Northwestern
McCORMICK SCHOOL
OF ENGINEERING

International Symposium on Quantum Information and Communication (ISQIC) – 2025

CPCC

CQuERE

tcg crest
Inventing Harmonious Future

In celebration of International Year of Quantum Science & Technology (IYQ) - 2025

March 31 – April 02, 2025

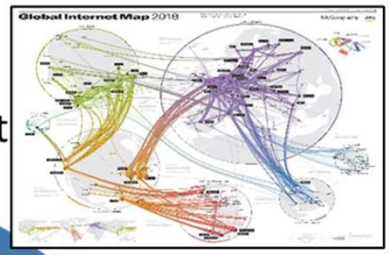
INTERNATIONAL YEAR OF
Quantum Science
and Technology

Engineering Challenges for the Emerging Quantum Networks

Prem Kumar
Professor, ECE & Physics
Center for Photonic Communication and Computing
Northwestern University
E-mail: kumarp@northwestern.edu

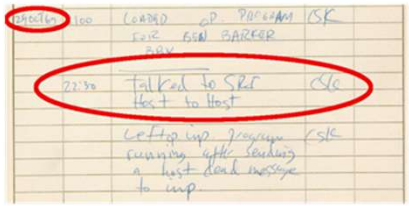
The Bit Revolution

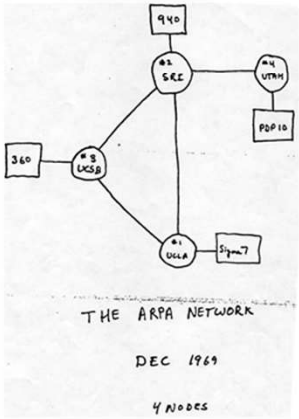
Google
1998
WWW
1990
NSFNET
Internet
1982
Ethernet
1976
TCP/IP
1973
ARPANET 1969
SRI
Utah
UCSB
UCLA
1984
Macintosh
1964-1979
IC
1959-1963
1st transistors used
1946
ENIAC, 1st Elec. gen. purpose Comp. using vacuum tubes
1942
Mark 1, 1st Elec. Mech. computer
M=5 tons
2010
Big Data/AI
?

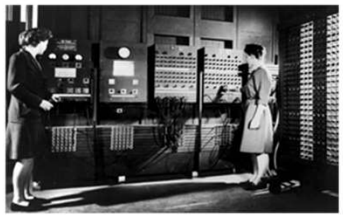


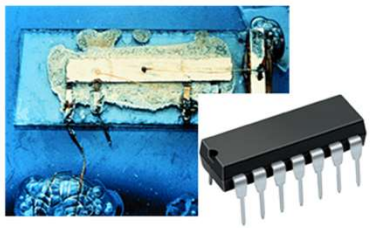
7	Application	Application
6	Presentation	
5	Session	
4	Transport	(Host-to-Host) Transport
3	Network	Internet
2	Data Link	Network Interface
1	Physical	(Hardware)

OSI Model | TCP/IP Model

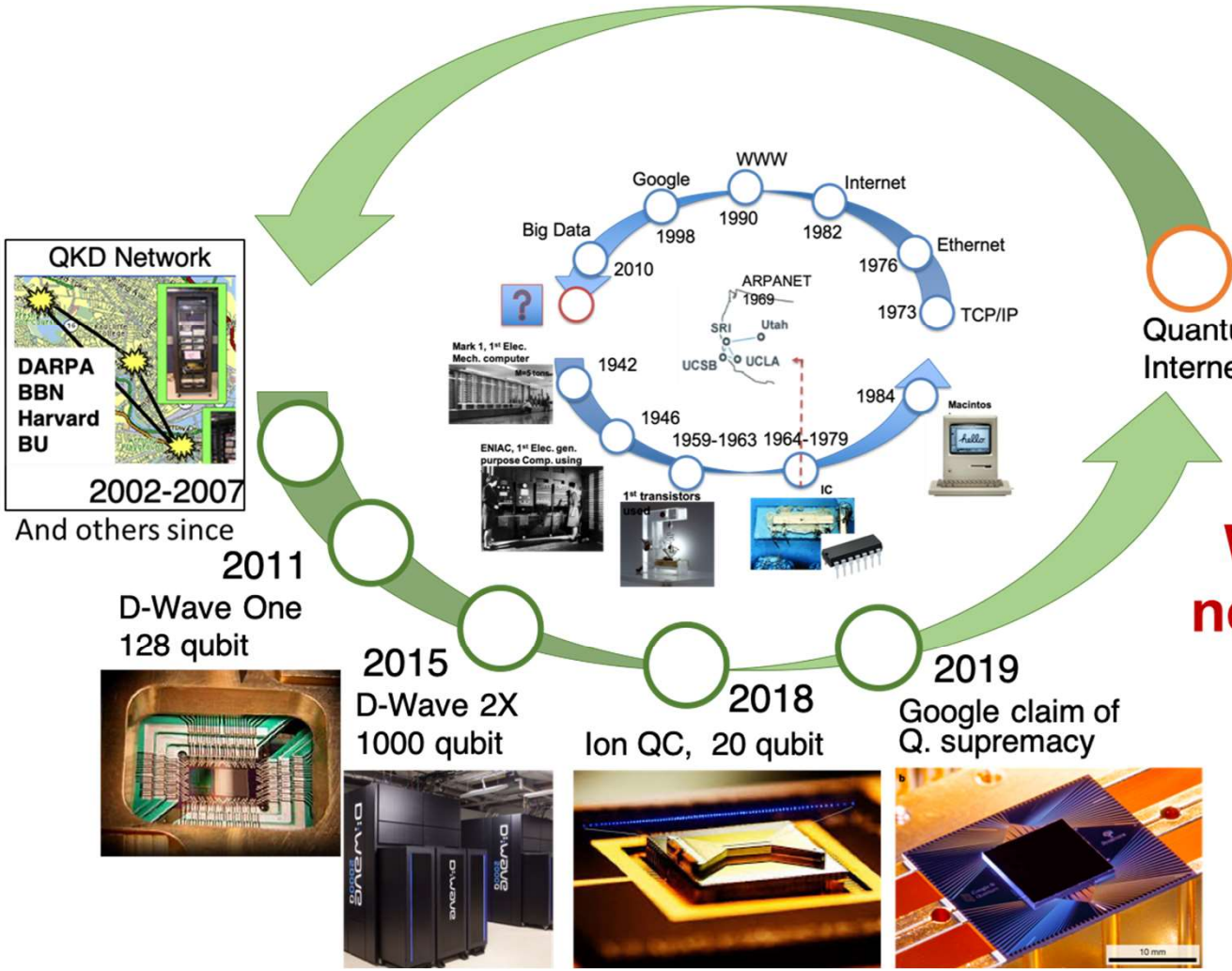








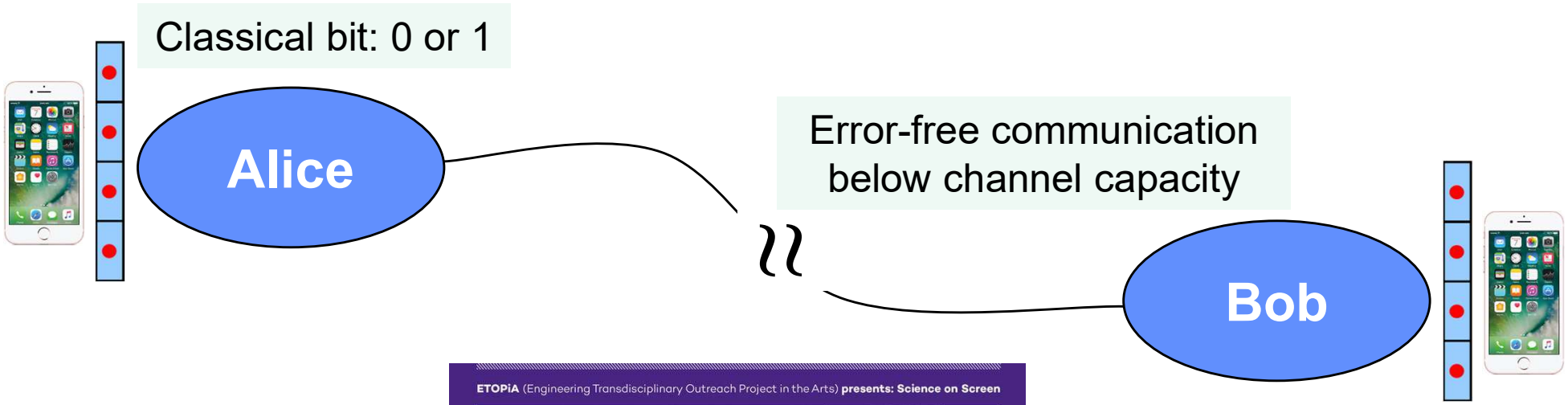
The Qubit Revolution…



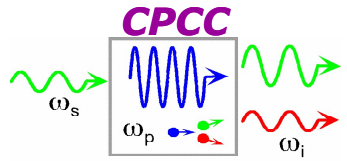
Early introduction of quantum networking is particularly important given the scalability issues in current quantum processors.

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

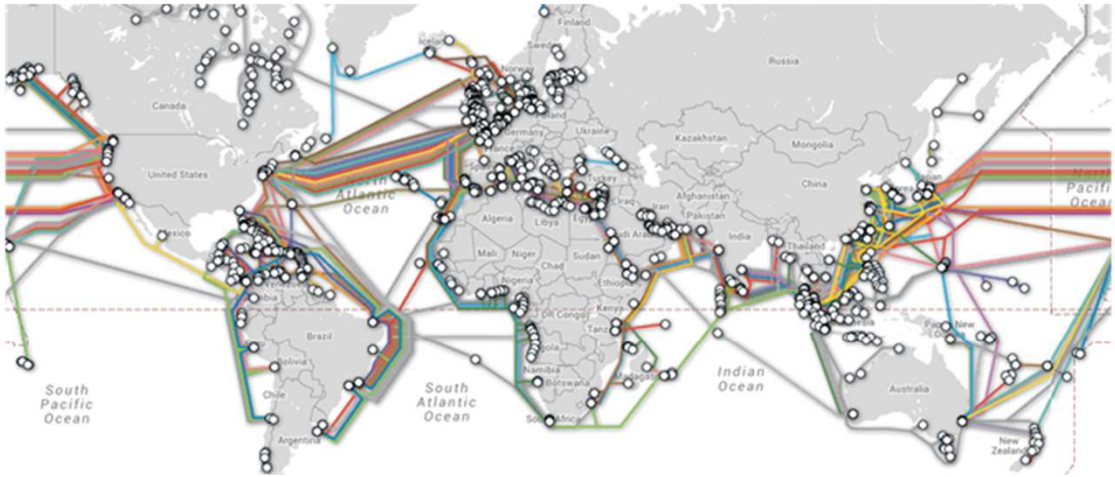
Classical Communications & Networking



Communications & Networking Today

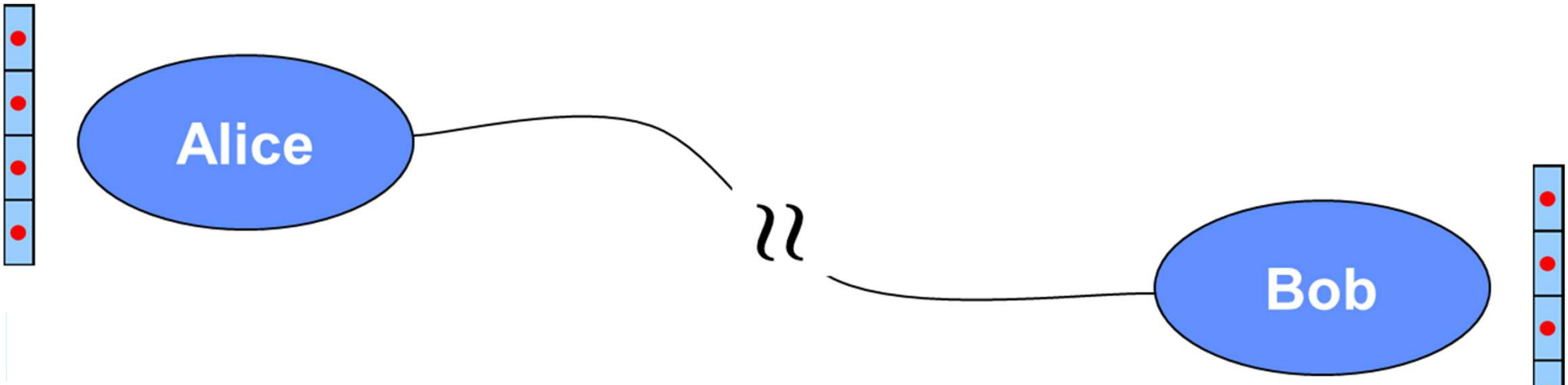


Supercomputer



Data Center

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

Alice

Bob

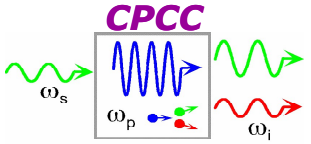
- Transmitter T and Receiver R share entangled qubits

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

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

Bennett *et al*. 1993

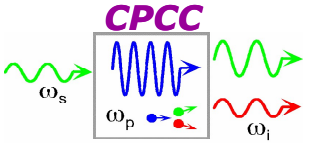
Requirements for Such Connectionless Quantum Communication



- 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

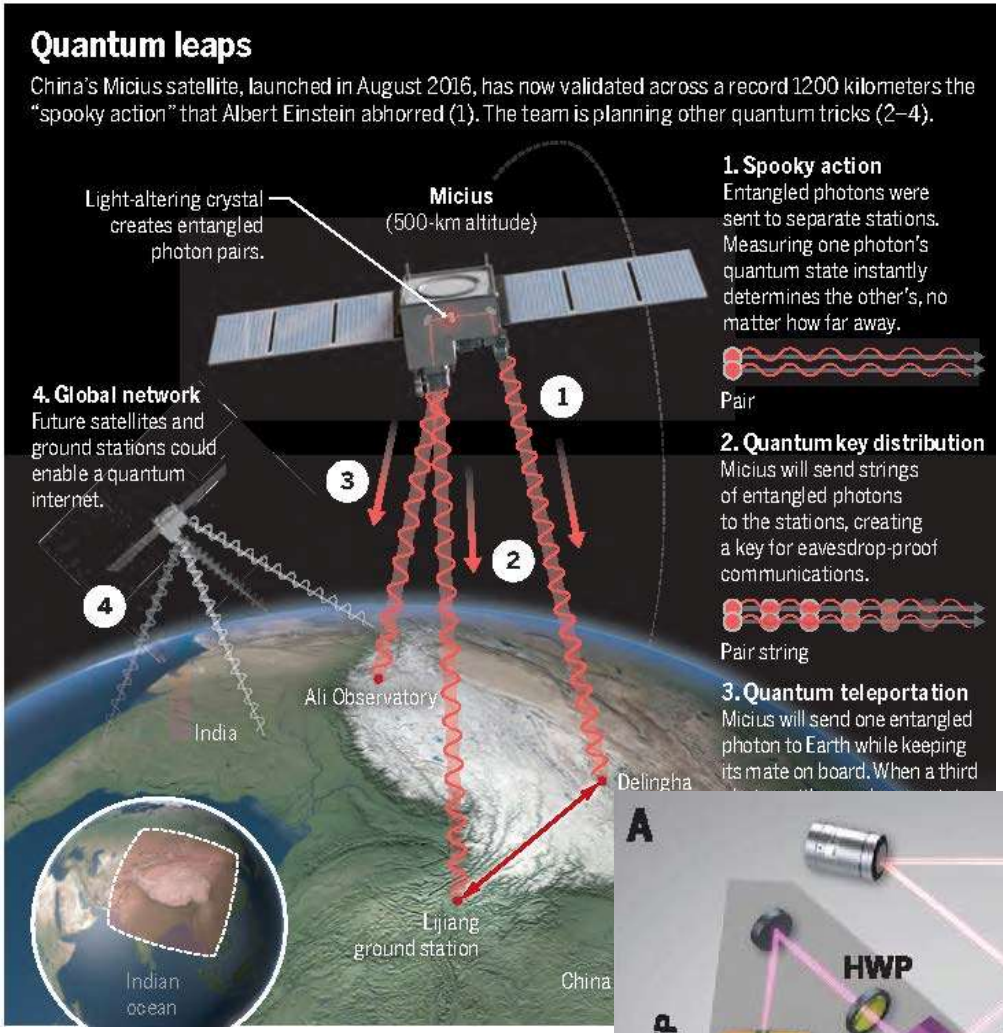
Photon loss is the bane of quantum communications !
And, of course, phase decoherence !!!

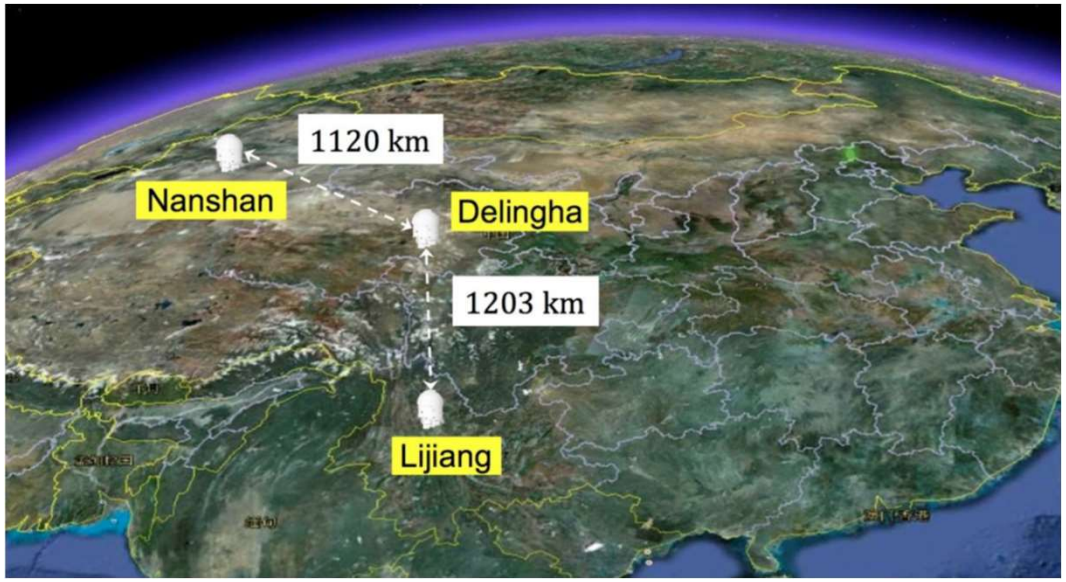
Quantum Networking: There is a Case



- NISQ (Noisy Intermediate Scale Quantum) technology is already here
  - IBM quantum experience (widely successful as a teaching tool)
  - Similar access by others as well (D-Wave, Google, …)
- Small scale quantum computers will be commercially available in not-too-distant future
  - "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

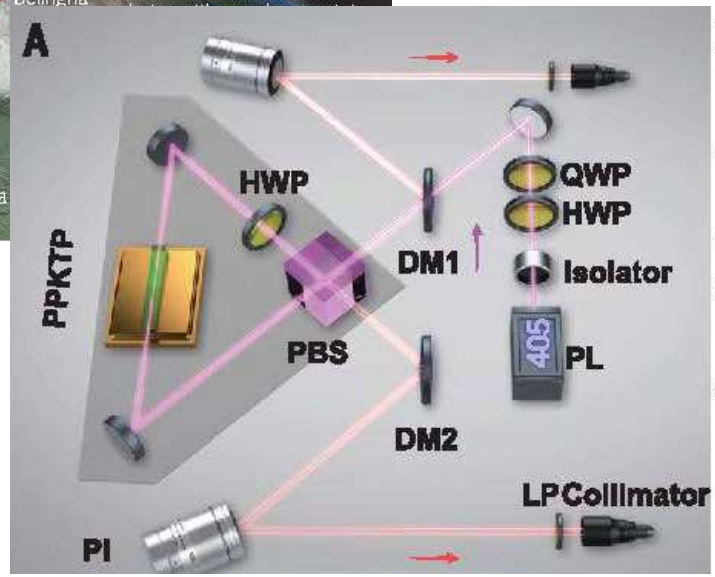
Source Aboard Satellite Micius
Entanglement Distribution over 1200 km

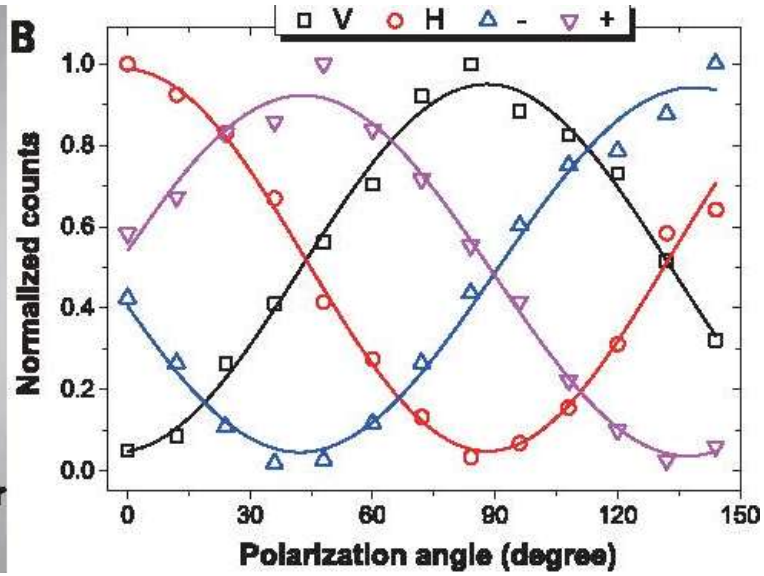




F. N. C. Wong *et al.*, Phys. Rev. A 73, 012316 (2006)

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





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

Bell inequality violation over 1200 km

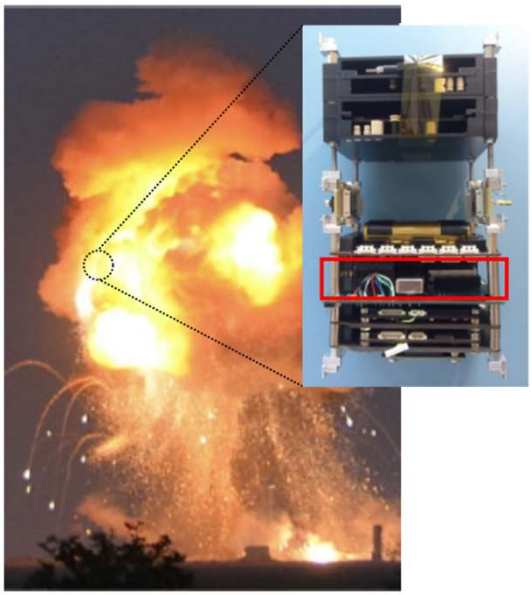
Robust (Rocket Explosion Proof) Source

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

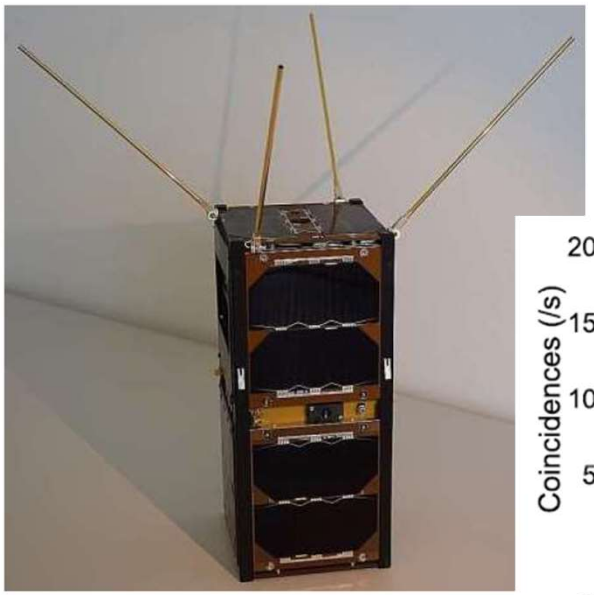
OPEN

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)

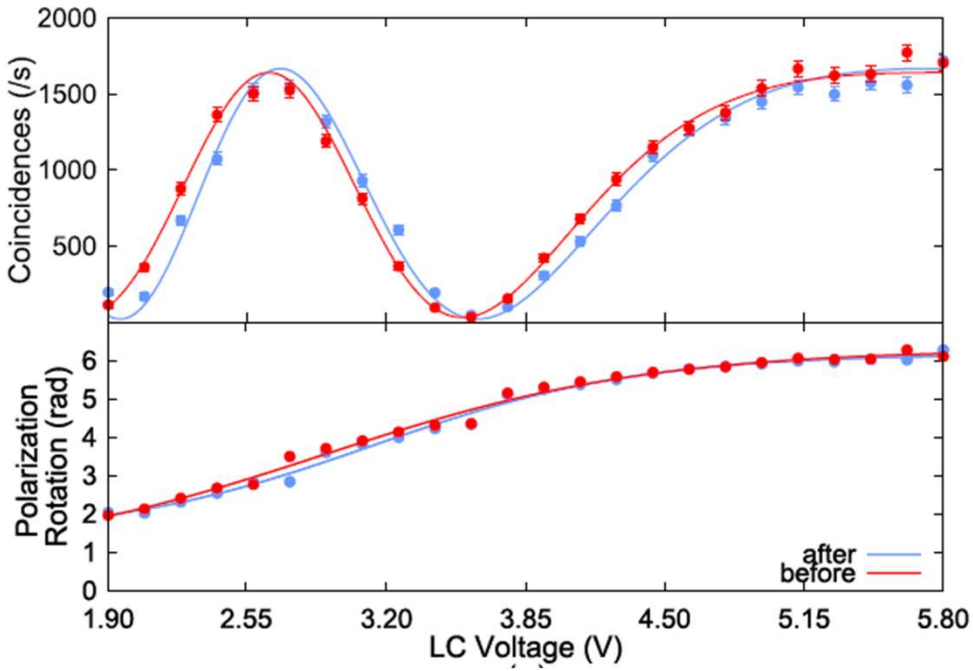
Figure 5.4: (a) GomX-2 CubeSat (without the solar panel) with SPEQS1.1-CS highlighted in red box (b) GomX-2 CubeSat after recovering from the explosion. Images courtesy of GOMspace.

GOMSPACE

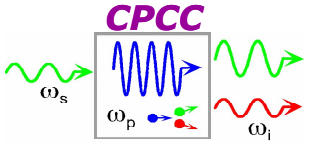
https://gomspace.com/home.aspx

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?
  - …

US National Quantum Initiative (NQI) Act Signed into Law on 21 Dec 2018

Illinois Express Quantum Network (IEQNET)

Illinois Express Quantum Network (IEQNET) – Metropolitan-Scale Experimental Quantum Network

Research team leads:

- Fermilab: *P. Spentzouris (PI), C. Pena, W. Wu, S. Xie*
- Argonne: *R. Kettimuthu, J. Chung*
- Caltech: *M. Spiropulu, N. Lauk, R. Valivarthi*
- Northwestern: *P. Kumar, G. Kanter*

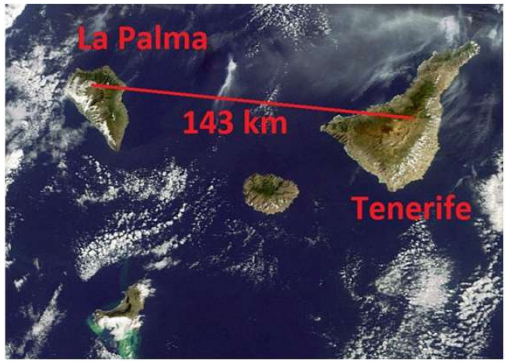
2 9/23/2021 IEQNET Collaboration

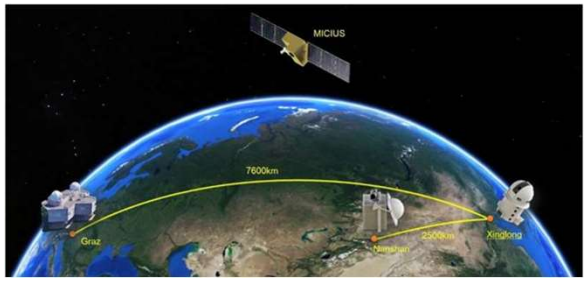
The IEQNET collaboration

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

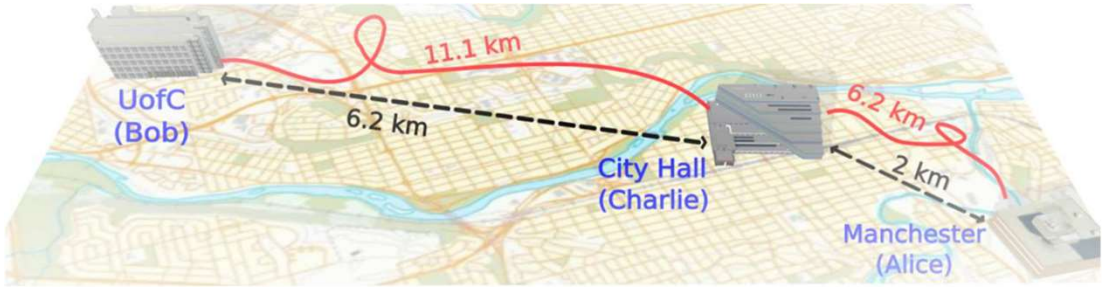
Motivation (Circa 2019): Repeaterless Metro-Area Quantum Network

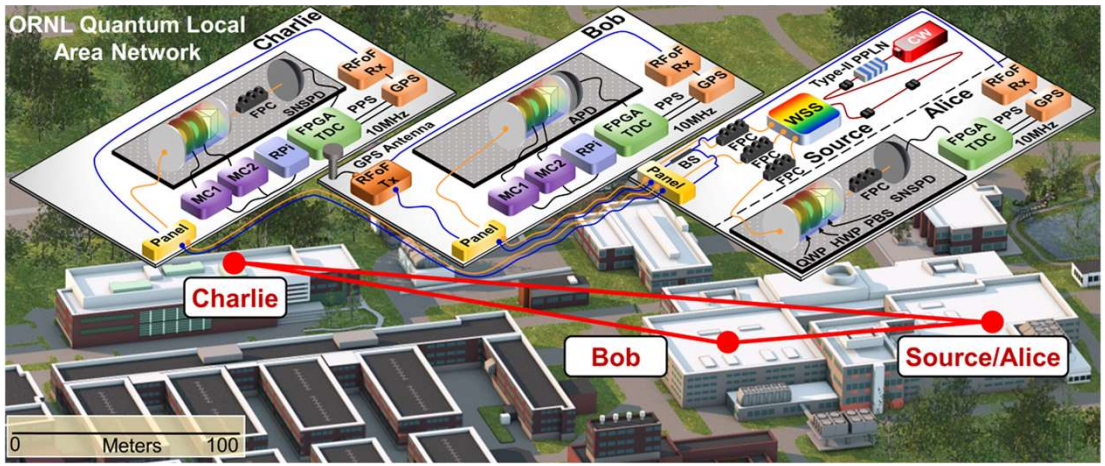
- Most quantum networking demonstrators focus on point-to-point or linear topologies



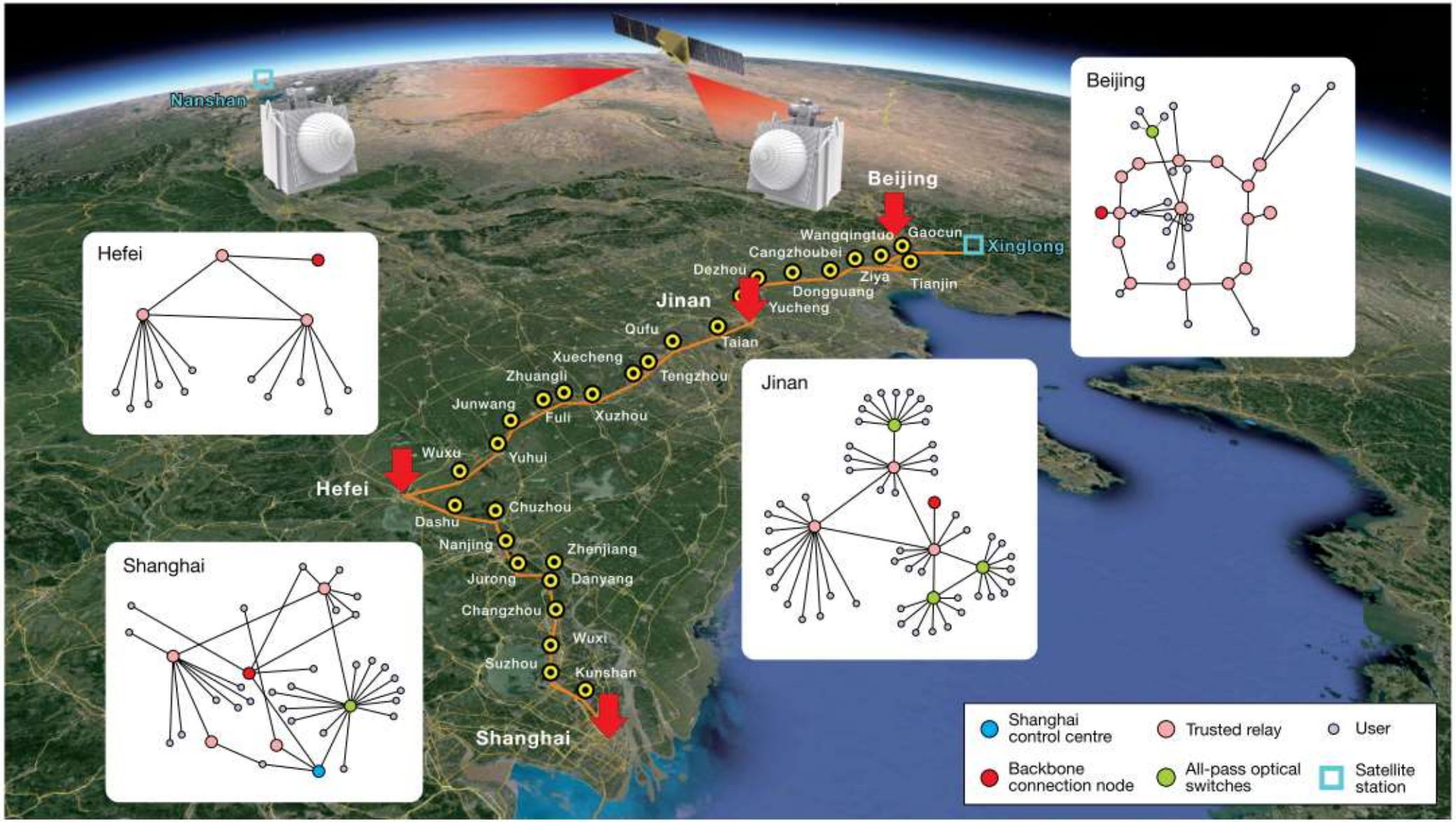


- There is great need to develop architectures for **fully dynamic and automated quantum networks** using existing technologies to **demonstrate multi-user, multi-node** capabilities at **metro scales** that go beyond linear topologies



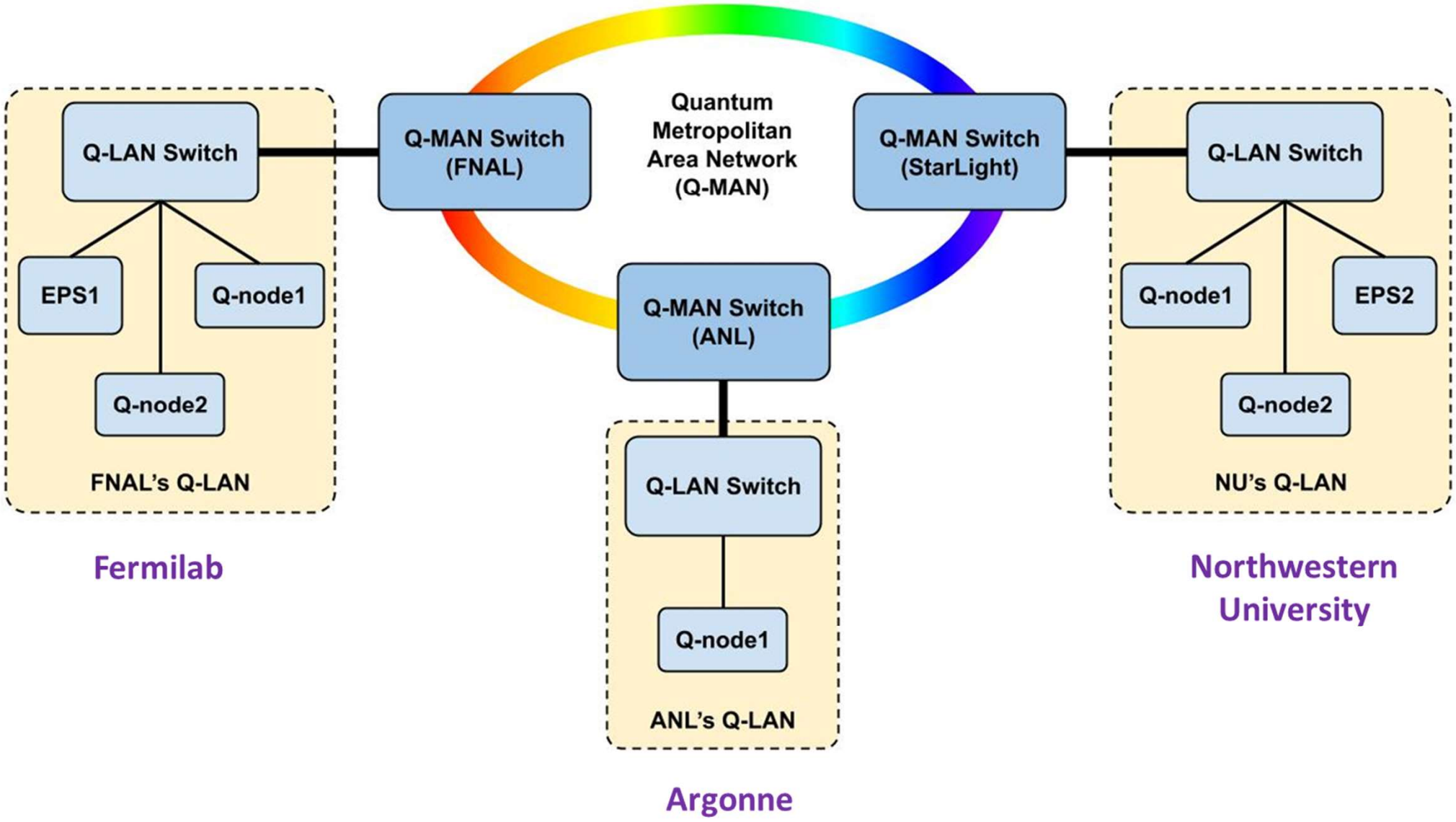


World's Largest Quantum Network (mostly QKD)



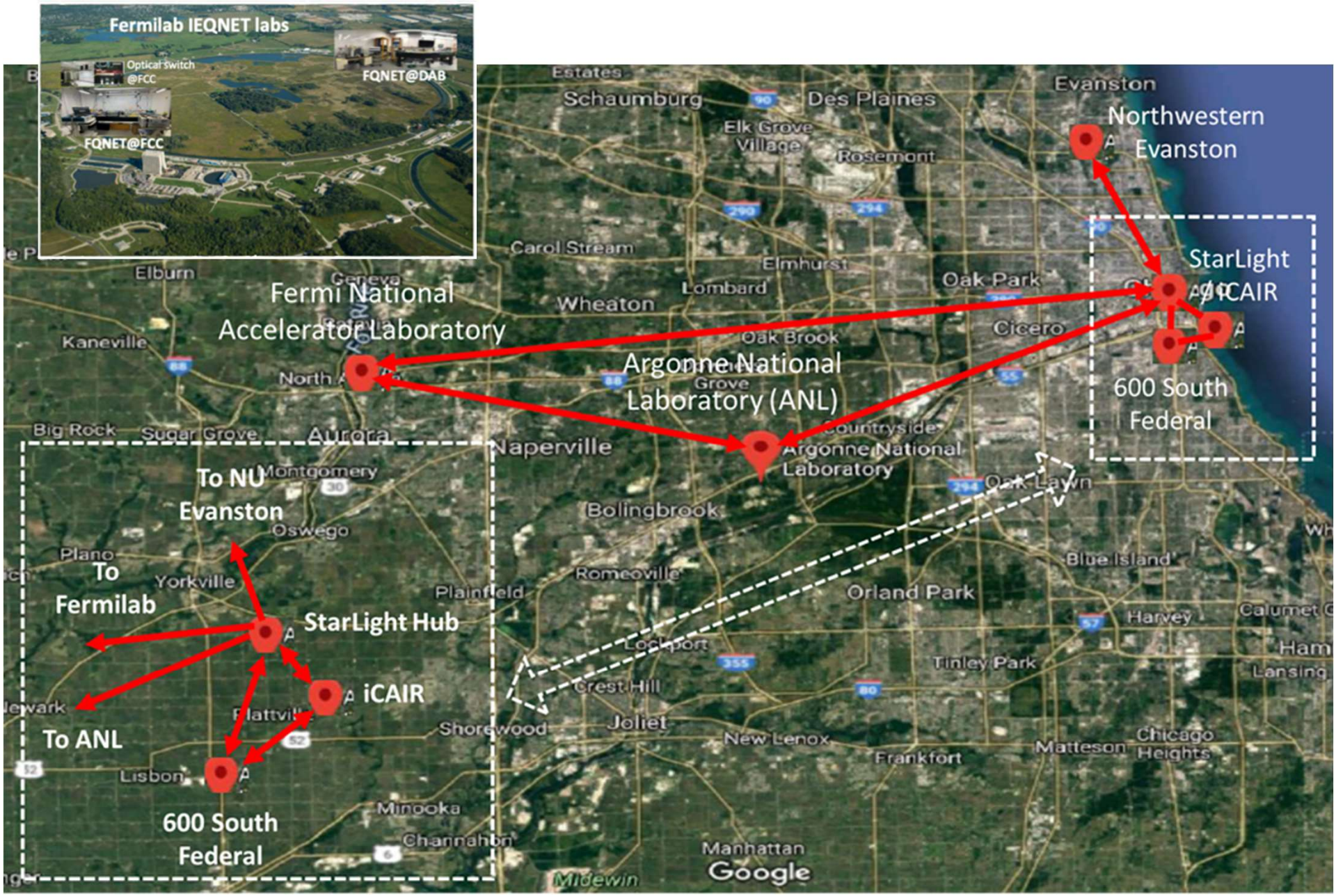
[1] Y. A. Chen *et al.*, "**An integrated space-to-ground quantum communication network over 4,600 kilometres**," *Nat. 2020 5897841*, vol. 589, no. 7841, pp. 214–219, Jan. 2021.

IEQNET Topology

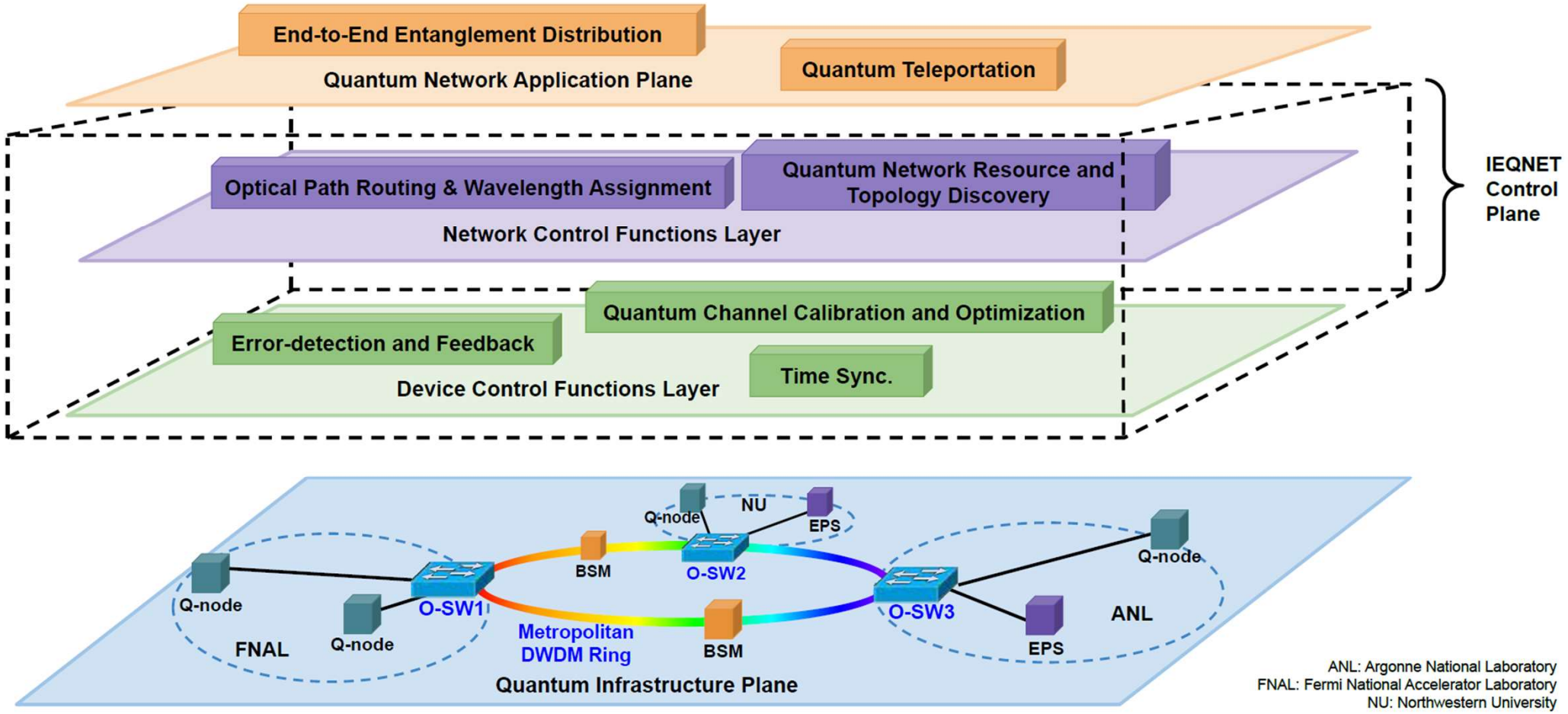


J. Chung, G. Kanter, N. Lauk, R. Valivarthi, W. Wu, R. R. Ceballos, C. Peña, N. Sinclair, J. Thomas, S. Xie, R. Kettimuthu, P. Kumar, P. Spentzouris, and M. Spiropulu, "Illinois Express Quantum Network (IEQNET): metropolitan-scale experimental quantum networking over deployed optical fiber," Proc. SPIE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

IEQNET Physical (proposed)



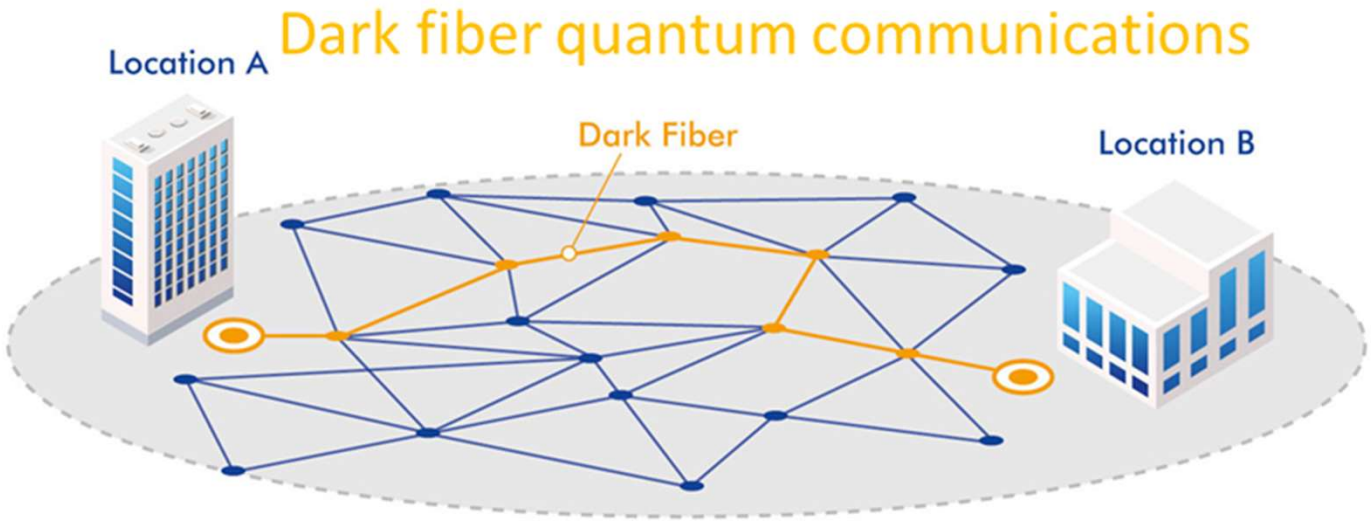
IEQNET's Quantum Networking Architecture (three planes)



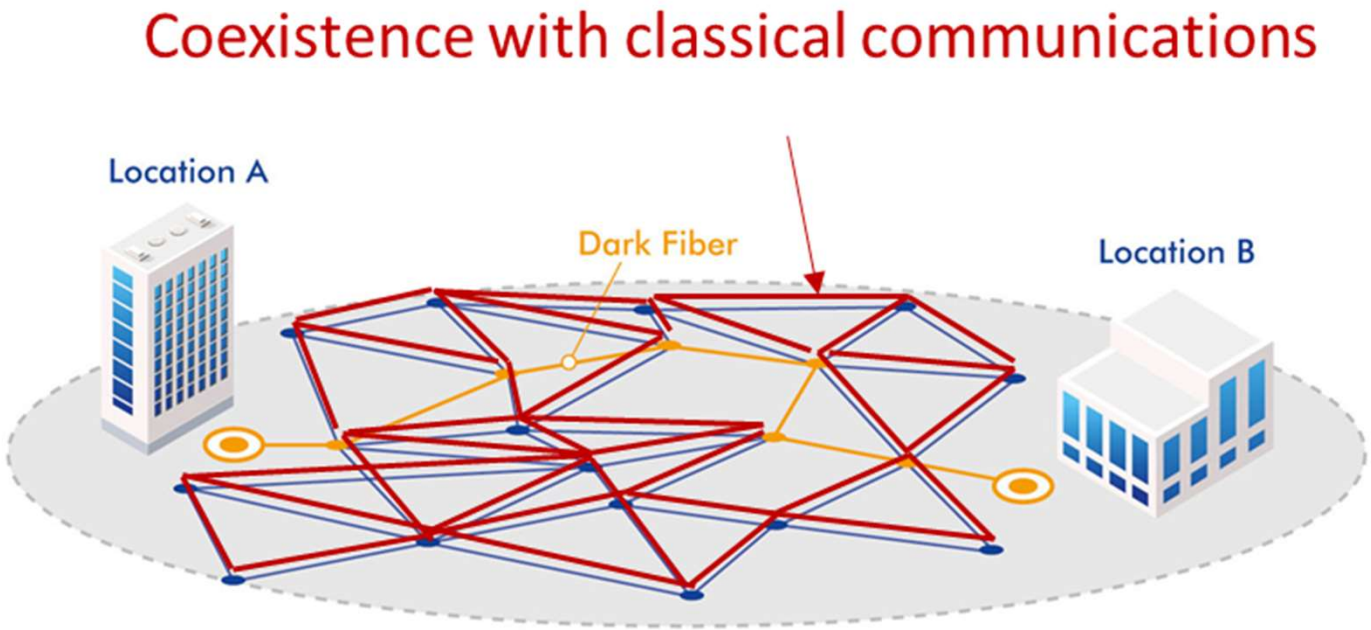
IEEE Transactions on Quantum Engineering Chung et al.: DESIGN AND IMPLEMENTATION OF THE ILLINOIS EXPRESS QUANTUM METROPOLITAN AREA NETWORK

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

Quantum-Classical Coexistence for Scalable Quantum Networks

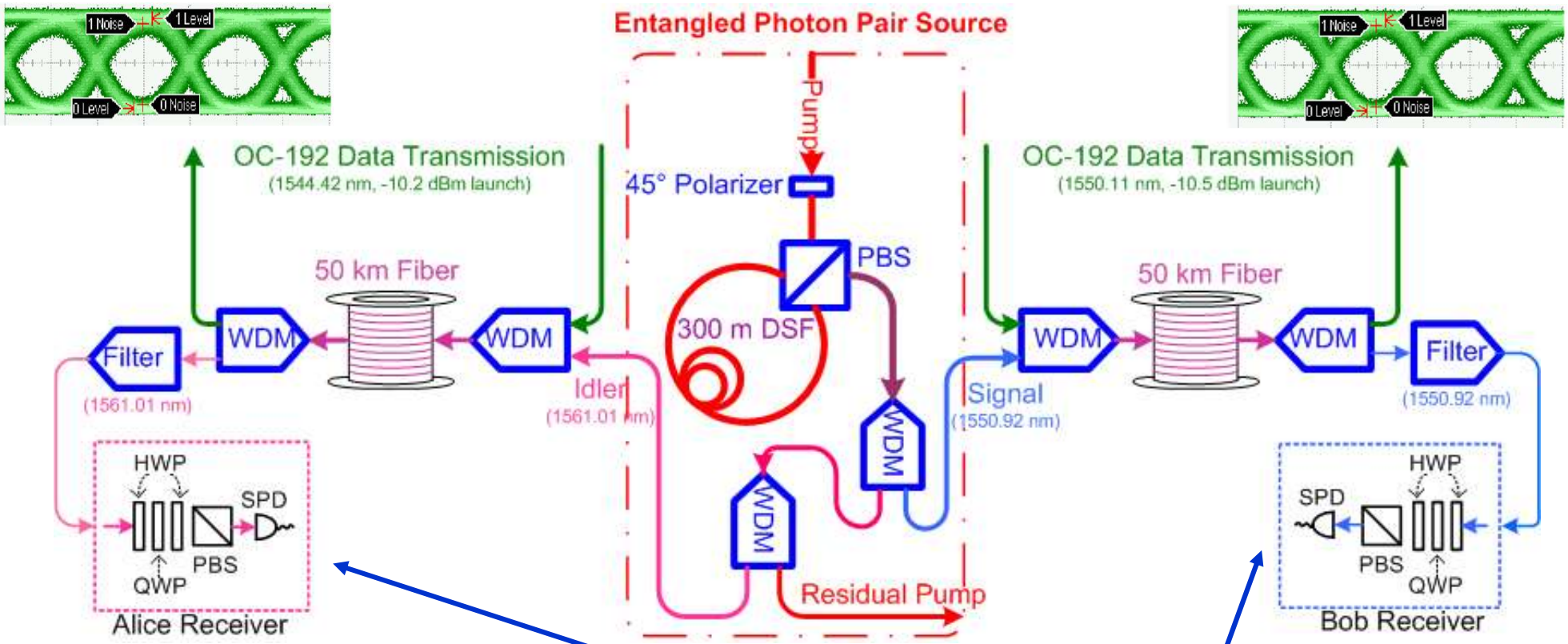


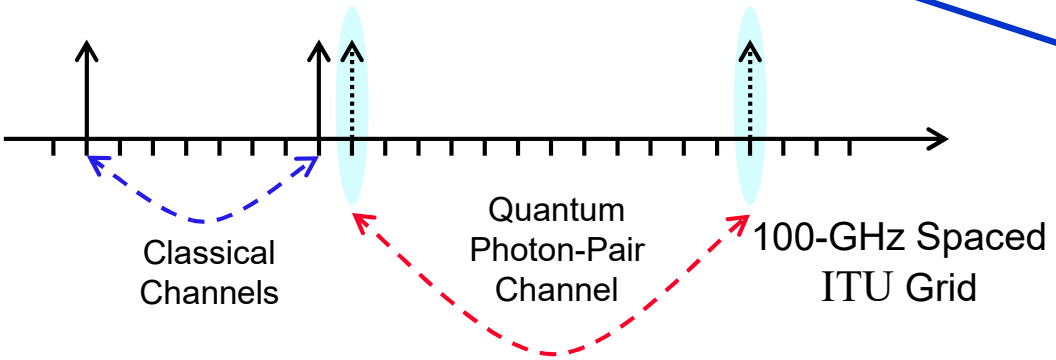
Unlikely to be cost effective

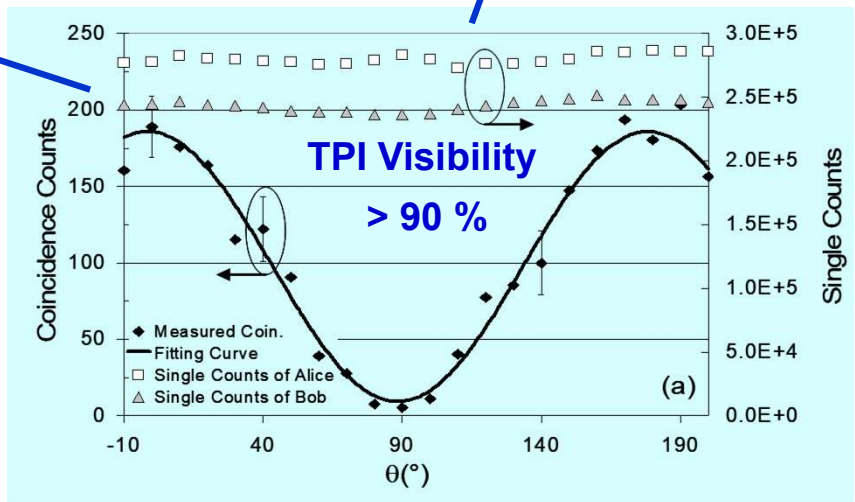


Must explore this option

Entanglement Distribution in WDM Environment





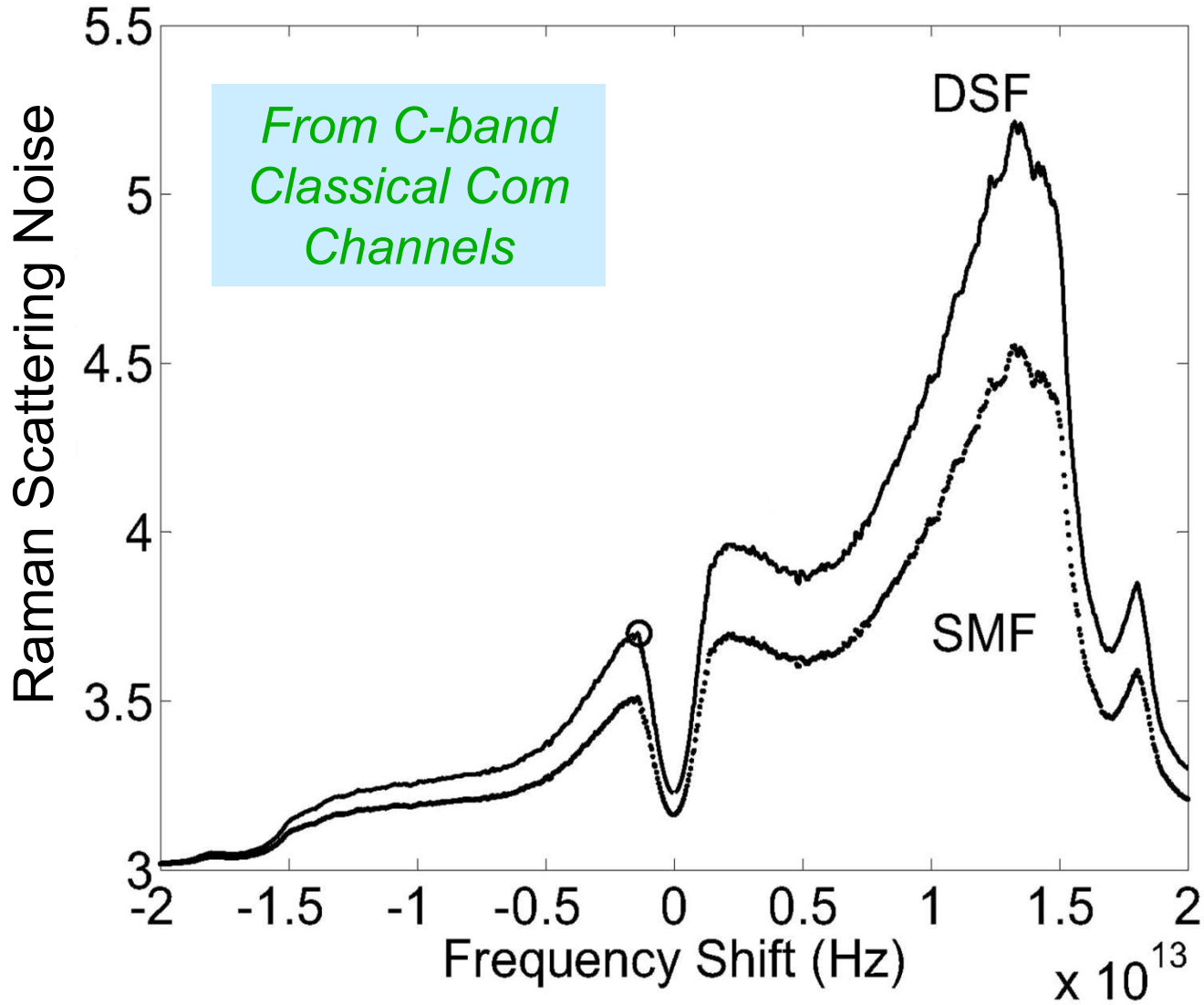


Liang *et al.*, *OFC 2006 postdeadline paper PDP35*

Towards Applications in Embedded Fiber Telecom Infrastructure

Create entangled photon-pairs in the 1310 nm band

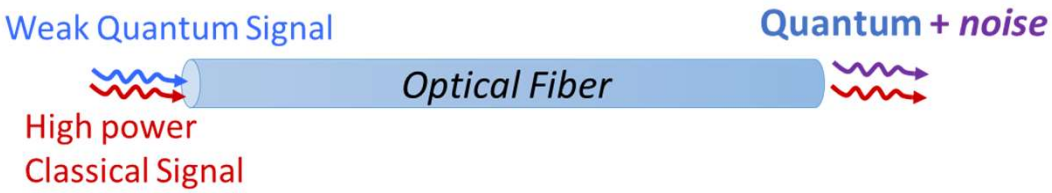
From C-band Classical Com Channels



1310 nm ← 35 THz → 1550 nm

Townsend, EL **33**, 188 (1997); Nweke *et al.*, Appl. Phys. Lett. **87**, 174103 (2005)

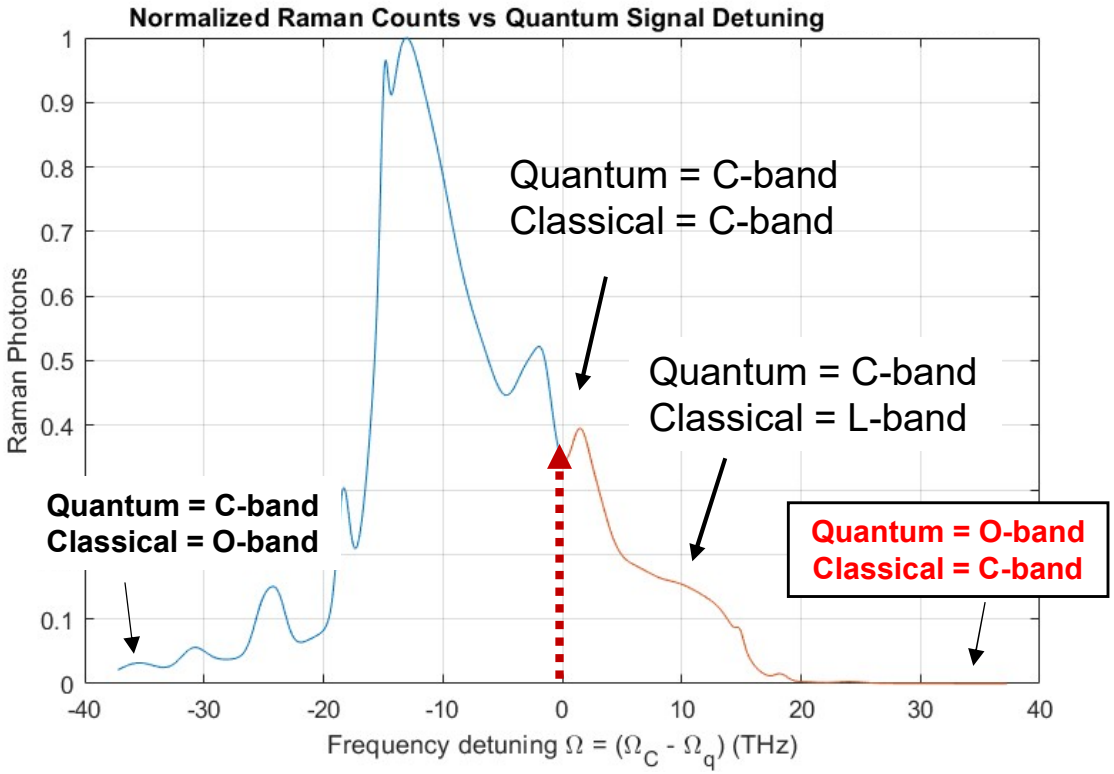
Spontaneous Raman Scattering Noise: Mitigation Methods



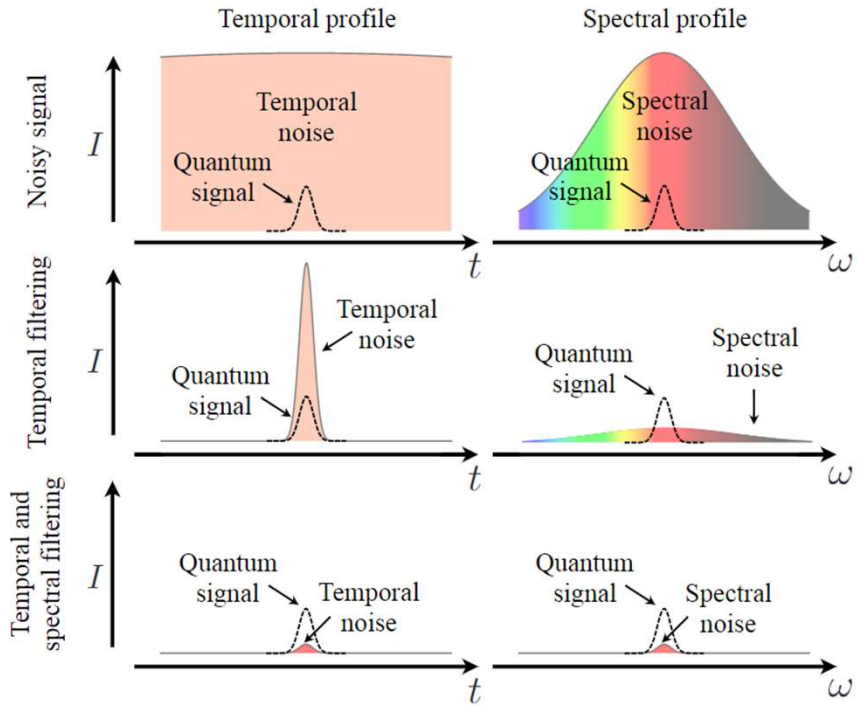
Without careful engineering, either:

1. Limited classical power levels (i.e., capabilities)
2. Decreased quantum fidelities

1. Wavelength assignment based on Raman noise spectrum



2. Narrow spectral-temporal filtering



Northwestern
McCORMICK SCHOOL
OF ENGINEERING

Quantum Classical Coexistence in the IEQNET

CPCC

1. Time Synchronization

1310 nm classical clock light coexisting with 1536 nm photon pairs for picosecond synchronization over 59 km

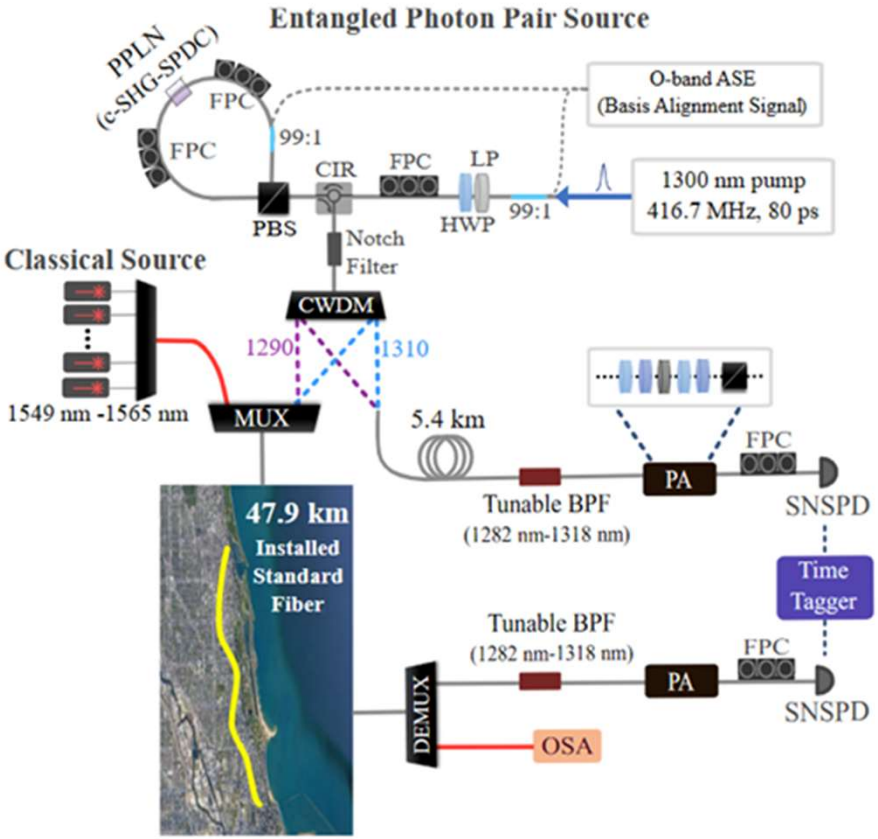
Fig. 1: This image depicts the separation of the nodes in our network. FNAL-FCC and FNAL-DAB are connected with 2 km of dark fiber and FNAL-FCC and ANL are connected with 57 km of dark fiber. We keep our master clock at FNAL-FCC, and distribute the signal to FNAL-DAB and ANL, choosing the path via an optical switch located at FNAL-FCC. The FNAL nodes are depicted by the blue rectangles and the ANL node is depicted by the red rectangle.

IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. XX, NO. XX, MONTH YEAR 1

Picosecond Synchronization System for the Distribution of Photon Pairs through a Fiber Link between Fermilab and Argonne National Laboratories

2. O-band Quantum Networking Beyond Dark Fiber

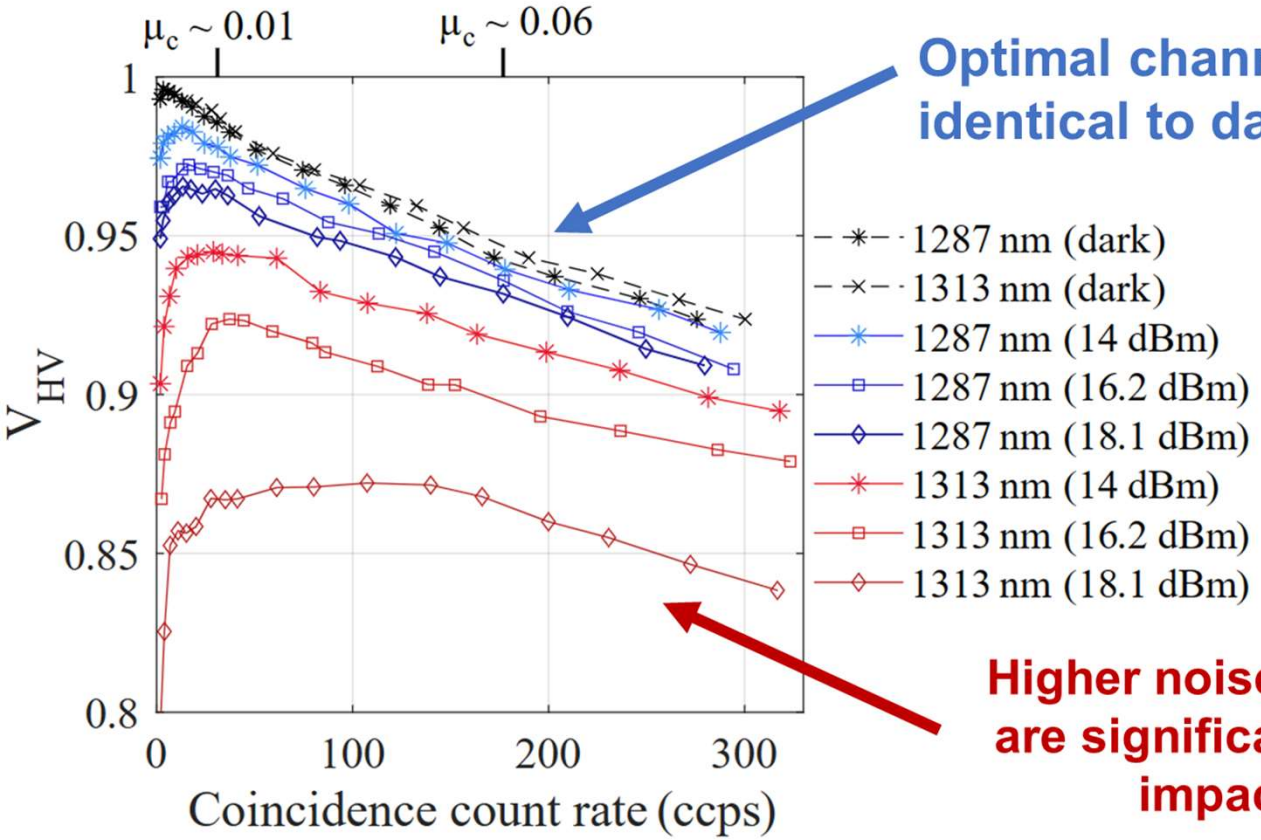
Coexistence with milliwatt power C-band classical light over >45 km fiber using O-band quantum entangled photons



Designing Noise-Robust Quantum Networks Coexisting in the Classical Fiber Infrastructure

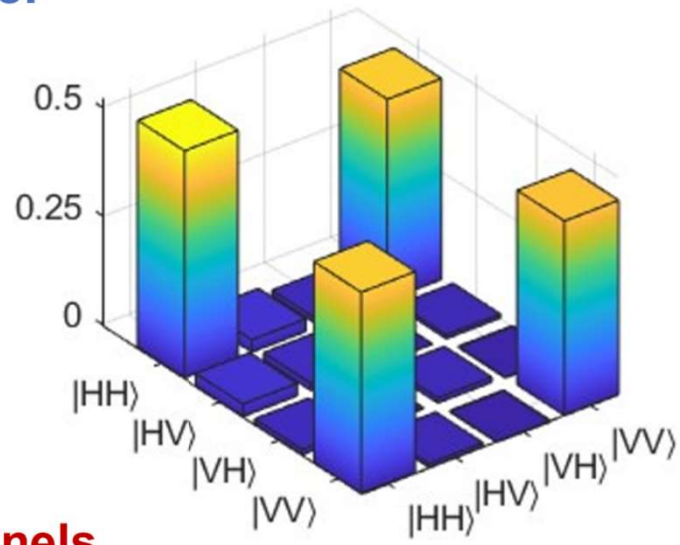
JORDAN M. THOMAS[1,*], GREGORY S. KANTER[1,3], AND PREM KUMAR[1,2]

O-band Pol. Ent. Visibility vs. Pair Rate w/ C-band Coexistance



Optimal channels nearly identical to dark fiber

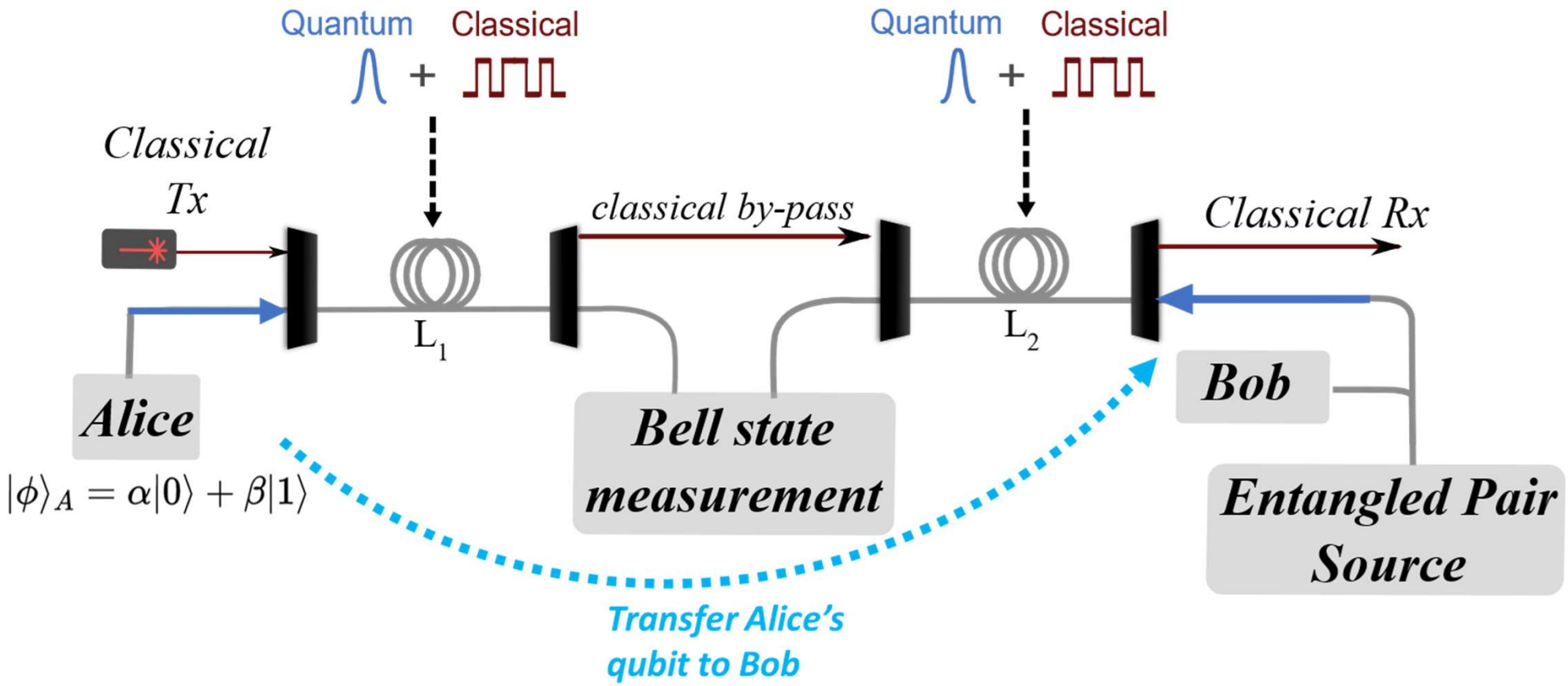
Higher noise channels are significantly more impacted



- Using the optimal quantum channel and narrow spectral-temporal filtering, >95% fidelity to the nearest Bell state is achieved with >18 dBm C-band power.

[2304.09076] Designing Noise-Robust Quantum Networks Coexisting in the Classical Fiber Infrastructure (arxiv.org)

Quantum Teleportation Over Optical Fibers Carrying Classical Data



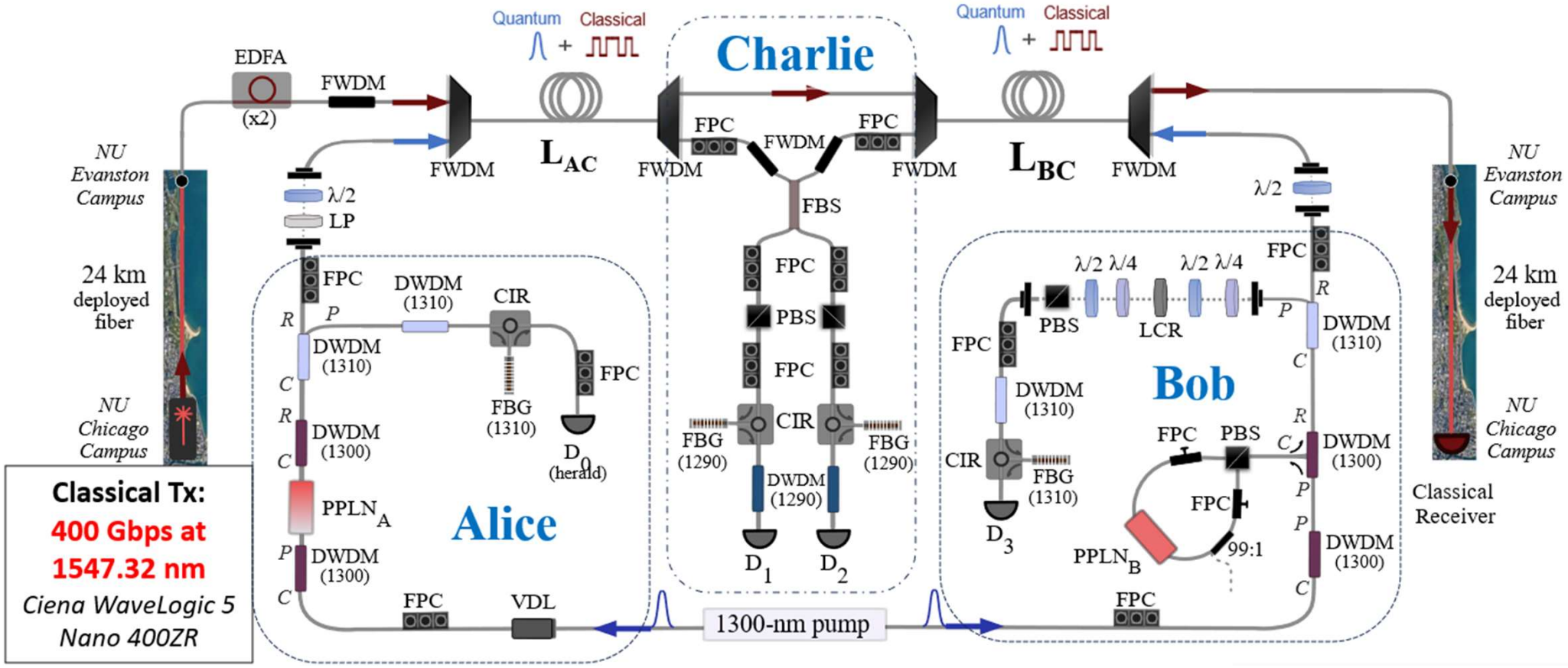
Alice's quantum state is transferred over the distance $L = L_1 + L_2$

Classical signal propagates the full fiber length L

Three-node O-band Teleportation System Coexisting with 400-Gbps C-band Classical Traffic

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]



Quantum state transfer distance = $L_{AC} + L_{BC}$

Classical link distance = 48 km + $L_{AC} + L_{BC}$

Coexistence = $L_{AC} + L_{BC}$

Pulse width = 65 ps
Rep. rate = 500 MHz
Mean generated photon pairs/pulse
Alice $\mu_A = 0.018$
Bob $\mu_B = 0.013$

Northwestern
McCORMICK SCHOOL
OF ENGINEERING

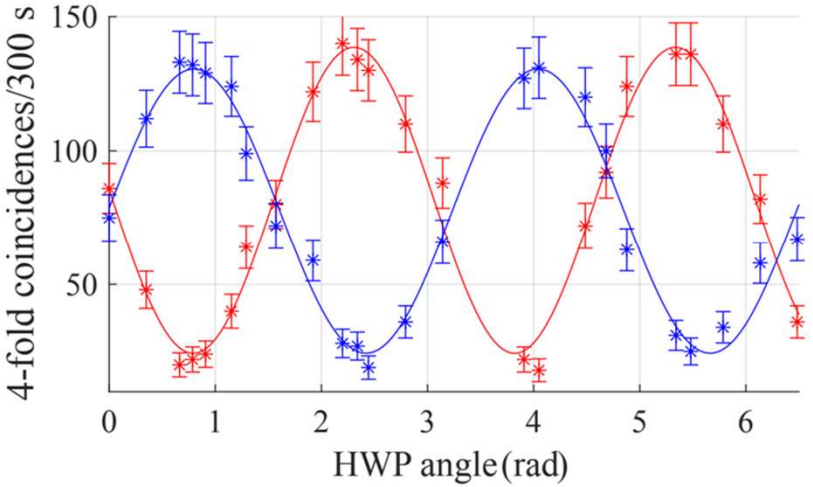
Quantum Teleportation Coexisting with 11 dBm 400 Gbps C-band Signal

CPCC

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

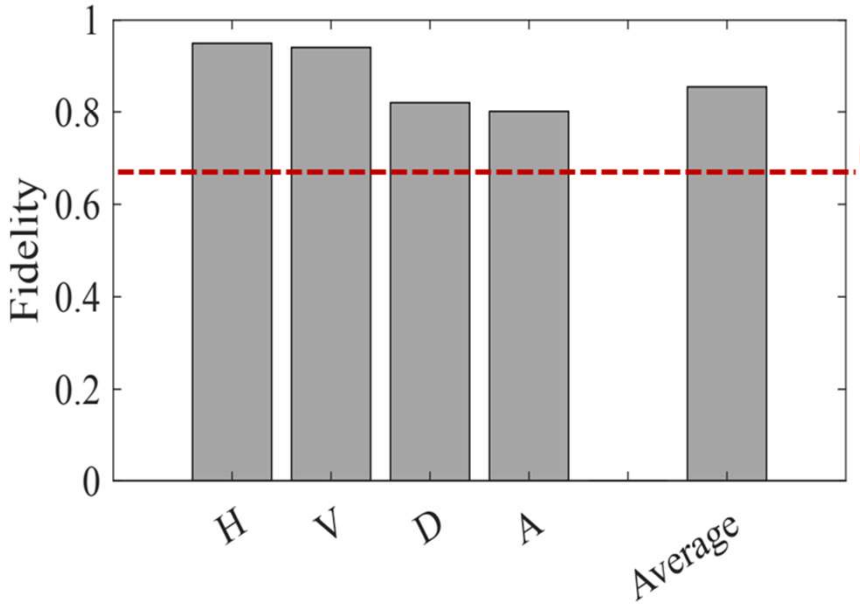
$$|D\rangle = \frac{1}{\sqrt{2}}|H\rangle + |V\rangle$$

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



Fidelities of Bob's qubit to Alice's ideal state, measured via quantum state tomography

$$F = \langle \phi_A | \rho_B | \phi_A \rangle$$



$$F_{\text{avg}} = 85.6 \pm 4.0\%$$

Quantum Teleportation Over Optical Fibers Carrying Conventional Classical Communications Traffic

Th.C.3.7

Jordan Thomas[1], Fei Yeh[2], Jim Chen[2], Joe Mambretti[2], Scott Kohlert[3], Gregory Kanter[4], Prem Kumar[1]

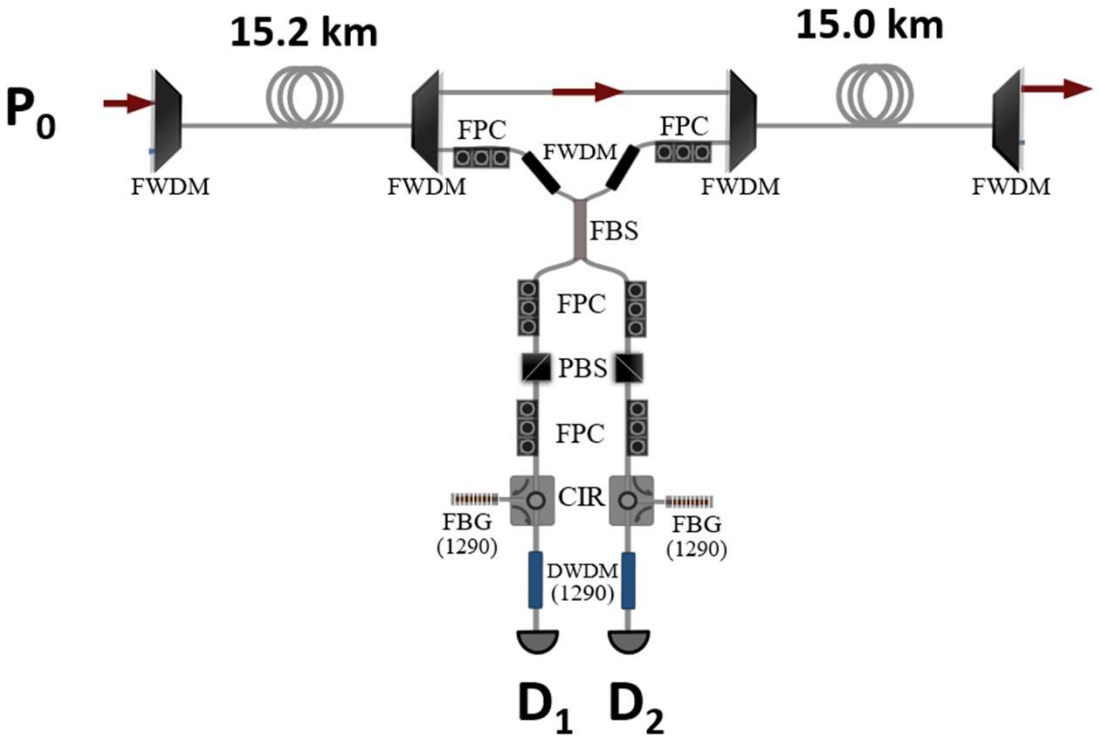
[1] Northwestern University, Evanston, USA. [2] International Center for Advanced Internet Research, Chicago, USA. [3] Ciena Corporation, Hanover, USA. [4] NuCrypt LLC, Park Ridge, USA

ECOC 2023

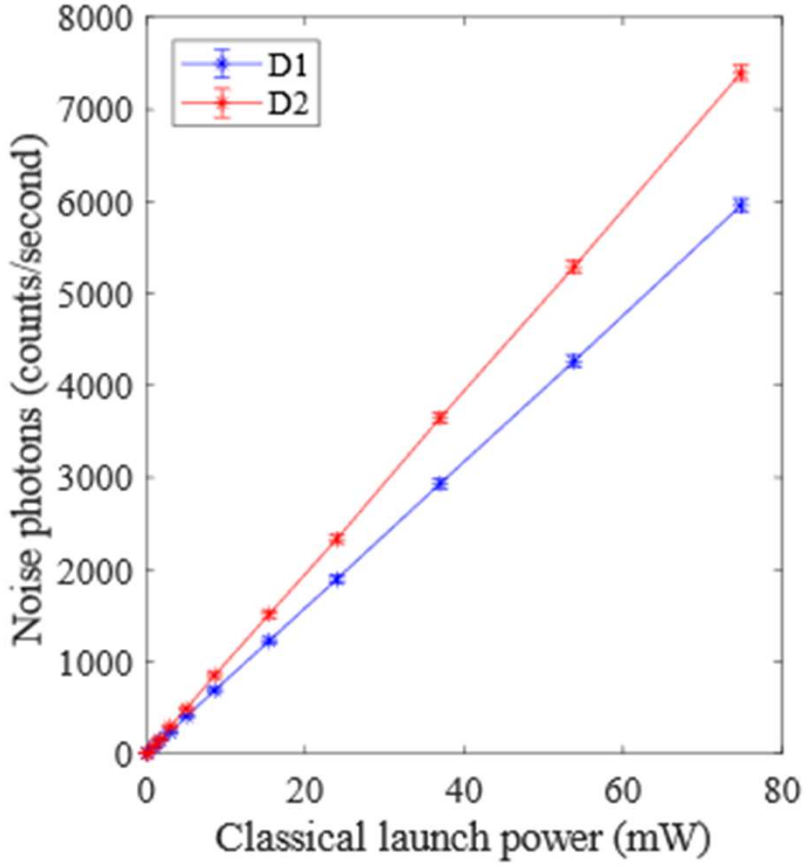
ciena

Results: SpRS Noise Rates vs. C-band Power
30.2-km link (15.2 km + 15.0 km)

Measure Raman Scattering Rates vs. Power without Quantum Signals



mW Powers Give Count Rates on the SNSPD Dark Count Level (~100 cps)

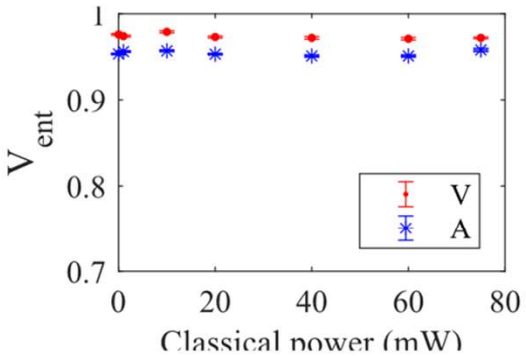


Northwestern
McCORMICK SCHOOL
OF ENGINEERING

Characterizing Entanglement Distribution and Hong-Ou-Mandel Interference over 30.2 km

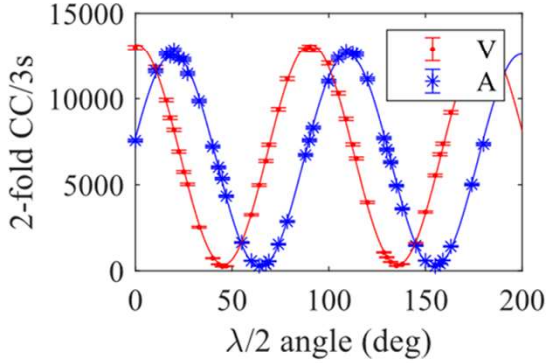
CPCC

Entanglement distribution over 15 km to Charlie



$$V_{\text{ent}} = \frac{(\mathbf{R}_{\max} - \mathbf{R}_{\min})}{(\mathbf{R}_{\max} + \mathbf{R}_{\min})}$$

$$V_V = 97.5 \pm 0.1\%$$
$$V_A = 95.3 \pm 0.2\%$$



Teleportation requires high visibility entanglement distribution and HOM interference

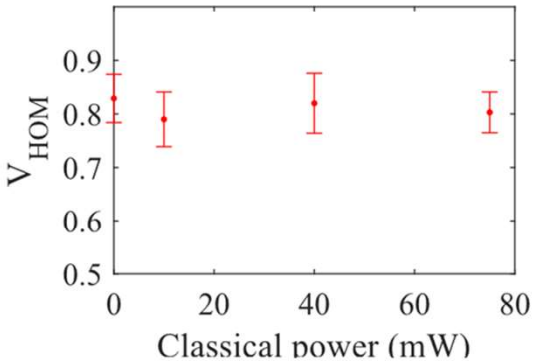
Bob's entanglement distribution quality and HOM interference between Alice+Bob's photons is well preserved with up to 18.7 dBm (74 mW) of C-band power

$P_{\text{classical}}$ = 18.7 dBm

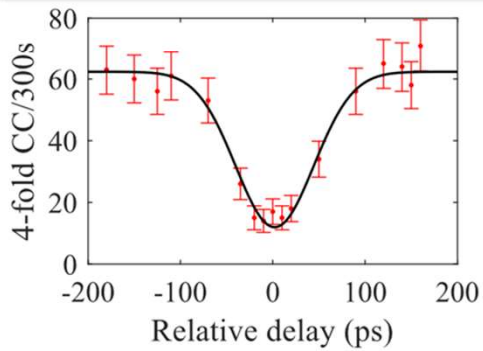
Quantum Teleportation Systems Coexisting with Conventional Classical Communications in Optical Fiber

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]

4-fold HOM interference over 30.2-km



$$V_{\text{HOM}} = \frac{(\mathbf{R}_{\max} - \mathbf{R}_{\min})}{\mathbf{R}_{\max}} = 80.3 \pm 3.8\%$$



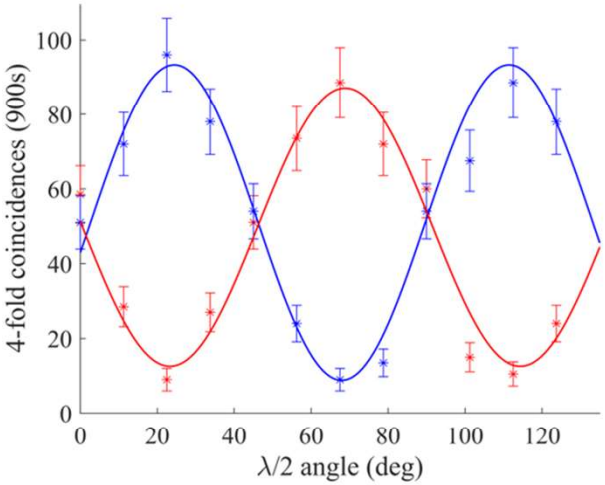
Northwestern
McCORMICK SCHOOL
OF ENGINEERING

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

CPCC

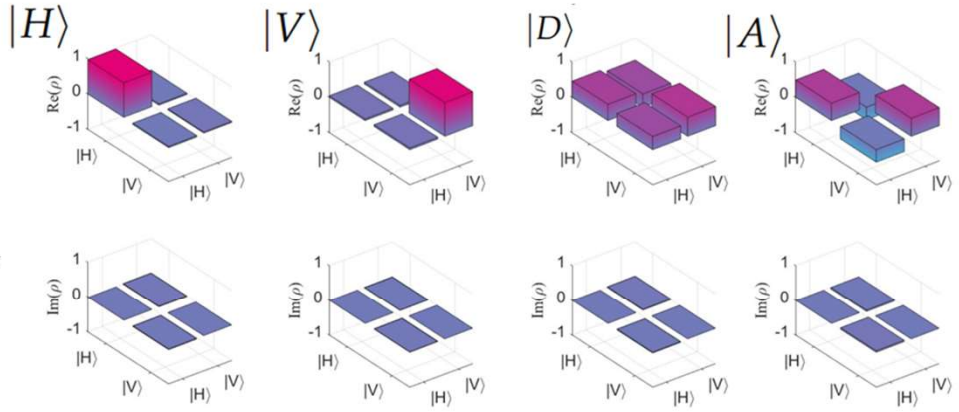
4-fold coincidence fringe as Bob rotates his polarization basis for Alice transmitting:

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



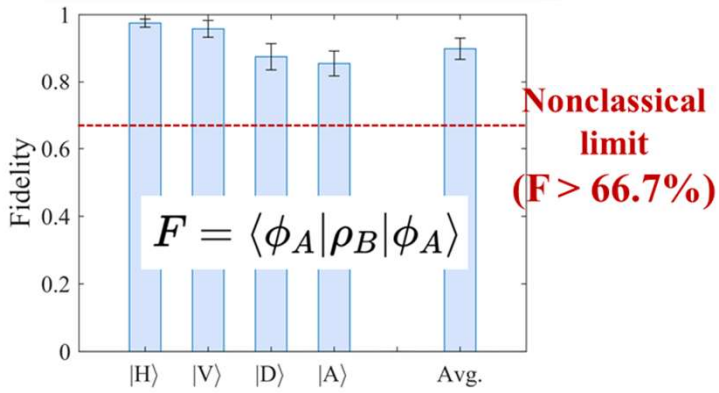
$V_D = 81.3 \pm 5.4\%$
$V_A = 74.7 \pm 4.7\%$

Quantum State Tomography



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

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

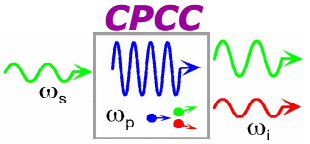


Quantum Teleportation Systems Coexisting with Conventional Classical Communications in Optical Fiber

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

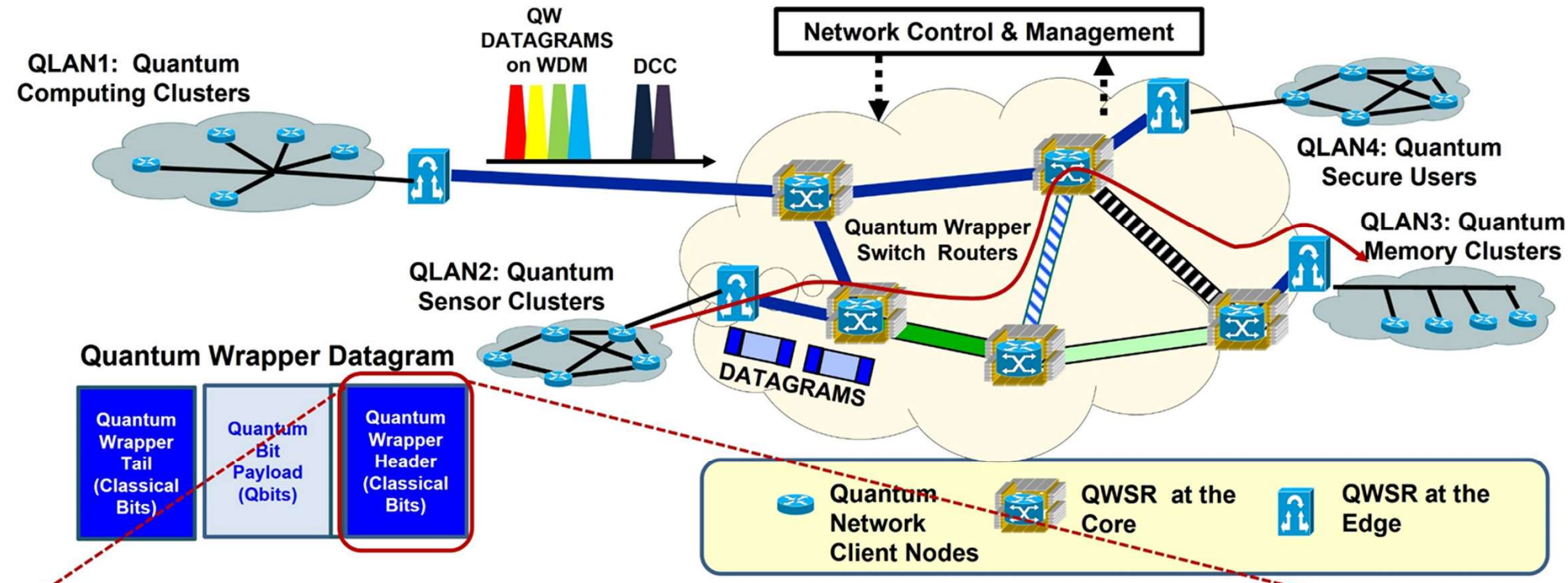


Quantum Wrapper Networking

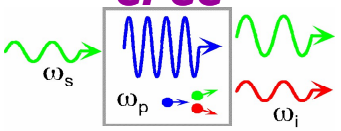
A collaboration with

Prof. Ben Yoo, UC Davis

Quantum Wrapper Networking



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)



Demonstration of Quantum Channel Monitoring via Quantum Wrappers

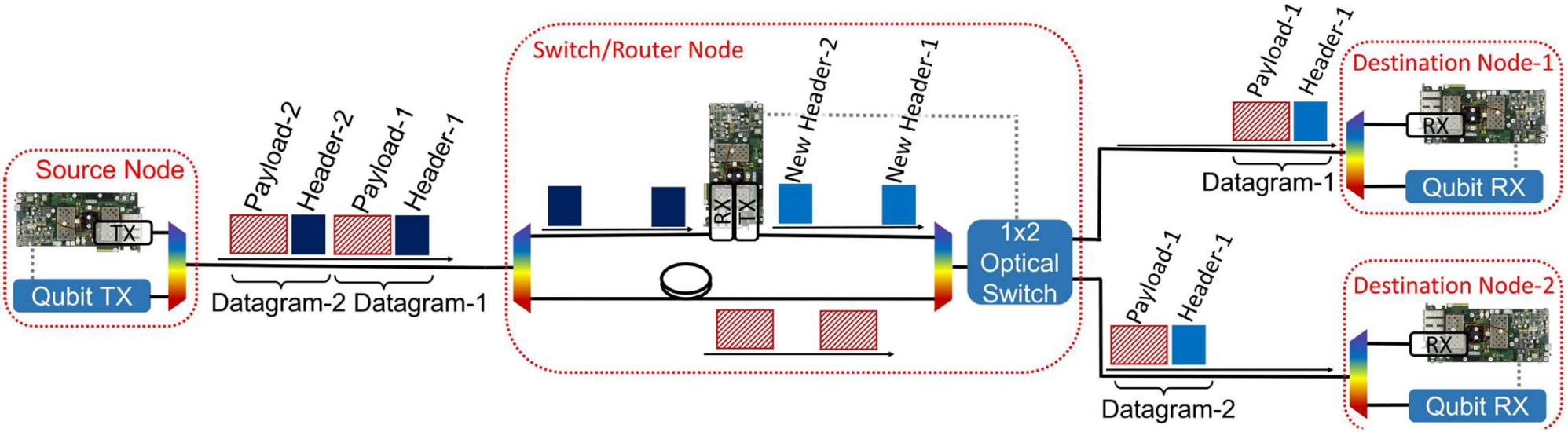
Mehmet Berkay On[1], Sandeep Kumar Singh[1], Gamze Gul[2], Gregory S. Kanter[2], Roberto Proietti[3], Prem Kumar[2] and S. J. Ben Yoo[1]

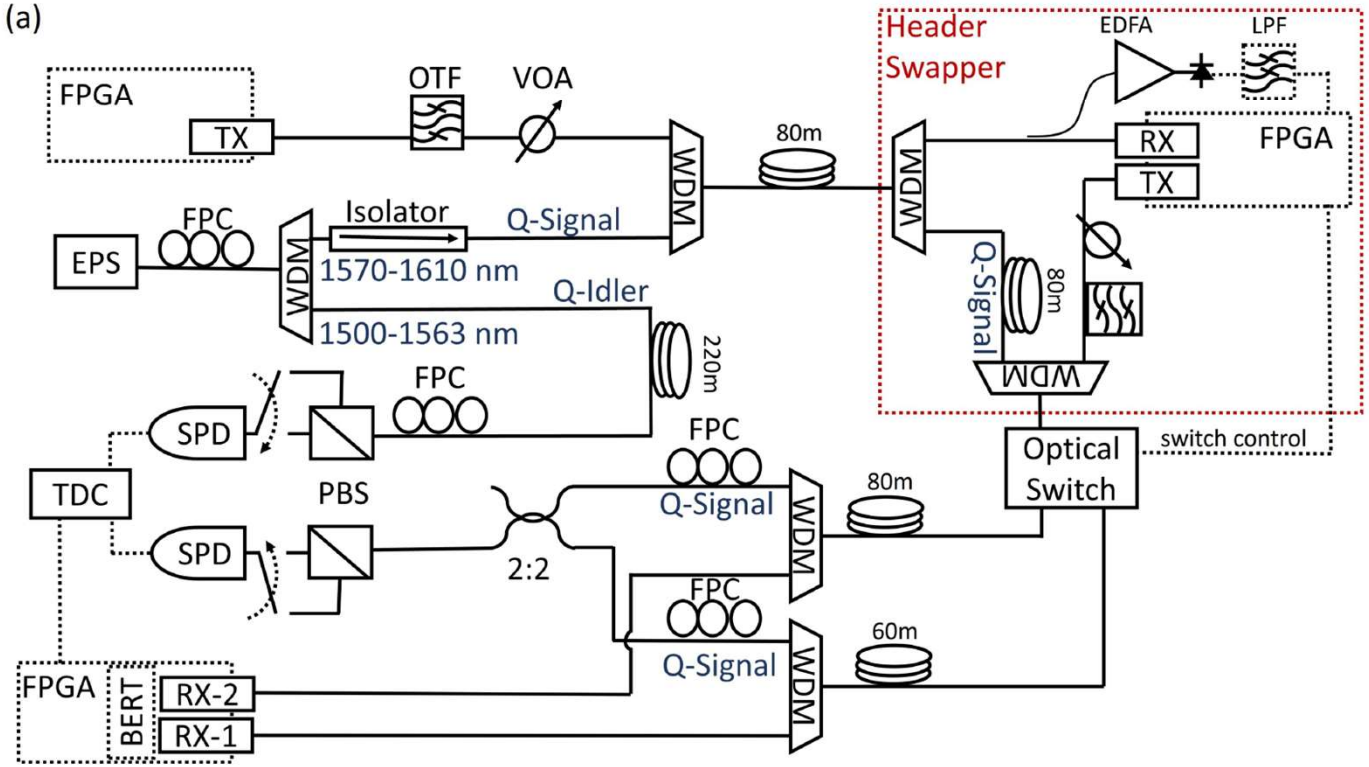
[1]Department of Electrical and Computer Engineering, University of California, Davis, CA 95616 USA
[2]Department of Electrical and Computer Engineering, Northwestern University, Evanston, IL, 60208,USA
[3]Dipartimento di Elettronica e Telecommunicazioni, Politecnico di Torino, 10129, Italy

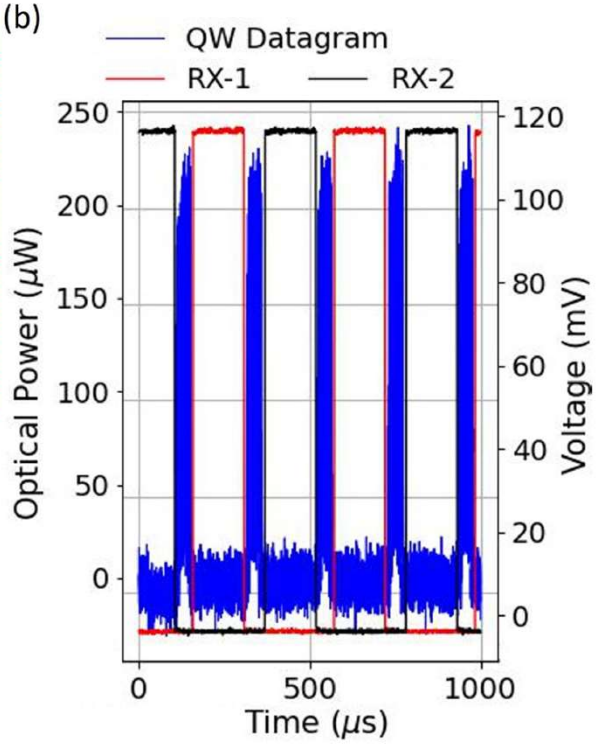
OFC 2023, paper # Tu3H.4

This work is supported by the U.S. DOE, Office of ASCR program under Award Number DE-SC-0022336.

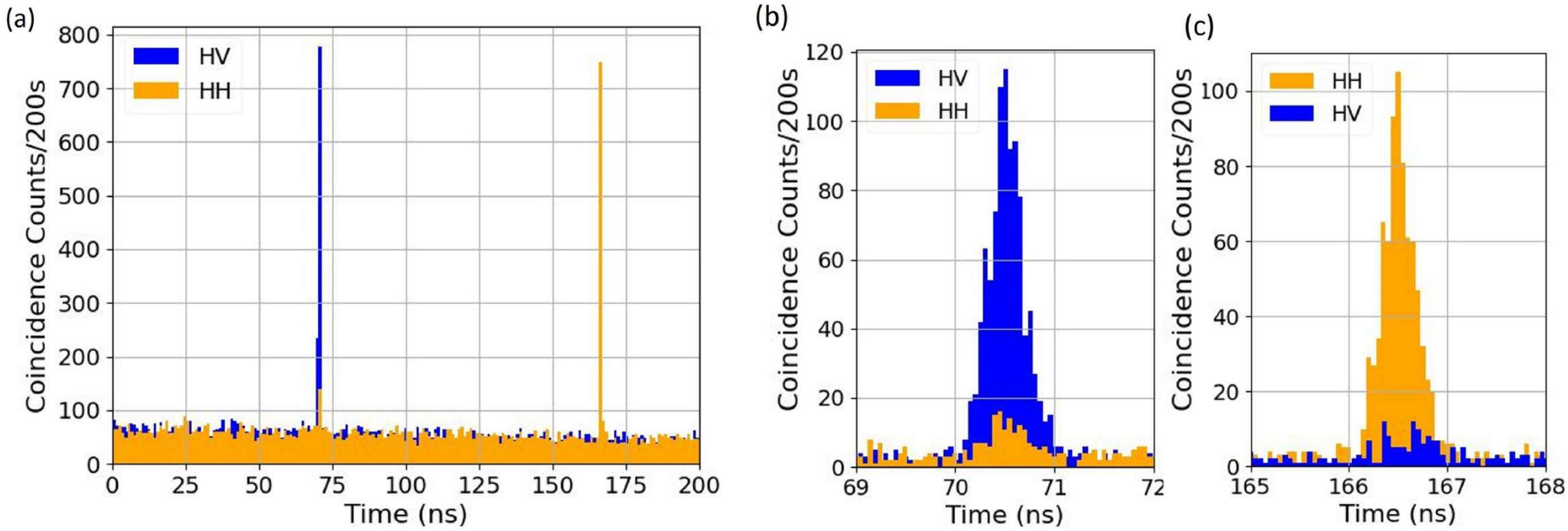
Quantum Packet Switching in Quantum Wrapper Networks (ECOC'23)



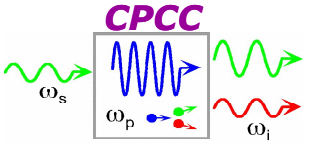




QW Networking: Demonstration of Quantum Packet Switching



Coincidence count histograms with polarization bases of “HH” (“H” idler and “H” signal) and “HV” (“H” idler and “V” signal), (a) bin size 1 ns, (b-c) bin size 50 ps



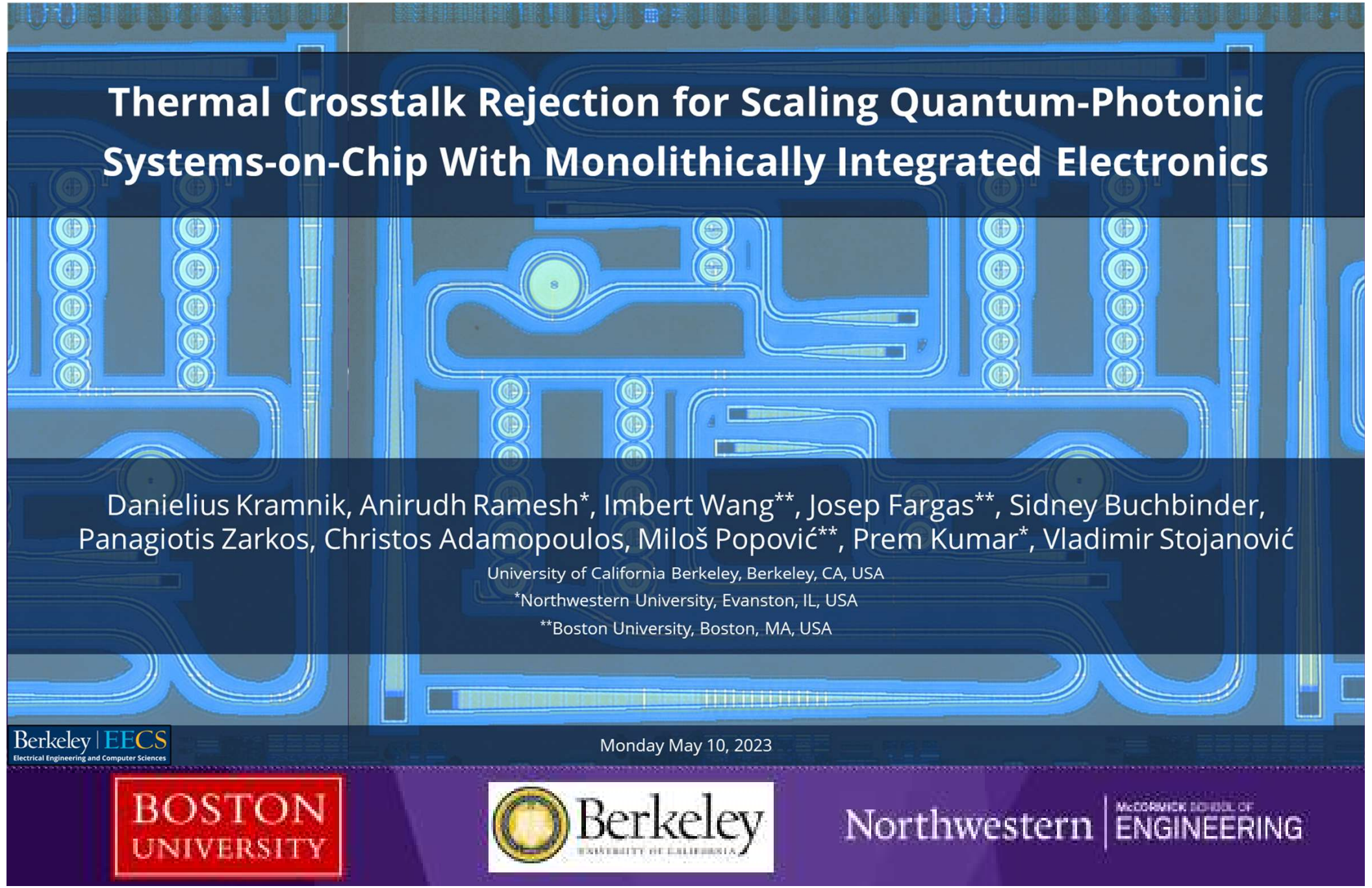
Electronic-Photonic Quantum Integration in Zero-Change CMOS

A collaboration with

Prof. Miloš Popović, Boston University

& Prof. Vladimir Stojanović, UC Berkeley

Electronic-Photonic-Quantum Integration in Zero-Change CMOS



Thermal Crosstalk Rejection for Scaling Quantum-Photonic Systems-on-Chip With Monolithically Integrated Electronics

Danielius Kramnik, Anirudh Ramesh*, Imbert Wang**, Josep Fargas**, Sidney Buchbinder, Panagiotis Zarkos, Christos Adamopoulos, Miloš Popović**, Prem Kumar*, Vladimir Stojanović

University of California Berkeley, Berkeley, CA, USA
*Northwestern University, Evanston, IL, USA
**Boston University, Boston, MA, USA

Berkeley | EECS
Electrical Engineering and Computer Sciences

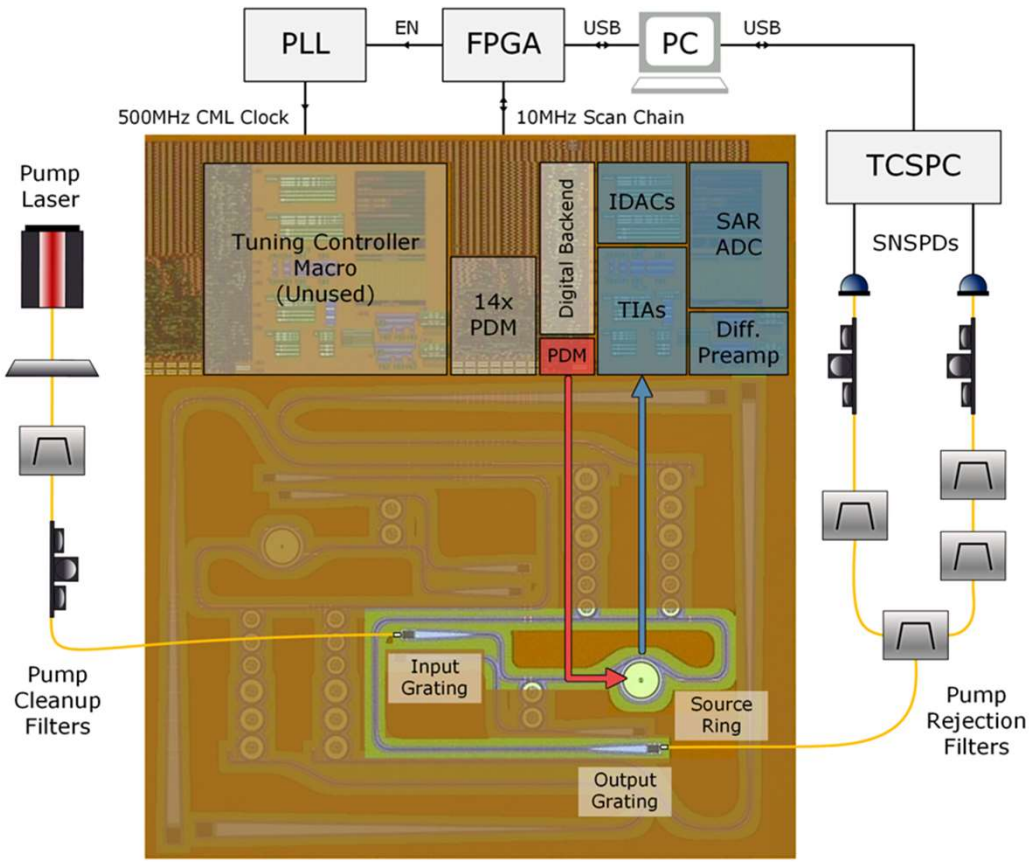
Monday May 10, 2023

BOSTON UNIVERSITY

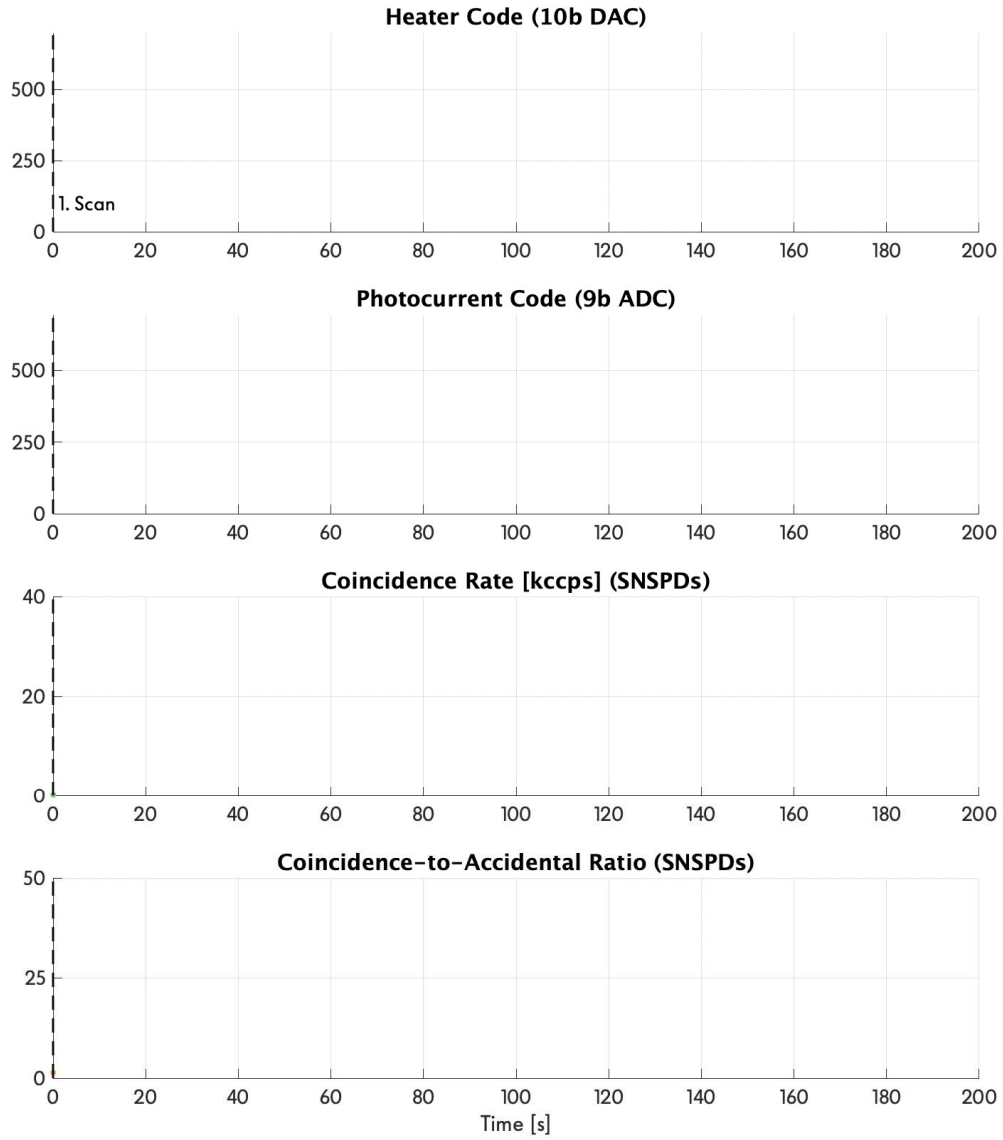
Berkeley
UNIVERSITY OF CALIFORNIA

Northwestern | McCORMICK SCHOOL OF ENGINEERING

Photon-Pair Generation with *In-Situ* Feedback Locking

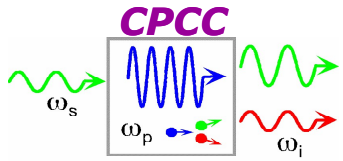


D. Kramnik *et al.* , **"Quantum-Correlated Photon-Pair Source with Integrated Feedback Control in 45nm CMOS"**, IEEE European Solid-State Circuits Conference (2022)



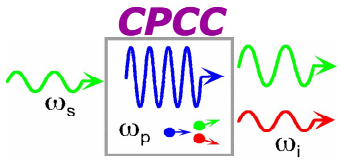
D. Kramnik, A. Ramesh, *et al.*, "**Thermal Crosstalk Rejection for Scaling Quantum-Photonic Systems-on-Chip with Monolithically Integrated Electronics**," presented at CLEO 2023, San Jose, CA, 07–12 May 2023; paper SM3P.2.

In Conclusion…



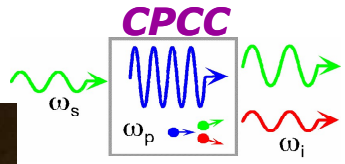
- Quantum networking presents unique engineering challenges that are beginning to be addressed
  - Developed an architecture for fully dynamic and automated quantum network services that utilize existing technologies to demonstrate multi-user, multi-node capabilities at metro scales. Architecture capable 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.

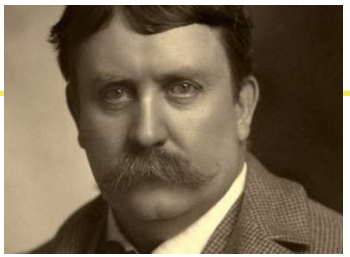
Outlook…



I have only touched the tip of the proverbial iceberg. There is a lot going on in the quantum space at Northwestern, and other institutions in the greater Chicago area. Our Governor J. B. Pritzker is a great fan of the Quantum! He along with City of Chicago and the Cook County have announced big plans for Quantum in the Chicago region.

Make no little plans; they have no magic to stir men's blood (circa 1890)





Daniel Burnham

[Former South Works Site Could Become Quantum Computing Campus By 2027, Officials Say (blockclubchicago.org)](#) July 25, 2024