04 September 2025

HYPERION RESEARCH

Quantum internet: what is it, why do we need it, and how do we engineer it?

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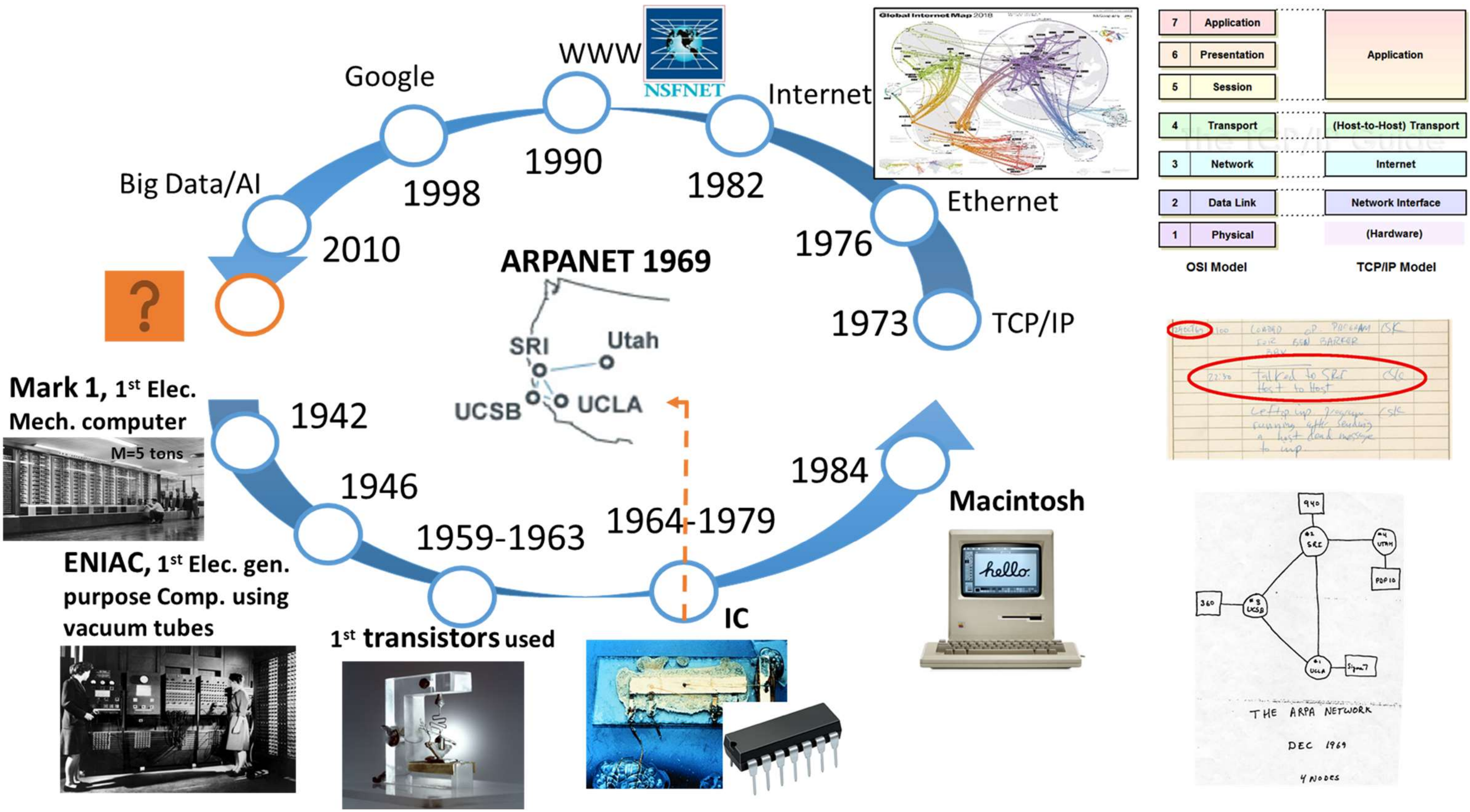
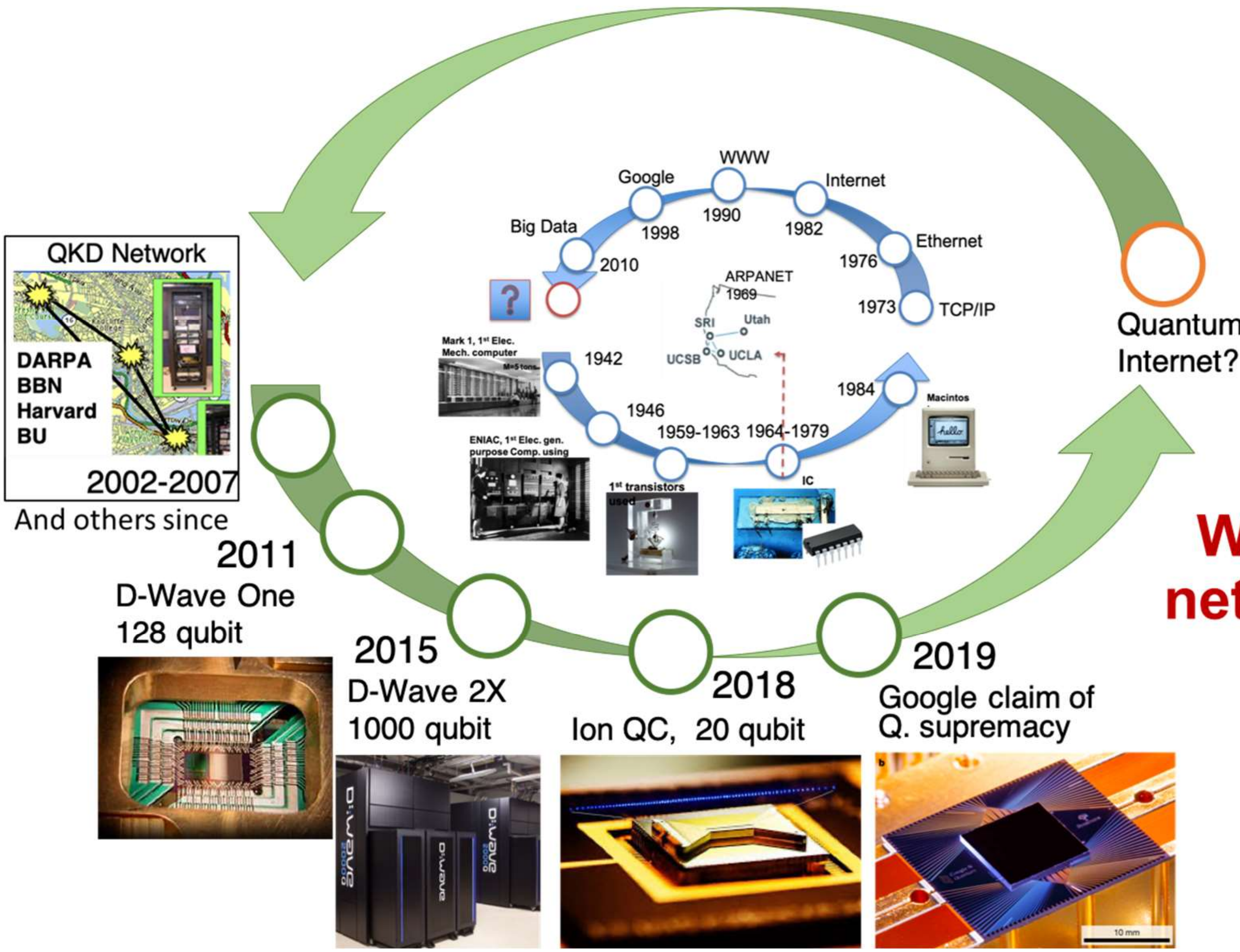
The Bit Revolution



The Qubit Revolution…



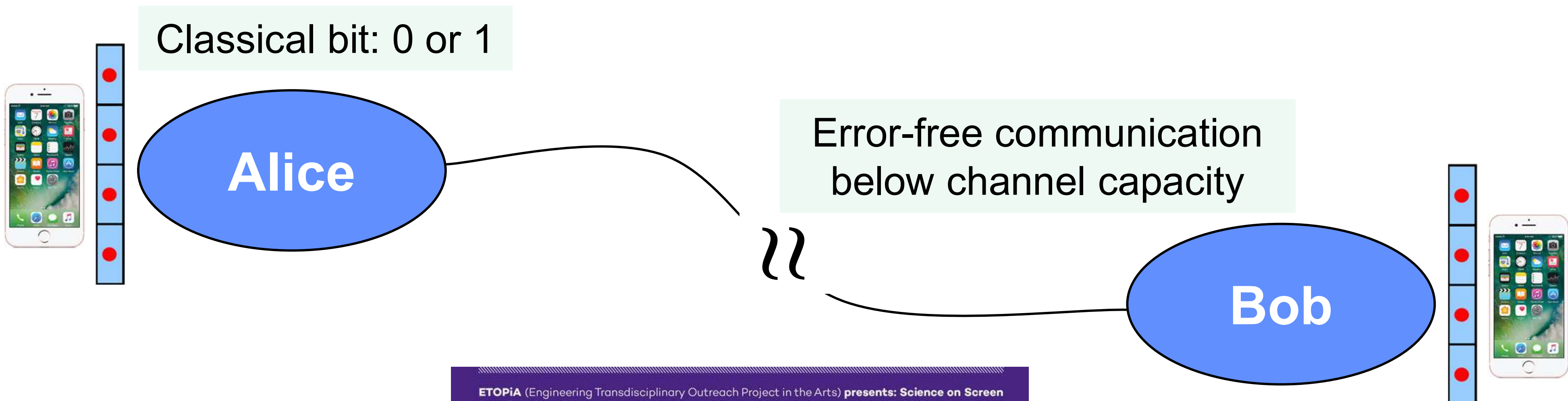
Early introduction of quantum networking is particularly important given the scalability issues in current quantum processors.

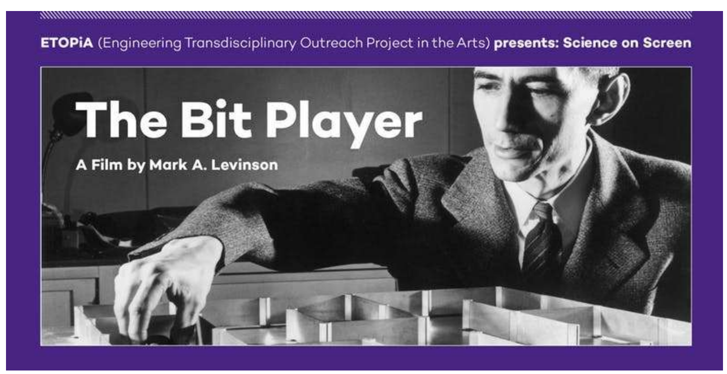
What should a quantum network look like and how should it operate?

A Brief (incomplete) History of 'Quantum 2.0' from Comms Perspective

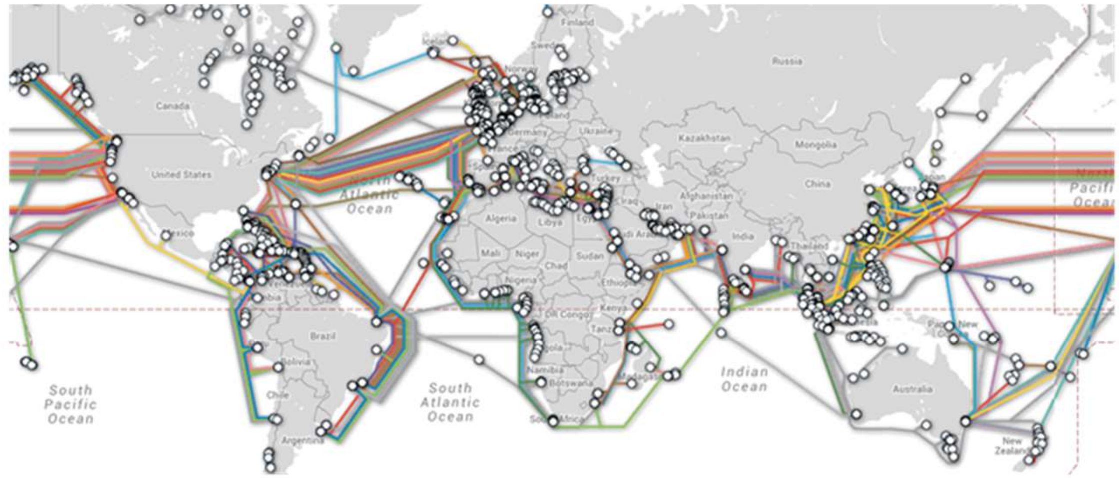
- 1982: Feynman proposes quantum computing (QC) to simulate quantum electrodynamics (scientific application)
- 1984: Bennet & Brassard propose BB84 quantum key distribution (QKD) protocol
- 1991: Ekert proposes E91, entanglement based QKD protocol
- 1993: Bennett *et al*. invent the quantum teleportation protocol
- 1994: Shor invents quantum factoring algorithm, threatening growing e-commerce relying on RSA
- ~1994: Race is on to build a quantum computer
- ~1995: Quantum error correction (QEC) and fault tolerance introduced
- ~2010: Realization that Shor factorizer is difficult to build
- ~2010: Emphasis shifts back to scientific applications of QC (i.e., no QEC), such as simulation, optimization, …
- ~2015: Public and private investments in QC take off
- ~2015: Focus shifts from QKD to quantum communications in general
- ~2020: NISQ Processing (Noisy Intermediate Scale Quantum)
- ~2025: Fault-Tolerant Quantum Computing – scaling remains a challenge

Classical Communications & Networking

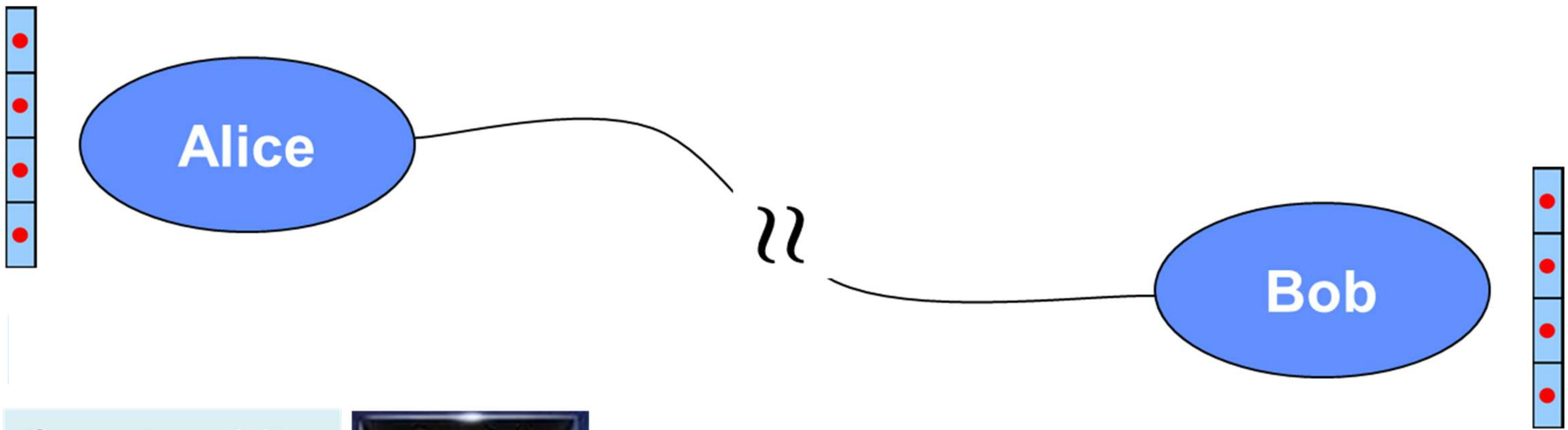




Communications & Networking Today



Quantum Communications & Networking



Quantum bit:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

?

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Conflict with Quantum Mechanics

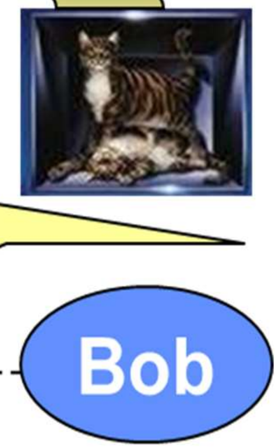
- No-cloning theorem
  - It is impossible to duplicate an unknown quantum state
- Heisenberg uncertainty principle
  - It is impossible to know a quantum state

Quantum Teleportation

- Transmitter T and Receiver R share entangled qubits

$$|\psi\rangle_{TR} = \left(|0\rangle_T|1\rangle_R - |1\rangle_T|0\rangle_R\right)/\sqrt{2}$$

- Teleportation protocol bypasses the conflicts with QM, but requires ubiquitous availability of entanglement



Bennett *et al*. 1993

Applicable to stationary qubits (matter: electrons, atoms, etc.) used in computing or flying qubits (photons) used in communications or hybrid scenarios

Requirements for Such Connectionless Quantum Communication

- Ubiquitous availability of entangled photon pairs
  - Efficient sources of entangled photon pairs
  - Efficient distribution of quantum entanglement
- Technologies for storage and on-demand recall of entangled photons for the users
  - Technologies for mapping entanglement from one modality to another, e.g., from photonic states to matter states
  - Or one qubit in matter states while the other on a photon
- Technologies for quantum measurements (Bell states)
  - Efficient single/correlated photon detection
  - Unconditional bell-state measurements/analysis

Photon loss is the bane of quantum communications !
And, of course, phase decoherence !!!

Rate-Distance Bottleneck: How to Get Around?

- Recall the history of classical optical communications
  - Distance was limited by loss and signal-to-noise in the late 1980's to early 1990's
  - Invention of the erbium optical amplifier changed everything
  - Exponential decay of SNR with distance changed to linear degradation with distance: enabled global reach
  - Wave division multiplexing (WDM) and electronic mitigation of channel distortions was another big step
  - Interfaces to wireless systems led to the omnipresent connectivity we enjoy today
- Can same be done for quantum communications?
- Two approaches have been followed:
  - Trusted satellites (deployed)
  - Quantum repeaters (in development)

Quantum internet, what is it?

ACM SIGCOMM Computer Communications Review
Volume 34, Number 5: October 2004 , pp. 9 – 20

Infrastructure for the Quantum Internet

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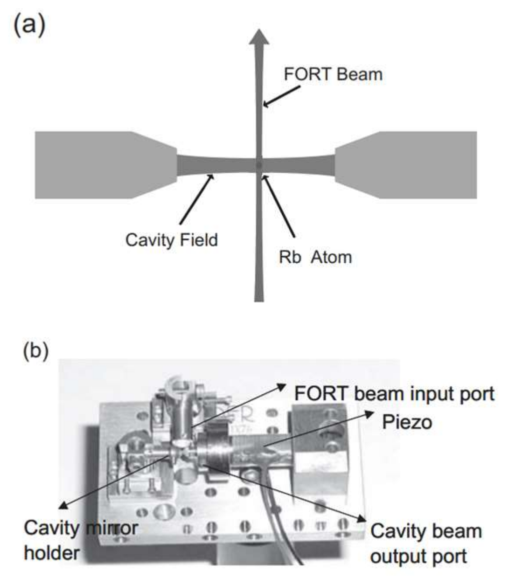


Figure 11: (a) Schematic of the trapped-atom QMU; (b) integrated cavity-FORT for realizing the QMU.

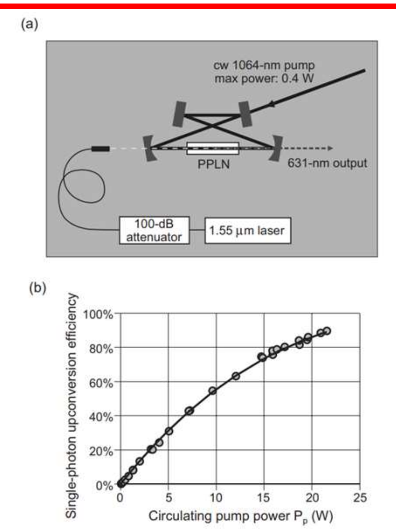


Figure 10: Frequency upconversion: (a) schematic of sum-frequency mixing upconversion with a ring cavity configuration for the continuous-wave (cw) pump; (b) single-photon upconversion efficiency.

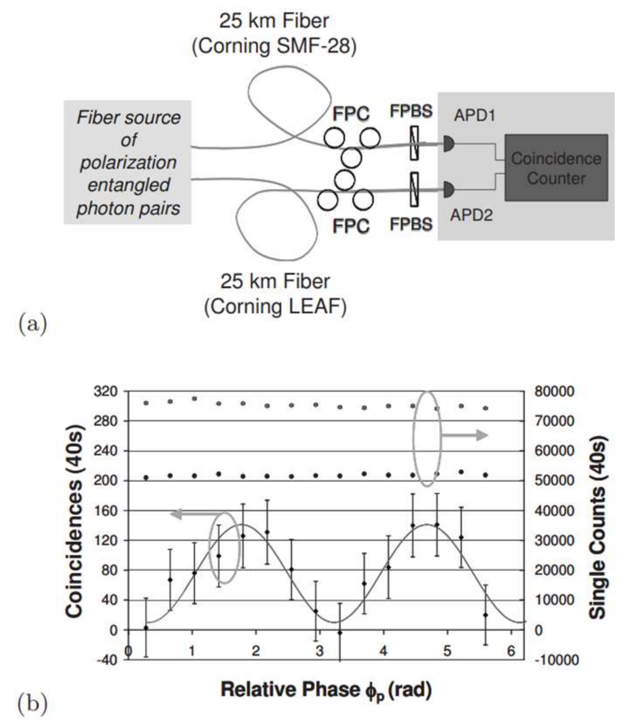
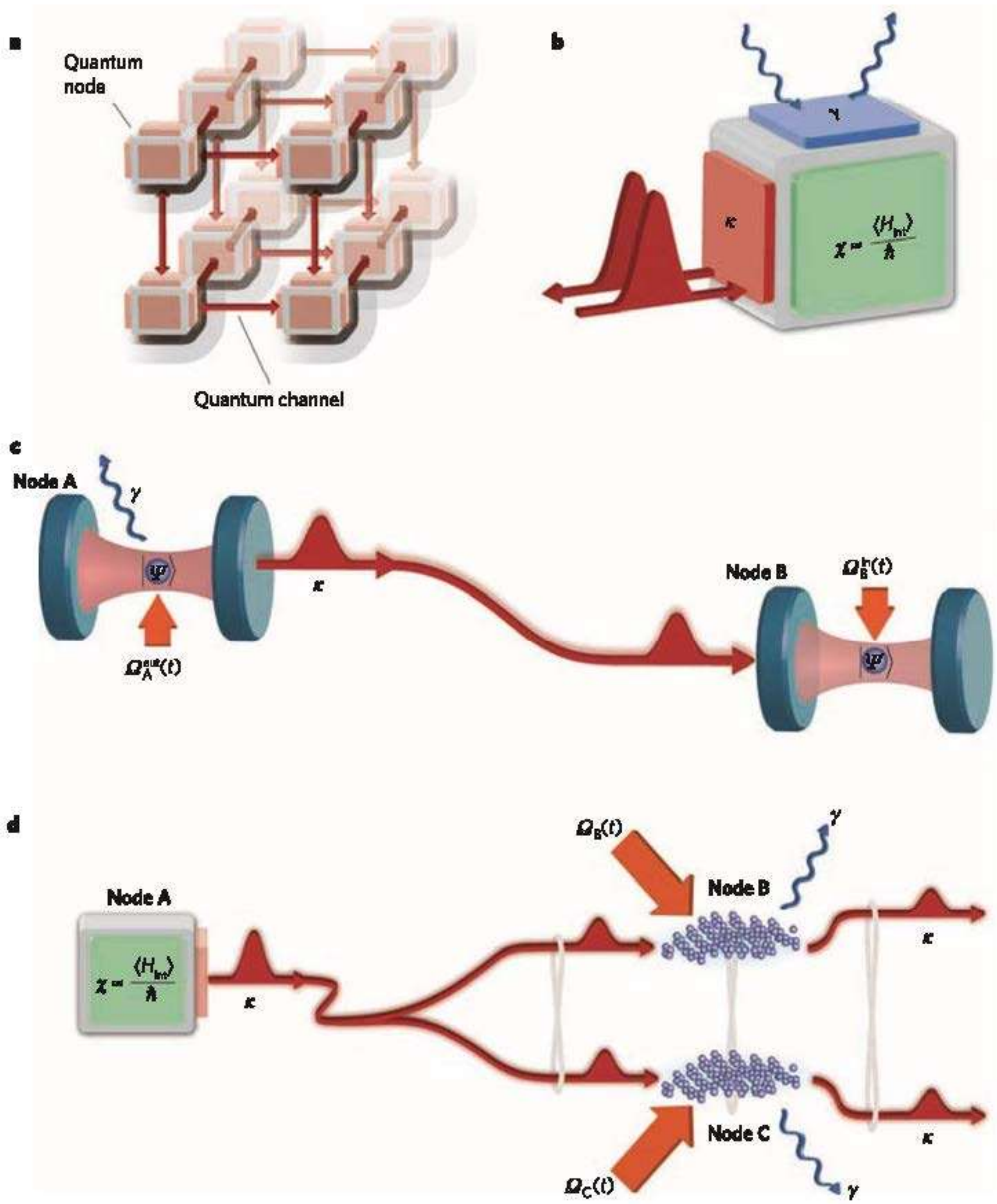


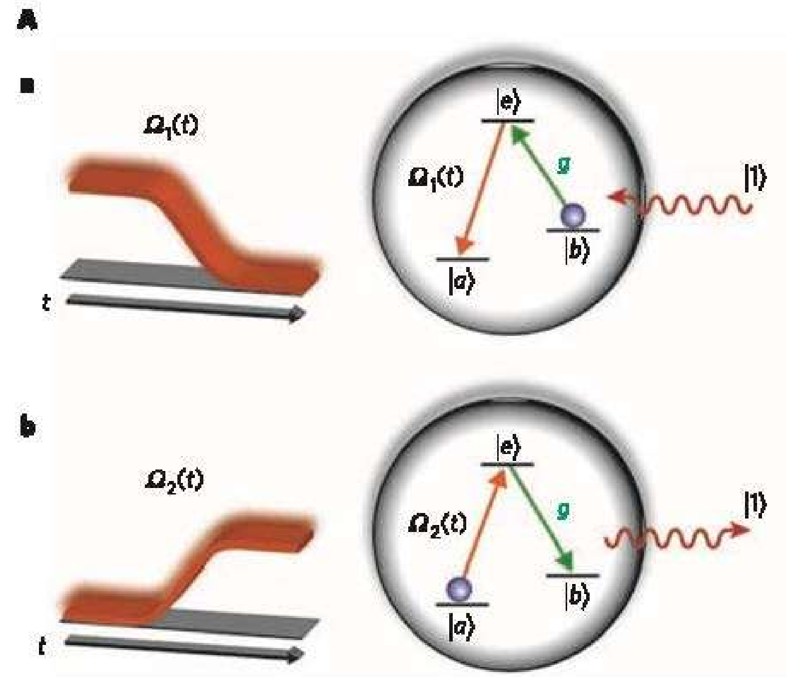
Figure 9: (a): Schematic of the experimental setup to demonstrate long-distance entanglement distribution. FPC, fiber polarization controller; FPBS, fiber-pigtailed polarization beam splitter; APD, avalanche-photodiode based photon-counting detector. (b): Single counts (right ordinate) and coincidence counts (left ordinate) registered by the detectors of Stokes and anti-Stokes photons versus the relative phase between the source's two pump pulses. The contribution of accidental coincidences has been subtracted.

The quantum internet

H. J. Kimble[1]

NATURE|Vol 453|19 June 2008|doi:10.1038/nature07127 INSIGHT REVIEW



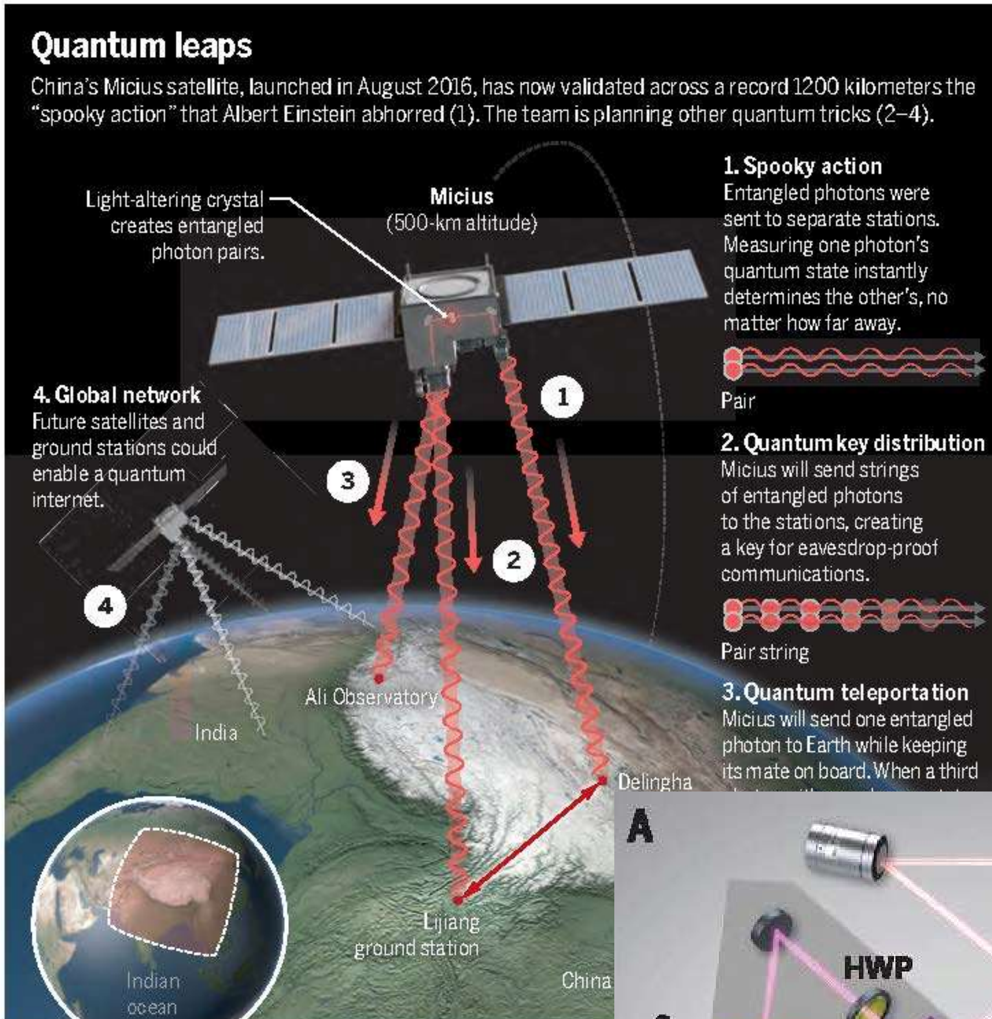


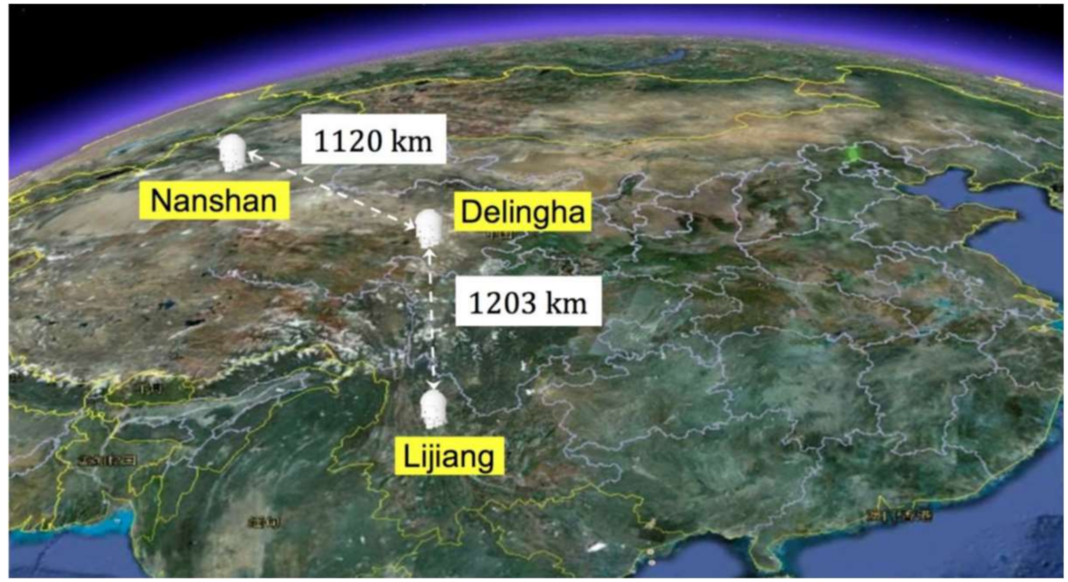
Quantum internet, why do we need it?

- NISQ (Noisy Intermediate Scale Quantum) technology is already here; fault tolerance is emerging
  - IBM quantum experience (widely successful as a teaching tool)
  - Similar access by others (D-Wave, Google, Amazon, …)
- Quantum computers are commercially available and growing in size and scale
  - "Quantum advantage" on the horizon, although a moving target
  - Once in "discovery zone," all bets are off
  - How to verify? Experimentation on small systems (chemical, optimization, etc.) will build confidence
- Vendors will not stop at building one
  - Networking them would be the natural next step; that's what happened with classical networking
- Network *m* *n*-qubit machines: $m \times 2^n$ vs. 2^{mn} ?
  - Classical networked computing can teach us a lot

Quantum internet, how do we engineer it?

Source Aboard Satellite Micius
Entanglement Distribution over 1200 km



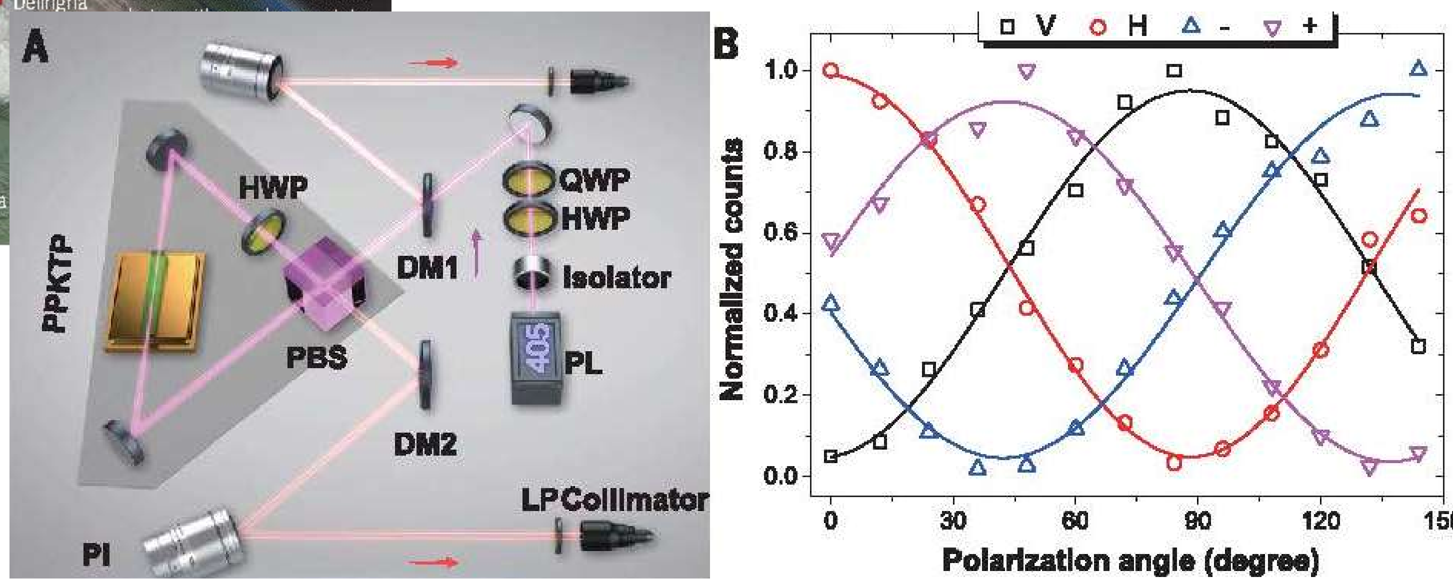


Yin *et al*., Science **356**, 1140–1144, June 2017.

Bell inequality violation over 1200 km

F. N. C. Wong *et al*., Phys. Rev. A 73, 012316 (2006)

Phase stable Type-II SPDC in a pol. Sagnac loop



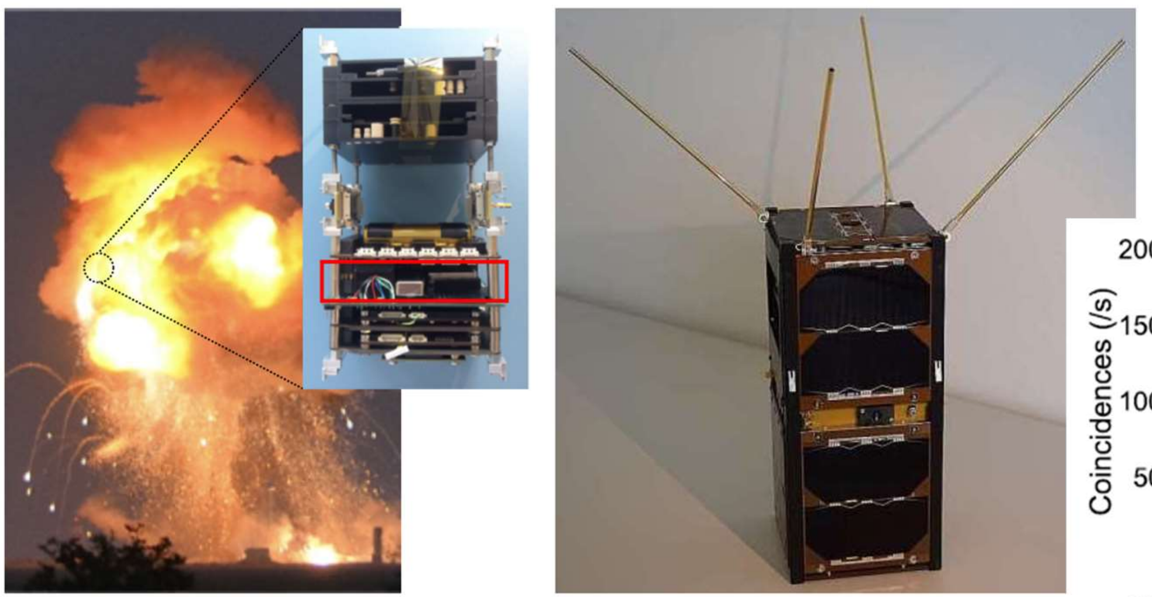
Robust (Rocket Explosion Proof) Source

SCIENTIFIC REPORTS | 6:25603 | DOI: 10.1038/srep25603 **(2016)**

OPEN

The photon pair source that survived a rocket explosion

Zhongkan Tang[1], Rakhitha Chandrasekara[1], Yue Chuan Tan[1], Cliff Cheng[1], Kadir Durak[1] & Alexander Ling[1,2]



(a) (b)

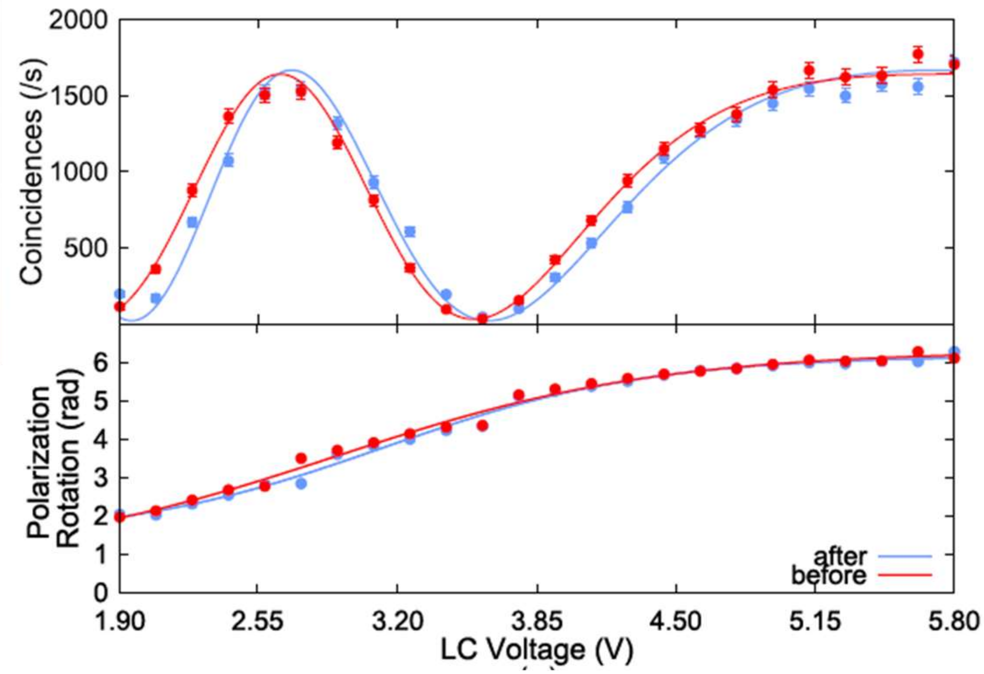
Figure 5.4: (a) GomX-2 CubeSat (without the solar panel) with SPEQS1.1-CS highlighted in red box (b) GomX-2 CubeSat after recovering from the explosion. Images courtesy of GOMspace.

GOMSPACE

https://gomspace.com/home.aspx

Z. Tang, Ph.D. Thesis
National University of Singapore (2018)

Type-I, collinear, nondegenerate SPDC in BBO



Operational Technical Challenges

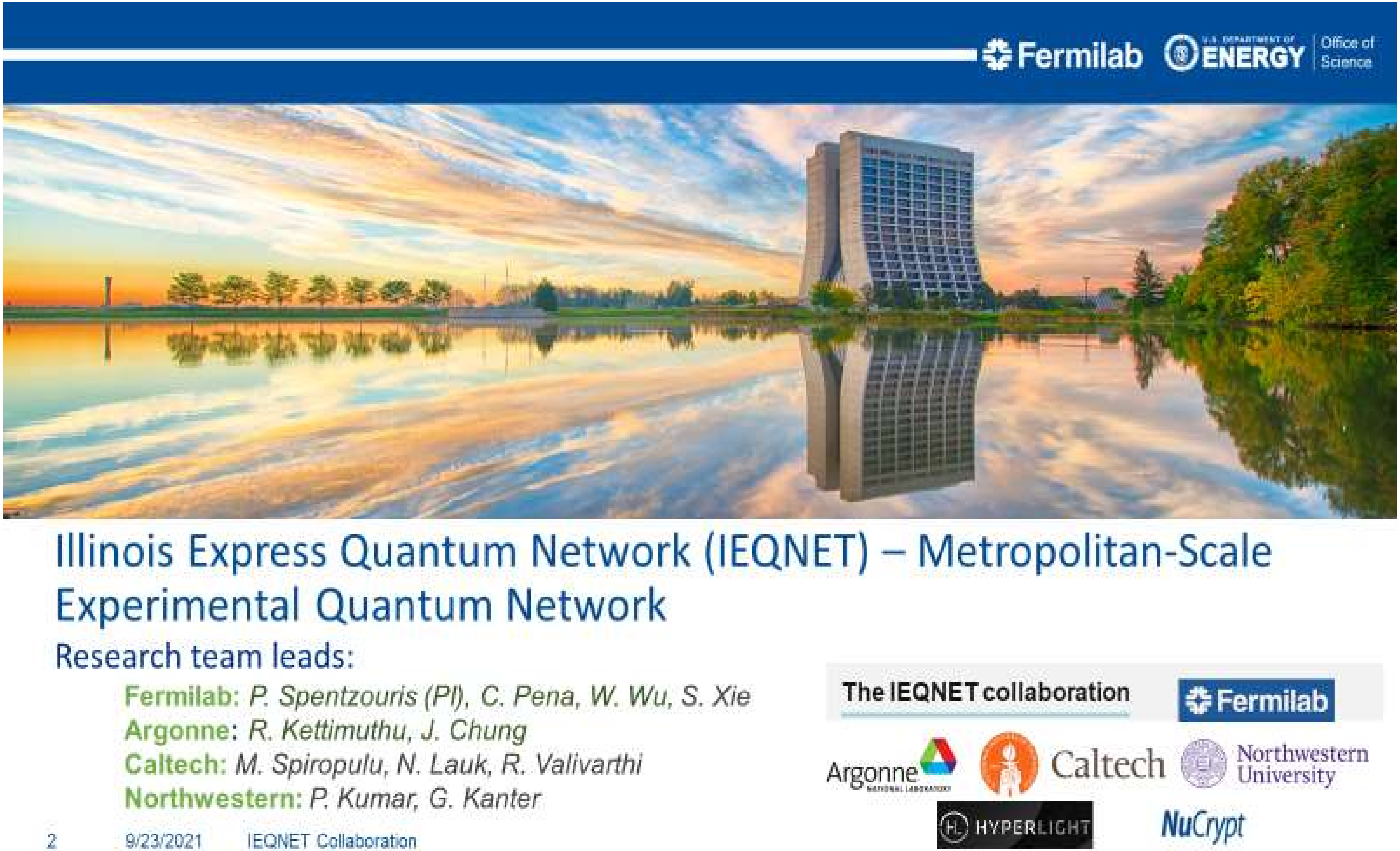
Building the Foundations for Quantum Industry | NIST

https://www.nist.gov/news-events/events/2017/10/building-foundations-quantum-industry

Organized by Jake Taylor at NIST Gaithersburg, 05 October 2017

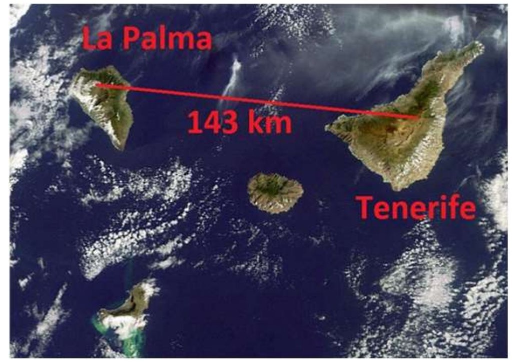
- How would we architect the quantum internet?
  - Would it have a layered structure like the classical network?
  - How would those layers be determined? Would entanglement distribution be a separate layer?
  - How would quantum channels and classical channels co-exist? After all, classical communication is an integral part of quantum communication; quantum teleportation requires it!
  - …
- How would we control and operationalize it?
  - How to share common quantum channels among the users?
  - What's the best way to distribute entanglement to various users?
  - Would there be entanglement factories that the users can subscribe to? Would there be quantum ISPs?
  - What about the quality of service? How would we measure it?
  - What about software and algorithms to manage the quantum network?
  - …

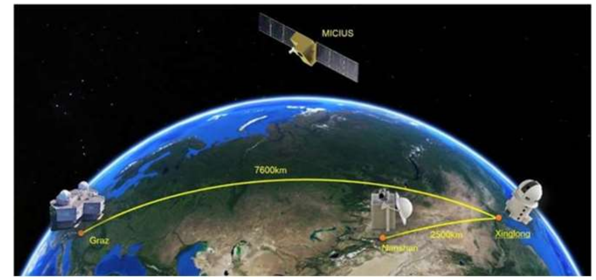
Illinois Express Quantum Network (IEQNET)



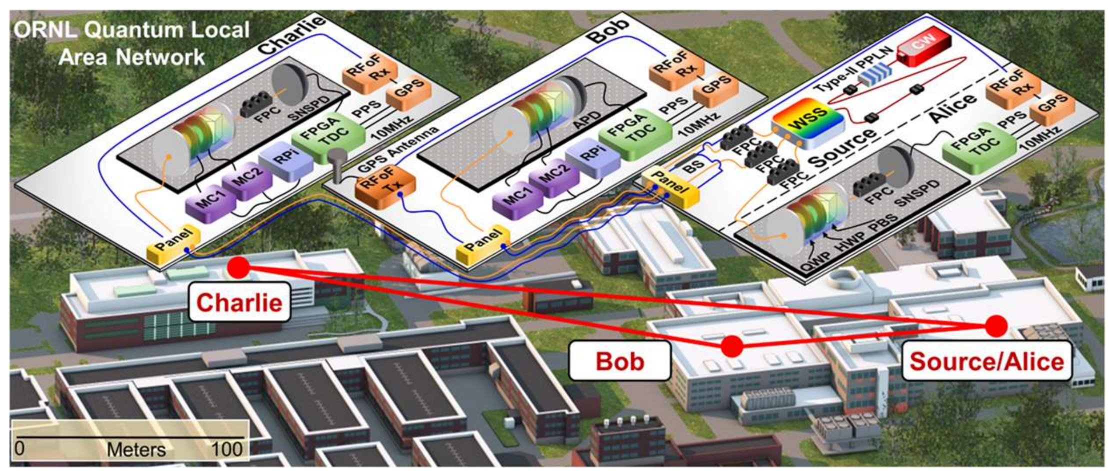
Motivation (Circa 2019): Repeaterless Metro-Area Quantum Network

- Most quantum networking demonstrators focus on point-to-point or linear topologies

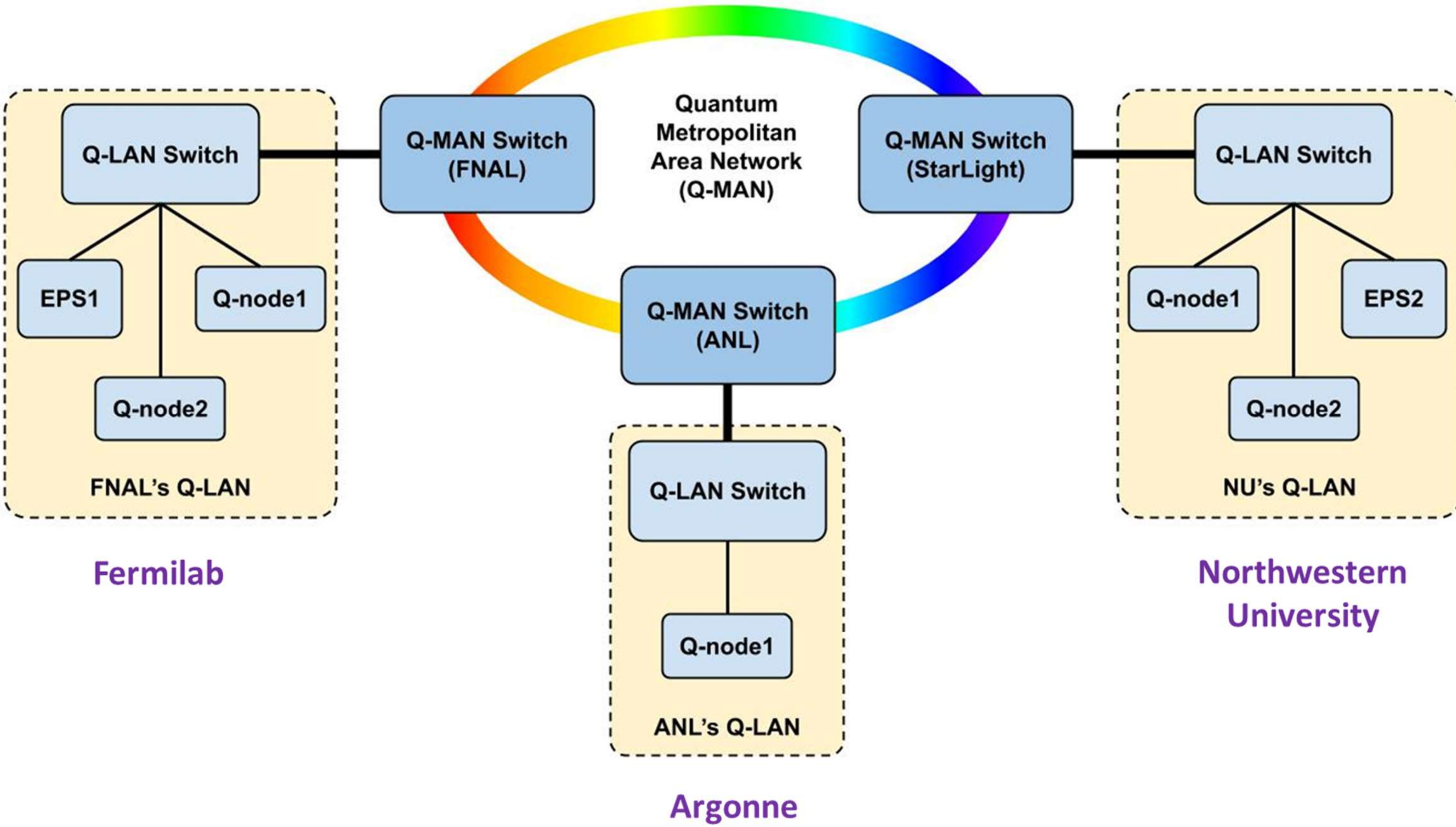




- There is great need to develop architectures for **fully dynamic and automated quantum networks** using existing technologies to **demonstrate multi-user, multi-node** capabilities at **metro scales** that go beyond linear topologies

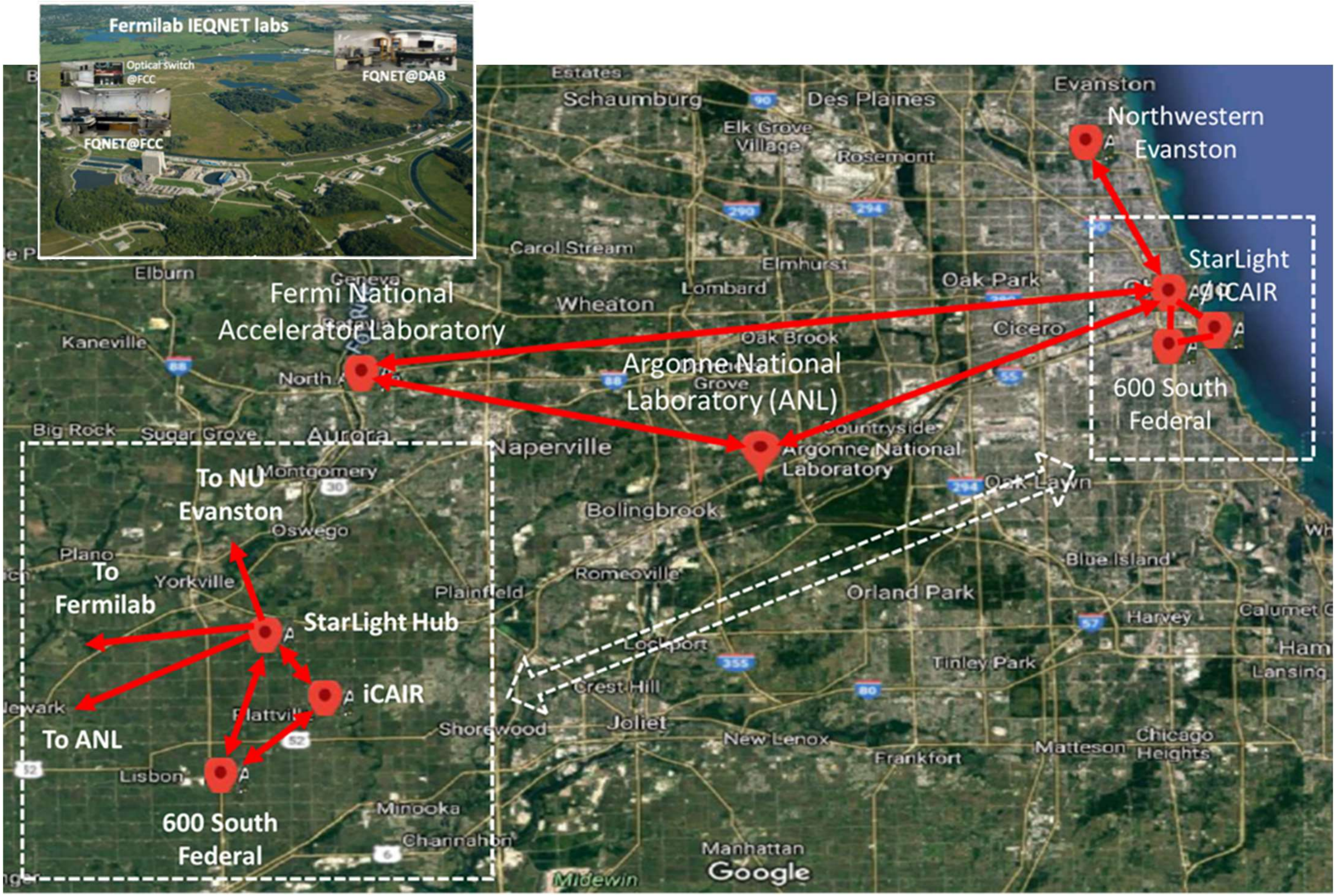


IEQNET Topology

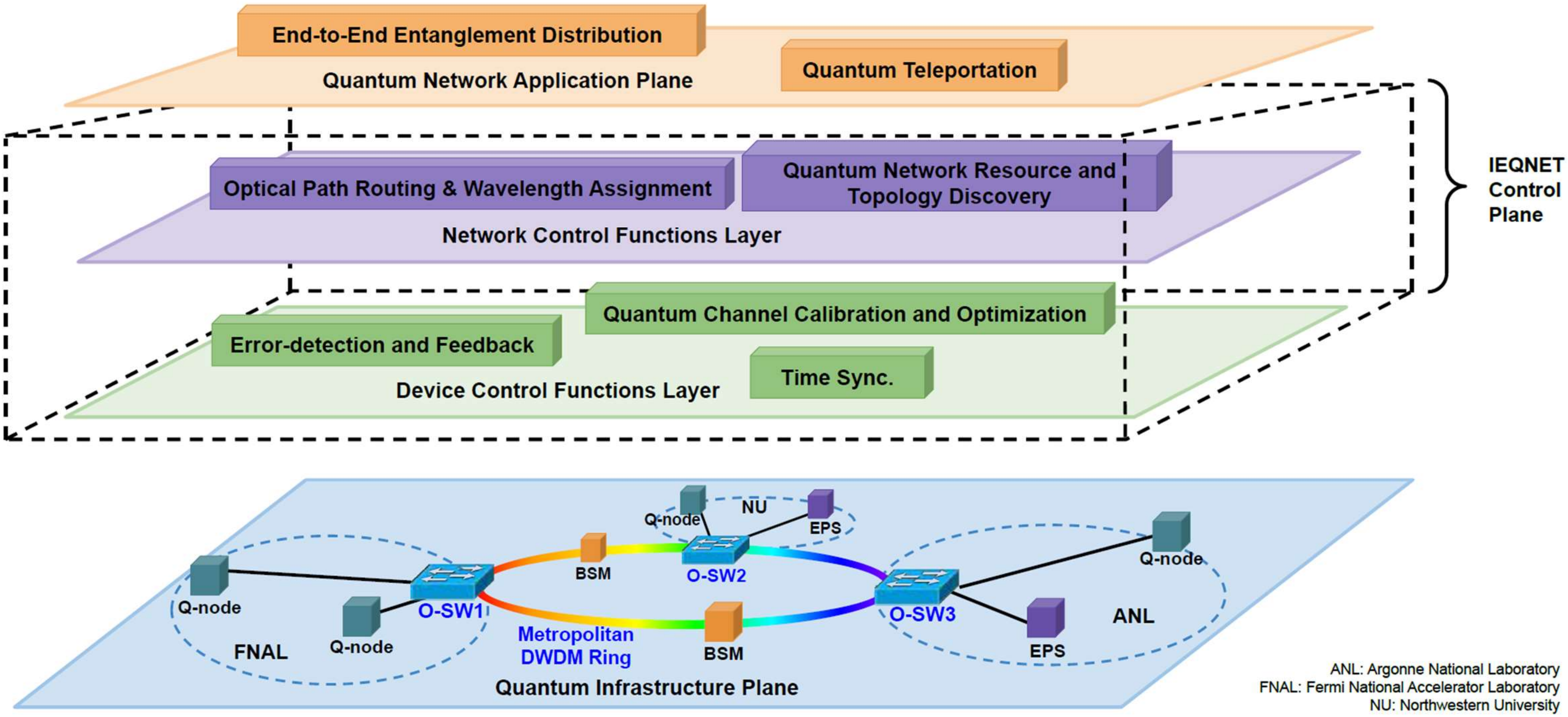


J. Chung, G. Kanter, N. Lauk, R. Valivarthi, W. Wu, R. R. Ceballos, C. Peña, N. Sinclair, J. Thomas, S. Xie, R. Kettimuthu, P. Kumar, P. Spentzouris, and M. Spiropulu, "Illinois Express Quantum Network (IEQNET): metropolitan-scale experimental quantum networking over deployed optical fiber," Proc. SPIE 11726, 1172602 (12 April 2021); https://doi.org/10.1117/12.2588007.

IEQNET Physical (proposed)



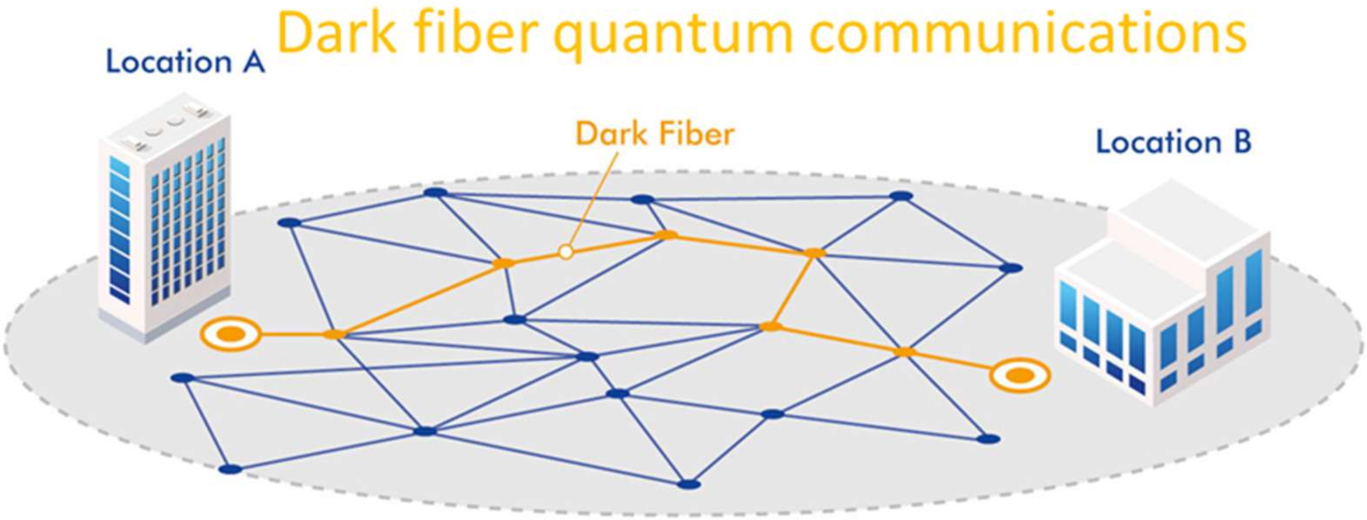
IEQNET's Quantum Networking Architecture (three planes)



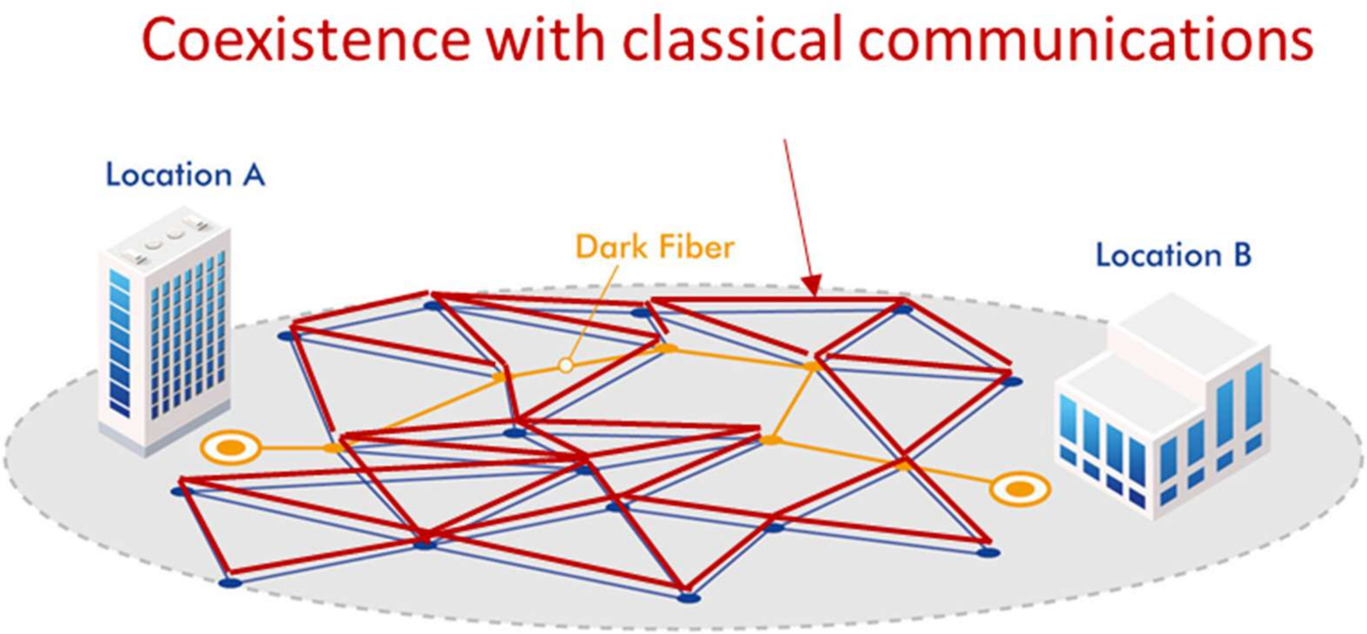
IEEE Transactions on Quantum Engineering Chung et al.: DESIGN AND IMPLEMENTATION OF THE ILLINOIS EXPRESS QUANTUM METROPOLITAN AREA NETWORK

Vol. 3, 4100920 (2022) | *Digital Object Identifier 10.1109/TQE.2022.3221029*

Coexistence of Quantum and Classical Light on the Same Fiber



Unlikely to be cost effective



Must explore this option

Teleportation Coexisting with 18.7 dBm of 400-Gbps C-band Power Over 30.2 km

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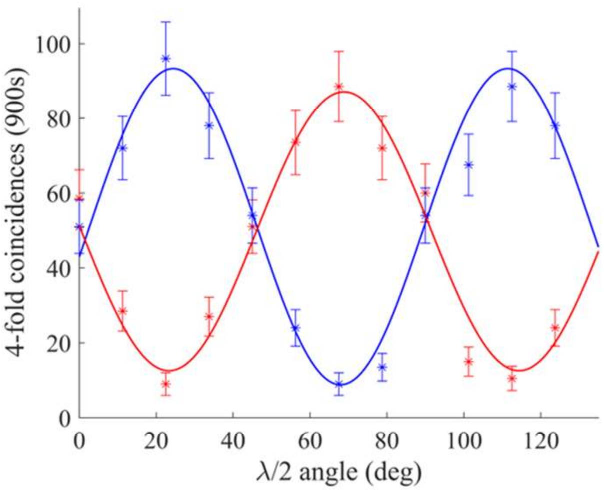
CPCC

4-fold coincidence fringe as Bob rotates his polarization basis for Alice transmitting:

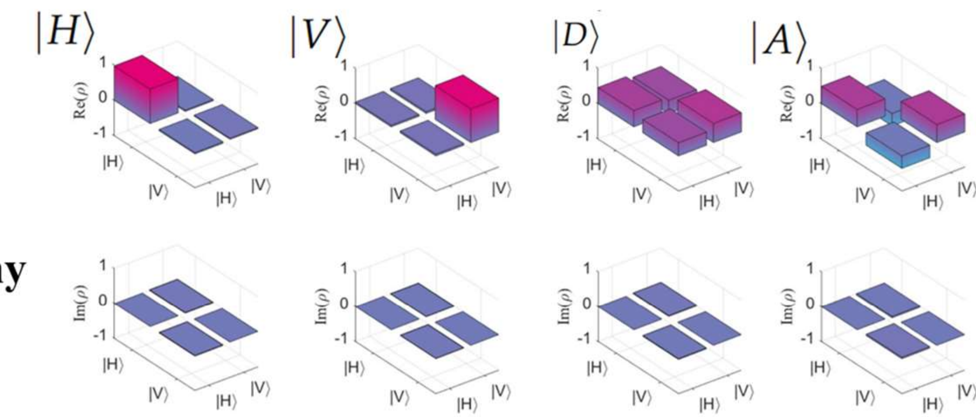
$|D\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$

$|A\rangle = \frac{1}{\sqrt{2}}(|H\rangle - |V\rangle)$



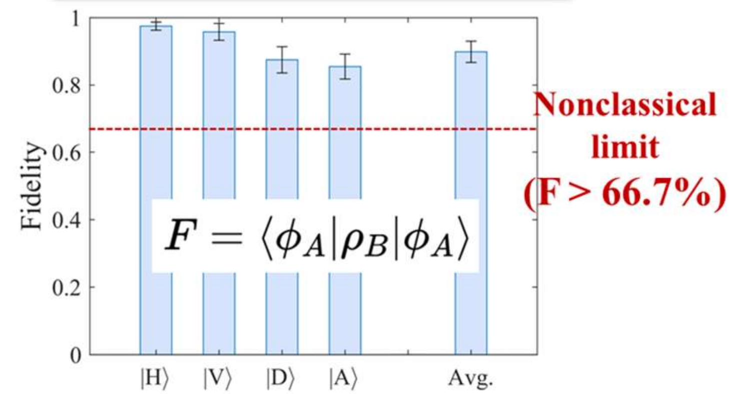
$$V_D = 81.3 \pm 5.4\%$$
$$V_A = 74.7 \pm 4.7\%$$

Quantum State Tomography



Demonstrated non-classical teleportation with powers capable of 10's of terabits/s C-band classical data rates

$$F_{AVG} = 89.8 \pm 3.1\%$$



Quantum Teleportation Systems Coexisting with Conventional Classical Communications in Optical Fiber

JORDAN M. THOMAS[1,*], FEI I. YEH[2], JIM HAO CHEN[2], JOE J. MAMBRETTI[2], SCOTT J. KOHLERT[3], GREGORY S. KANTER[1,4], AND PREM KUMAR[1,5]

1700 Vol. 11, No. 12 / December 2024 / *Optica* **Research Article**

OPTICA

λ-Selective Distribution of Pol. Ent. Over Deployed Fiber

CLEO 2023 | FF3A.7 | QUANTUM NETWORKING

Argonne NATIONAL LABORATORY

WAVELENGTH-SELECTIVE DISTRIBUTION OF POLARIZATION ENTANGLEMENT OVER DEPLOYED FIBER

The IEQNET collaboration

Fermilab, Argonne, Caltech, Northwestern University, HYPERLIGHT, NuCrypt

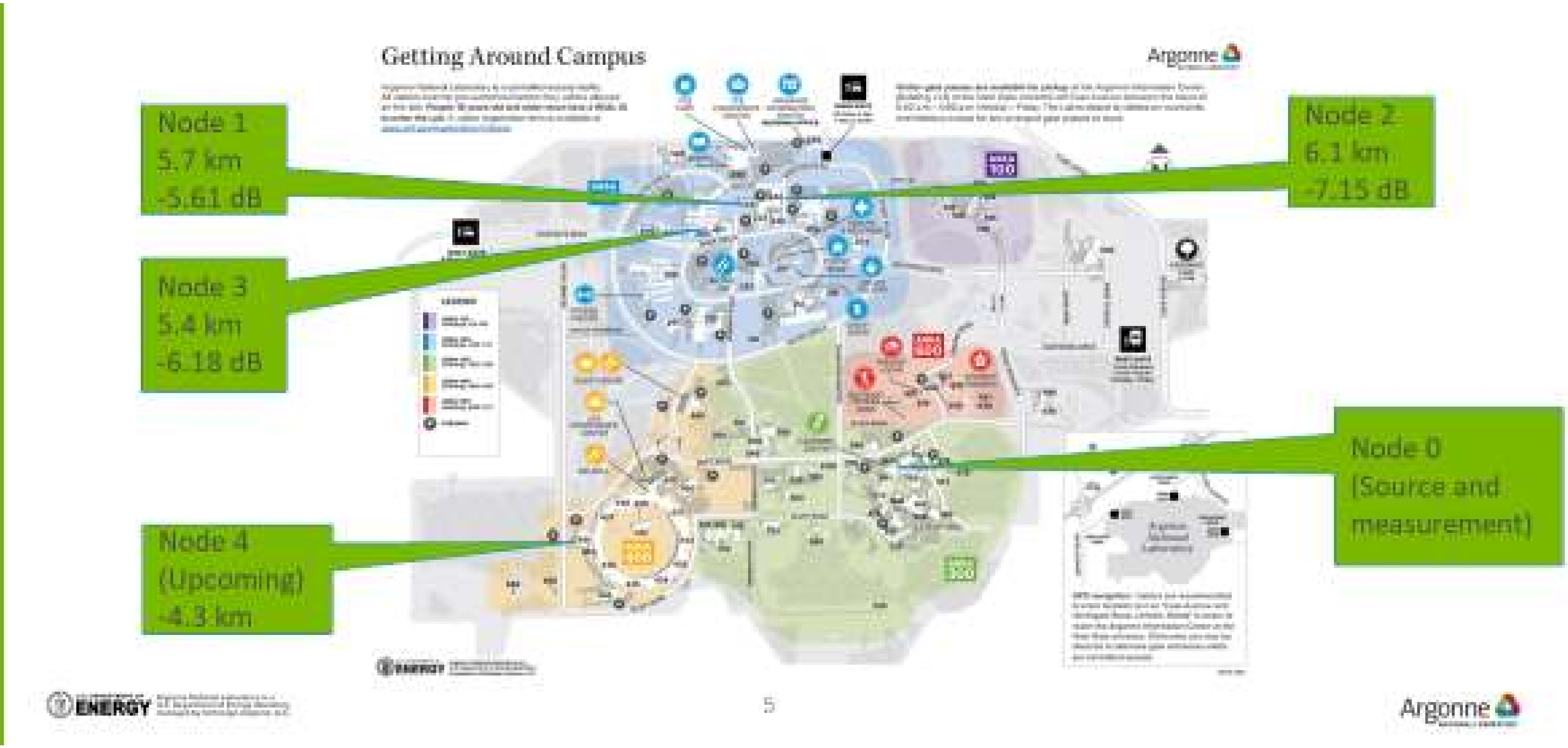
ANIRUDH RAMESH
Argonne National Laboratory
Northwestern University

Joaquin Chung, Rajkumar Kettimuthu, **Argonne National Laboratory**
Gregory Kanter, **Northwestern University/NuCrypt LLC**
Cristián Peña, Robert Plunkett, Si Xie, Panagiotis Spentzouris, **Fermi National Accelerator Laboratory**
Prem Kumar, **Northwestern University/ Argonne National Laboratory**

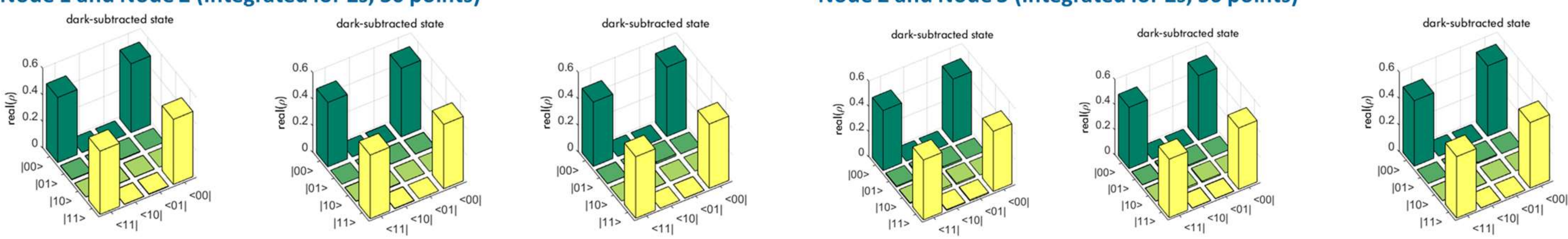
12 May 2023
San Jose, CA

U.S. DEPARTMENT OF ENERGY

ARQNET: Argonne Quantum Network



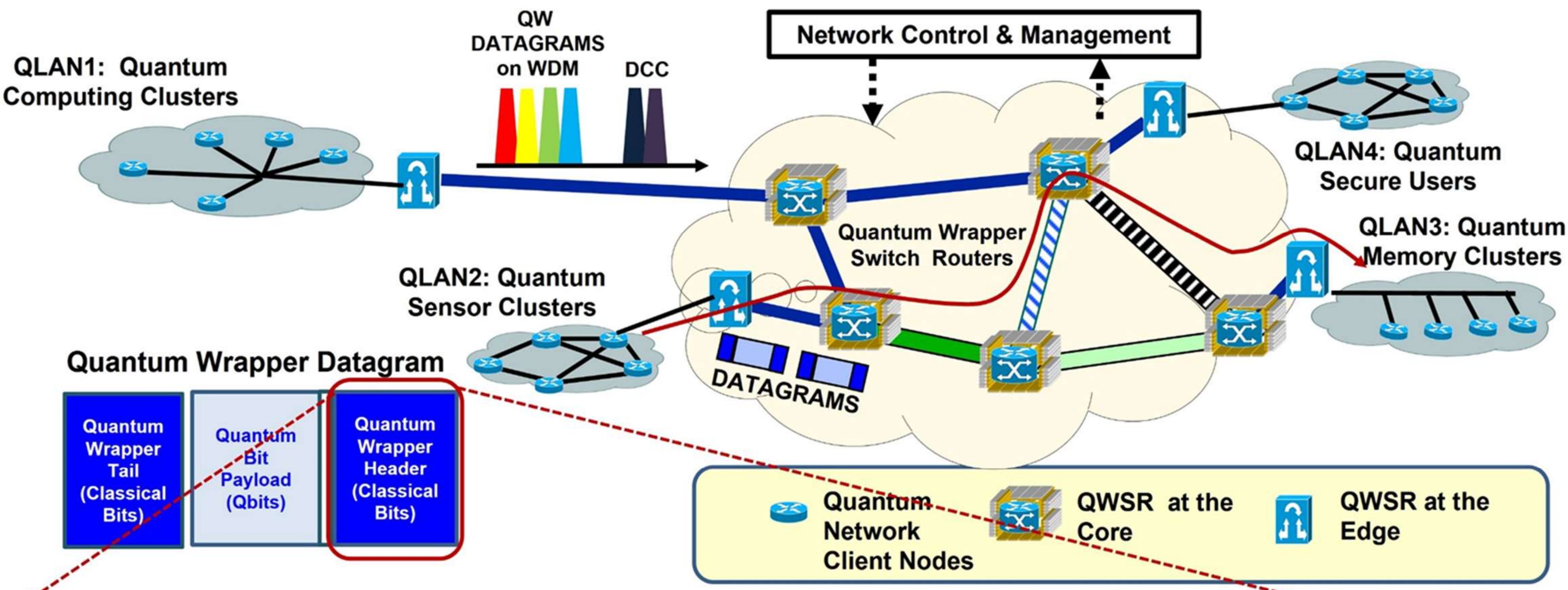
Node 1 and Node 2 (Integrated for 2s, 36 points) **Node 2 and Node 3 (Integrated for 2s, 36 points)**



Node 1 and 2, C46 and C22 | Node 1 and 2, C45 and C23 | Node 1 and 2, C44 and C24 | Node 2 and 3, C44 and C24 | Node 2 and 3, C44 and C24 | Node 2 and 3, C44 and C24

Quantum Wrapper Networking

(w/ Ben Yoo at UC Davis)



Pre-amble	Label (Circuit ID)	Priority	Duration	Type of Quantum Application	Quantum Data Format	Type of Entanglement	QoS	ToS	Parity Bits for error estimate (ChkS)

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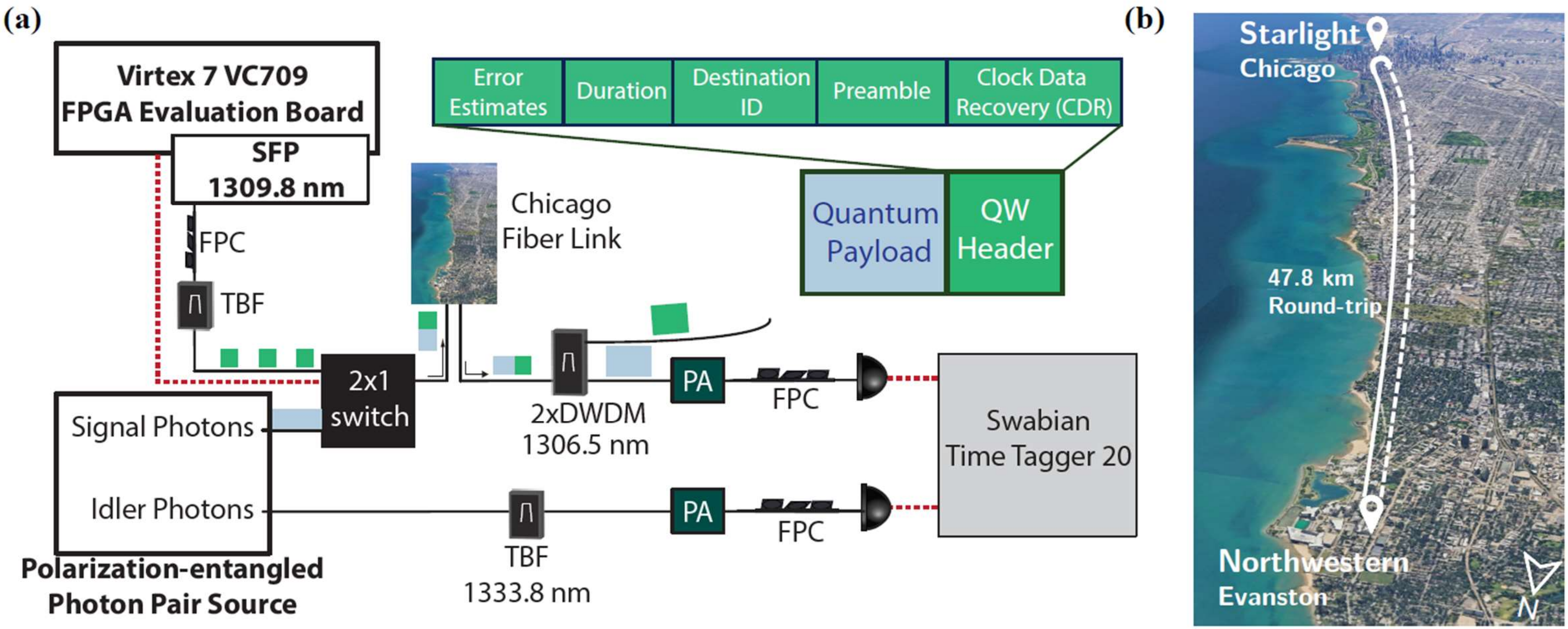
Noise Impact of Classical Headers on Quantum Payload in Quantum Wrapper Networking

CPCC

Research Article Vol. 3, No. 3 / 25 June 2025 / *Optica Quantum* 303

OPTICA QUANTUM



Current Projects (ASCR/DOE)

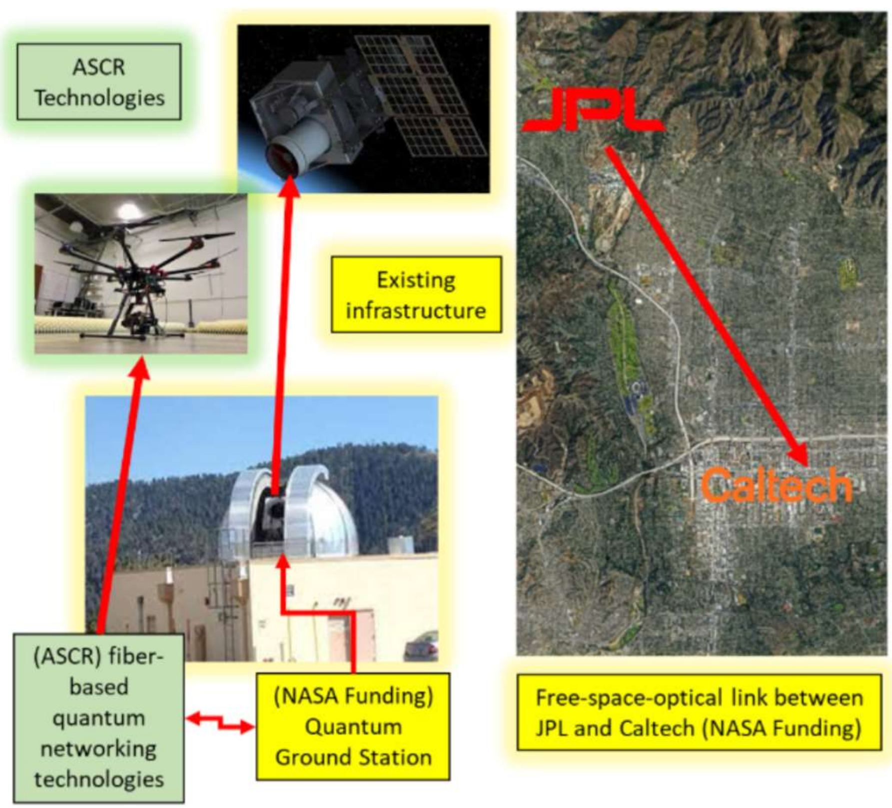
(that I am part of)

Argonne NATIONAL LABORATORY

Advance Quantum Networks for Science Discovery (A-QNET)

Cristián Peña
October 31, 2023

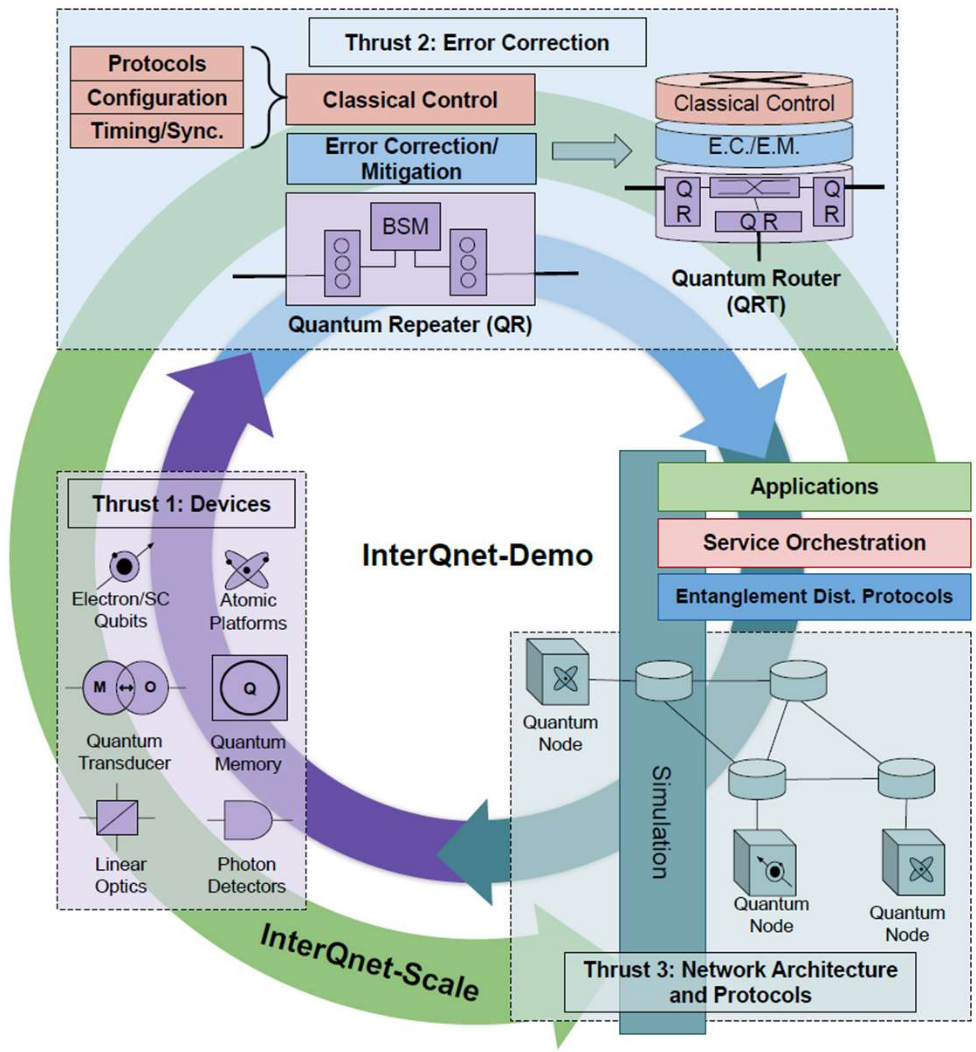
Northwestern University
JPL
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN



InterQnet: Systems Approach to Scalable Quantum Communications

PI: Raj Kettimuthu at ANL

NU, UChicago, UIUC, Fermilab



Conclusions / Outlook

- Quantum networking presents unique engineering challenges that are beginning to be addressed
  - Developed an architecture for fully dynamic and automated quantum network services that utilize existing technologies to demonstrate multi-user, multi-node capabilities at metro scales. Architecture capable of incorporating new device technologies as they are developed.
  - Basic quantum network services like teleportation requires classical communication along with quantum signaling. Therefore, must address classical/quantum coexistence.
  - Pairwise synchronization is much more challenging and may require optical clock signals to copropagate with quantum signals.
  - Introduced Quantum Wrapper networking protocol for qubit transport over a conventional optical network. Much more work is needed in this direction for inferring the health of qubits as they flow through the network. Qumodes can be handled in a similar way.
  - Developing monolithic quantum electronic-photonic systems on chip for ubiquitous availability of quantum entangled sources and detectors. Tremendous efforts underway worldwide in this direction.
  - Quantum transduction and repeater technologies are needed for extending the reach of quantum networks.