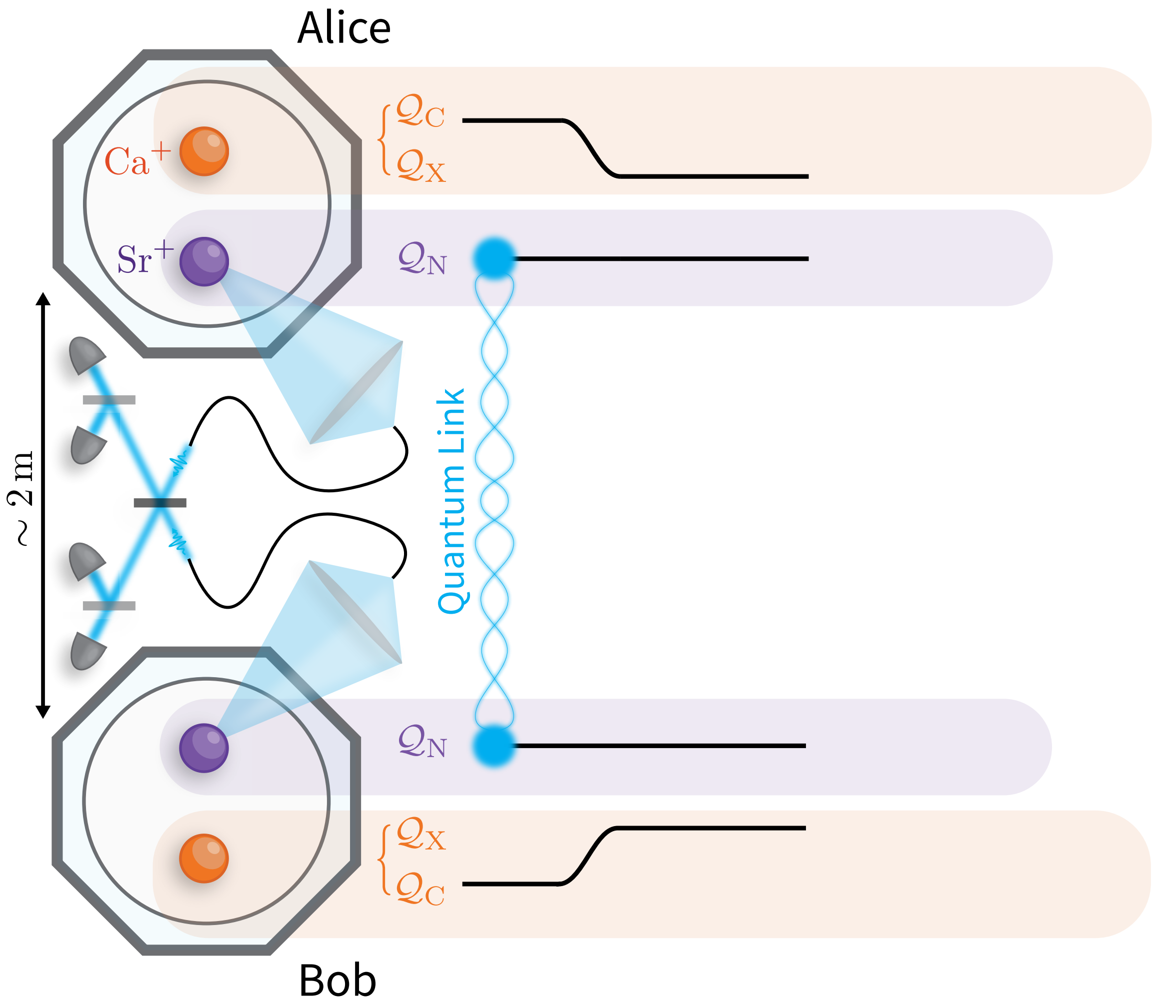

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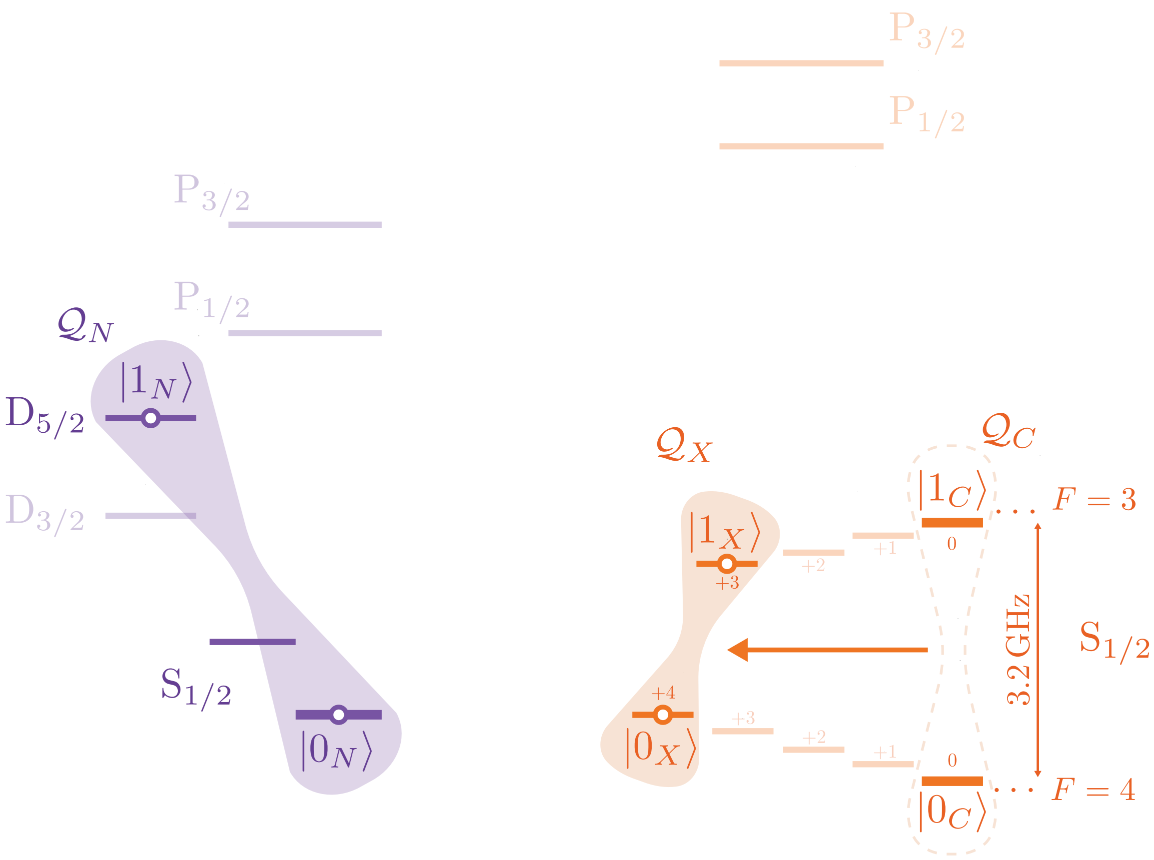

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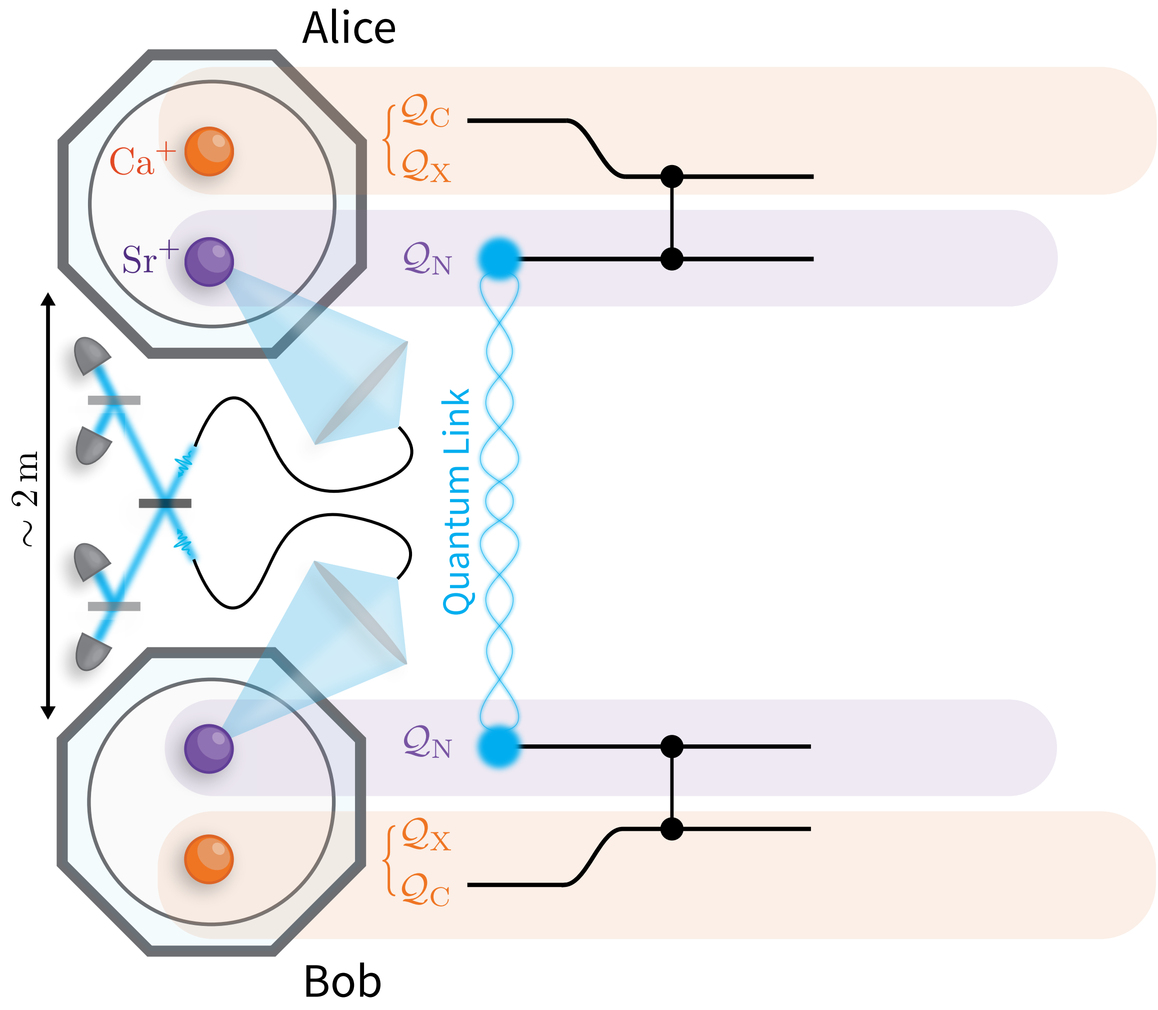

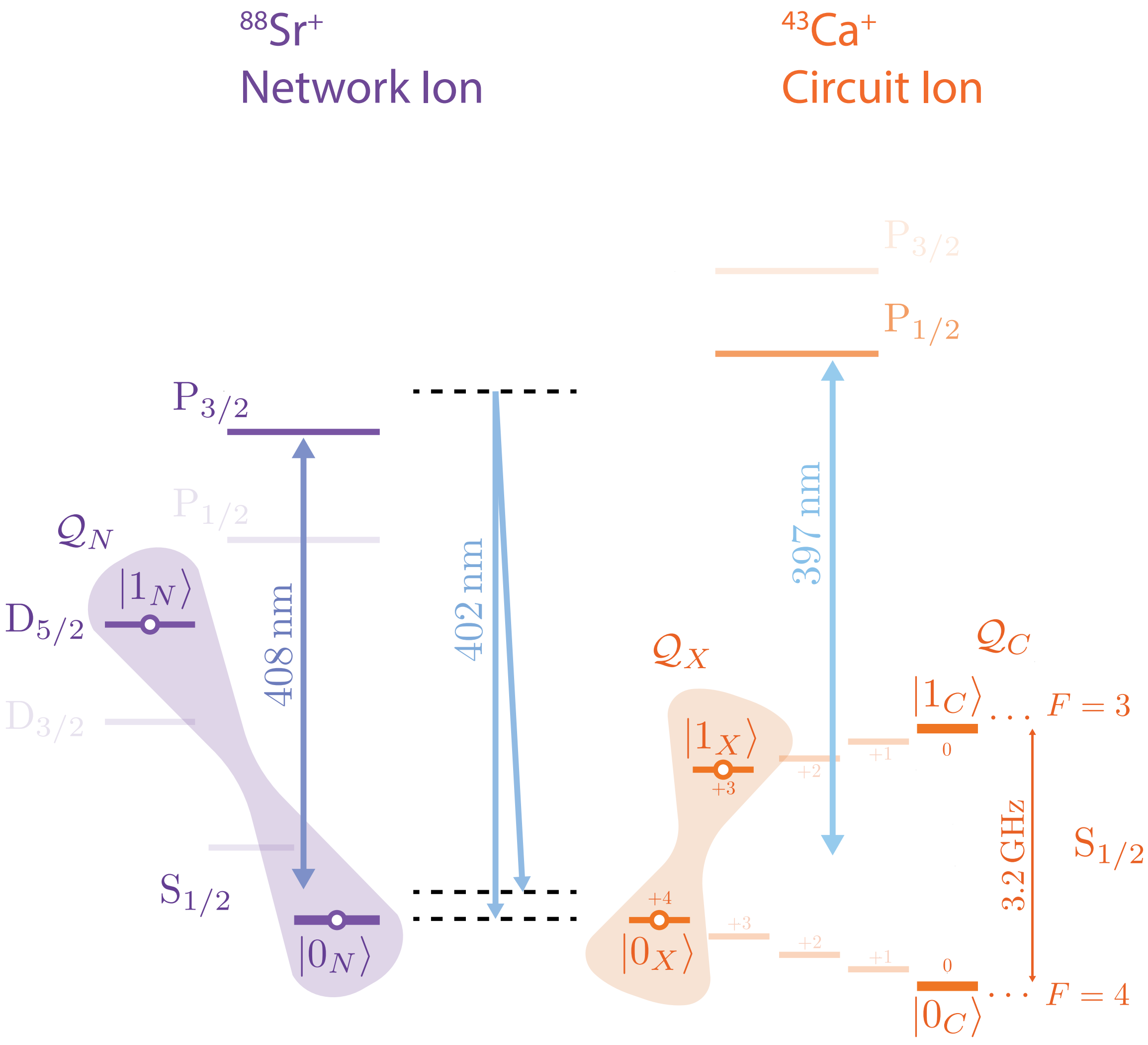

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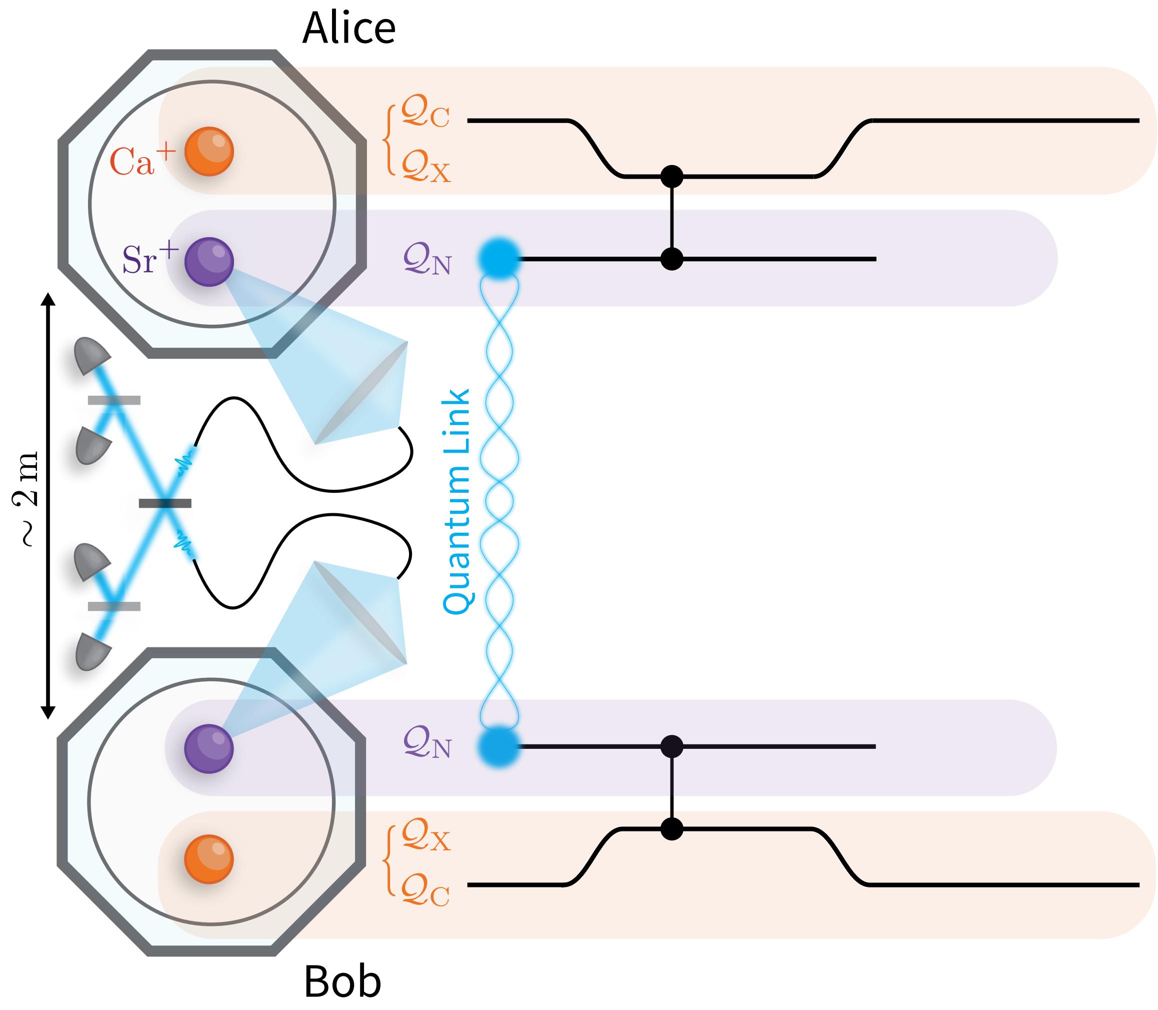

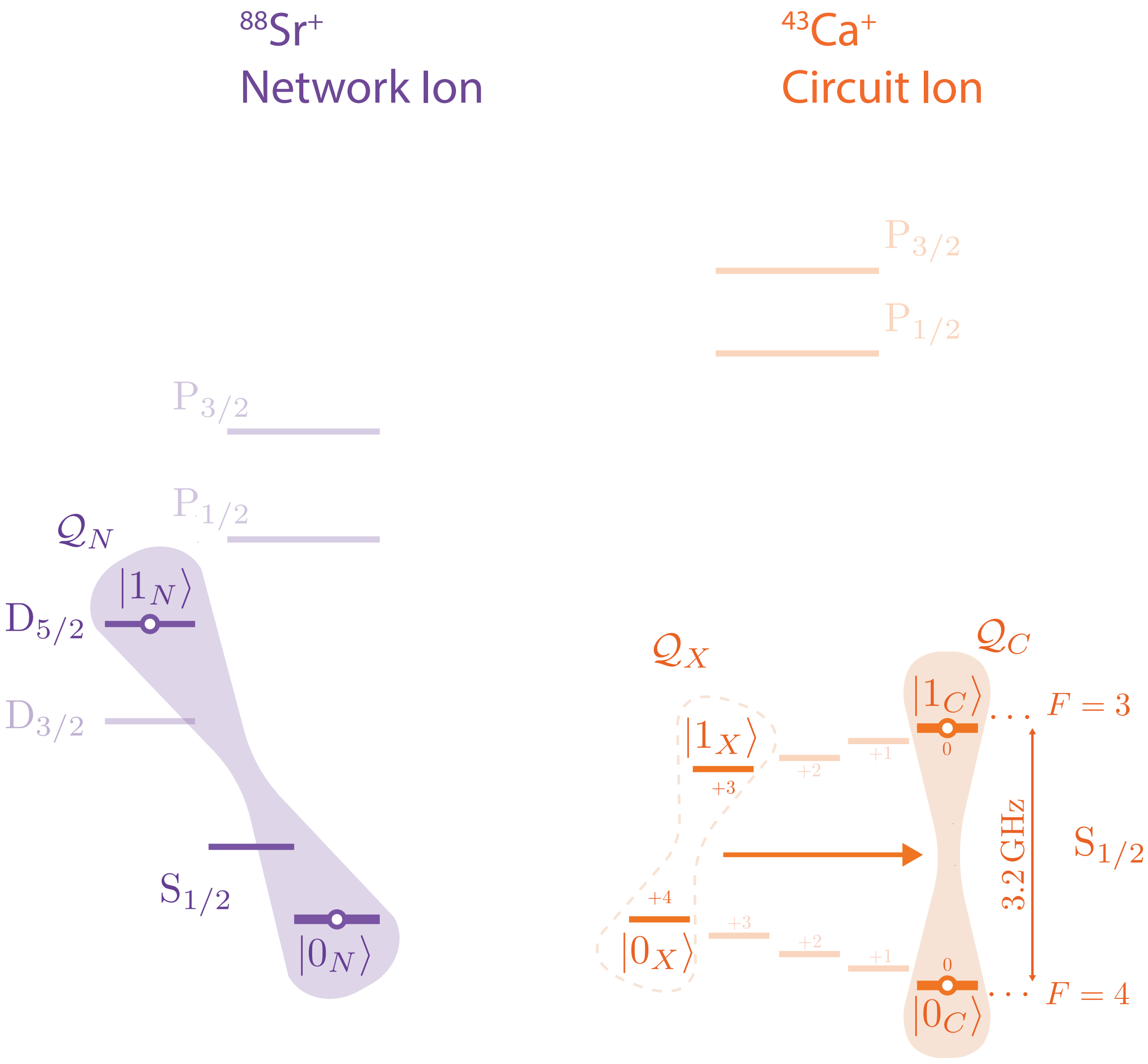

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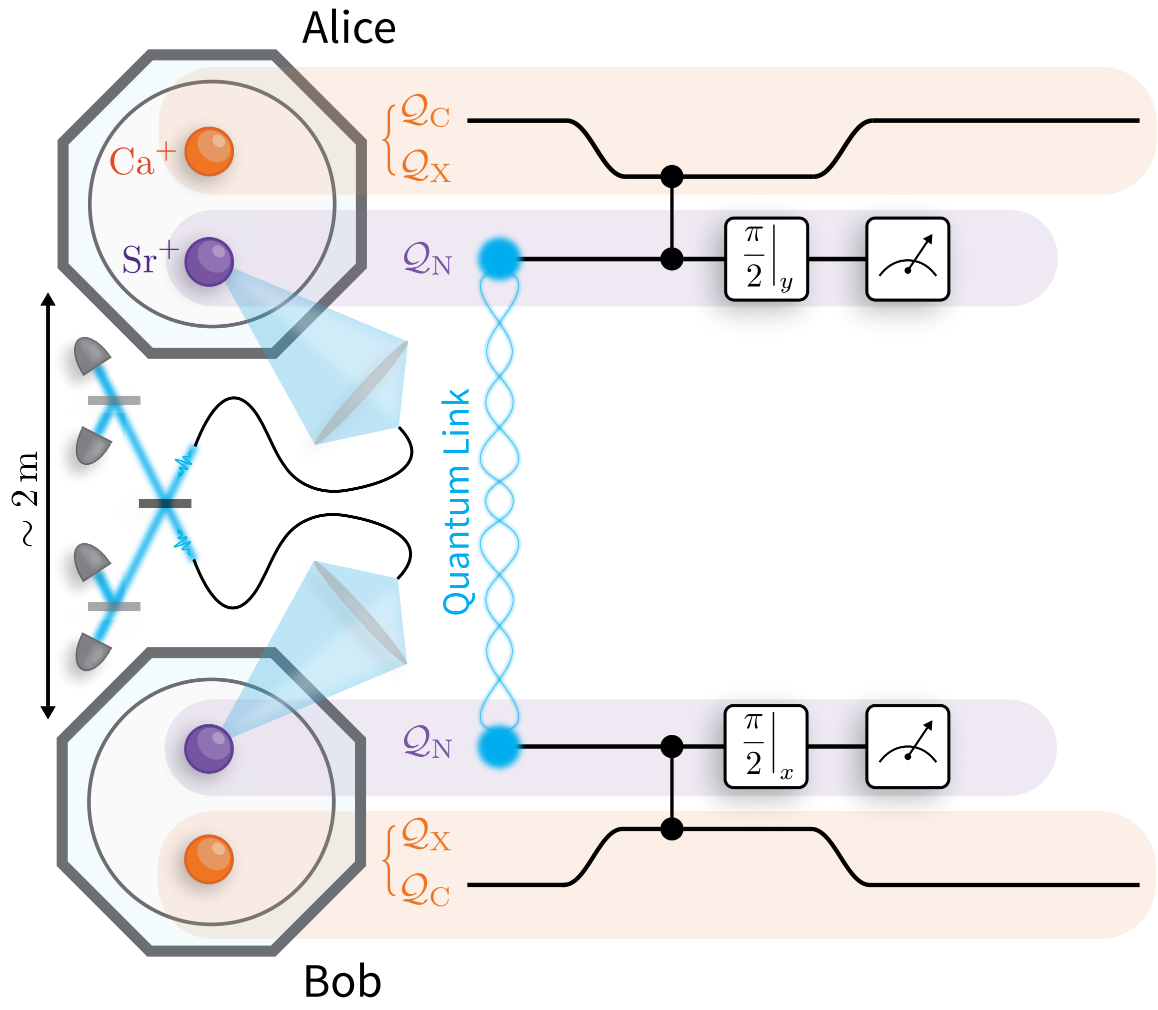

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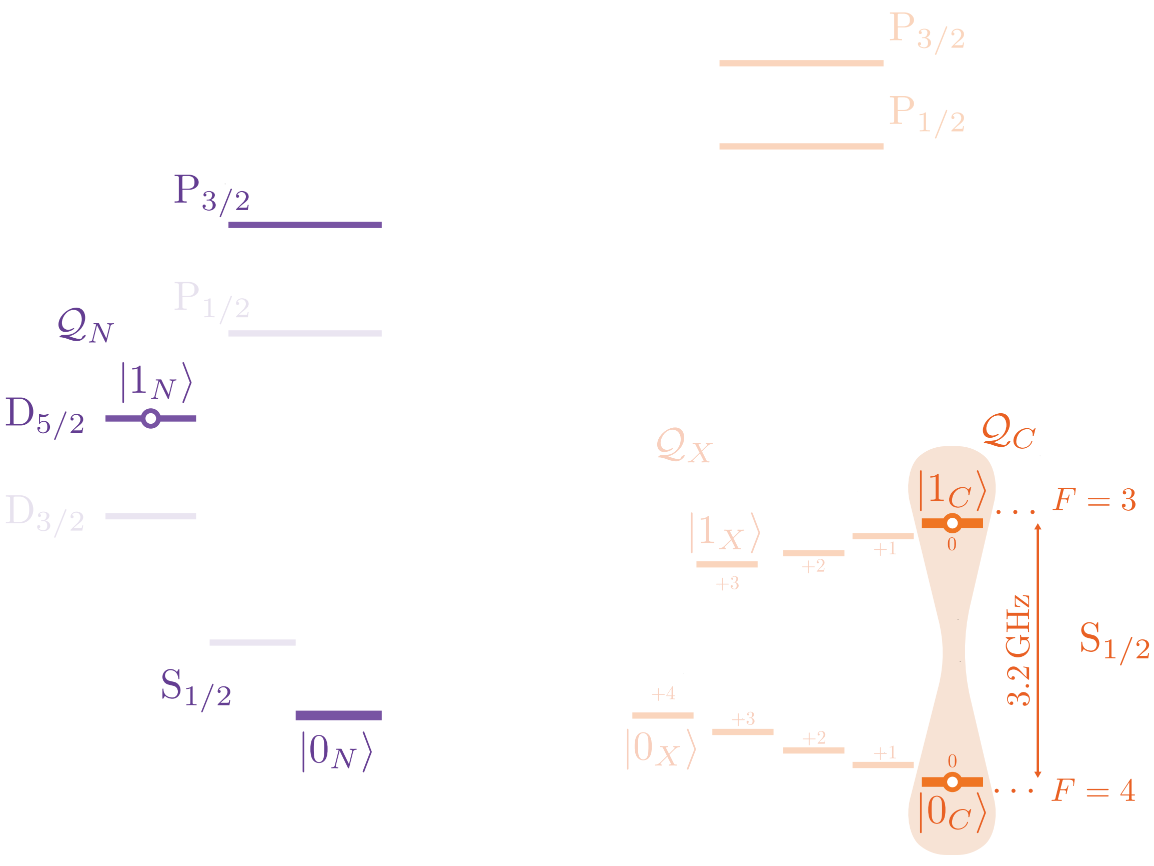

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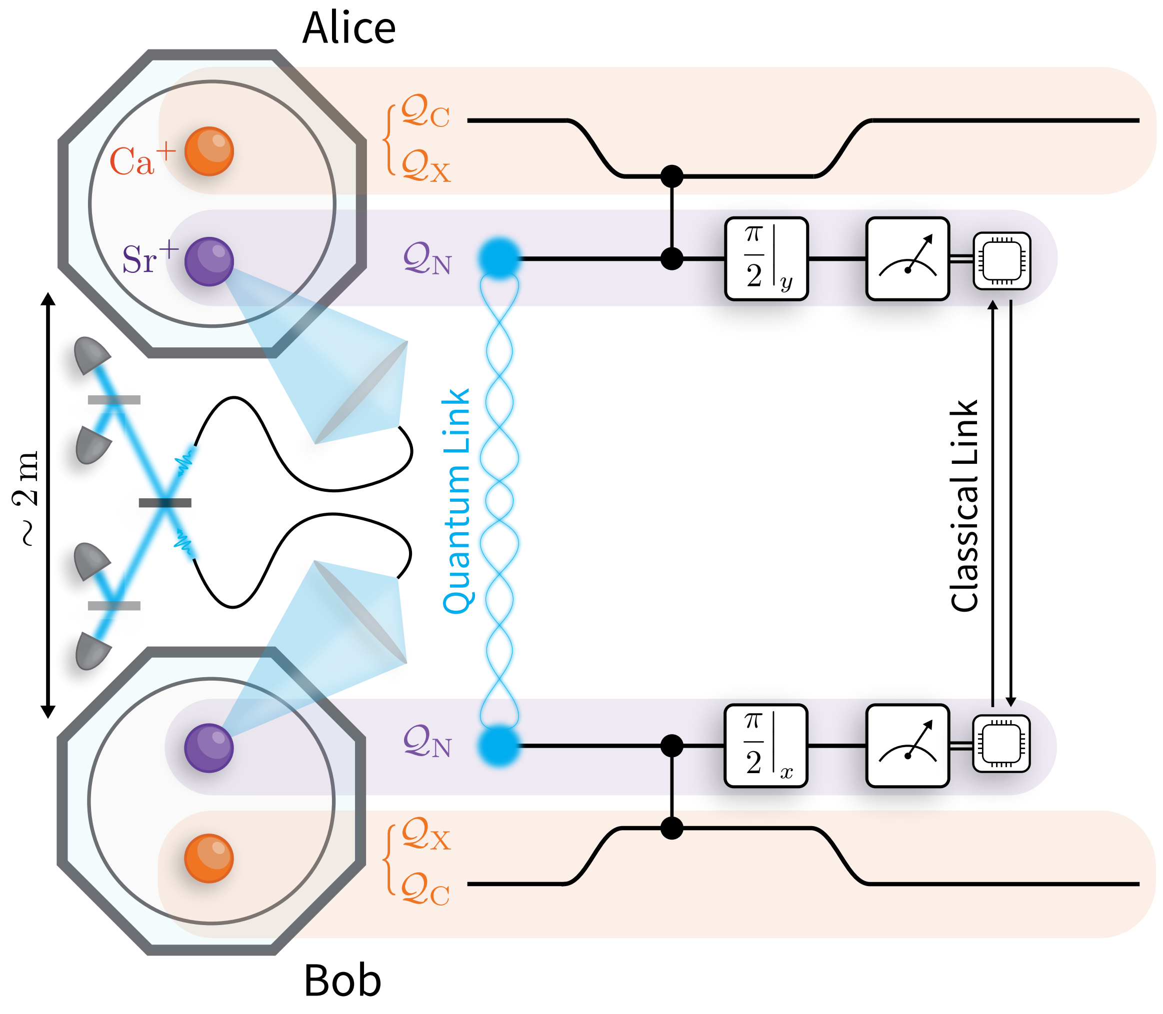

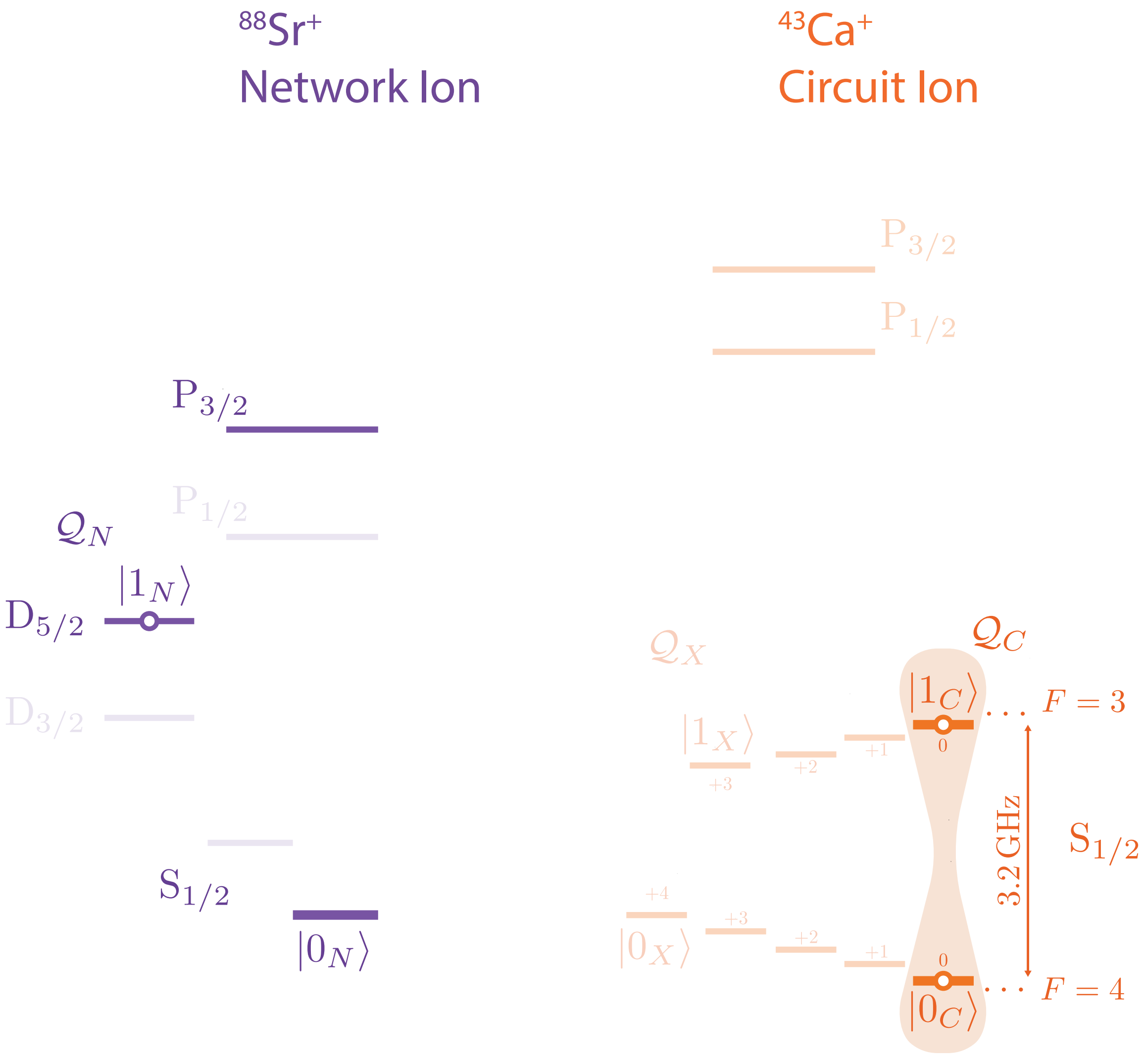

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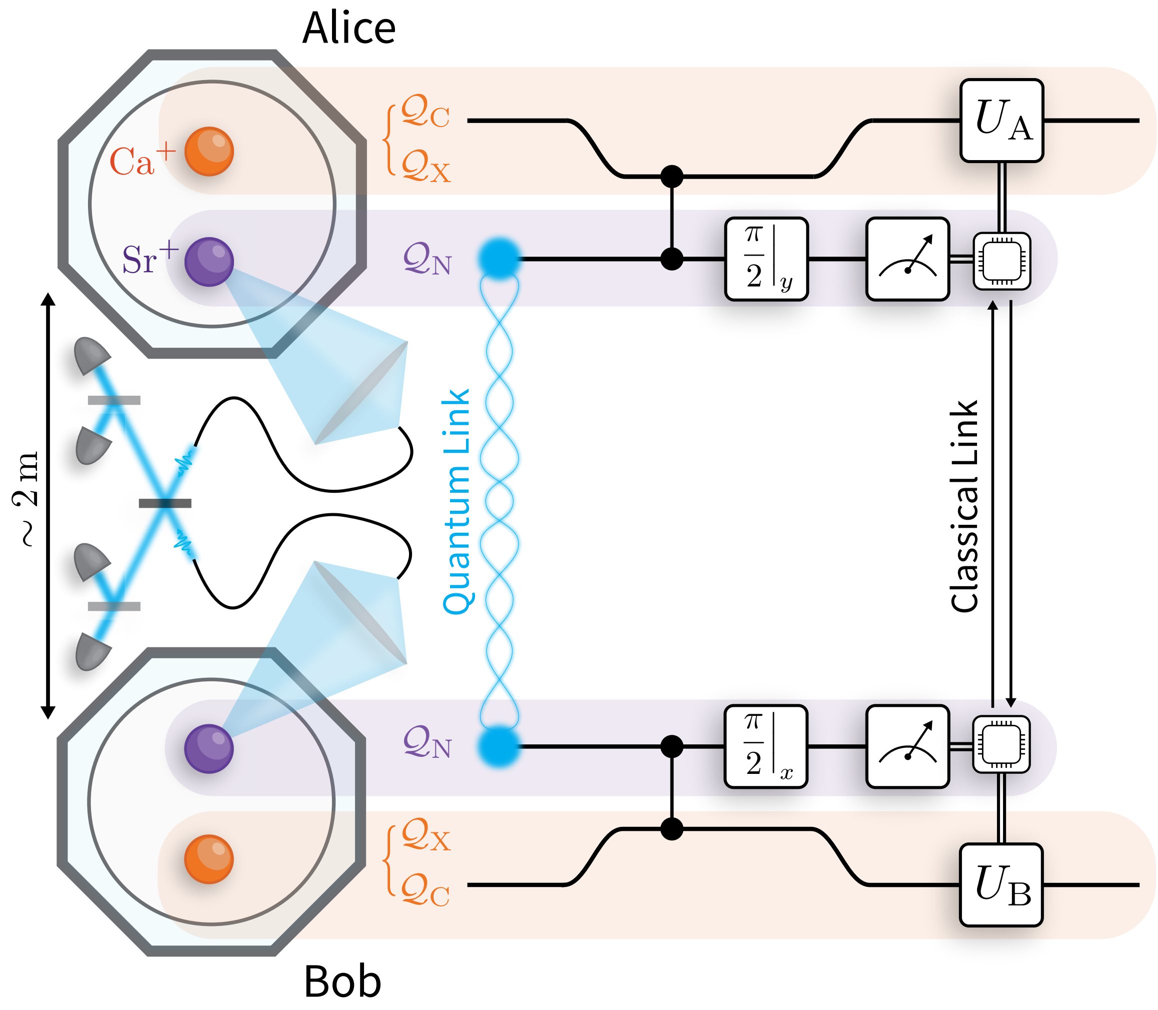
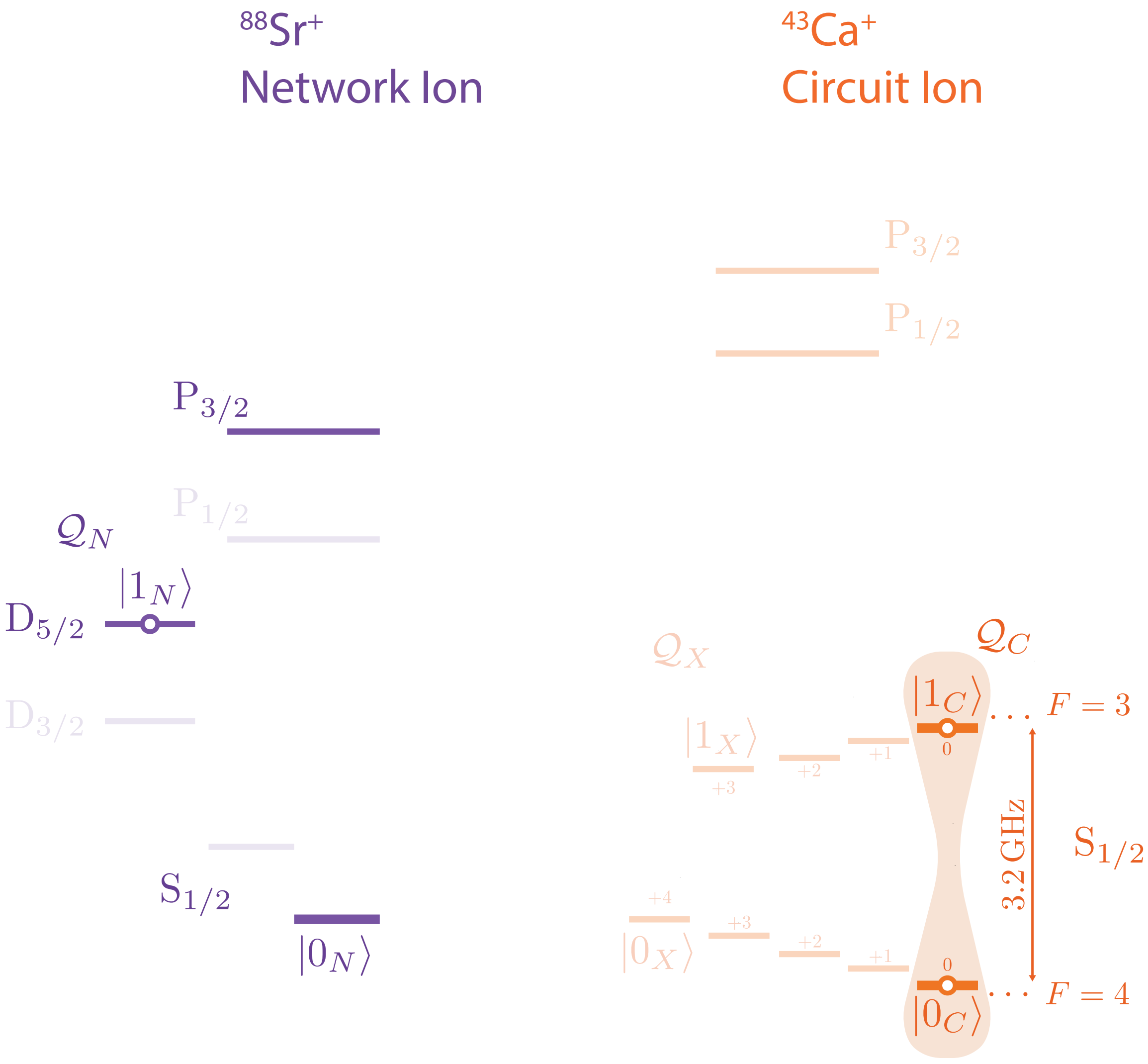
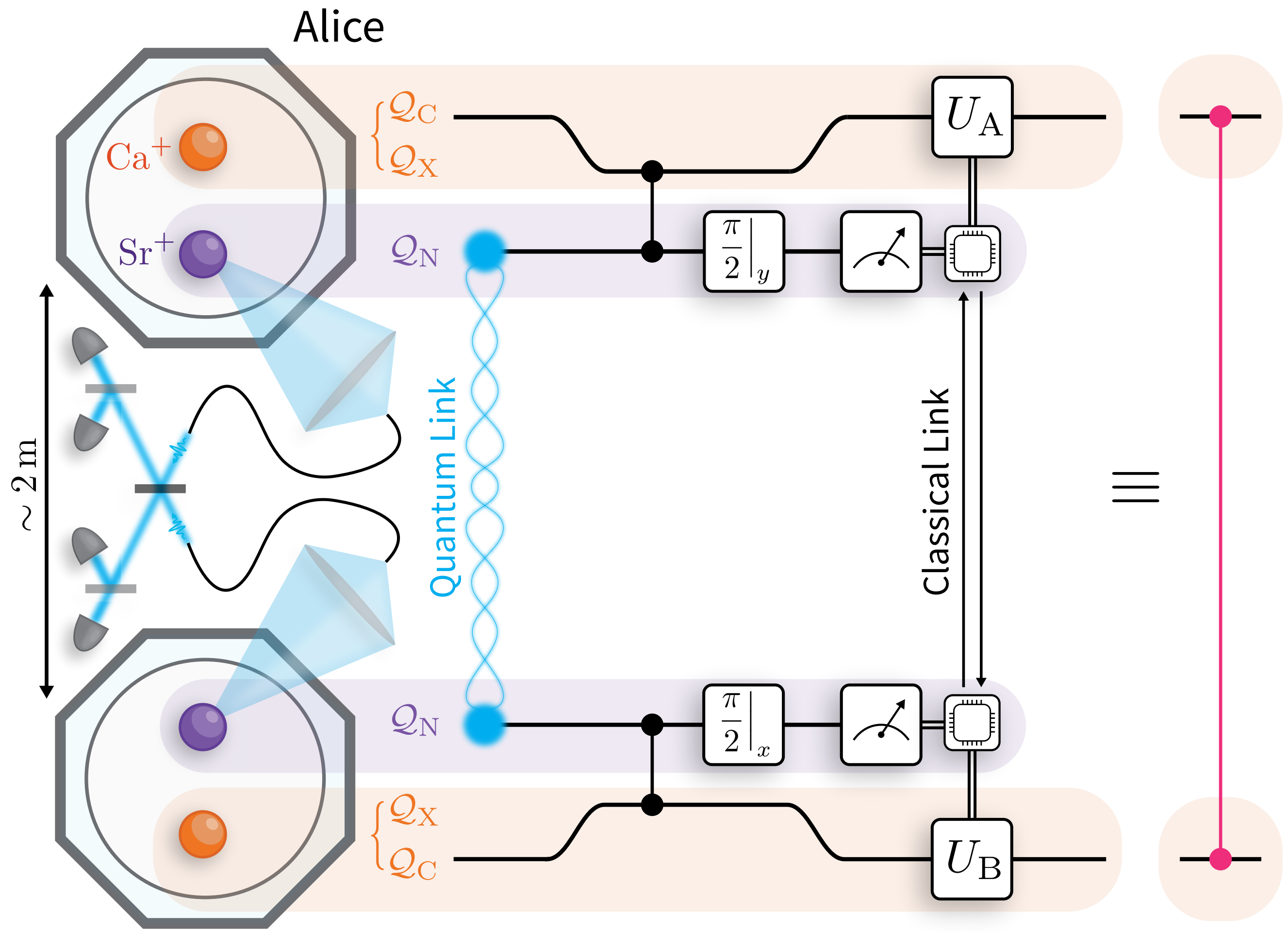
Quantum Gate Teleportation: Protocol

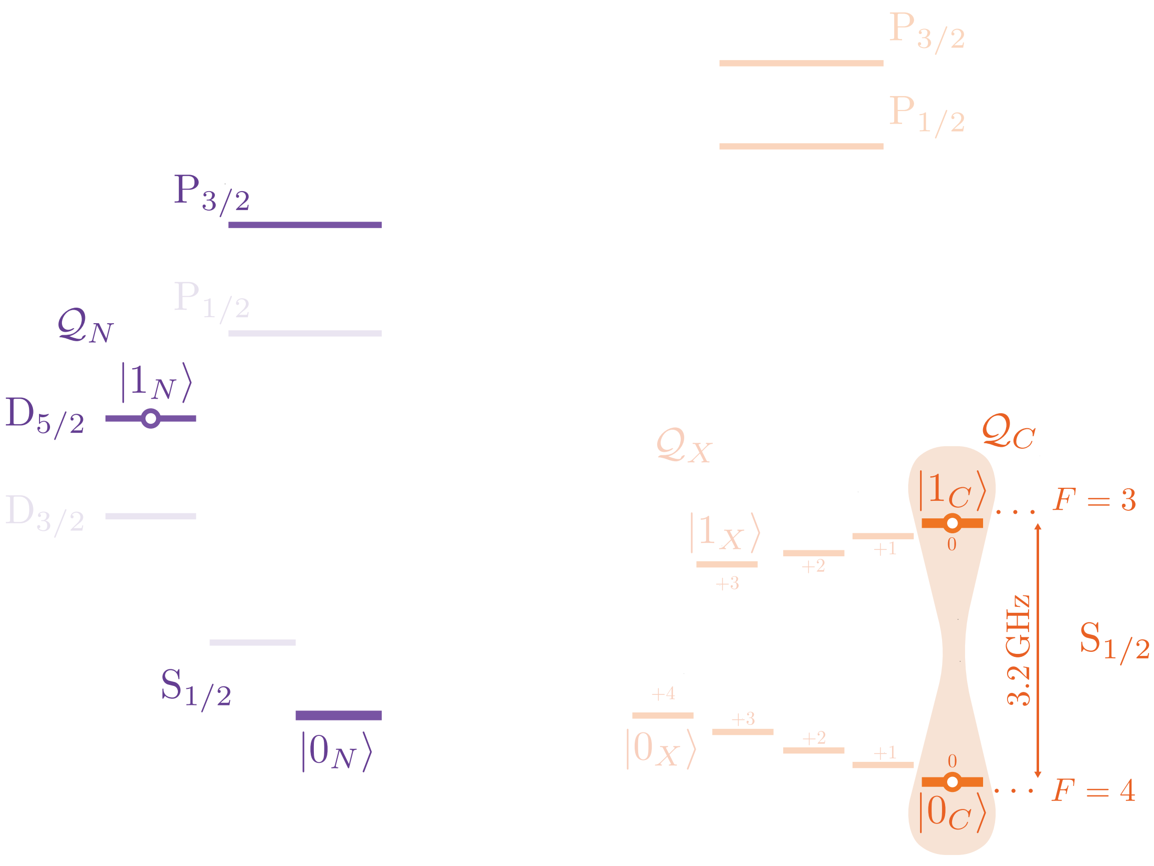




Input: $|\psi_C^{AB}\rangle \in \mathcal{Q}_C^{\otimes 2}$

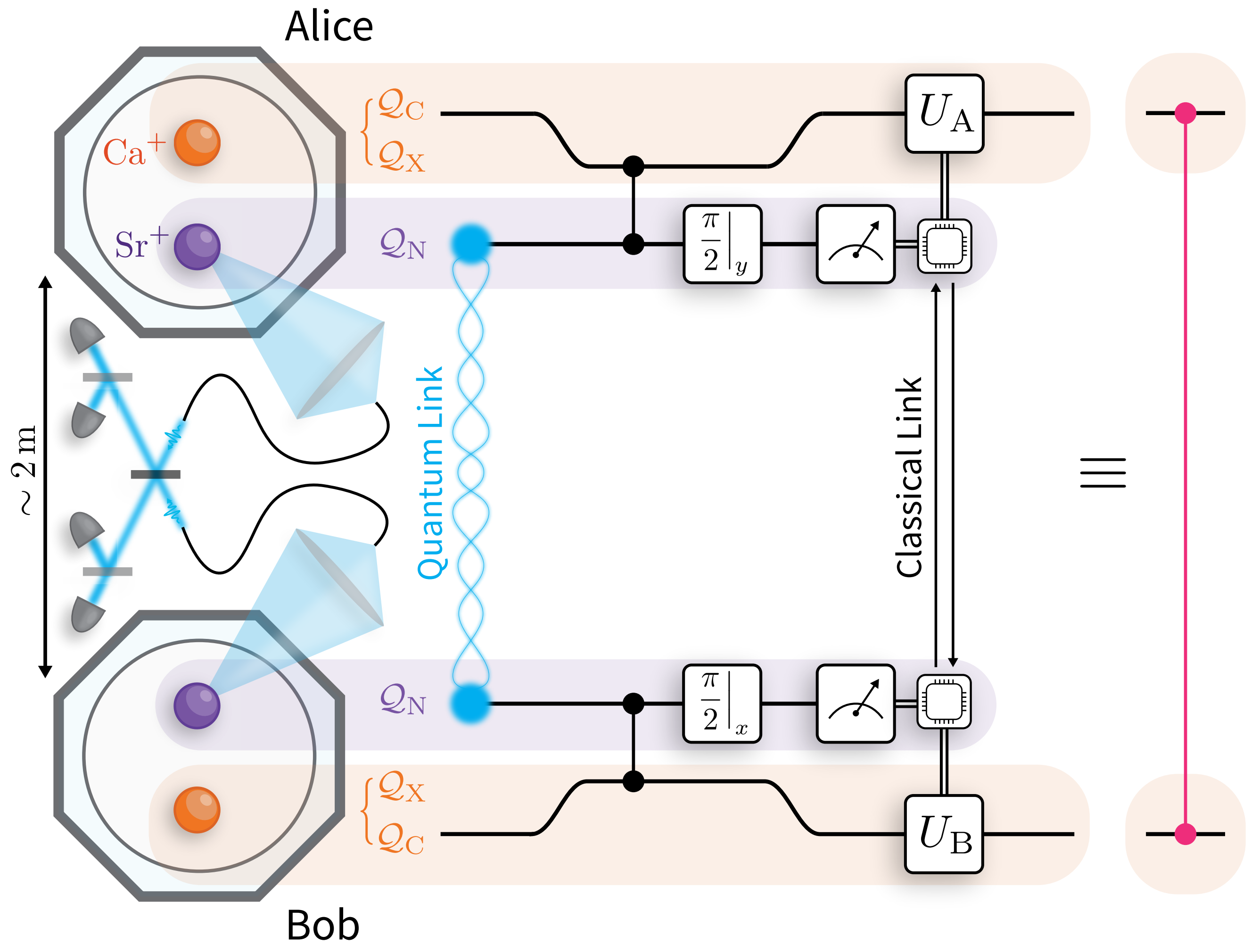
Quantum Gate Teleportation: Protocol





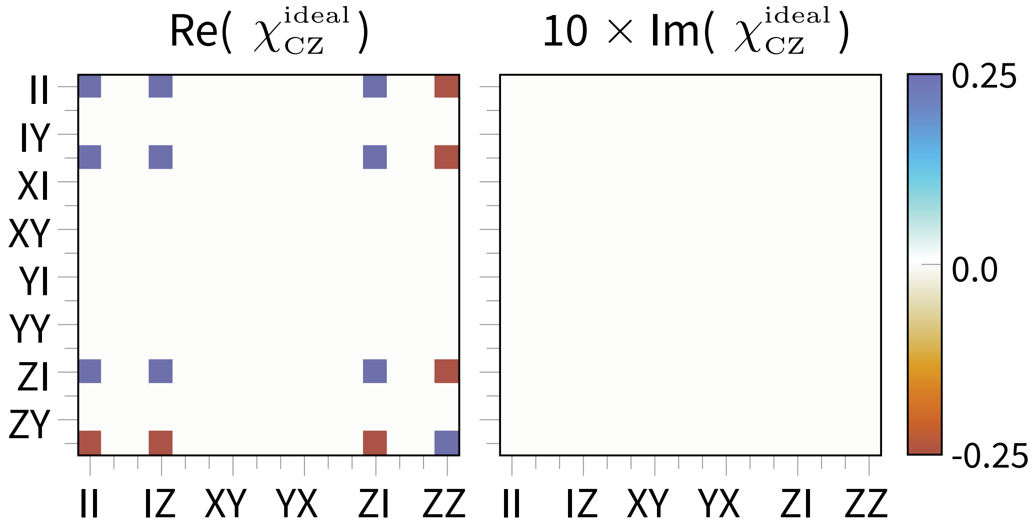
Input: $|\psi_C^{AB}\rangle \in \mathcal{Q}_C^{\otimes 2}$ **Output:** $CZ\,|\psi_C^{AB}\rangle$

Quantum Gate Teleportation: Results

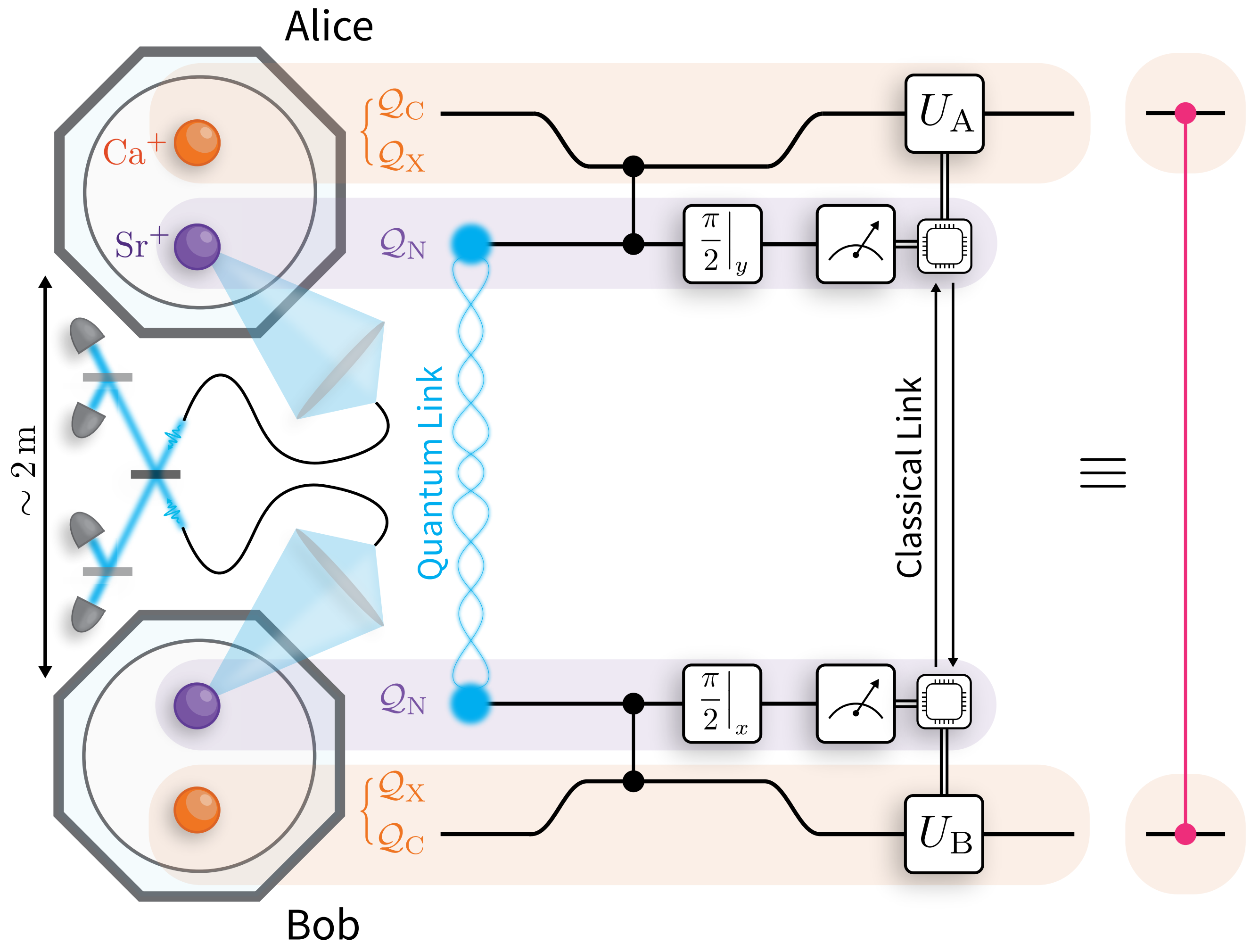


Ideal Process

$$|\psi_C^{AB}\rangle \rightarrow CZ\,|\psi_C^{AB}\rangle \in \mathcal{Q}_C^{\otimes 2}$$

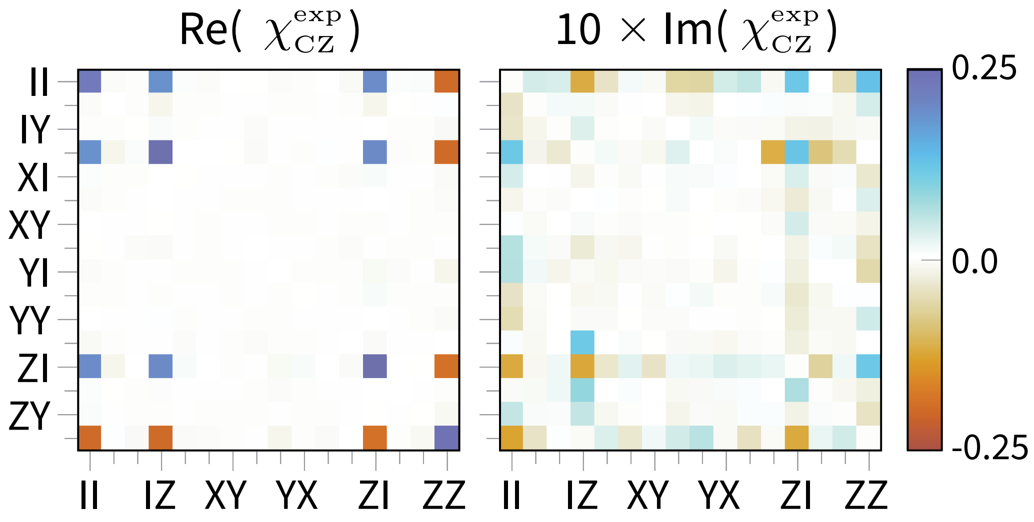


Quantum Gate Teleportation: Results



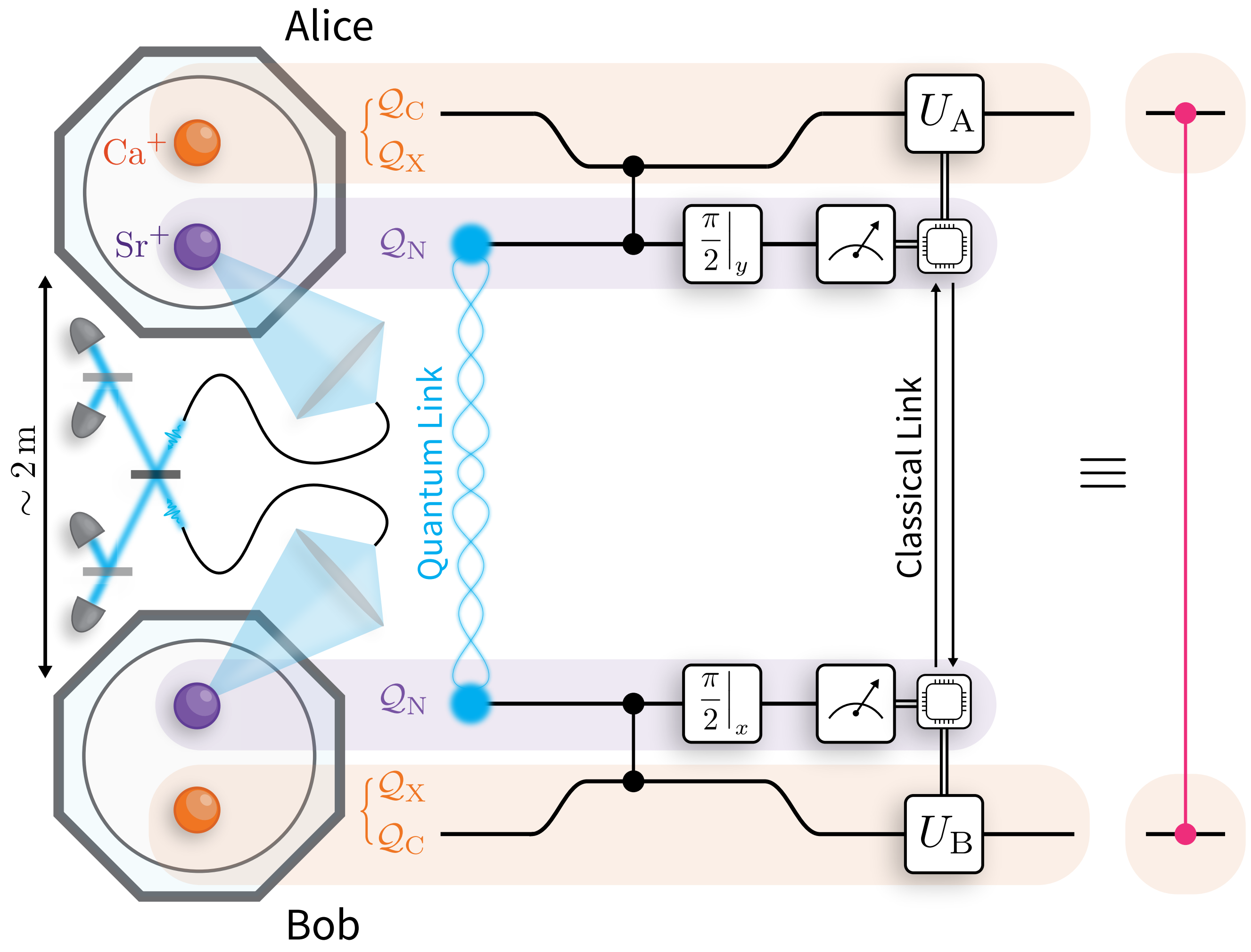
Process Tomography

$$\rho \to \mathcal{E}_{CZ}(\rho) \in L\left(\mathcal{Q}_C^{\otimes 2}\right)$$



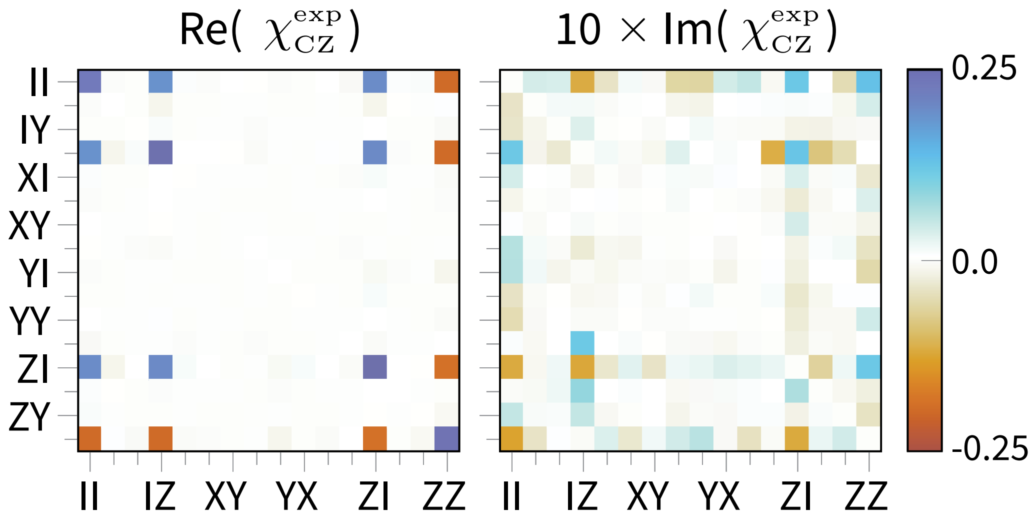
Average gate fidelity to controlled-Z gate: **86.1(9)%**

Quantum Gate Teleportation: Results



Process Tomography

$$\rho \to \mathcal{E}_{CZ}(\rho) \in L\left(\mathcal{Q}_C^{\otimes 2}\right)$$



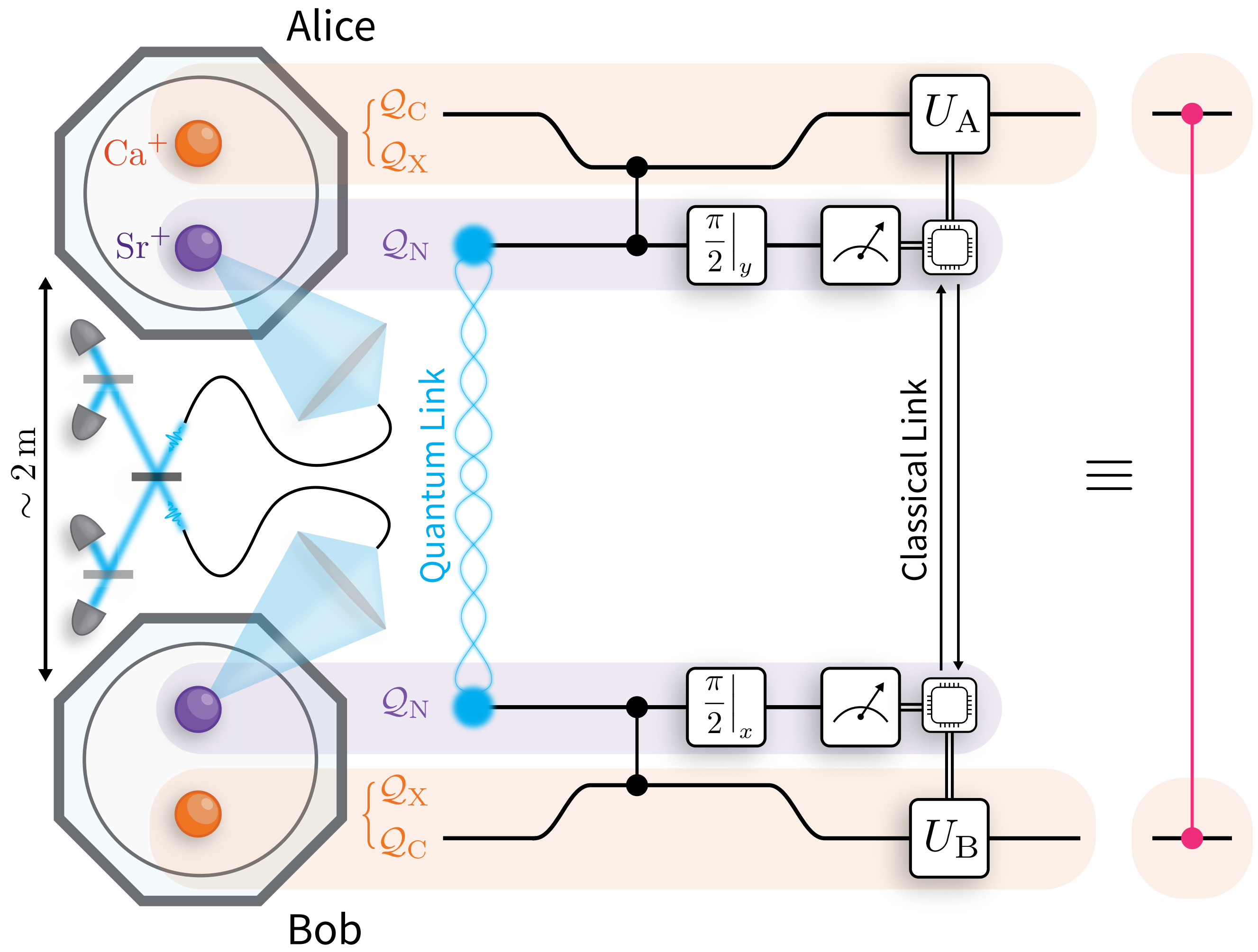
Average gate fidelity to controlled-Z gate: **86.1(9)%**

Circuit qubits in **separate devices**, separated by **~ 2 m**

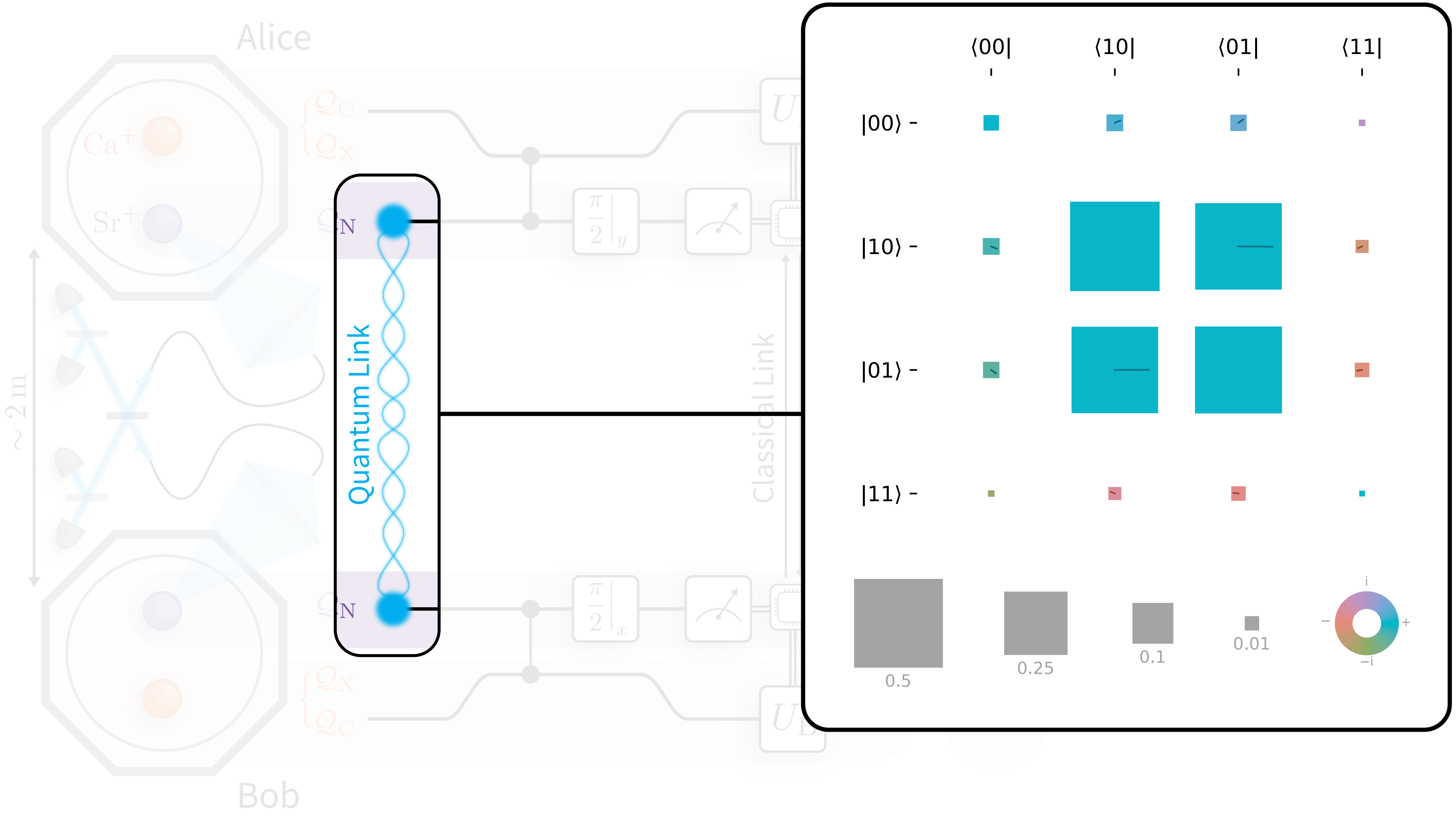
Deterministic ✓

Robust quantum memory enables **multiple instances** of QGT ✓

Quantum Gate Teleportation: Error Budget



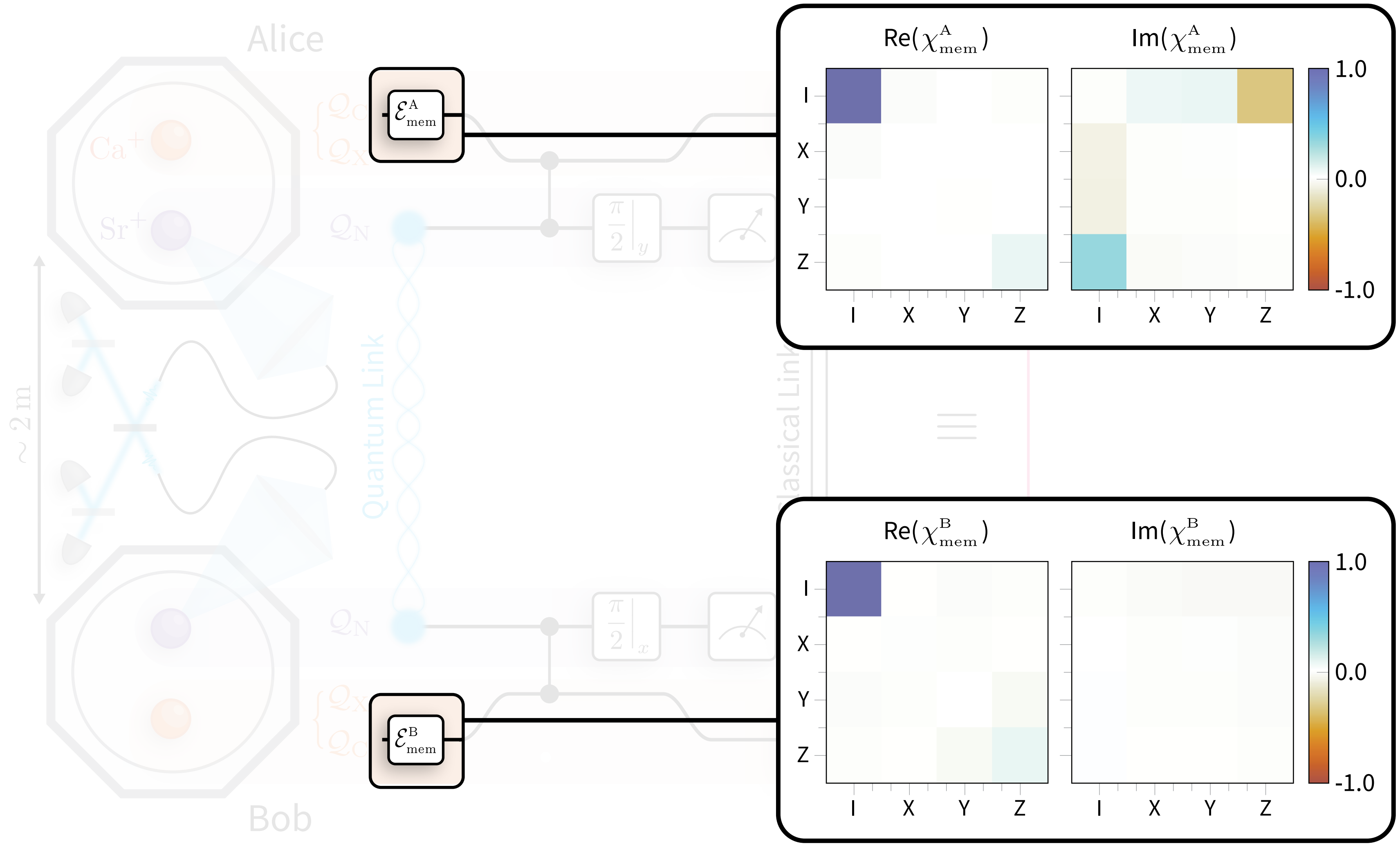
Quantum Gate Teleportation: Error Budget



Fidelity to Ψ^{+}: 97.15(9)%

Rate: ~ 10 s^{-1}

Quantum Gate Teleportation: Error Budget

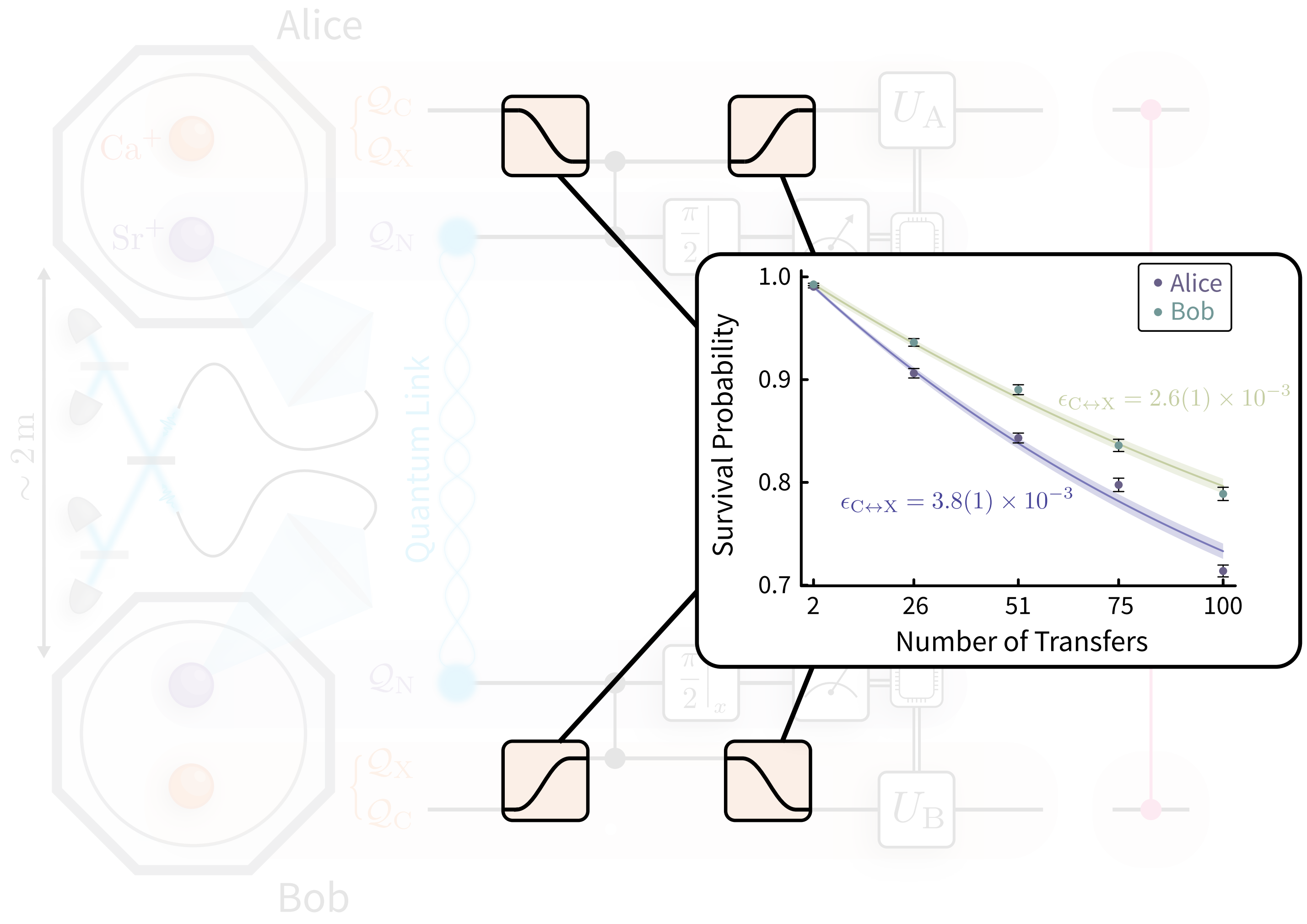


Dynamical decoupling of the **circuit qubits** during **entaglement generation**

Alice storage error: 1.9(4) %

Bob storage error: 1.8(5) %

Quantum Gate Teleportation: Error Budget

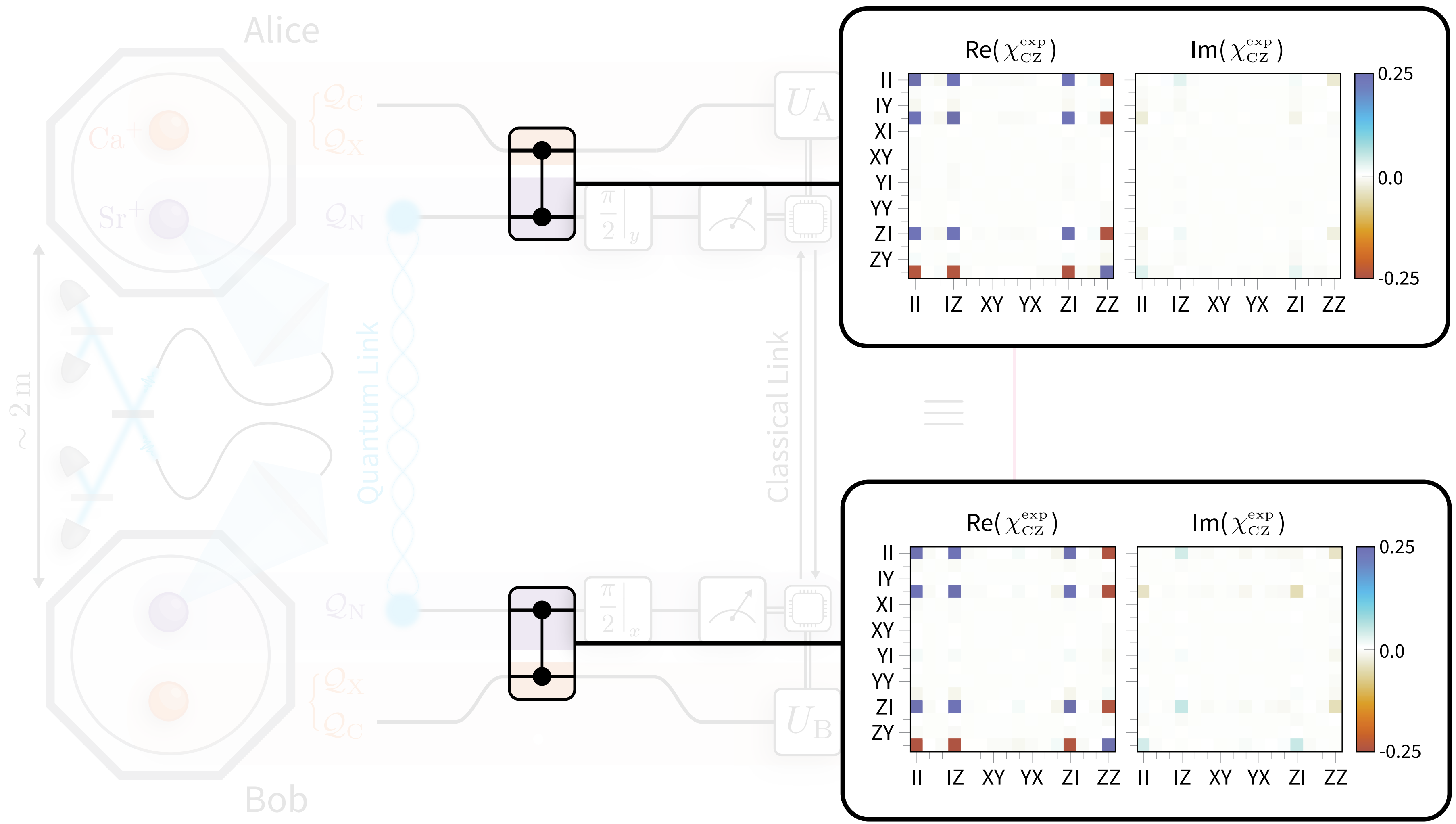


Coherent transfer between circuit and auxiliary qubits

Alice: 0.38(1) % error per transfer

Bob: 0.26(1) % error per transfer

Quantum Gate Teleportation: Error Budget

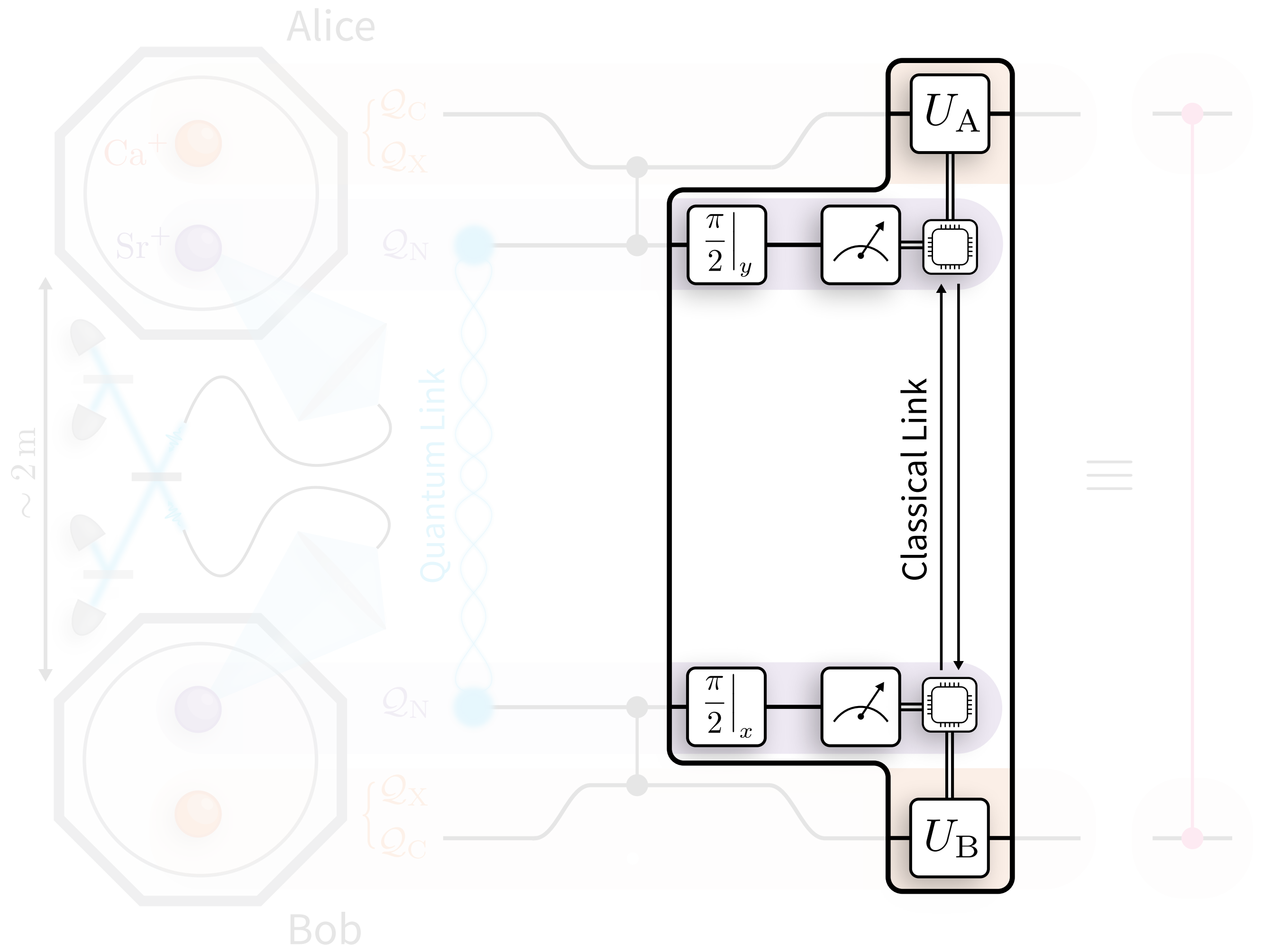


Local mixed-species CZ gates

Alice gate fidelity: 97.5(2) %

Bob gate fidelity: 98.0(2) %

Quantum Gate Teleportation: Error Budget



$$U_A = \begin{cases} S^\dagger & \text{if } m_A \oplus m_B = 0, \\ S & \text{otherwise,} \end{cases}$$

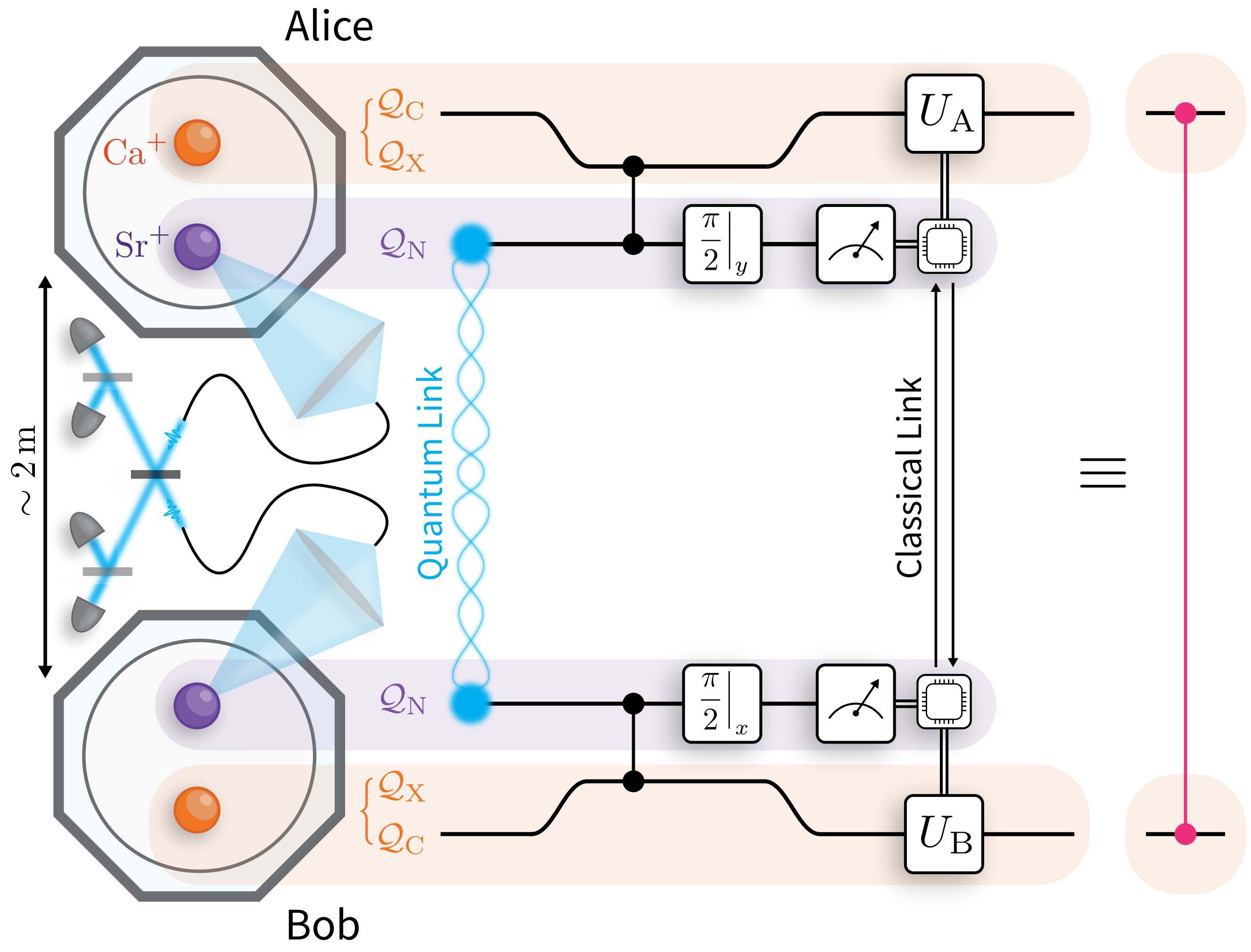
$$U_B = \begin{cases} S & \text{if } m_A \oplus m_B = 0, \\ S^\dagger & \text{otherwise,} \end{cases}$$

Mid-circuit measurement errors result in the wrong conditional unitaries applied

Alice measurement error: 0.091(3)%

Bob measurement error: 0.122(3)%

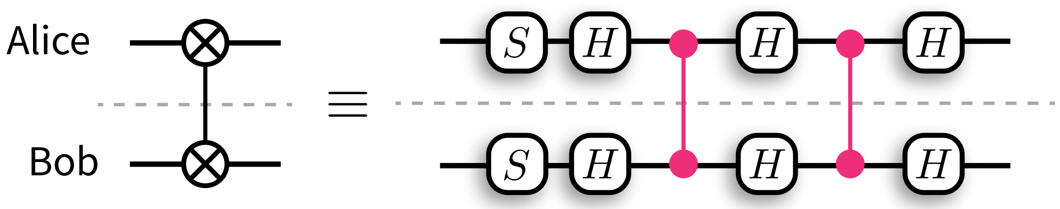
Quantum Gate Teleportation: Error Budget



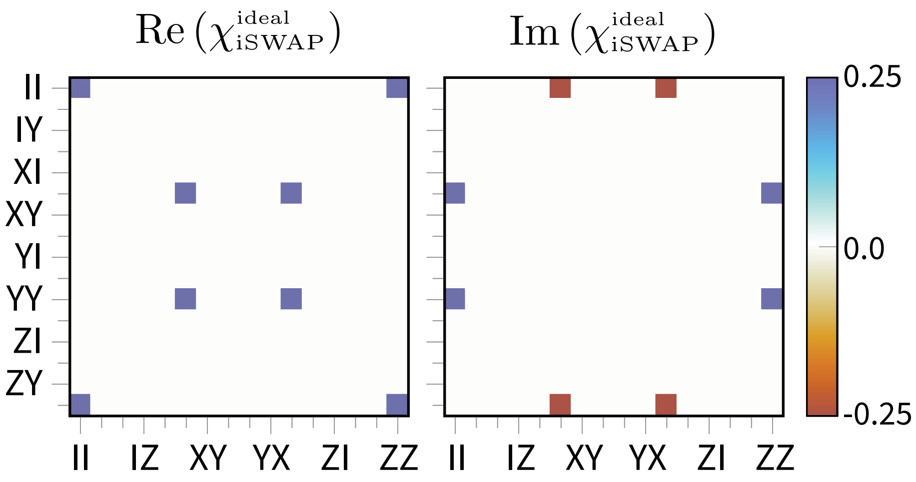
Source	Error (Alice)	Error (Bob)
Raw entanglement	2.85(9) %	
Mixed-species gate	2.5(2) %	2.0(2) %
$\mathcal{Q}_C$ decoherence	1.9(4) %	1.8(5) %
$\mathcal{Q}_X \leftrightarrow \mathcal{Q}_C$ transfer	0.76(3) %	0.52(1) %
Mid-circuit measurement	0.091(3) %	0.122(2) %
$\mathcal{Q}_C$ rotations	0.016(1) %	0.015(1) %
Predicted total error	11.9(6) %	

Distributed Quantum Computing

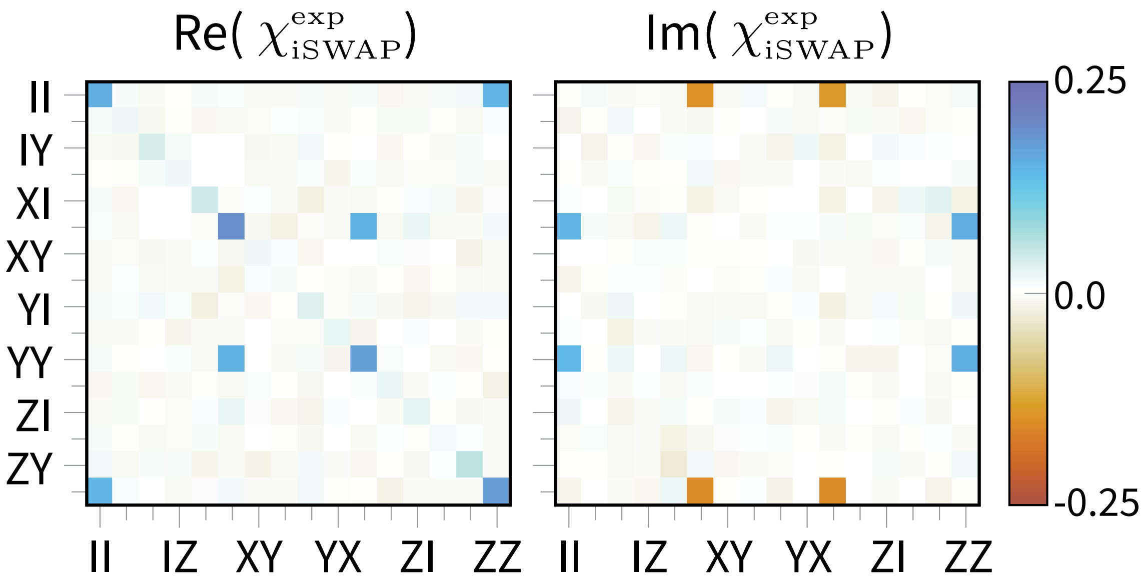
iSWAP gate



Ideal process



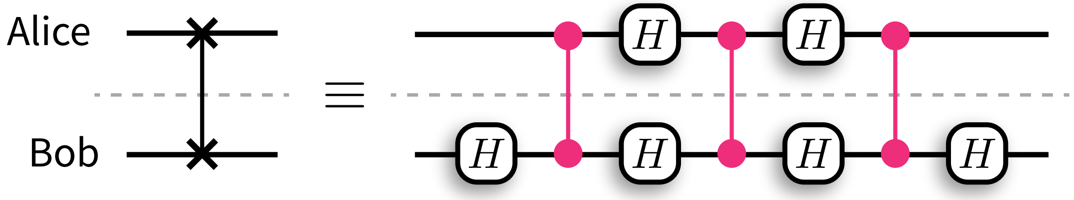
Process Tomography



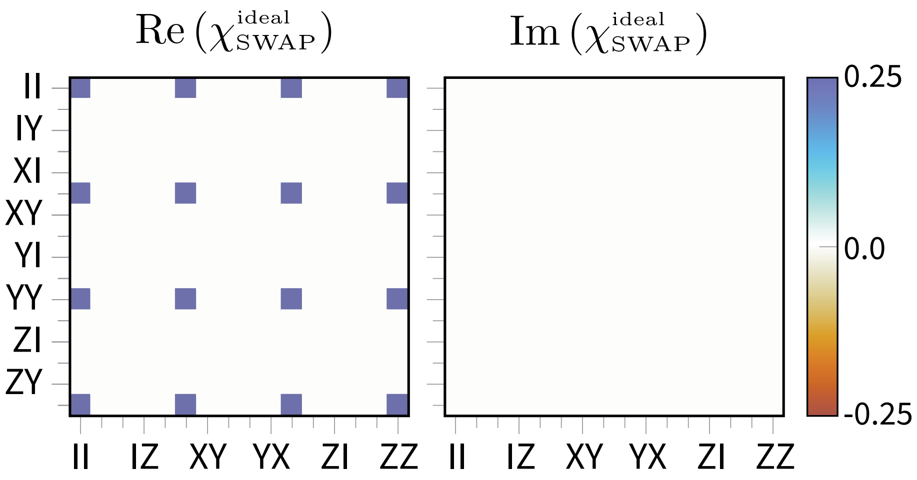
Average gate fidelity to iSWAP gate:
70(2)%

Distributed Quantum Computing

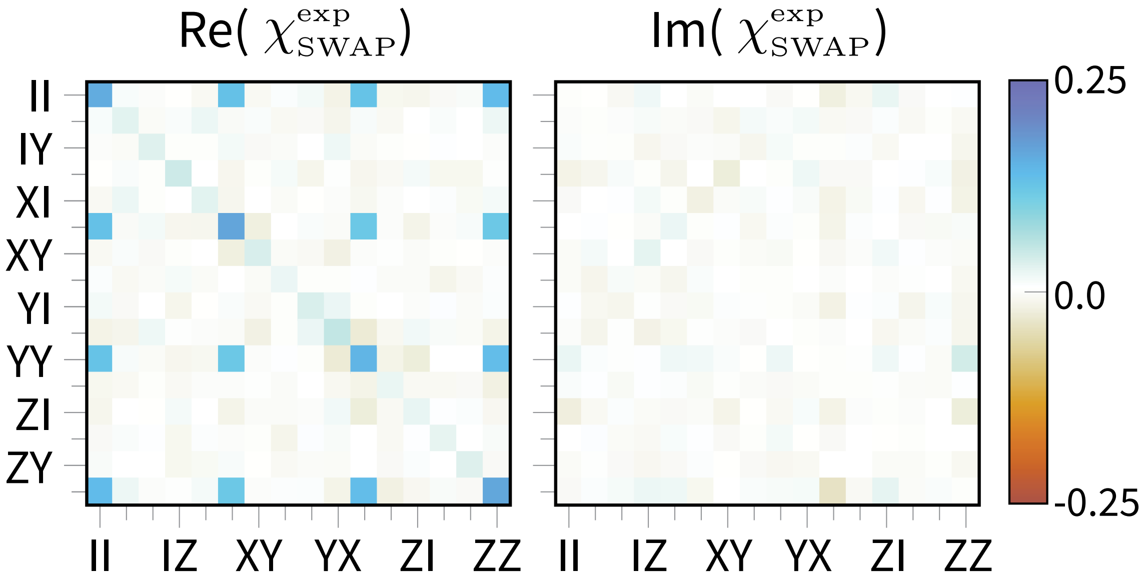
SWAP gate



Ideal process



Process Tomography

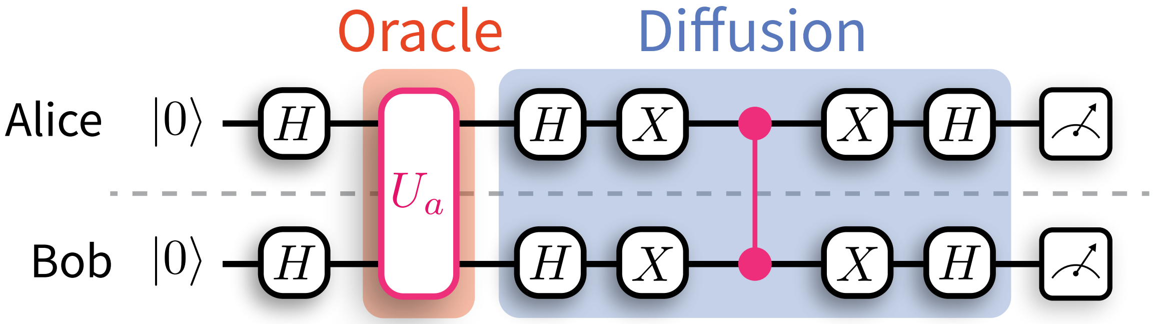


Average gate fidelity to SWAP gate:
64(2)%

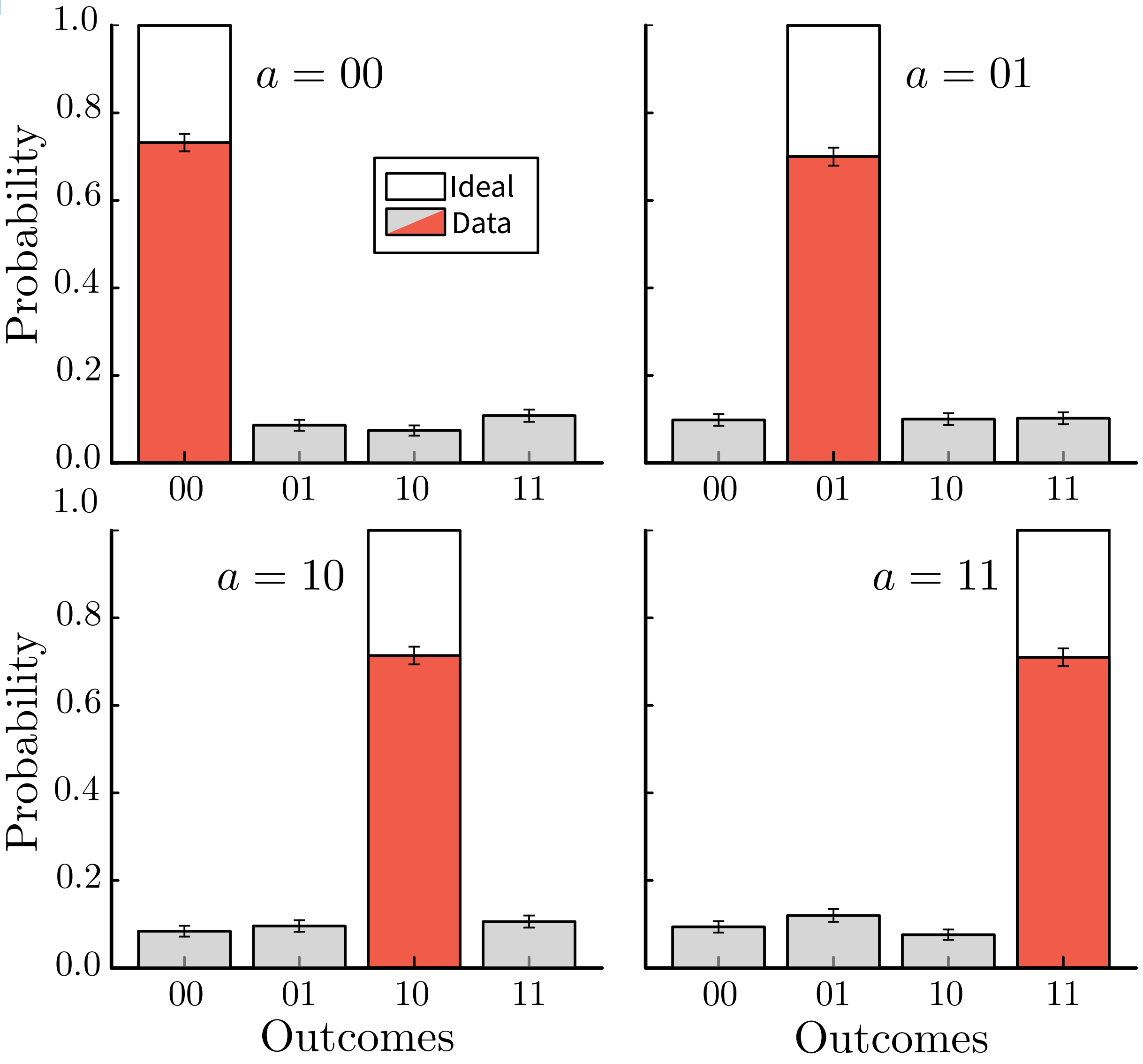
Distributed Quantum Computing

Grover's algorithm

executed on a distributed quantum computer



For each **marked state**, we obtain the correct result with an average success rate of **71.4%**



People

Pictured (left to right)

Bethan Nichol
David Nadlinger
Raghu Srinivas
David Lucas (PI)
Gabriel Araneda
Ellis Ainley
Dougal Main
Ayush Agrawal
Peter Drmota

Not pictured

Péter Juhász
Chris Ballance

Our paper is now on arXiv!

Quantum Computing & Simulation Hub

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

UK Research and Innovation

EPSRC Pioneering research and skills

Pathway to High-Fidelity DQC

Source	Error	
	Alice	Bob
Raw entanglement	2.85(9) %	
Mixed-species gate	2.5(2) %	2.0(2) %
$\mathcal{Q}_C$ decoherence	1.9(4) %	1.8(5) %
$\mathcal{Q}_\mathrm{X} \leftrightarrow \mathcal{Q}_\mathrm{C}$ transfer	0.76(3) %	0.52(1) %
Mid-circuit measurement	0.091(3) %	0.122(2) %
$\mathcal{Q}_\mathrm{C}$ rotations	0.016(1) %	0.015(1) %
Predicted total error	11.9(6) %	

Pathway to High-Fidelity DQC

Source	Error	
	Alice	Bob
Raw entanglement	2.85(9) %	
Mixed-species gate	0.2(1) %	
$\mathcal{Q}_C$ decoherence	1.9(4) %	1.8(5) %
$\mathcal{Q}_X \leftrightarrow \mathcal{Q}_C$ transfer	0.76(3) %	0.52(1) %
Mid-circuit measurement	0.091(3) %	0.122(2) %
$\mathcal{Q}_C$ rotations	0.016(1) %	0.015(1) %
Predicted total error	11.9(6) %	

Benchmarking a High-Fidelity Mixed-Species Entangling Gate

A. C. Hughes,[†] V. M. Schäfer,[*,†] K. Thirumalai,[†] D. P. Nadlinger, S. R. Woodrow, D. M. Lucas, and C. J. Ballance
Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, United Kingdom

Pathway to High-Fidelity DQC

Source	Error	
	Alice	Bob
Raw entanglement	2.85(9) %	
Mixed-species gate	0.2(1) %	
$\mathcal{Q}_C$ decoherence	~ 0.1 %	
$\mathcal{Q}_X \leftrightarrow \mathcal{Q}_C$ transfer	~ 0.1 %	
Mid-circuit measurement	< 0.1 %	
$\mathcal{Q}_C$ rotations	< 0.1 %	
Predicted total error	~ 3 %	

Benchmarking a High-Fidelity Mixed-Species Entangling Gate

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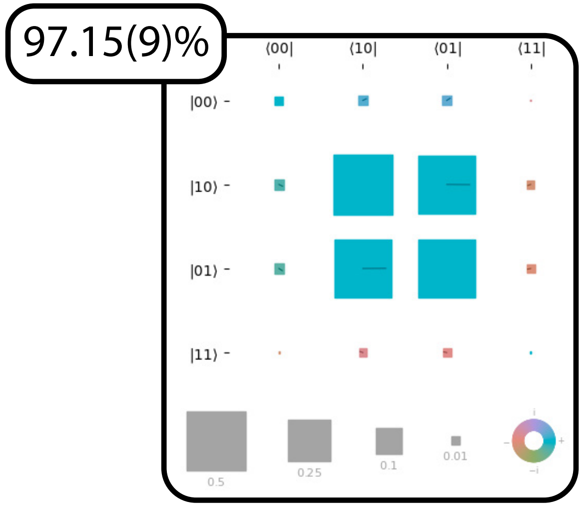
Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, United Kingdom

Dominated by noise in the quantum channel interconnecting the modules

Pathway to High-Fidelity DQC

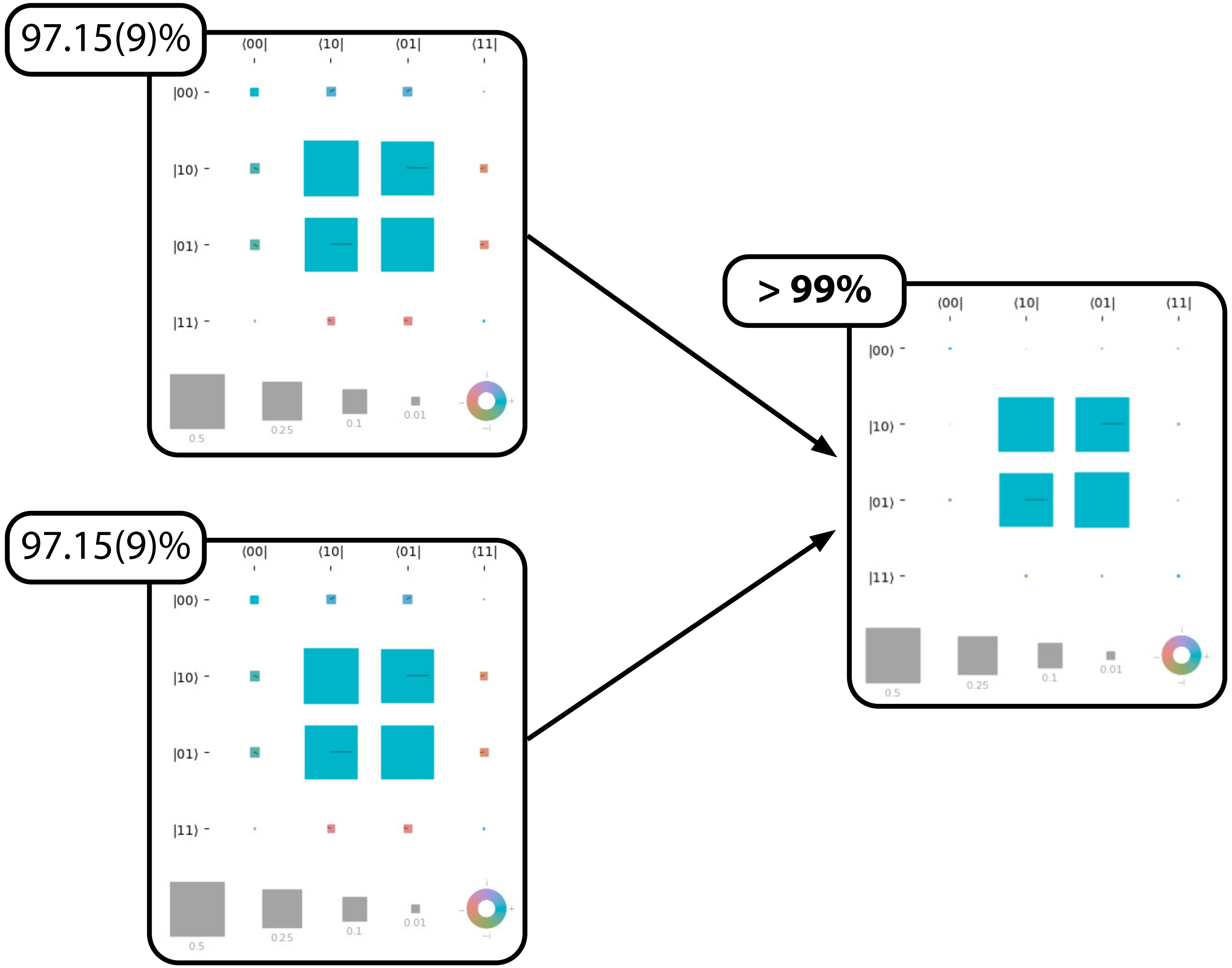
Quantum interconnects will be **noisy** and **lossy**



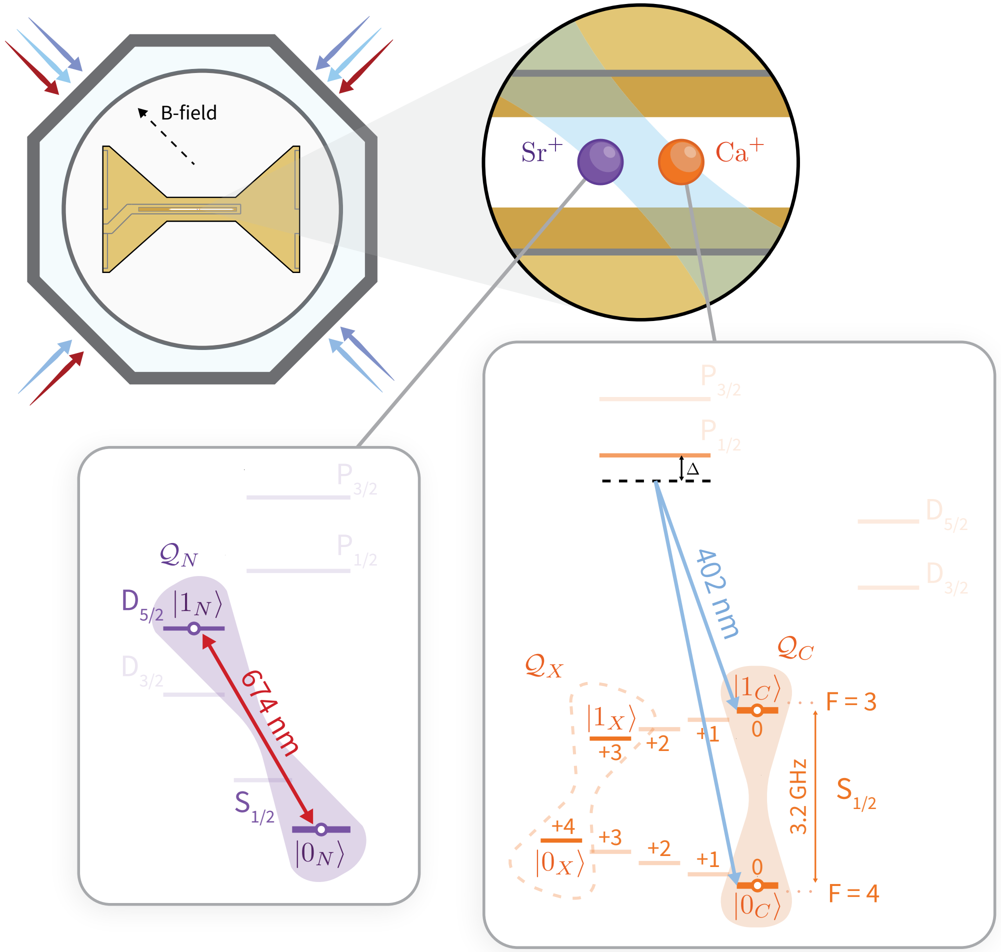
Pathway to High-Fidelity DQC

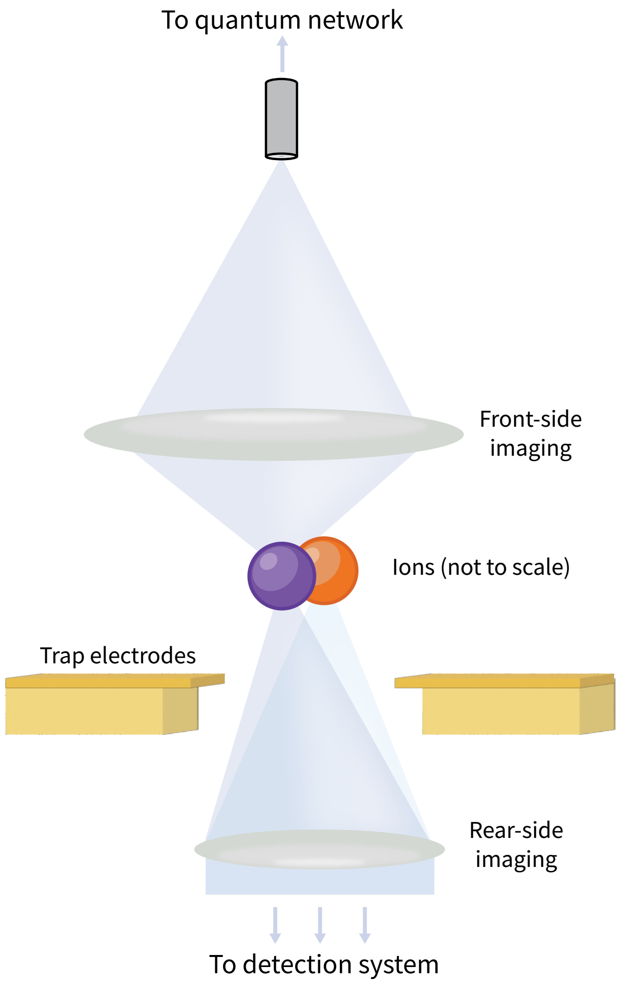
Quantum interconnects will be **noisy** and **lossy**

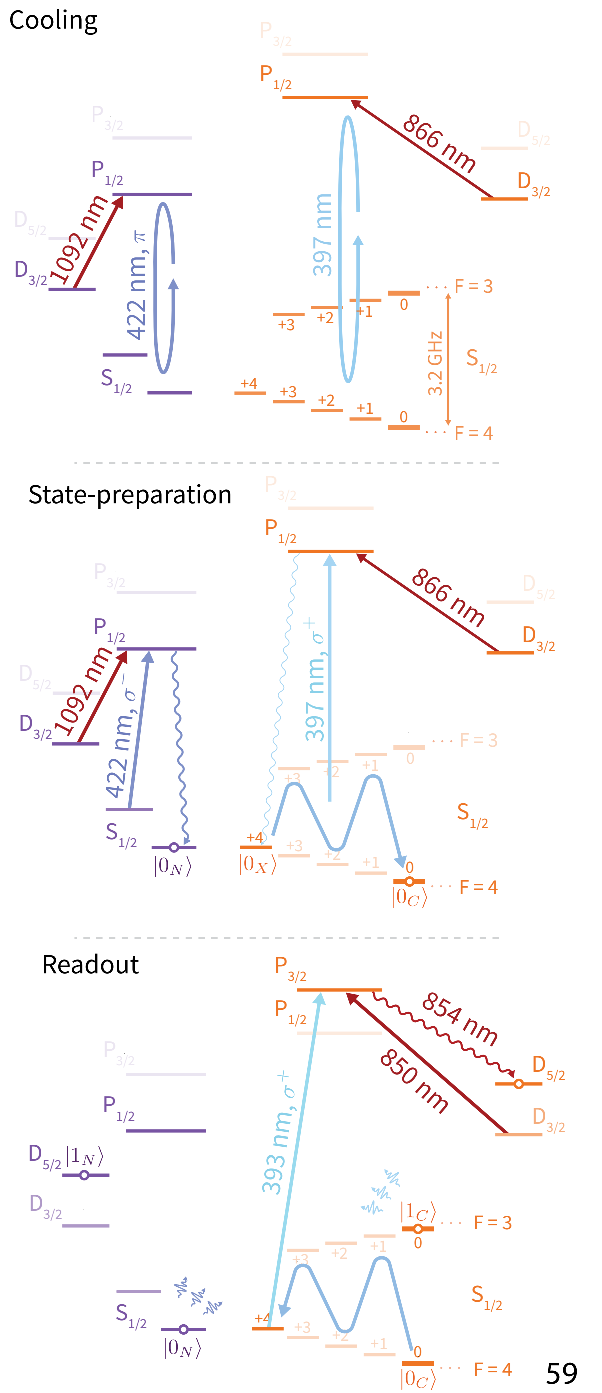
Entanglement distillation would enable distribution of **high-fidelity entanglement**



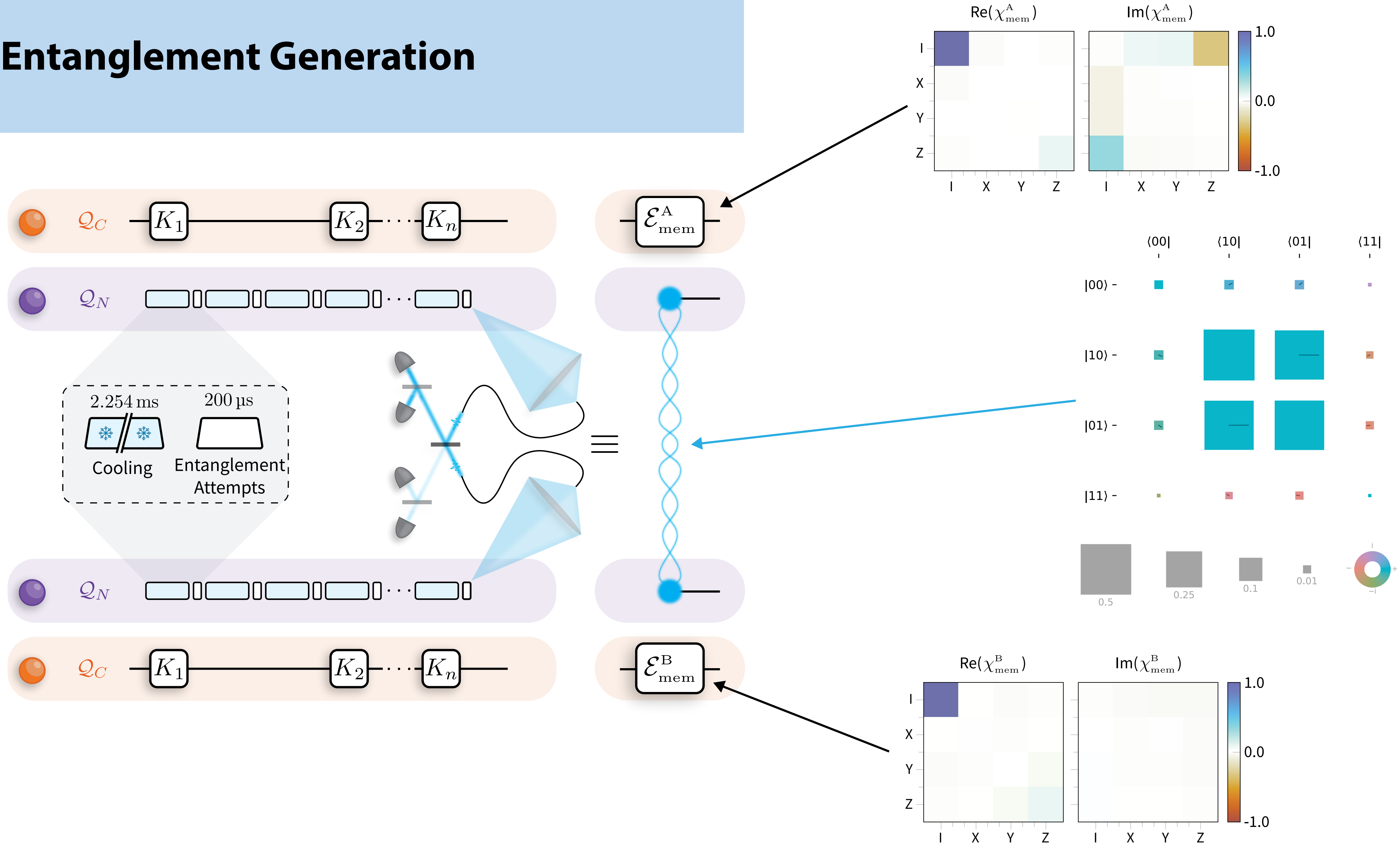
Trapped-Ion Module



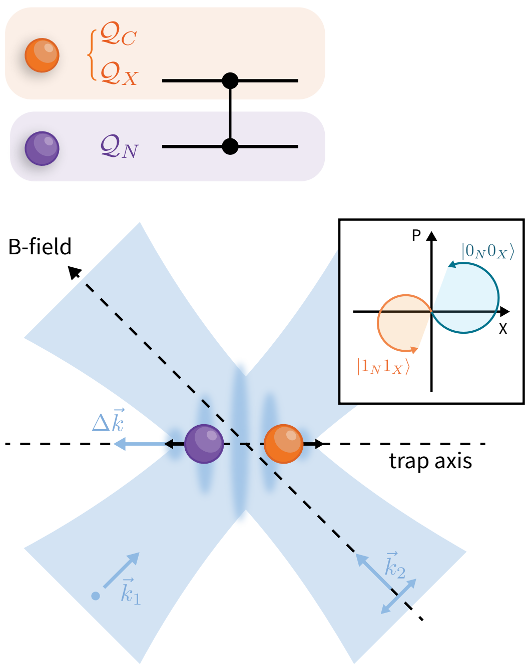


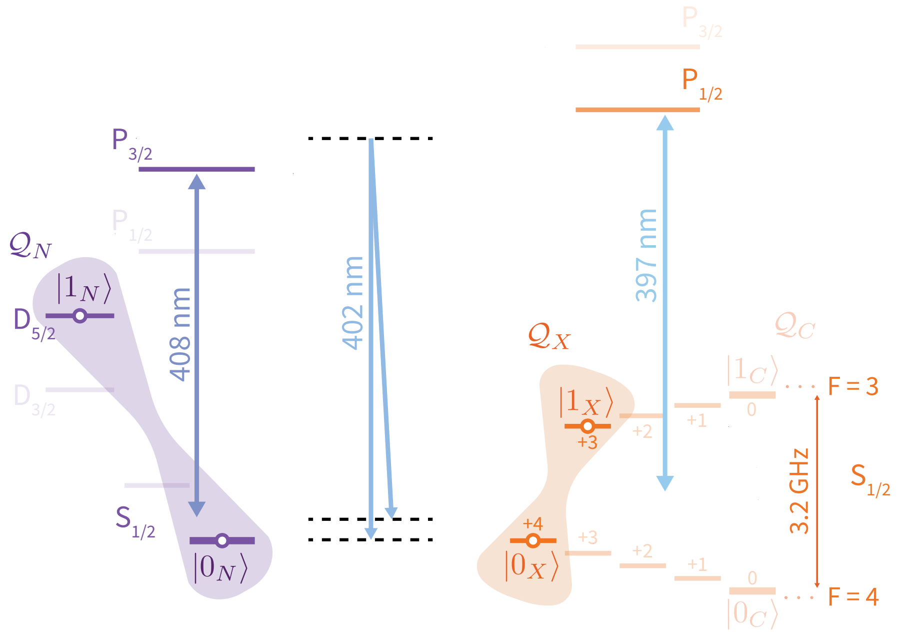


Entanglement Generation

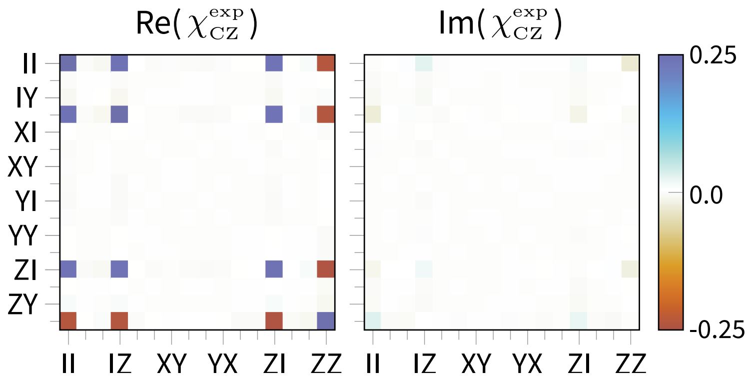


Mixed-Species Gates

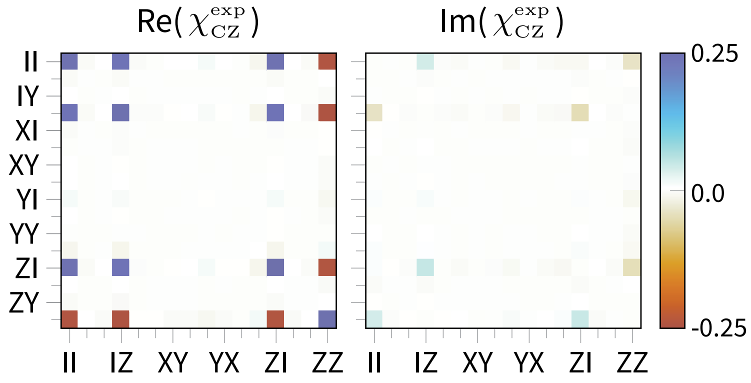




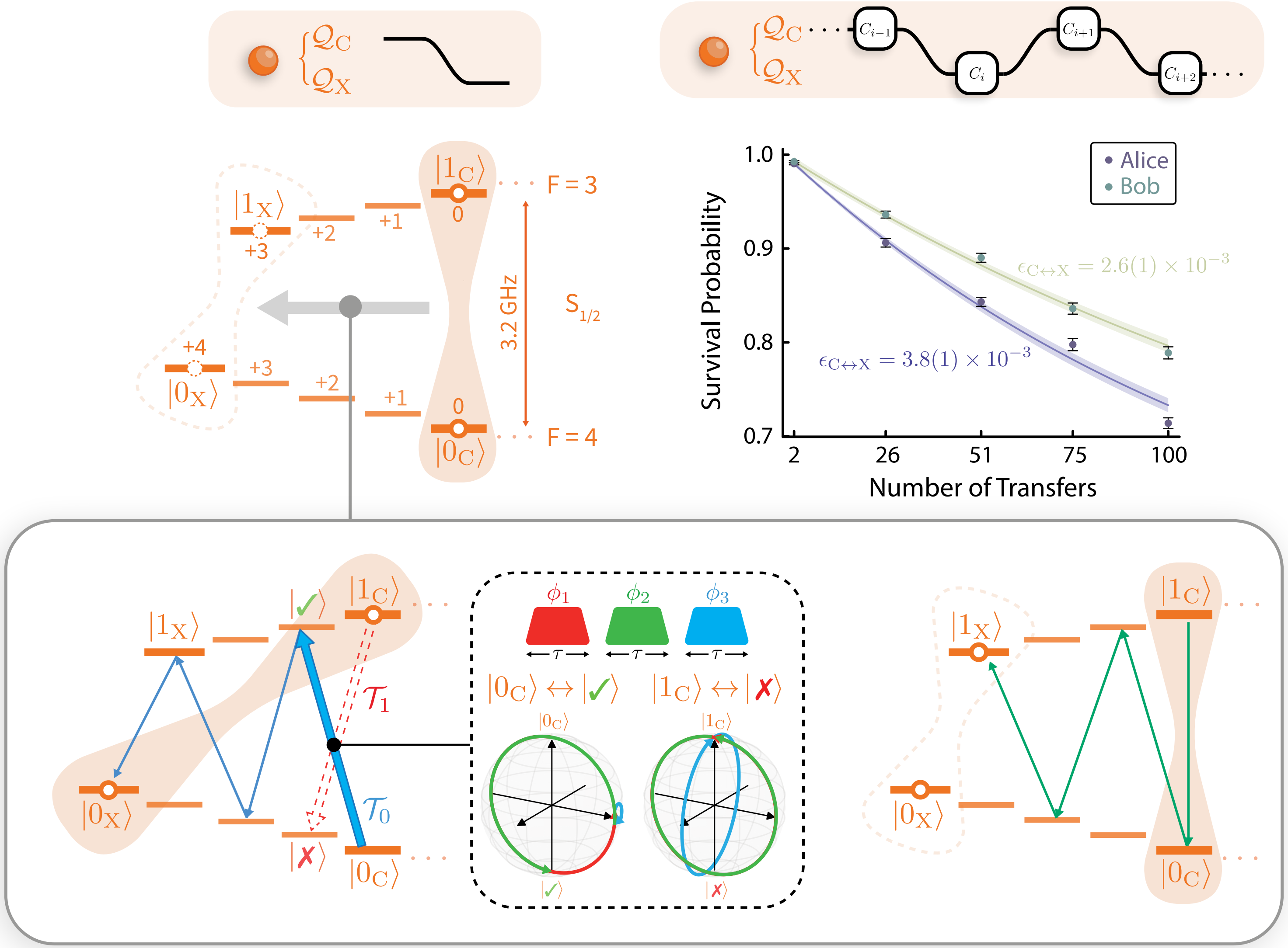
Alice



Bob

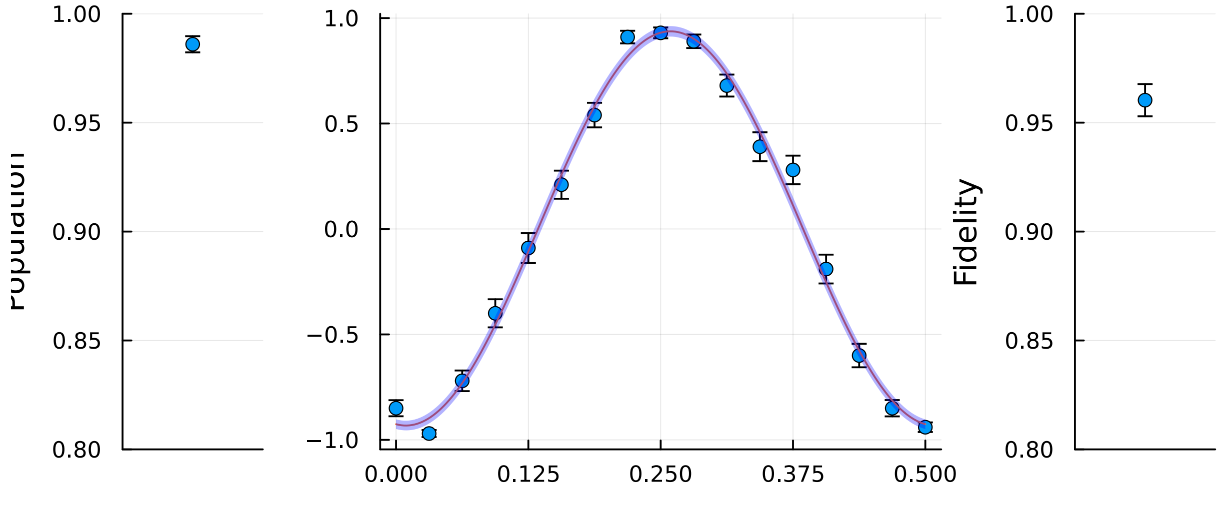


Hyperfine Transfer

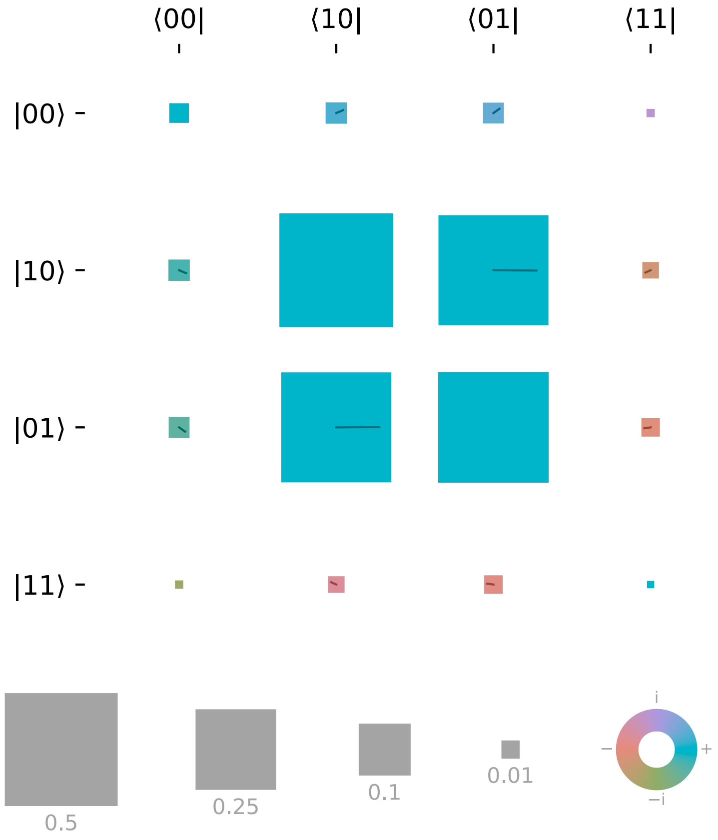


Mixed-Species Remote Entanglement

Sr-Sr "Raw" Remote Entanglement



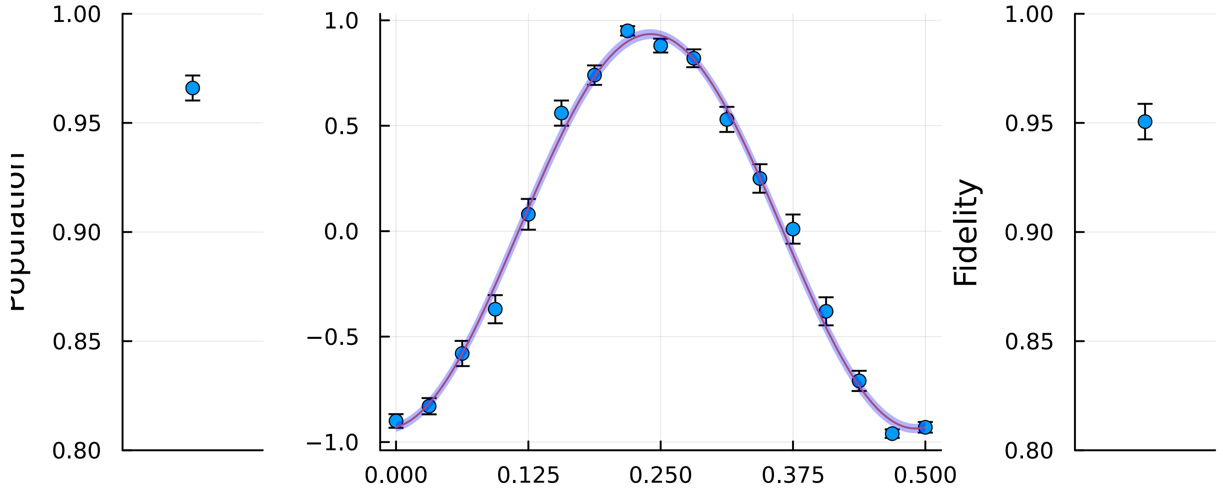
$$\frac{|01\rangle + |10\rangle}{\sqrt{2}}$$



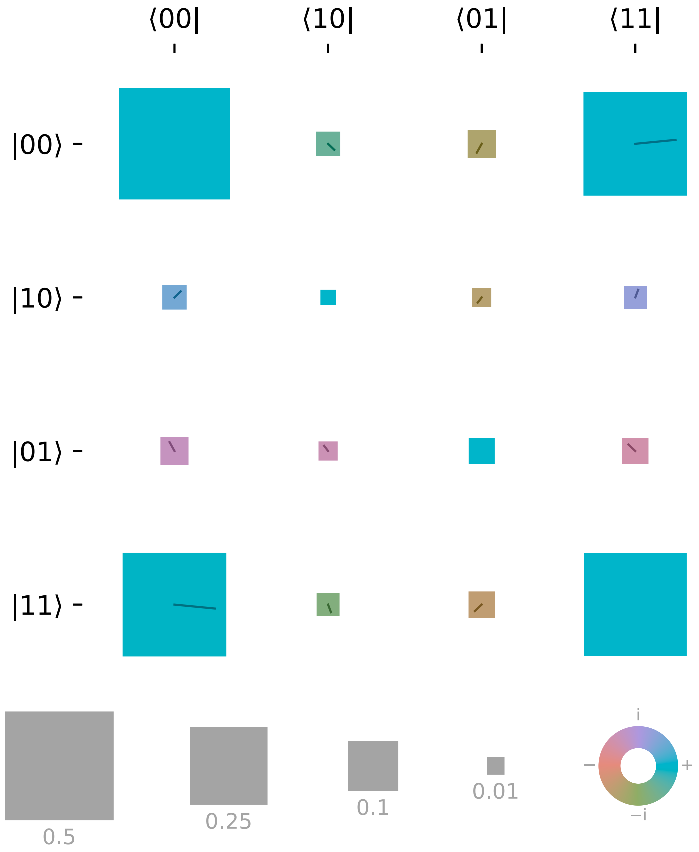
Fidelity to nearest Bell-state: 97.15(9) %

Mixed-Species Remote Entanglement

Sr-Ca Mixed-Species Remote Entanglement



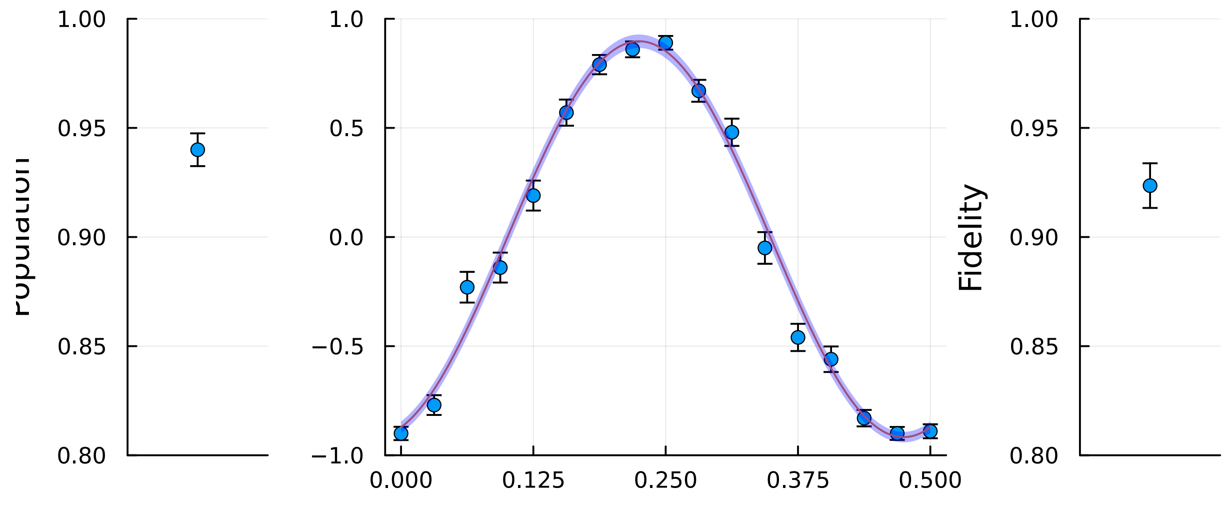
$$\frac{|00\rangle + |11\rangle}{\sqrt{2}}$$



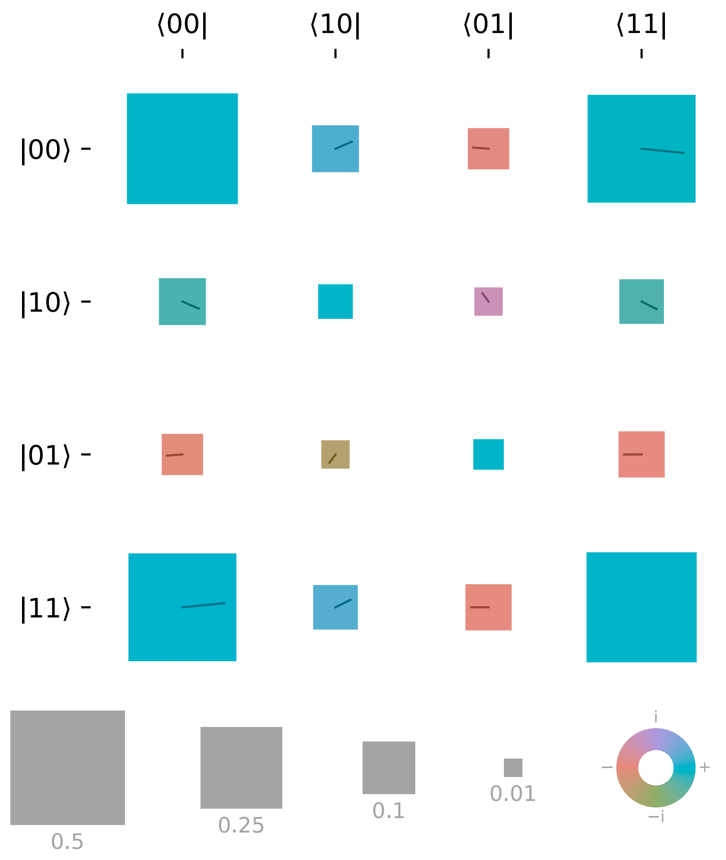
Fidelity to nearest Bell-state: 94.0(5)%

Mixed-Species Remote Entanglement

Ca-Ca Remote Entanglement



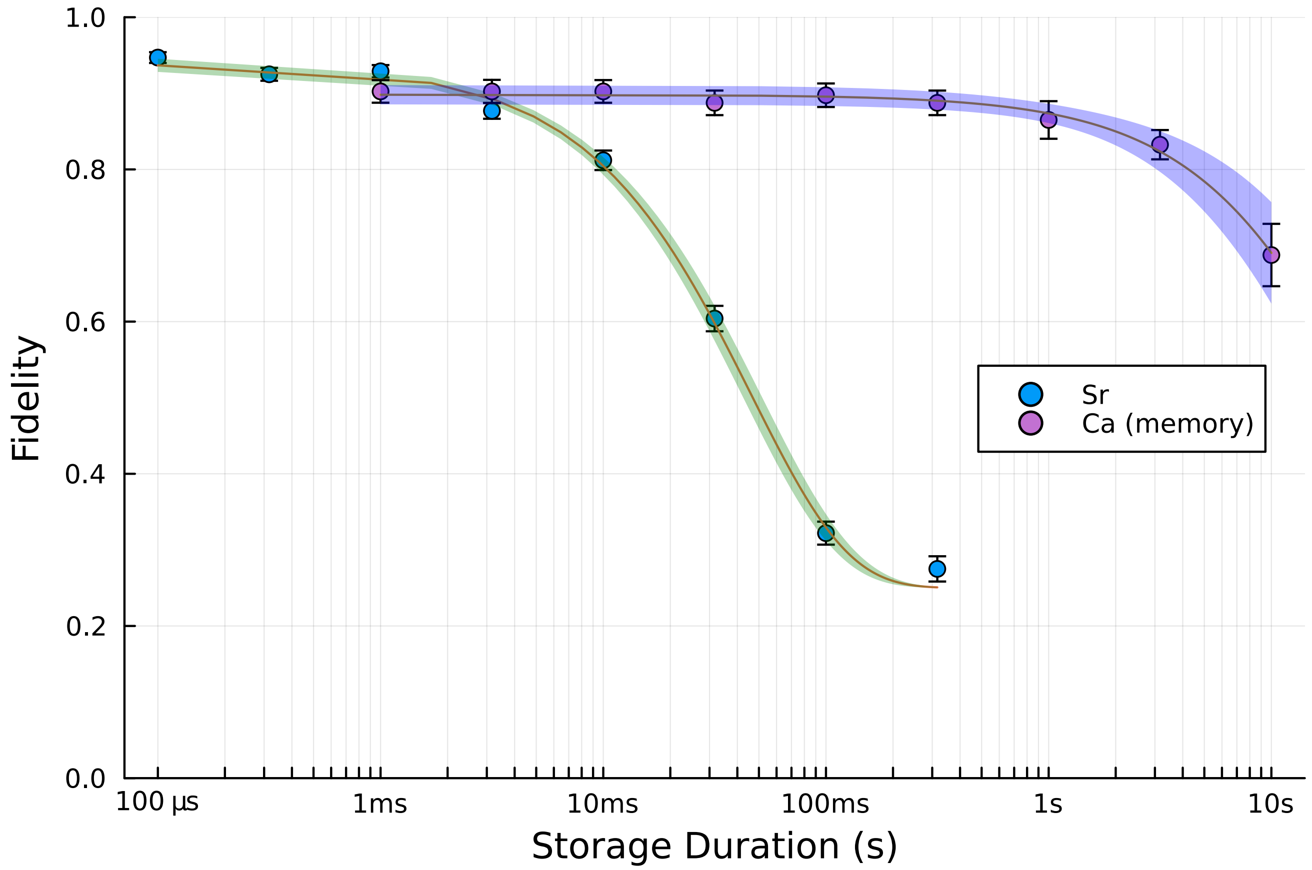
$$\frac{|00\rangle + |11\rangle}{\sqrt{2}}$$



Fidelity to nearest Bell-state: 92.9(7)%

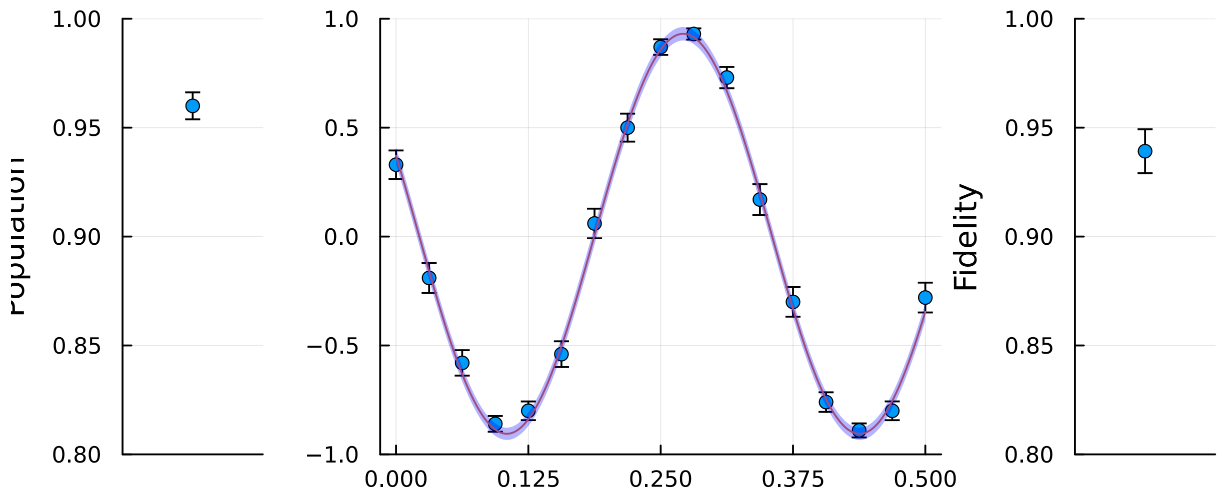
Mixed-Species Remote Entanglement

Ca memory performance

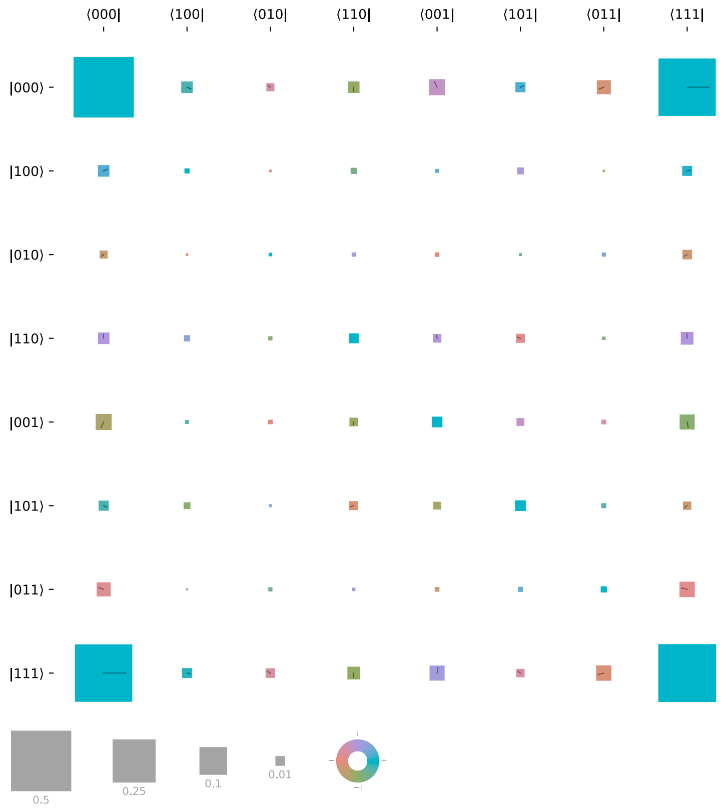


Mixed-Species Remote Entanglement

Sr-Sr-Ca Mixed-Species GHZ State



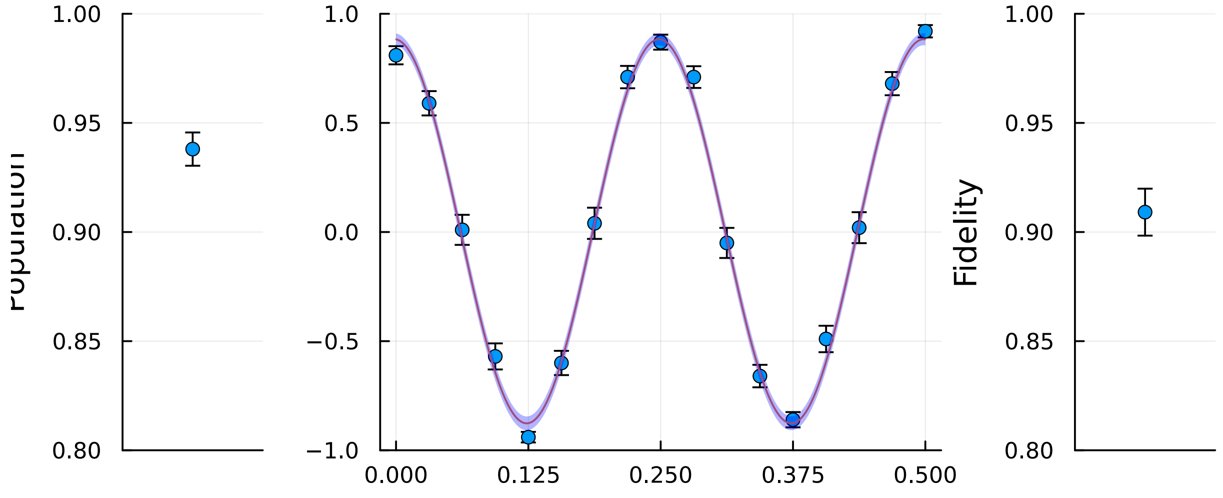
$$\frac{|000\rangle + |111\rangle}{\sqrt{2}}$$



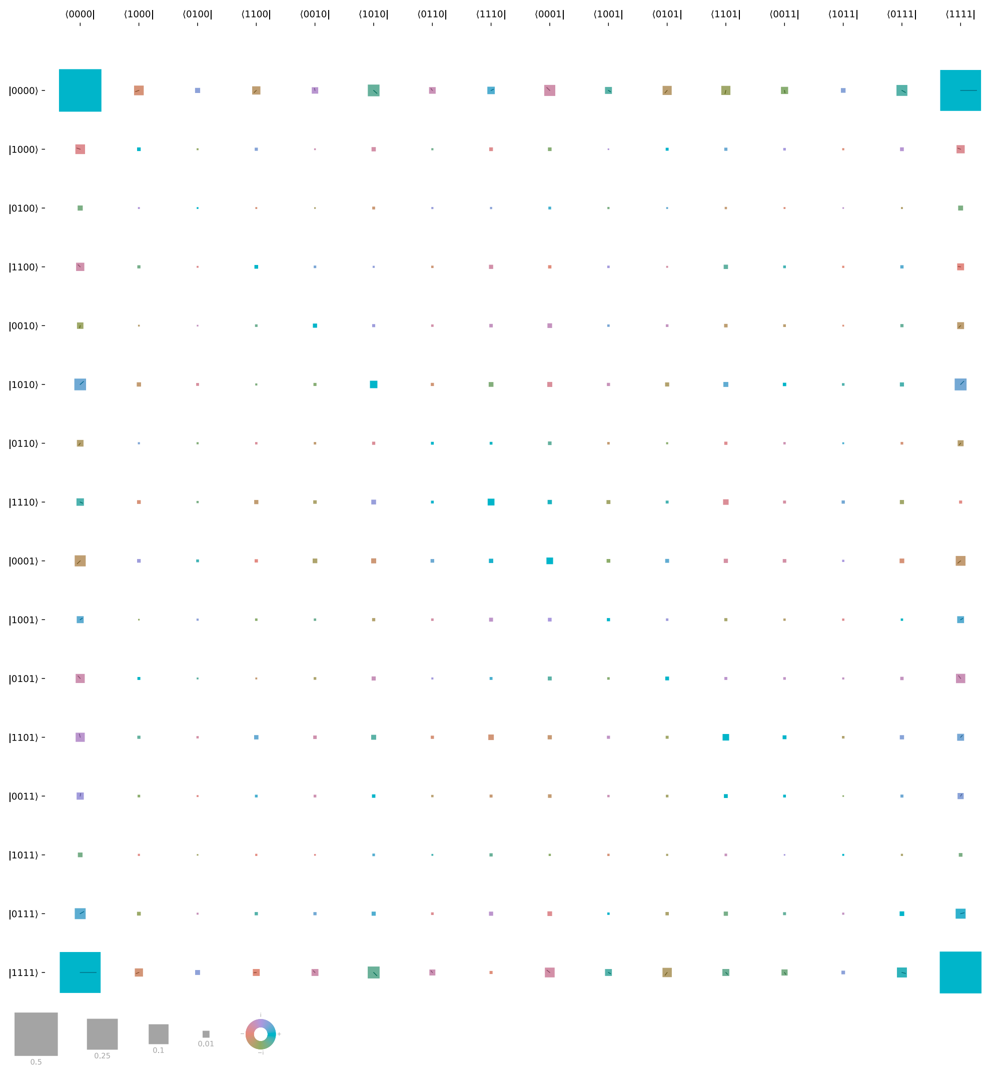
Fidelity to GHZ state: 92.9(8)%

Mixed-Species Remote Entanglement

Sr-Sr-Ca-Ca Mixed-Species GHZ State



$$\frac{|0000\rangle + |1111\rangle}{\sqrt{2}}$$



Fidelity to GHZ state: 91.6(8)%