Quantum Internet to Accelerate Scientific Discovery

DOE.ASCR Program Manager: Dr. Carol Hawk

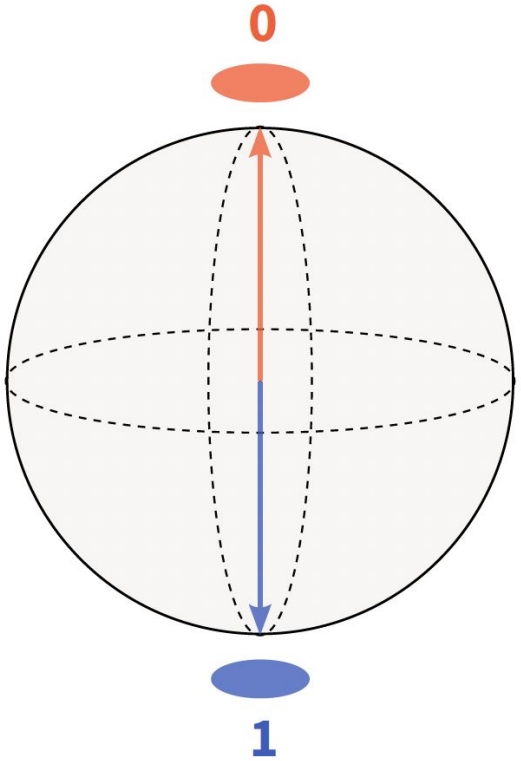
Quantum Application Network Testbed for Novel Entanglement Technology: QUANT-NET

Inder Monga, LBNL (Principal Investigator)
Hartmut Häffner, Alp Sipahigil, UC Berkeley (Co-Investigators)
Maria Spiropulu, Caltech (Co-Investigator)
Thomas Schenkel, LBNL (Co-Investigator)

Quantum Principles
(relevant to this talk)

Qubit (Quantum Bit)

- All classical bits in digital communications can only take on two values: a zero or a one
- A qubit can have any value on this sphere
- In fact, the qubit can have both the values of 0 and 1 at the same time
- This property is called “superposition”
- In QIS, a logical qubit state is the superposition of two basis states $|0\rangle$, $|1\rangle$
- The whole world is made up of matter like this, and it is stable
- If you interact with this object, it is considered an ‘observation’ and the superposition collapses
    - Aka the object only has one value



What does it mean?

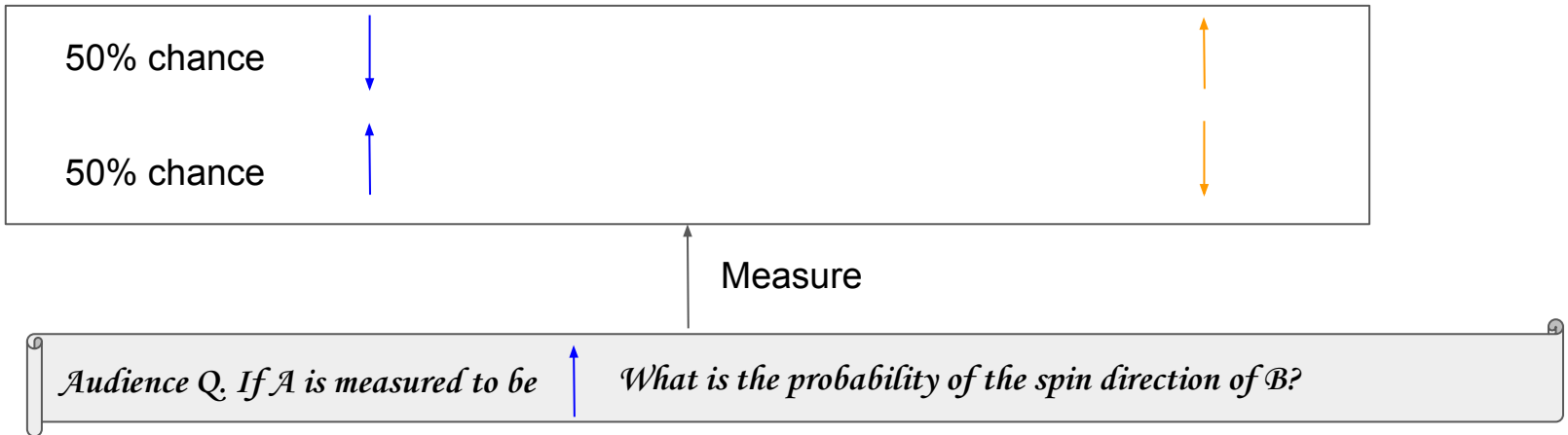
- If information is encoded into a qubit, then if **someone external** interacts with that qubit, a value would be retrieved and superposition will collapse.

- The person or system interacting with the qubit cannot determine if the value retrieved is the right value, and they cannot convert the qubit back to its original state and send it onwards to the intended recipient as if nothing happened. This information is “destroyed”.

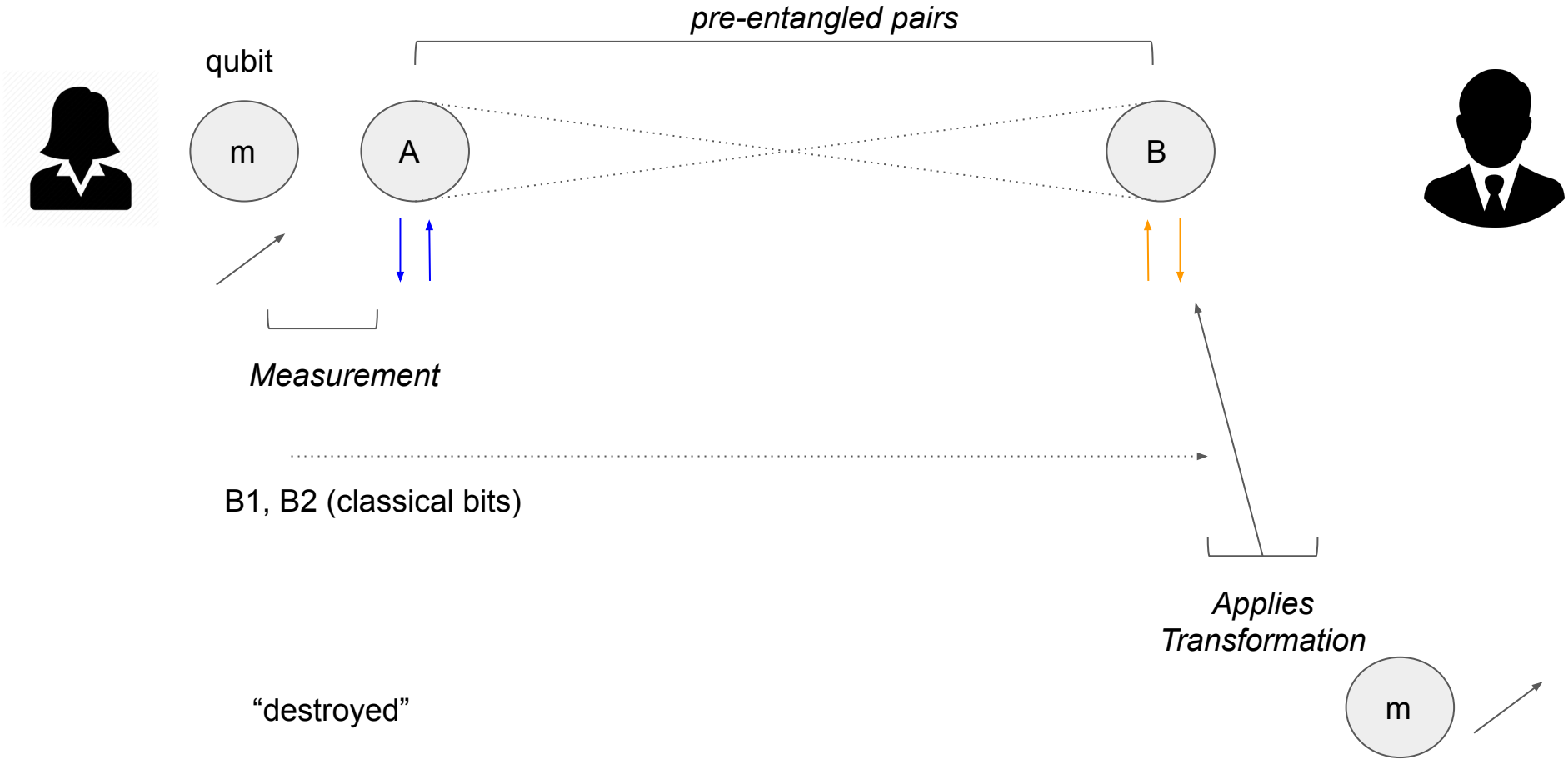
In short, trying to read quantum information changes the information, which means it can’t be intercepted, copied or observed. (no cloning principle)

Entanglement

- A and B are entangled if, measuring A, affects the state of B (aka makes it more or less deterministic)
- For example,



Teleportation (textbook version)



The Quantum Internet: notional view

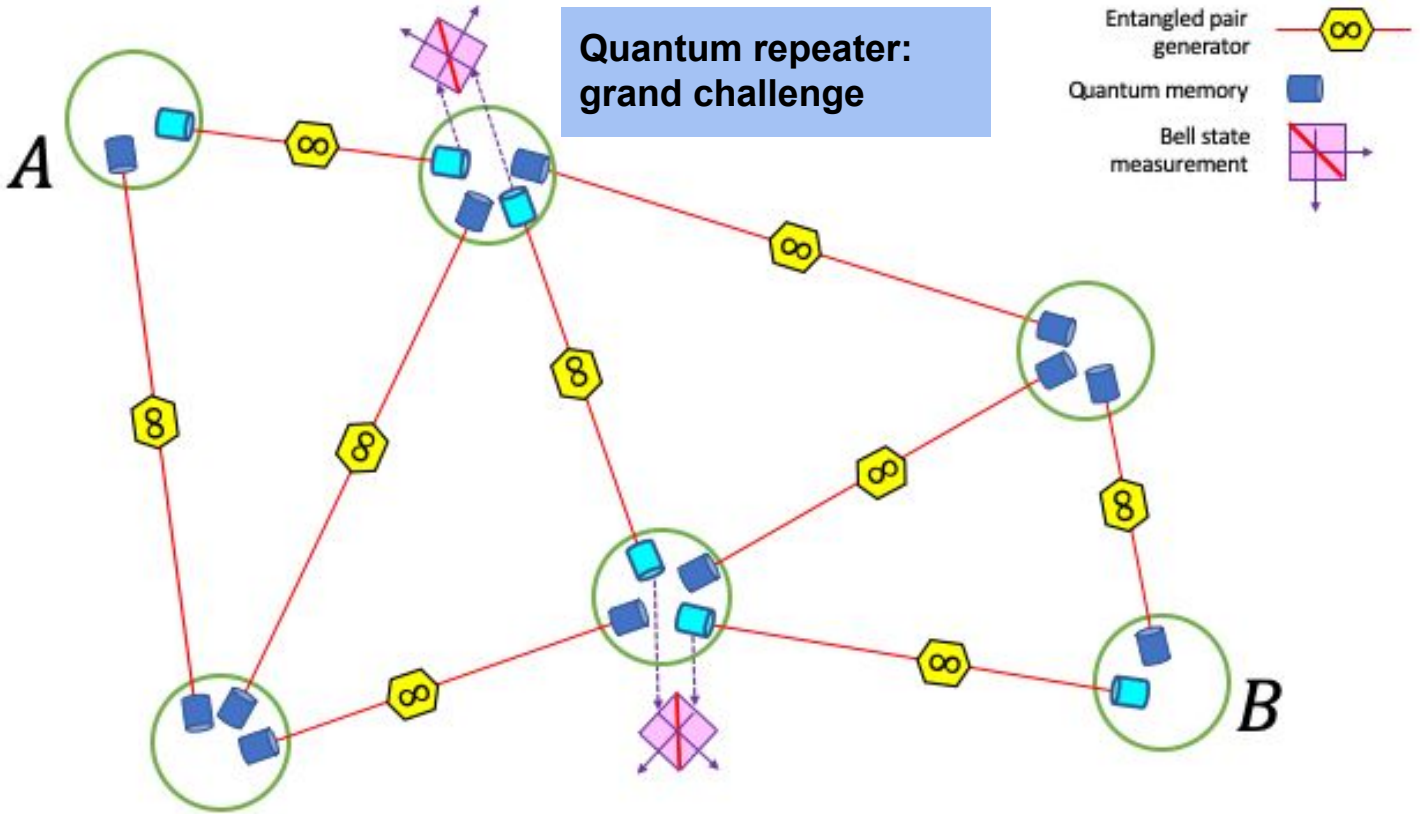
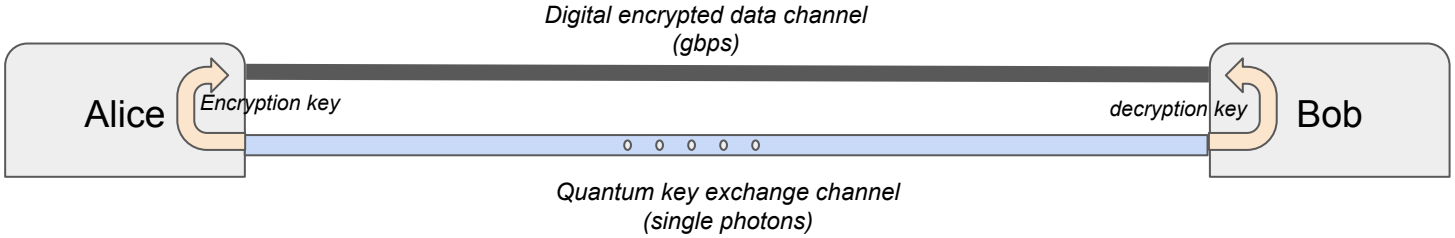


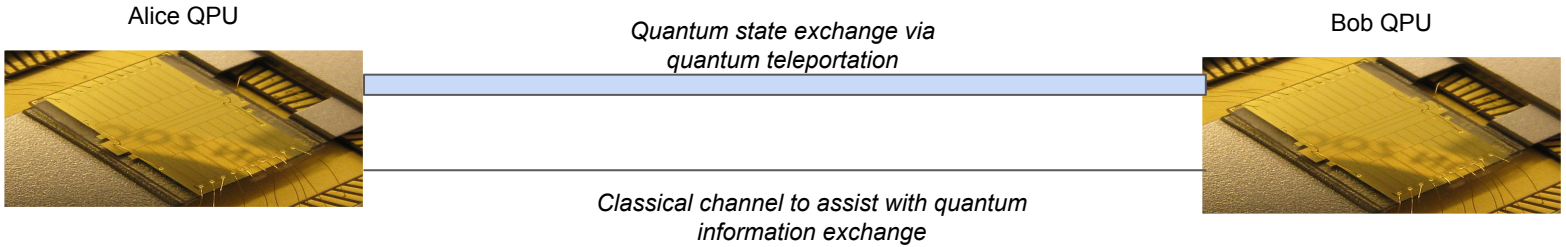
Diagram by Eden Figueroa

Quantum Key Distribution vs Quantum networking

This talk



QKD uses a quantum properties to exchange a private key used to encrypt/decrypt our classical channels.



Quantum networking/communication is a mechanism to exchange quantum states between quantum devices that the classical network is incapable of doing.

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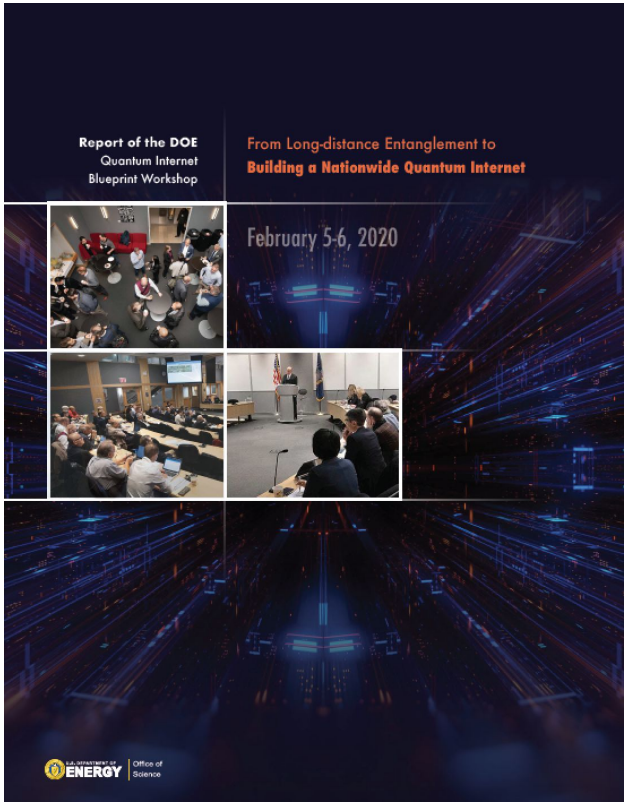
Quantum Internet to Accelerate Scientific Discovery FOA



DEPARTMENT OF ENERGY
OFFICE OF SCIENCE
ADVANCED SCIENTIFIC COMPUTING RESEARCH

QUANTUM INTERNET TO ACCELERATE SCIENTIFIC DISCOVERY

DOE NATIONAL LABORATORY PROGRAM ANNOUNCEMENT NUMBER:
LAB 21-2495

ANNOUNCEMENT TYPE: INITIAL

Announcement Issue Date:	April 13, 2021
Submission Deadline for Proposals:	May 28, 2021 at 5:00 PM Eastern Time

5 year proposals

Program Manager: Carol Hawk

2 proposals funded

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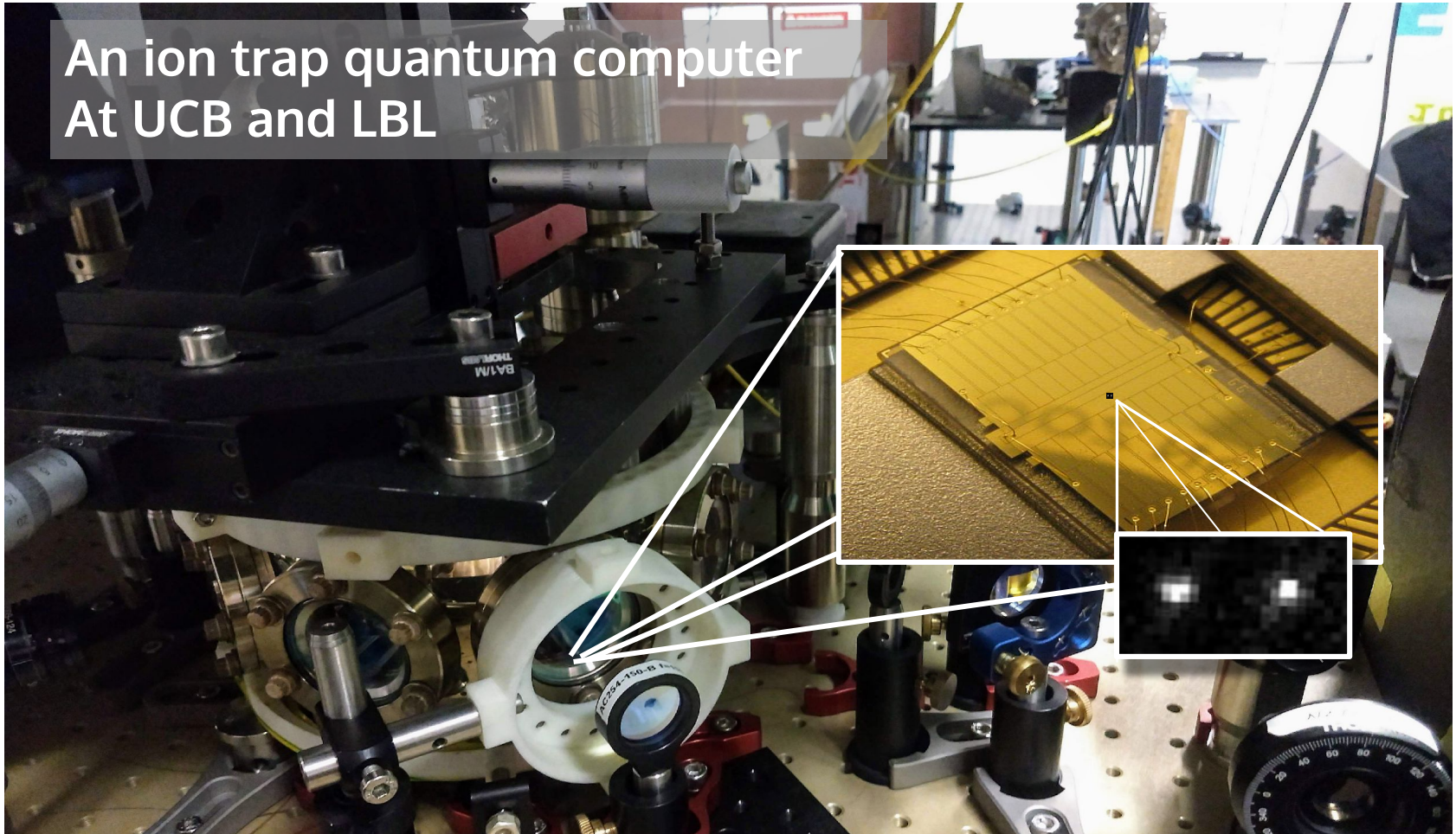
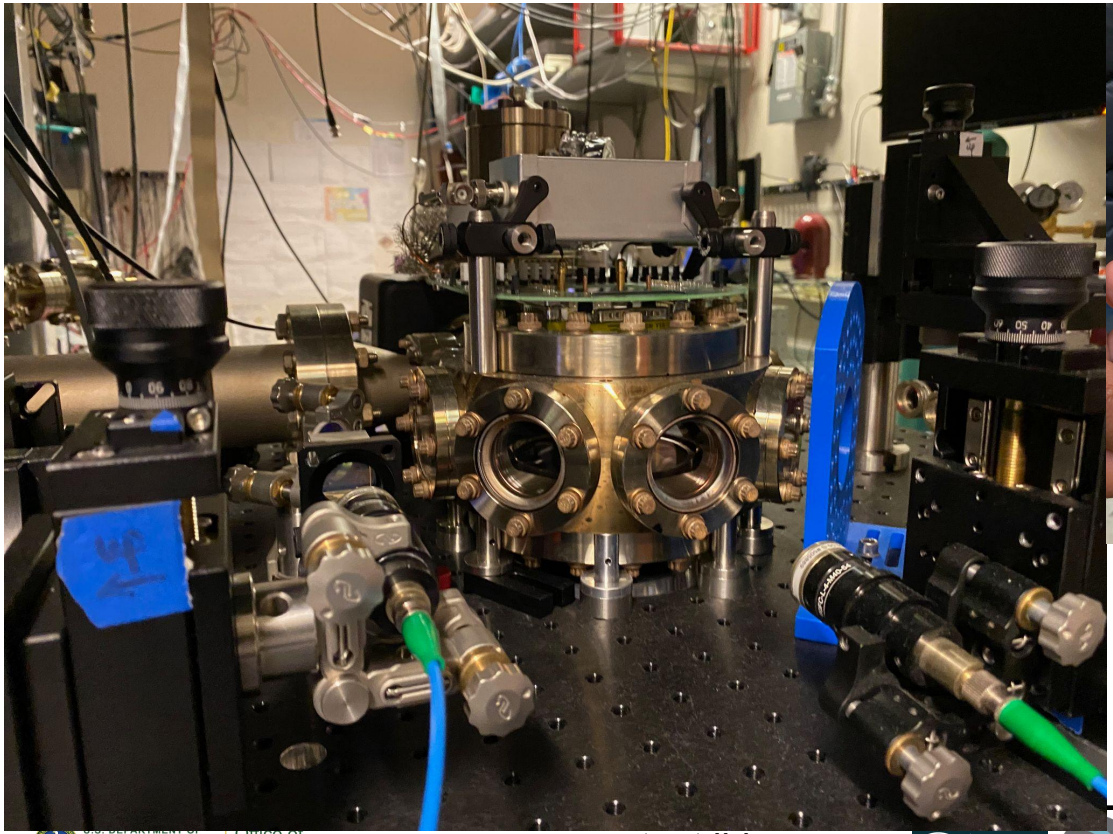
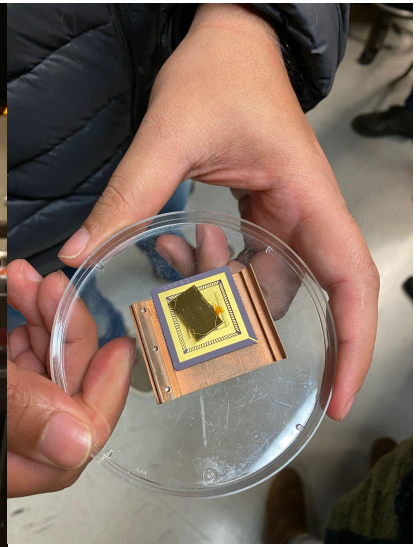
Distributed Quantum Computing



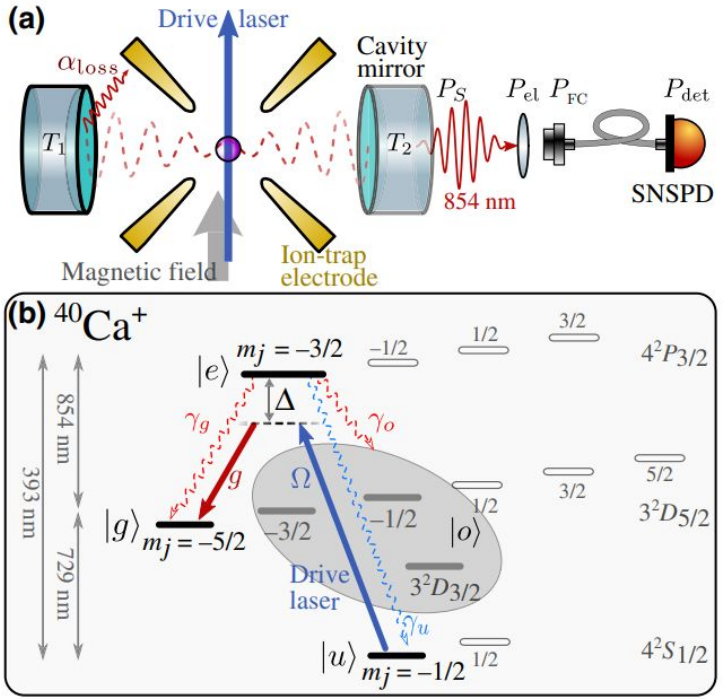
Ion Trap in UC Berkeley





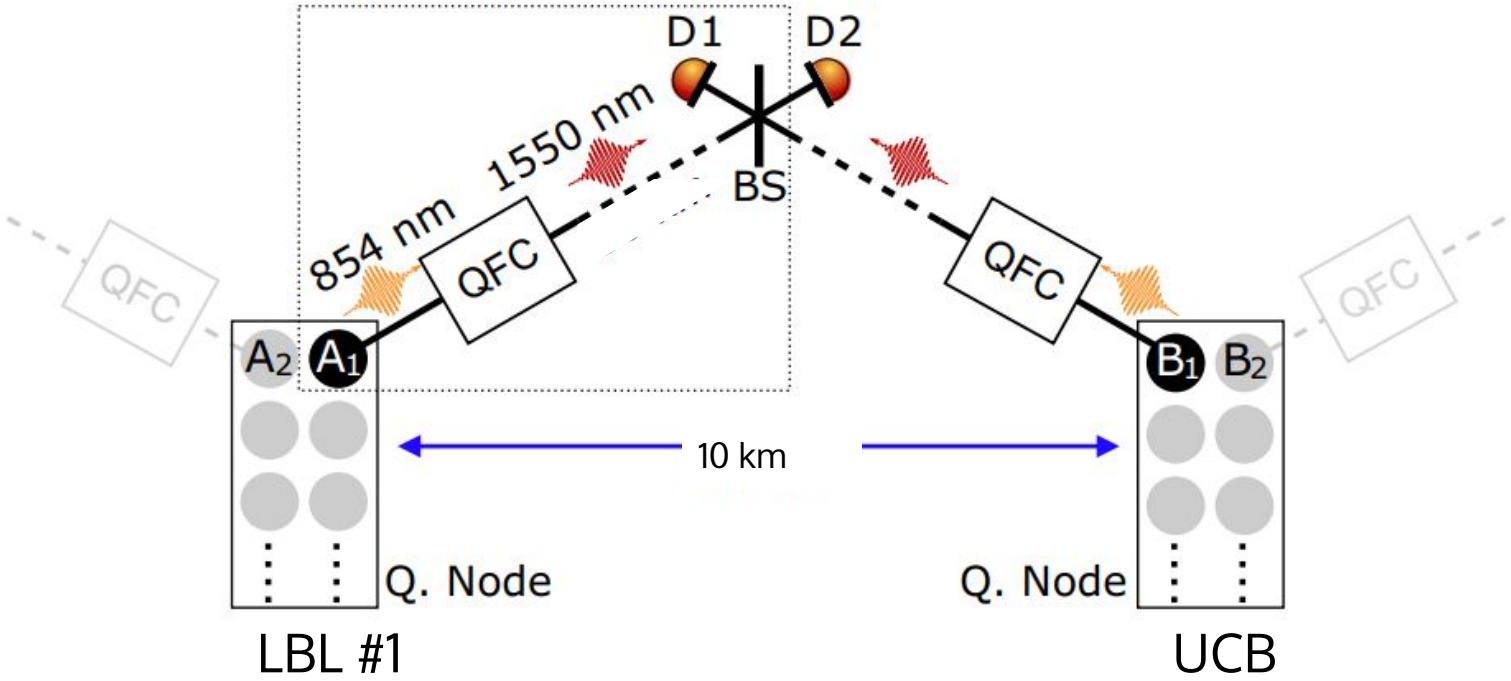
Trapped Ion System

- Surface Trap
- $^{40}Ca^{+}$ ions
- Cavity



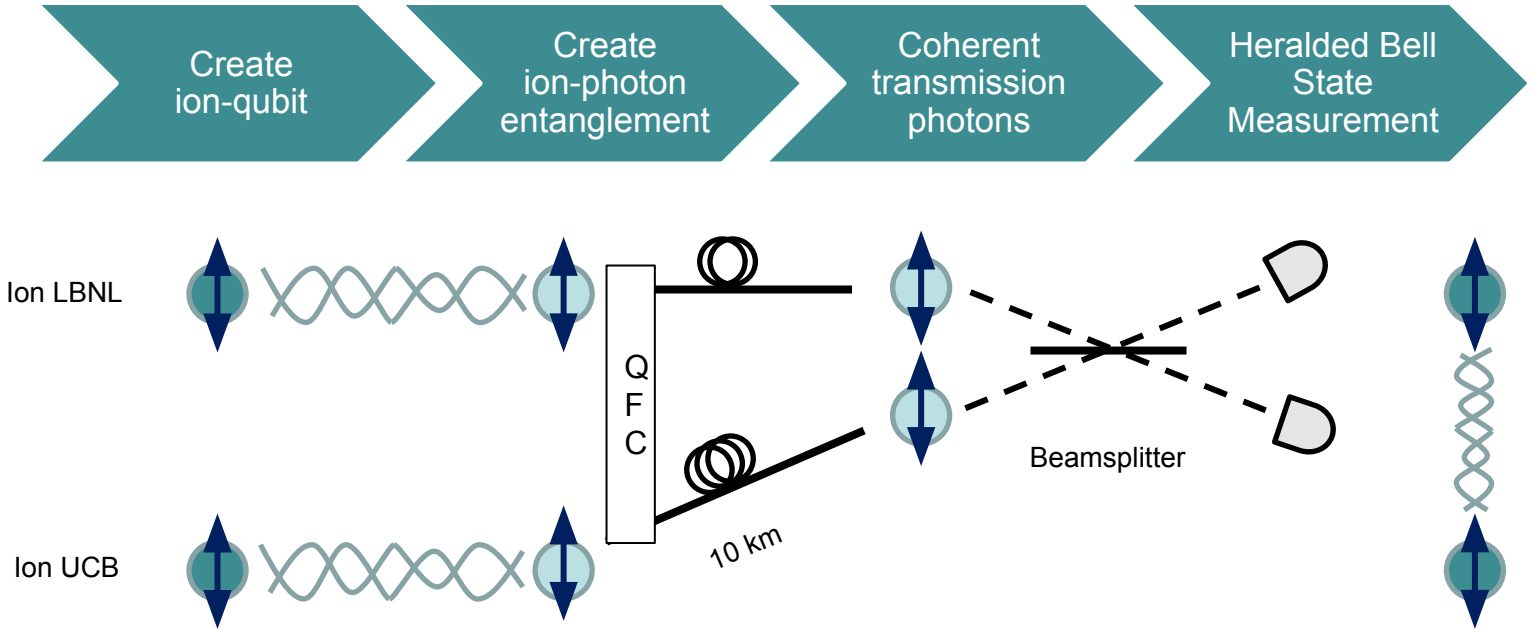
From Schupp et al., PRX Quantum 2, 020331 (2021)

Transfer quantum state across two ion–traps, LBL#1 and UCB Using indistinguishable photons over fiber: basic building block of distributed quantum computing



Adapted from Krutyanskiy et al., NPJ Quant. 5, 72 (2019)

Top-level Process (*Outlook*)



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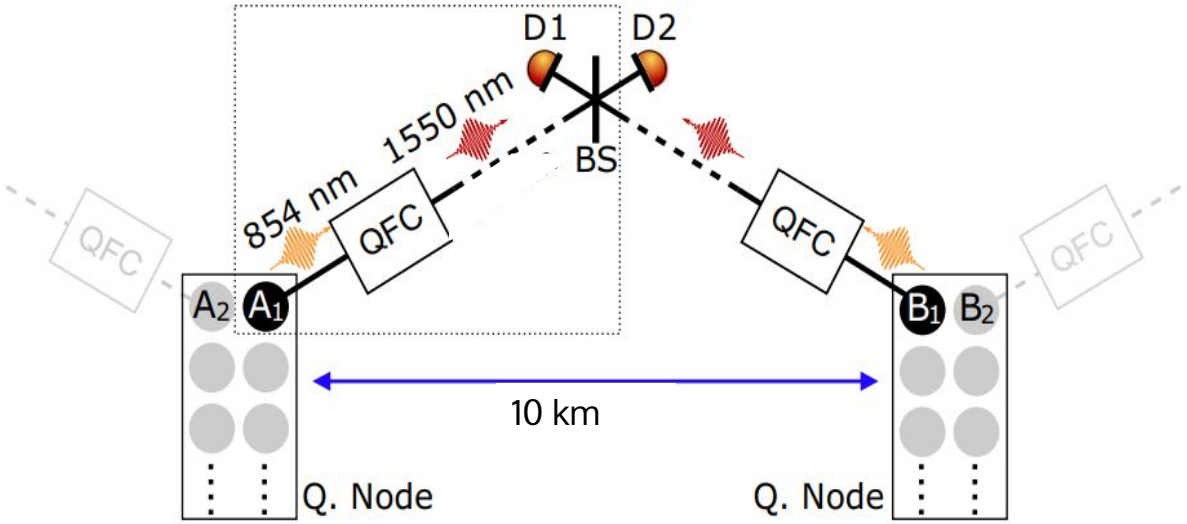
Steps to Quantum Repeater (1)

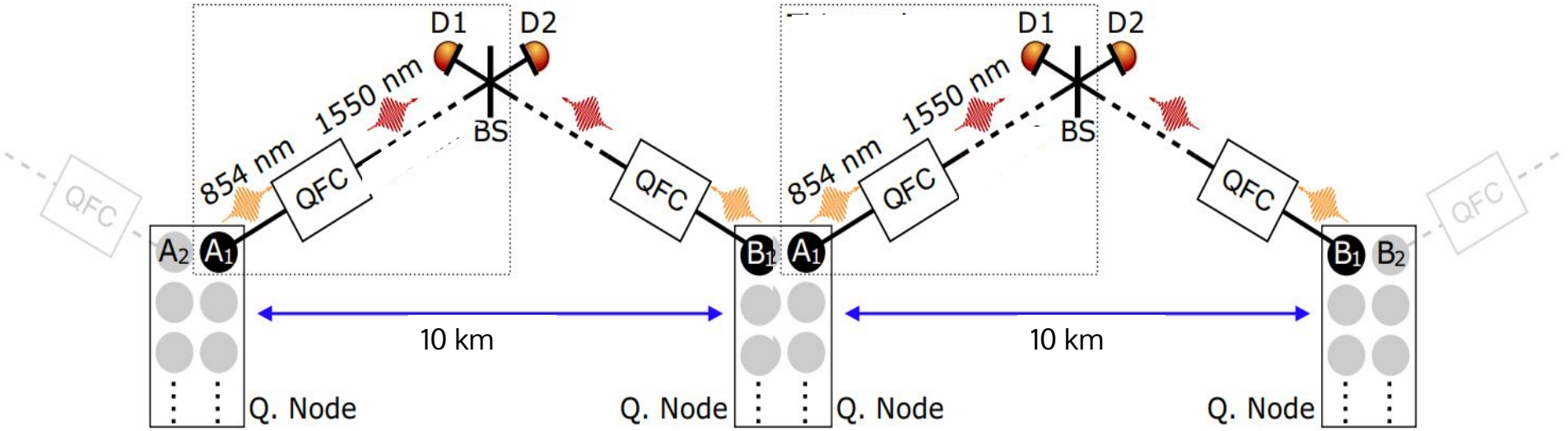
LBL #1 ↔ UCB: Repeat until successful



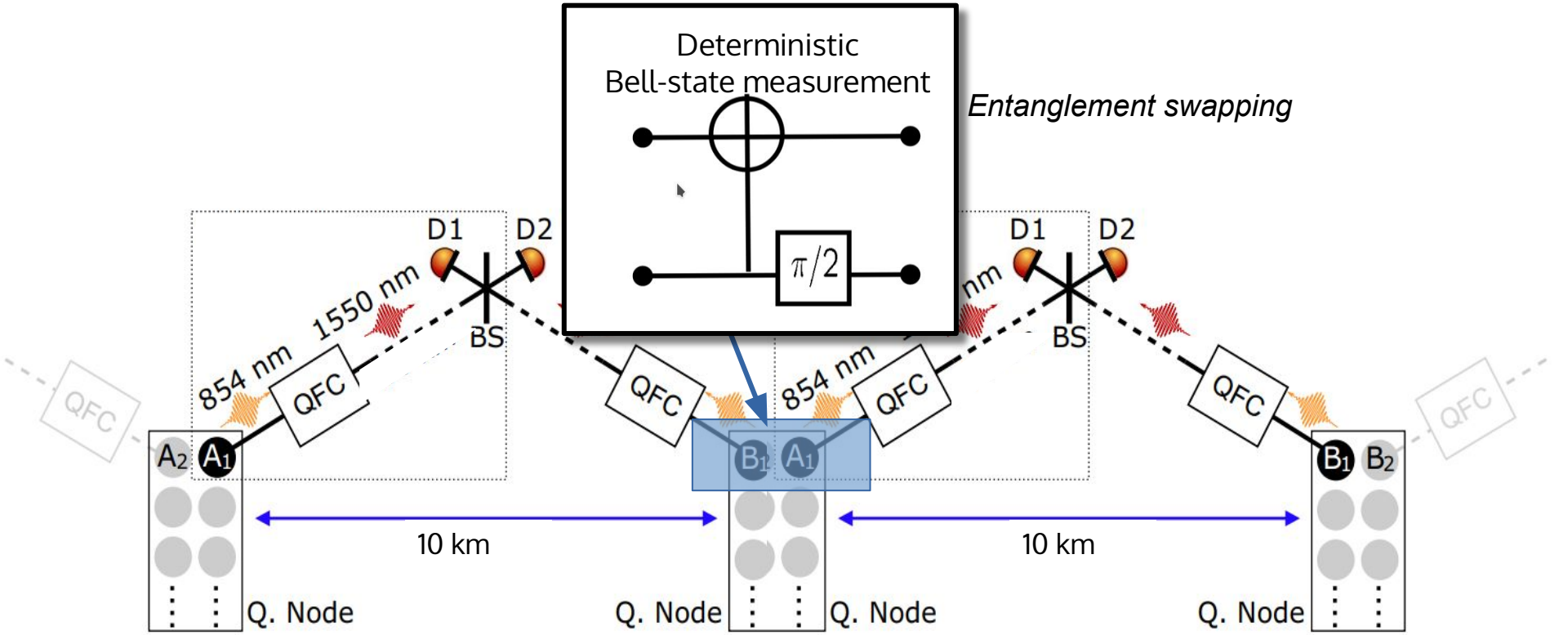
Steps to Quantum Repeater (2)

LBL #1 ↔ UCB: Repeat until successful

UCB ↔ LBL #2: Repeat until successful



Steps to Quantum Repeater (3, final)



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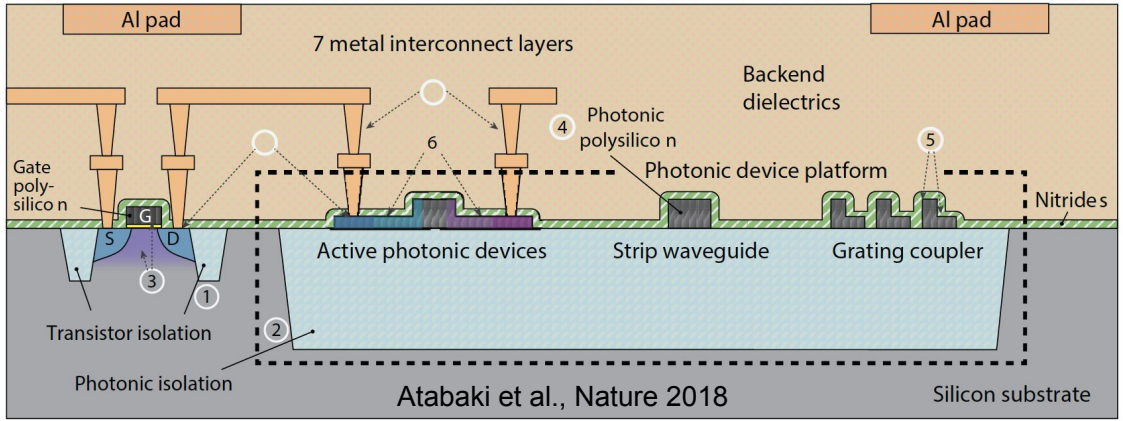
Quantum network nodes in silicon

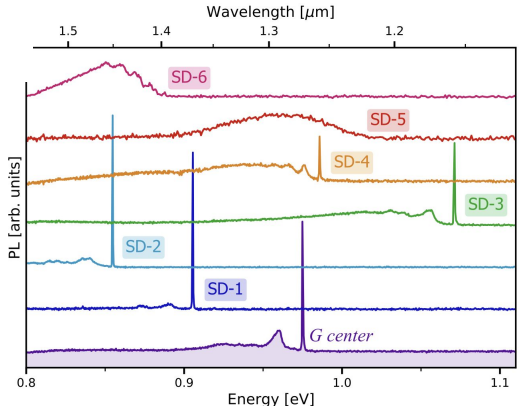
Silicon: Ideal material platform for integrated and scalable electrical and photonic devices



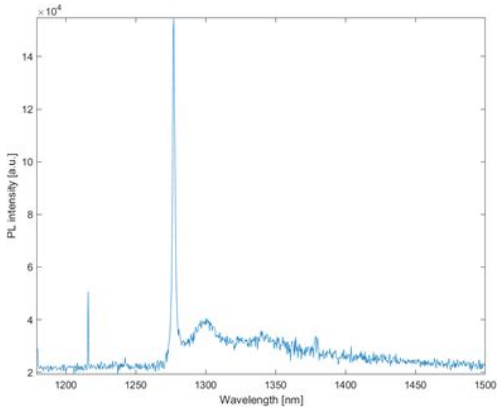
Can we leverage the (classical) semiconductor infrastructure for practical repeater nodes?
No known single photon emitters in silicon until 2020…

Quant-net silicon node

2020: Several bright, telecom-band single photon emitters discovered in silicon



Durand et al., PRL 2021

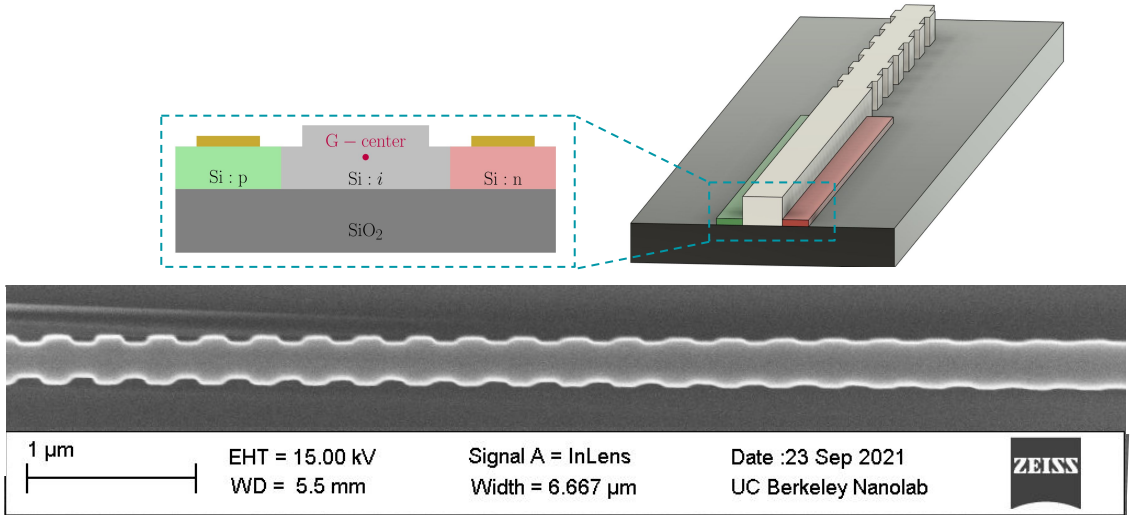


Telecom-band color centers created at Berkeley Lab (T. Schenkel, 2021)

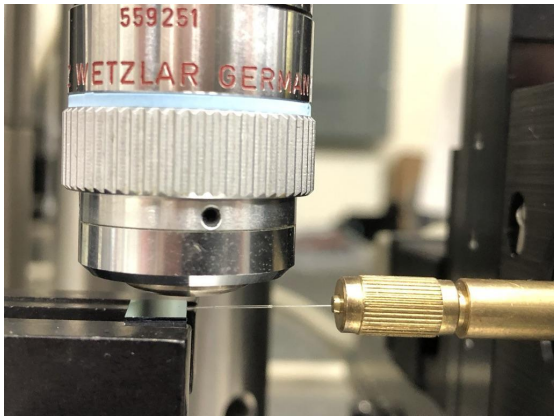
Current work at LBL & UC Berkeley:

- Novel, reproducible, high-yield creation of color center arrays (T. Schenkel)
- Systematic survey of new emitters (Sipahigil)
- Color center photonic device integration (Sipahigil)
- Color center nodes will be integrated into QUANT-NET in **Year 3+**:
    - Teleportation of a single photon qubit from a color center to an ion trap

Silicon node development for QUANT-NET



Silicon photonic waveguides for efficient color center- fiber coupling.



Room temperature characterization setup for the UC Berkeley silicon node

Network testbed will also leverage ongoing NSF and DOE projects at the Berkeley Quantum Devices Group:

- Color center photonic device integration (Sipahigil, Berkeley, NSF)
- Systematic screening of better emitters (Sipahigil, Berkeley, DOE BES)

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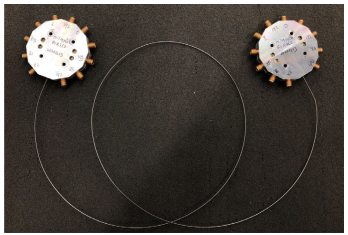
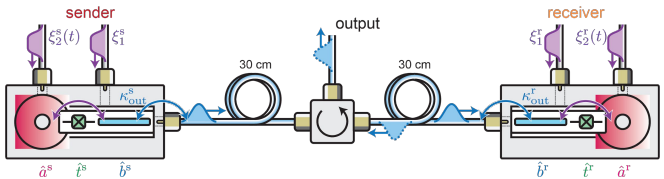
Prior Experimental Efforts

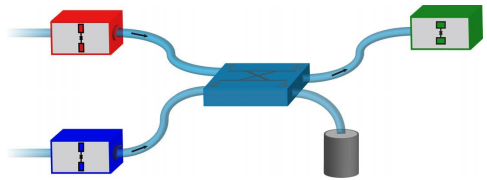
Y Zhong, A. N. Cleland et al., Nature (2021)



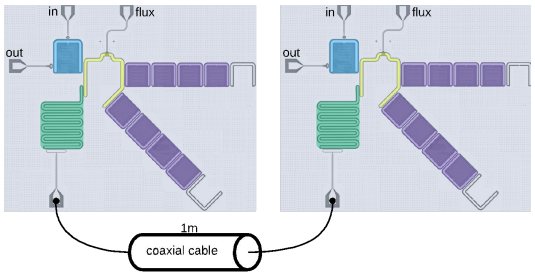
C. Axline, L. Burkhart, W. Pfaff, M. H. Devoret, R. J. Schoelkopf et al., Nature Physics (2018)



A. Narla, M. H. Devoret, R. J. Schoelkopf et al., PRX (2016)



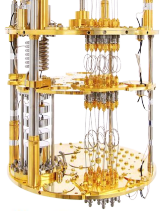
N. Leung, Y. Lu, and D. I. Schuster et al., npj Quantum Inf 5, 18 (2019)



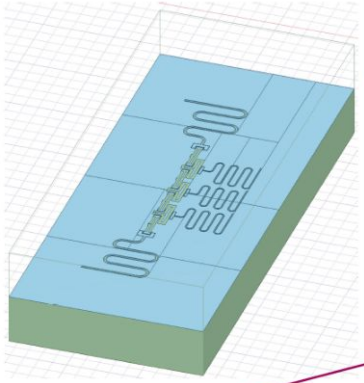
- Prior Work:
  - **Multi-qubit** entanglement between **two quantum nodes**
  - **Heralding** based entanglement generation between **two quantum nodes**

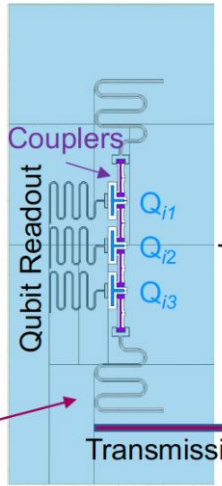
- MQN's New Goal:
  - **Multi-qubit** entanglement between **multi-nodes** via **heralding**

Baseline MQN Demonstration: Building a LAN version of quantum repeater in Superconducting Qubit fridges



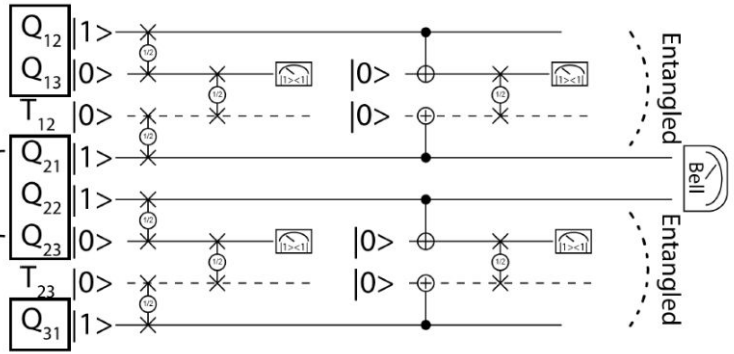
Device Engineering: Node-*i*





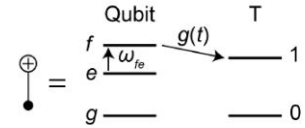
Communication Resonator

Loss-Resistant Entanglement Protocol Between Node-1 and Node-3

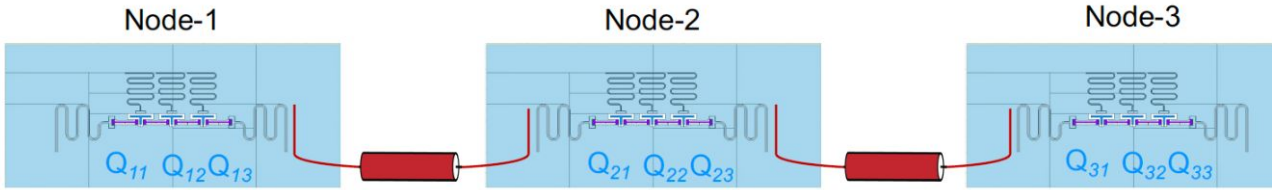


Q_{ij}: Qubit-*j* in Node-*i*

T_{ij}: Transmission line mode connecting Node-*i* and Node-*j*



A. Narla, M. H. Devoret, R. J. Schoelkopf et al., PRX (2016)



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QUANT-NET Control Plane:
Stack of Layered Quantum Network Protocols

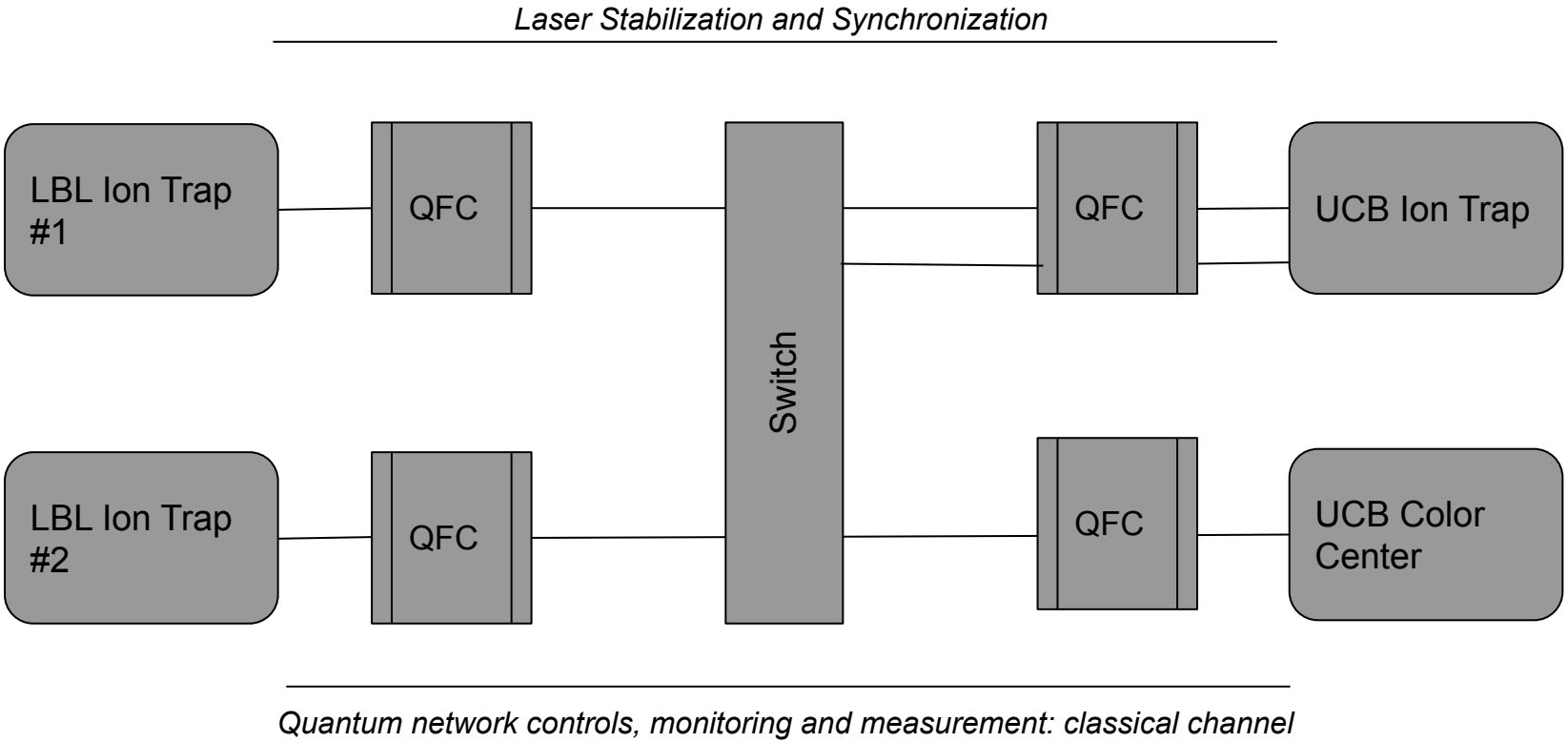
- A layered abstraction and architecture design shared by other pioneer Quantum Internet research groups (like IETF QIRG)
- Inspired by the Classical Internet TCP/IP/MAC stack and prior work on “connection-oriented services”
- Tuned to address unique hardware implementation in this project
- Delivers a *quantum entanglement as a service* capability
- Facilitate operations (*entanglement generation*, *repeating* and *gate teleportation*) of the LBNL-UCB testbed as well as research and development of future Quantum Internet control mechanisms

Three spheres of control

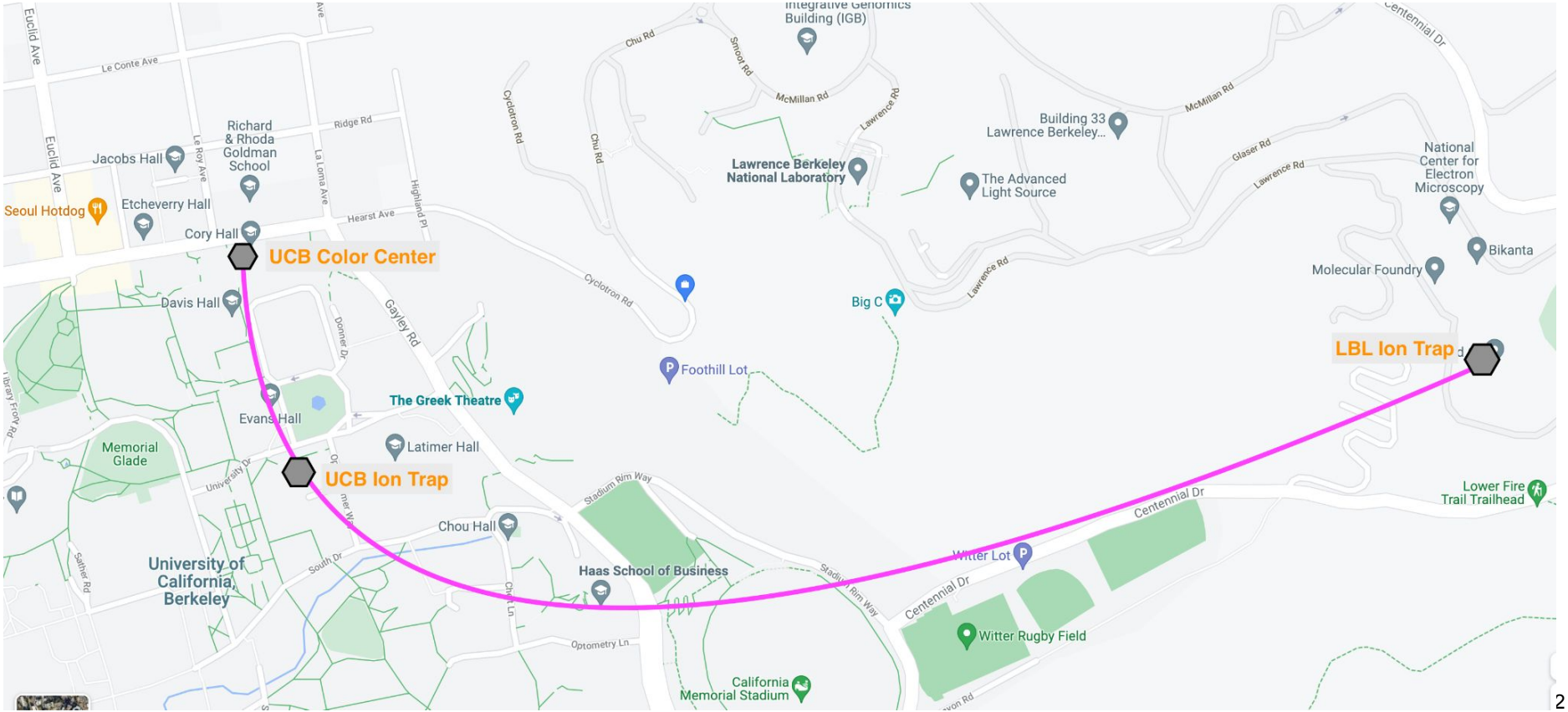
1. Orchestration
   a. Coordination of local resource managers aka quantum device controllers
   b. Manages policy between different locations
   c. APIs
2. Protocols for quantum information on classical data channel
   a. Apply mapping of current classical protocol stacks to quantum equivalents (physical layer, link layer etc)
   b. Managing information relating to entanglement link generation, and entanglement as a resource
   c. Network layer including routing across repeater chains, purification and distillation protocols
3. Quantum node/device protocols
   a. Specific to quantum technologies and approaches used in an experiment
   b. From ion-trap to QFC
   c. Highly dependent on device properties and materials

Monitoring: Developing protocols and techniques for monitoring all layers.
Collecting research data for optimization

Overview of the testbed



Physical view of the testbed locations and fiber path



Milestones

Setup Phase

Science Results Phase

FY 2022	FY2023	FY2024	FY2025	FY2026
• Setup the lab and physical infrastructure • Detailed Design • Entanglement generation for MQN	• Basic testbed components working • Entanglement and QFC • Control Plane design • Entanglement swapping for MQN	• Entanglement between UCB and LBNL • Basic error correction in MQN • Control plane and monitoring prototype • Synthesize color centers	• Gate Teleportation • Mode matching between color centers and ion emission • Numerical simulation and AI based optimization • Data collection and monitoring	• Quantum repeater operation • Color center-ion two photon qubit teleportation

Summary

- Quantnet is a challenging research project, with many fundamental unanswered research questions
  - Steady streams of new approaches and results in peer-reviewed papers every month
- It is not just about understanding the physics, but will require intricate engineering to make this work
- Combination of materials, physics, engineering, software, control-theory, photonics, quantum mechanics, laser engineering, accurate timing, quantum computing etc….the skills needed to succeed require multi-disciplinary engagement with scientists, experimenters and networkers (co-design)
- While challenging, the future of quantum networking, and first-hand experience building one is going to be rewarding for the R&E community