

# Exploring The Challenges and Opportunities Of Quantum Communications And Networking

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**PI StarLight SDX, Co-PI Chameleon, PI-iGENI, PI-OMNINet**

**11th CEF Networks Workshop 2023**

**Prague, Czech Republic  
April 18-19, 2023**



# Introduction to iCAIR:



Accelerating Leading Edge Innovation and Enhanced Global Communications through Advanced Internet Technologies, in Partnership with the Global Community

- **Creation and Early Implementation of Advanced Networking Technologies - The Next Generation Internet All Optical Networks, Terascale Networks, Networks for Petascale Science**
- **Advanced Applications, Middleware, Large-Scale Infrastructure, NG Optical Networks and Testbeds, Public Policy Studies and Forums Related to NG Networks**
- **Three Major Areas of Activity: a) Basic Research b) Design and Implementation of Prototypes and Large Scale Research Testbeds (Currently ~ 25) c) Operations of Specialized Communication Facilities (e.g., StarLight International/National Communications Exchange Facility)**

# Selected Applications



**GENI**  
www.geni.net



**GLEON**  
www.gleon.org



**USGS EROS**  
www.usgs.gov/centers/eros



**NEON**  
www.neonscience.org



**Open Storage Network**  
www.openstorage.network.org



**OSIRIS**  
www.osris.org



**XSEDE**  
www.xsede.org



**Blue Waters**  
bluewaters.ncsa.illinois.edu



**PRAGMA**  
www.pragma-grid.net



**CENTRA**  
www.globalcentra.org



**OSG**  
www.openscience.grid.org



**GRP**  
theglobalresearchplatform.net/



**PRP**  
pacificresearchplatform.org



**CHASE-CI**  
www.calit2.net/newsroom/article.php?id=2910



**SAGE2**  
sage2.sagecommons.org



**Polar Geospatial Center**  
www.pgc.umn.edu



**IceCube**  
icecube.wisc.edu



**Chameleon**  
www.chameleoncloud.org



**Jetstream**  
www.jetstream-cloud.org



**Genomic Science Program**  
genomicscience.energy.gov



**LSST**  
www.lsst.org



**Pierre Auger Observatory**  
www.auger.org



**Belle II**  
www.belle2.org



**LBNF/DUNE/ProtoDUNE**  
lbnf.fnal.gov



**ISS**  
www.nasa.gov/station



**SKA**  
www.skatelescope.org



**XENON**  
xenon.astro.columbia.edu



**NOVA**  
novaexperiment.fnal.gov



**Virgo**  
www.virgo-gw.eu



**LIGO**  
www.ligo.caltech.edu



**SDSS**  
www.sdss.org



**ALMA**  
www.almaobservatory.org



**LHC**  
home.cern/science/accelerators/large-hadron-collider



**LHCONE**  
twiki.cern.ch/twiki/bin/view/LHCONE/WebHome



**LHCOPN**  
twiki.cern.ch/twiki/bin/view/LHCOPN/WebHome



**IVOA**  
www.ivoa.net

# Next Generation Distributed Environment For Global Science



**GLOBAL RESEARCH PLATFORM**



# Quantum Science Research: A Priority For Many Nations

- **Multiple Interdisciplinary Research Domains**
  - Physics
  - Quantum Science
  - Information Theory
  - Information Science
  - Optimization Theory
  - Materials Science
  - Quantum Components
  - Quantum Computing
  - Quantum Communications
  - Quantum Networking
  - Many, Many Other Topics
- **Undertaken By Many Organizational Cooperative Consortia**
- **World Quantum Day: April 14th — or “4.14” — Rounded 1st 3 Digits of Planck’s Constant, Value That Sets The Quantum Scale**



# Selected NSF Quantum Research Topics

- **Quantum Fundamentals**

- Understanding, Controlling, Minimizing Quantum Decoherence
- Generating, Characterizing, Manipulating Quantum Entangled States
- Characterizing, Verifying, Exploiting Quantum Algorithms
- Discovering, Analyzing, Understanding Fundamental Properties Of Quantum Many-Body States of Matter With Exploitable Properties, e.g., Control of Many Degrees of Freedom Using High Resolution Light-Matter Interactions

- **Quantum Metrology and Control (Enhancing Measure, Modeling, Control, And Exploiting Quantum Phenomena In Single and Multi-Particle Systems)**

- Utilizing Quantum Superposition of States, Entanglement and Quantum Squeezing in Metrology;
- Characterizing, Minimizing Noise, Developing, Testing, Implementing Quantum Error Corrections
- Developing Efficient High-Resolution Methods to Generate, Control, Manipulate, Read, and Write Qubits.

- **Designing Quantum Systems - Stable, Controllable, Scalable, Error-Free, Low-Dissipation Platforms Many Types of States.**

- Interfacing Quantum & Classical Circuit & Computing Devices For Monolithic or Hybrid Systems
- Developing Quantum Circuits, System Designs and Programming Paradigms for Quantum Sensing, Computing and Communication; Developing, Validating Platforms for Quantum testbeds for Rapid Prototyping, System Characterization, Optimization; System Integration Techniques for Combining Quantum and Classical Platforms;
- Generating, Scalable Systems of Quantum Objects in Superposition States, Tailored for Specific Use, While Enabling Information Exchange Among Different Types of Such Objects and Across Quantum-Classical Boundaries

# Quantum Communications And Networks: Motivation

- **Quantum Enables Many New Applications**
  - Security – e.g., Quantum Key Distribution (QKD), Highly Secure Information Transmission, Quantum Encryption
  - Quantum Sensors
  - Quantum – e.g., Precise Clocks
  - New Applications Derived From Unique Properties (e.g., Superposition) And Novel Quantum Devices
  - Communications Among Quantum Computers, e.g., To Address Complex Computational Science Problems Through Distributed Quantum Environments (iCAIR's Quantum Research Focus)



# Complexity Of Challenges Requires Consortia

- **Northwestern University Established INQUIRE (Initiative at Northwestern for Quantum Information Research and Engineering), For Quantum Science Research**
- **This Initiative Participates in the Chicago Quantum Exchange and The Illinois Express Quantum Network, which includes the U.S. Department of Energy's Argonne National Laboratory, Fermi National Accelerator Laboratory, Multiple Research Universities, and Several Corporations.**
- **These National Laboratories, Northwestern University, Including the International Center for Advanced Internet Research (iCAIR), the StarLight International/National Communications Exchange Facility Consortium, the Metropolitan Research and Education Network (MREN), the Illinois Quantum Information Science and Technology Center (IQUIST) at the University of Illinois at Urbana-Champaign, And Other Research Partners, Including Internationally, Are Collaborating On This initiative.**





# A Few Terms

- Quantum Computers Utilize Several Attributes of Quantum States, Including:
- Superposition: A State Consisting Of a Sum Of Two Or More States
- Interference: Influencing Qubit Measurement To Result In One Or More Specified States
- Quantum/Photonic Entanglement (Einstein's "Spooky Action At a Distance"): Fundamental Quantum Mechanic Effect – Physical Properties Of Interlinked Particles Can Have Perfect Correlations, Even When Separated By Large Distances

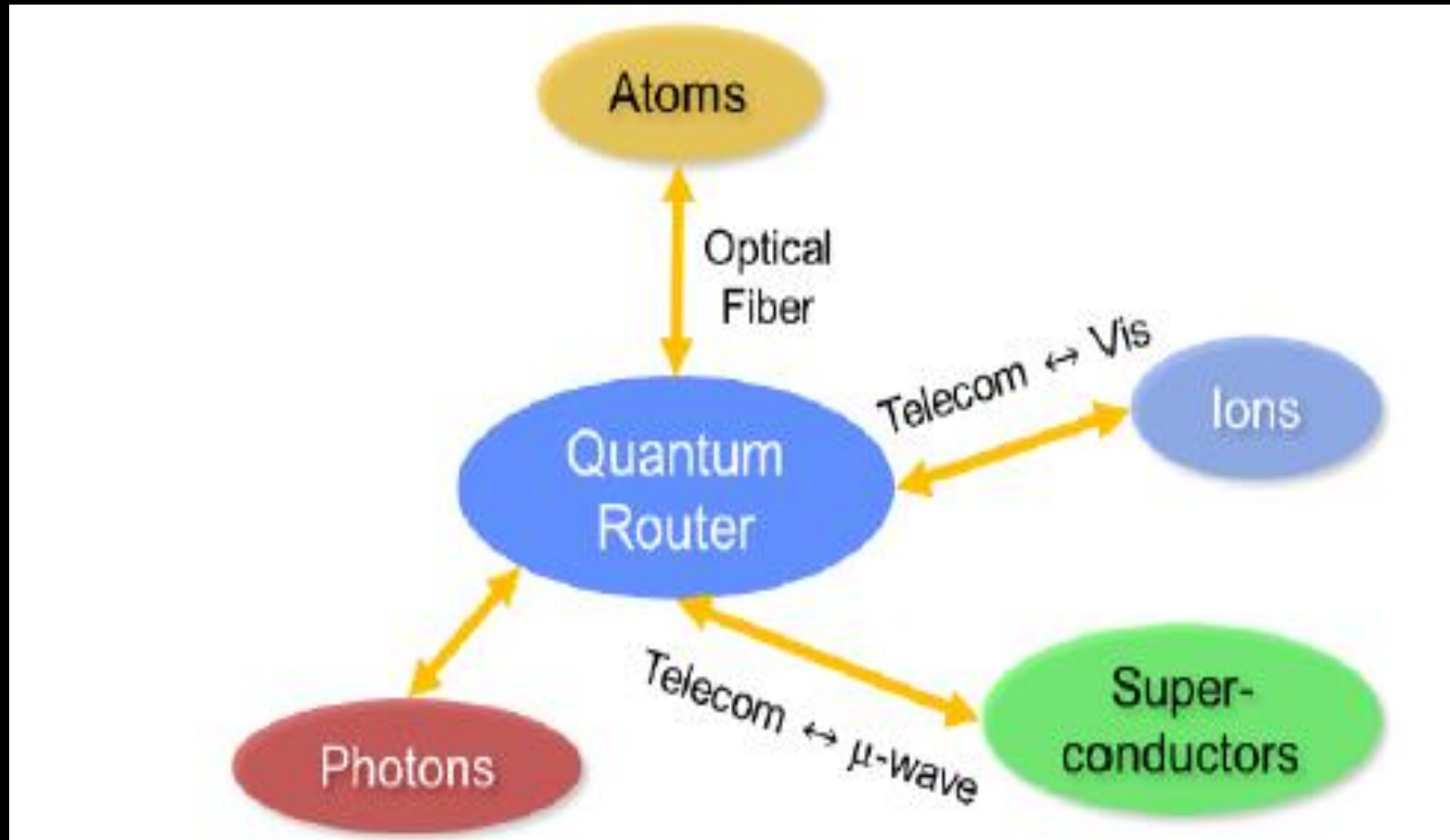


# A Few More Terms

- **Qubit, Quantum Bit:** Analog of Digital Bit, A Unit Of Information Represented By The State Of An Atom, Photon, Ion, Electron, Superconducting Circuits, Etc (e.g., Spin, Polarization, Position et al) That Can Represent Multiple Values Simultaneously, Often Described As A Two-State System (e.g., Can Be Both 1 and ) vs Only the 1 or 0 Of Binary Digits)
- **Transduction:** - High Fidelity Transfer Of A Quantum State Among Domains, e.g., Converting Quantum Signals Among Different Modalities, Media Frequencies, Functional Devices
- **Quantum Teleportation:** Transferring Quantum Information From One Place To Another (Paths For “Flying Qubits”)
- **Coherence/Decoherence:** *Quantum States Are Extremely Fragile, Challenging To Communicate While Maintaining High Fidelity State*



# Quantum Transduction



# Quantum Network Layers

- **Quantum Service Layer**
  - Quantum Entanglement Discovery And Distribution Service: e.g., Entangled Photonic Generation, Management, Distribution
- **Quantum Networking Layer**
  - SDN Control Functions, e.g., Wavelength Routing, Wavelength Assignment, Path Topology Creation Among Quantum Nodes, Related Devices
- **Quantum Link Layer**
  - Protocol Layer Manages Quantum signals and Messages Transmitted Through Quantum Channels Among Q-nodes, Monitors Quantum Link Status
- **Quantum Physical Layer**
  - Physical Connectivity (e.g., Optical Fiber )/Communication Among Quantum Nodes, Determines Quantum Channel Frequencies, Signal Rates, Photon Pulses Used For Quantum Signals et al



# Example Issues In Quantum Communications & Networking

- Designing Specialized Architecture, e.g., Customized For Applications
- Delineating Quantum “Services”
- Quantum Information Distribution, Specialized Carriers (e.g., Qubits, Entangled Photons)
- Determining What Functions Placed At What Level With What Components
- Topologies, Algorithms, Interfaces and Protocols? (No “Quantum TCP or “Quantum IP” Exist)
- Quantum Memory, Switching/Routing
- *Because No Repeaters Exist Yet, Fiber Distances Are Limited (Rate Declines Exponentially With Photon Transmission Probability – 150-200 Km Max) –Line of Site (e.g., Satellite Quantum Communications Extend Distances*
- Quantum Network Management, Control, And Data Planes
- Space vs Time Domains
- Integration With Classical Networks
- Quantum Measurements, Quantum Error Correction
- Fiber Types e.g., SMF-28 vs Hollow Core, Impedances, Wavelengths (Lightpaths) vs Dedicated Fiber, db Loss, etc.

# Qubit Transmission

- **Photons Require Exceptionally High Fidelity Transmission – From Source To Destination**
- **When They Arrive At Their Target, The Quality Of Their Entangled State Should Be Perfect**
- **One Challenge: Implementing A High Quality Spectrally Un-Entangled Source**
- **Goal: Qubits Entangled With A Single Degree of Freedom**
- **Multiple Degrees of Freedom Diminish Hong-Ou-Mandel Interference (H-O-M Effect)**



# Transitioning Qnets From Concepts And Lab Experiments To Field Trials

- Research in Quantum Communications and Networking Requires Real World Testbeds Supporting Empirical Experiments
- Currently, A Distance Limitation Exists On Communicating High Fidelity Qubits Over Fiber (No Quantum Repeaters)
- Consequently, Various Metro Scale Quantum Networking Testbeds Have Been Created
- Previously, iCAIR developed a Dedicated Fiber Quantum Testbed That Supported Experimentation In Photonic Entanglement and Quantum Key Distribution.
- With Consortium Partners, iCAIR Is Participating Design And Development Metro Scale Quantum Networking Testbeds, Particularly To Interconnect Quantum Computers, Eventually Quantum Clouds
- A Potential Exists For Extending These Testbeds To International Sites Via Satellite (Line-of-Sight Optics), Eventually “Quantum Repeaters”

# Quantum Networking Testbed Building Blocks

- **Advanced Networking And Exchange Facilities**
- **Architecture (Defining QNode Capabilities, QNet Topology Discovery, Path And Wavelength Assignment, Clock Distribution, Entanglement Distribution Protocols)**
- **Heterogeneous Components**
- **High Quality Dedicated Fiber**
- **Management And Control Planes Based On Classical Networking (Software Defined Networking Techniques)**
- **Interfaces, Protocols, Algorithms**
- **Low dB Loss Optical Switches**
- **Quantum Memories As Proxies For Quantum Computers**
- **Measurement ↔ Management Integrations**





# Polatis All-Optical Switch

Achieve More with Optical Switching™

DATA SHEET

**HUBER+SUHNER**  
Polatis

**SERIES 6000i**  
Instrument  
Optical Matrix Switch

**SINGLE MODE INSTRUMENT OPTICAL SWITCH FROM 4x4 TO 192x192 PORTS**



Series 6000 Ultra 32x32 Optical Switch



Series 6000 192x192 Optical Switch

The Polatis Series 6000i Instrument optical switch is a high-performance, fully non-blocking all-optical matrix switch available in sizes from 4x4 up to 192x192. It is designed to meet the highest performance needs of the most demanding test and measurement applications with exceptionally low optical loss, superior connection stability and repeatability in a compact form factor. With support of Software-Defined Networks (SDNs) via embedded OpenFlow, NETCONF and RESTCONF control interfaces, the Series 6000i interfaces directly with cutting edge cloud-based network and infrastructure testing applications. The Series 6000i is based on Polatis' patented DirectLight® optical switching technology that has been proven in the most challenging defense, data center and telecom applications and is exclusively used by major network equipment manufacturers to automate testing of optical components and subsystems.

**KEY FEATURES**

- Non-blocking matrix switch sizes from 4x4 to 192x192
- Ultra-low insertion loss and superior optical specifications
- Exceptional optical stability and repeatability
- Dark fiber all-band single mode connectivity
- Fully bidirectional optics
- Available in NxN, MxN single-sided and customer configurable (NxOC) any-to-any port configurations
- Protocol and bit-rate agnostic up to 400Gbs and beyond
- Optional Optical Power Monitoring (OPMs) with user configurable optical power alarms
- Optional Variable Optical Attenuation (VOAs) on every switch connection
- Programmable port shutter for fiber break simulation
- SDN enabled with OpenFlow, NETCONF and RESTCONF command interfaces
- Configurable interface options with SNMP, TLI and SCPI control languages
- Built-in user-friendly web GUI
- High reliability distributed architecture
- High density switching in a compact chassis
- Eco-friendly energy efficiency

**DIRECTLIGHT TECHNOLOGY**

The Series 6000i 4x4 to 192x192 switch leverages Polatis' patented, highly reliable piezoelectric DirectLight beam-steering technology that sets the industry standard for lowest optical loss and highest optical performance. Polatis' beam-steering technology can be switched without light being present on the fiber. This allows operators to pre-provision paths as well as switch intermittent and variable-power test signals test over lit or dark fiber. The Polatis DirectLight technology can also switch bi-directional optical test signals for PON, FTTH, and other types of transmission systems.

**SDN ENABLED WITH USER FRIENDLY INTERFACES**

Polatis offers a full complement of Software Defined (SDN) interfaces including OpenFlow, NETCONF and RESTCONF. Optical switching with SDN allows infrastructure vendors and system test operators to dynamically and cost effectively setup, monitor and operate cloud-based manufacturing and network test configurations. Polatis also works closely with leading SDN companies and research organizations to provide leading edge SDN solutions. Polatis also offers traditional SNMP, TLI, GPIB and SCPI command languages that allow for seamless integration with test equipment controller systems. Each switch also has a user-friendly secure web browser GUI interface that can be used to provision, monitor and control the switch and the switch software can be easily upgraded in the field without affecting in-service switch operations.

**FLEXIBLE SWITCH MATRIX SIZE OPTIONS**

The Series 6000i switch is available in symmetric (NxN), asymmetric (MxN) and a single-sided (NxOC) customer configurable switch with any-to-any port connectivity. Matrix sizes from 4x4 to 192x192 are available allowing designers to select the optimum size for each application. Polatis offers three different size versions of the Series 6000i. The 4x4 to 32x32 high-performance 6000i-Ultra, with under 1.0dB max loss and superior stability and repeatability, is designed for the most demanding applications and fits in a compact 1RU size. The 36x36 to 48x48 6000i-Lite, with under 1.9dB max loss, is designed for applications that need larger matrix sizes while still maintaining instrument grade specifications.

**OPTIONAL POWER MONITORS AND OPTICAL TAPS**

Polatis switches can be customized to incorporate a wide variety of passive and active components to suit individual customer testing needs. Polatis Series 6000i switches include options for integrated Optical Power Monitors (OPMs) and optical taps on every connection. The power monitoring can also be used to provide Variable Optical Attenuation (VOA) on every connection. The power monitors and VOA can be used together to adjust signal test levels to test dynamic range, protect sensitive test equipment along with many other testing applications.

Rev. 6000-010217-001

## Polatis:

- SDN Enabled
- Minimum Insertion dB Loss
- Single Mode

# Polatis Optical Switch Specifications

<b>Performance Parameters</b>	<b>Polatis 6000i-Ultra Up to 32x32<sup>1</sup> and 64xCC</b>	<b>6000i-Lite and 6000i Up to 192x192<sup>1</sup> and 192xCC</b>
Typical Insertion Loss <sup>2</sup>	0.5dB	0.9dB
Maximum Insertion Loss <sup>2</sup>	1.0dB	1.9dB
Maximum Insertion Loss with single OPM <sup>2</sup>	1.3dB	2.2dB
Loss Repeatability <sup>3</sup>	+/-0.05dB	+/-0.1dB
Connection Stability <sup>3</sup>	+/-0.05dB	+/-0.1dB
<b>For All Switch Sizes</b>		
Operating Wavelength Range	1260-1675nm	
Return Loss (with APC connectors)	>50dB	
Max Switching Time	25ms	
Crosstalk	<-55dB	
Polarization Dependent Loss (PDL)	<0.1dB (C+L Bands) <0.3dB with optional OPM (1510-1610nm)	
Dark Fiber Switching	Yes	
Bi-Direction Optics	Yes	
Wavelength Dependent Loss (WDL)	<0.3 dB (C+L Band)	
Optional Optical Power Monitoring (OPM)	Calibrated wavelength range 1290-1330nm and 1450-1640nm Dynamic range -40dBm to +24dBm Accuracy +/-0.5dBm	
Maximum Optical Input Power	+27dBm	
Switch Lifetime	>10 <sup>9</sup> Cycles	
Operating Temperature	+10°C to +40°C <85% RH non-condensing	
Storage Temperature	-40°C to +70°C <40% RH non-condensing	



# StarLight – “By Researchers For Researchers”

StarLight: Experimental Optical Infrastructure/**Proving Ground For Next Gen Network Services**  
Optimized for High Performance Data Intensive Science  
Multiple 100 Gbps  
(80+ Paths & 16 400 Gbps Paths)  
StarWave  
100 G Exchange  
World's Most Advanced Exchange  
Multiple First of a Kind  
Services and Capabilities



View from StarLight

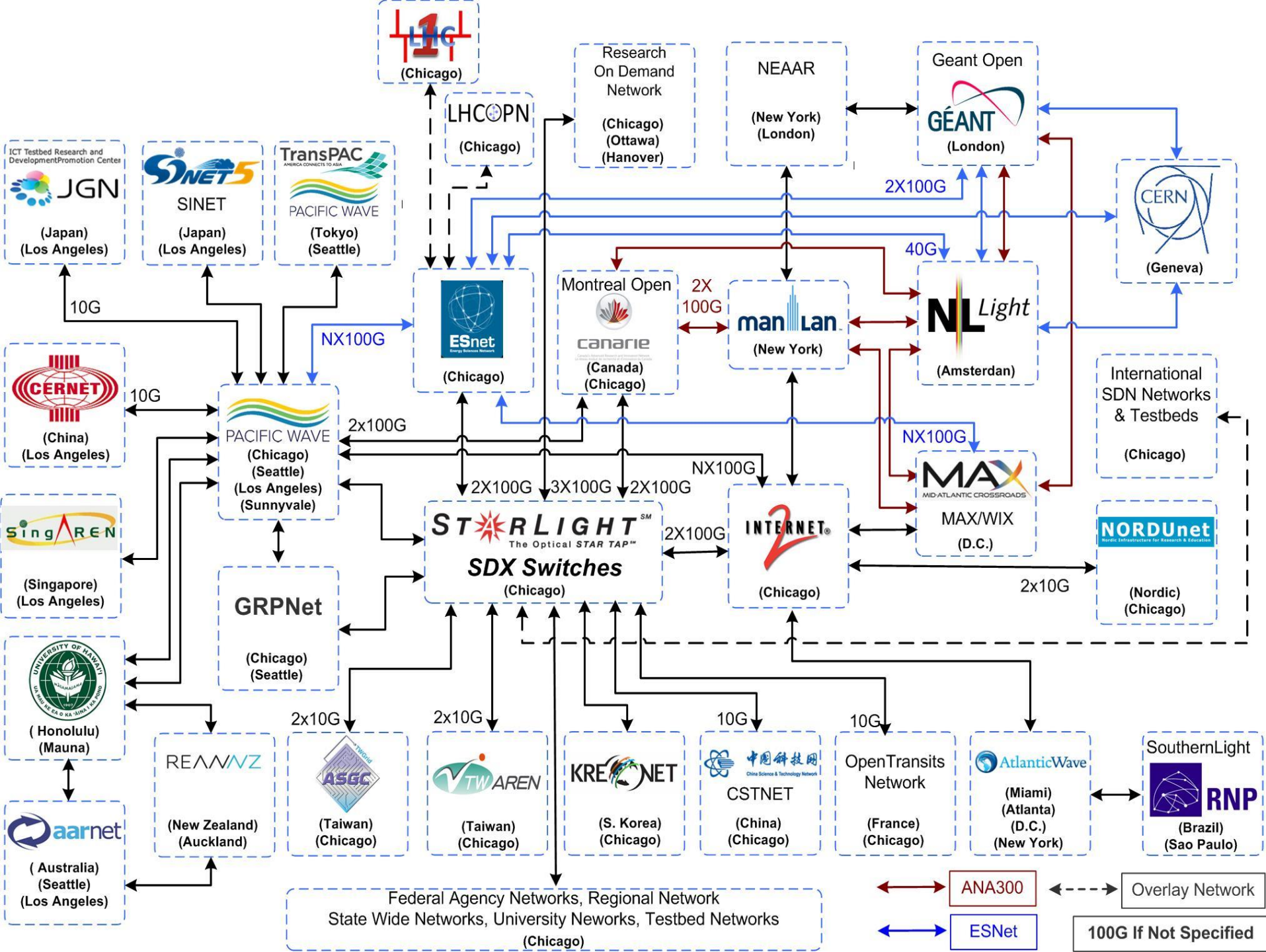


Abbott Hall, Northwestern University's Chicago Campus

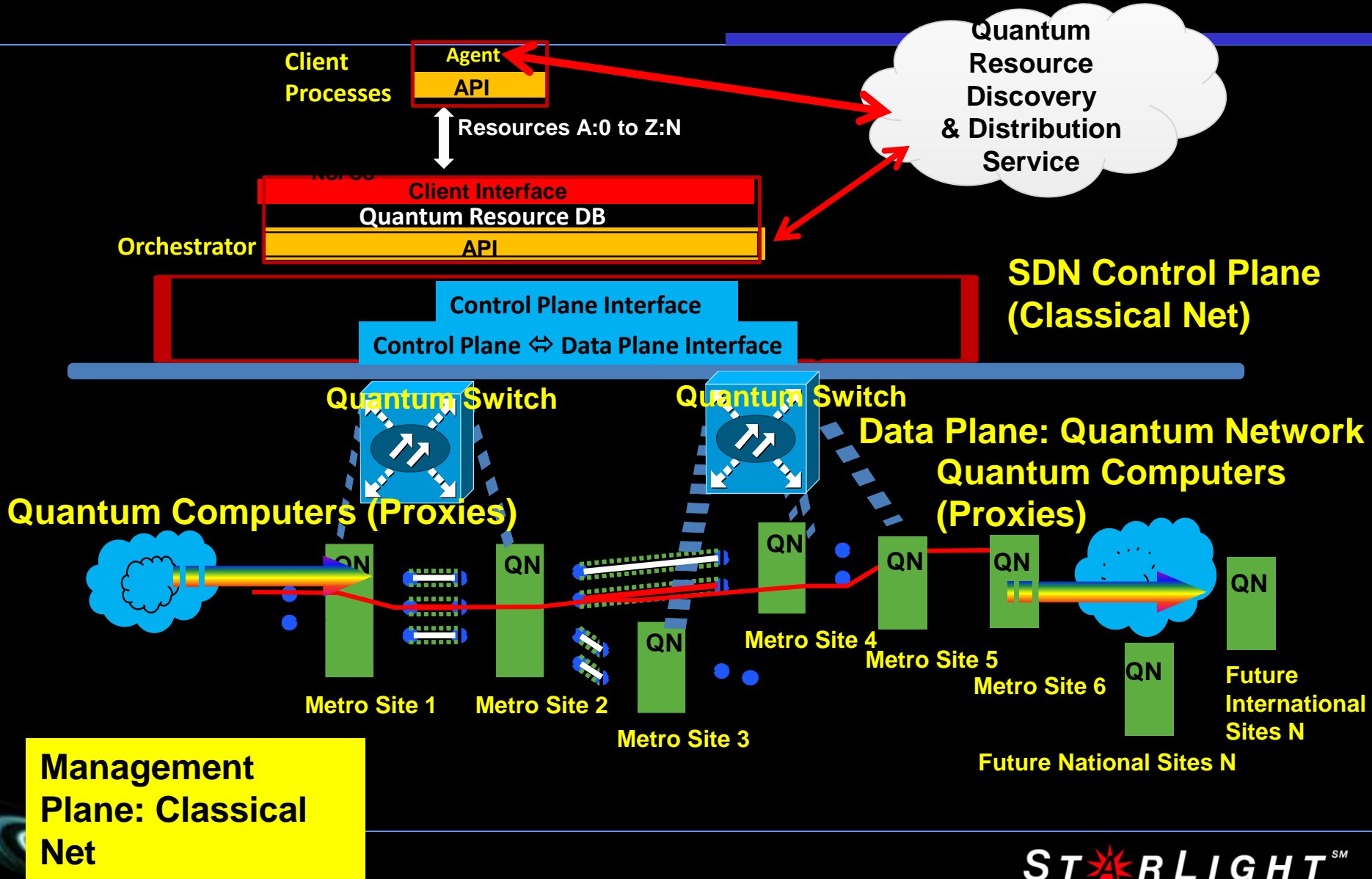


Transitioning To 400 Gbps, 800 Gbps, Tbps

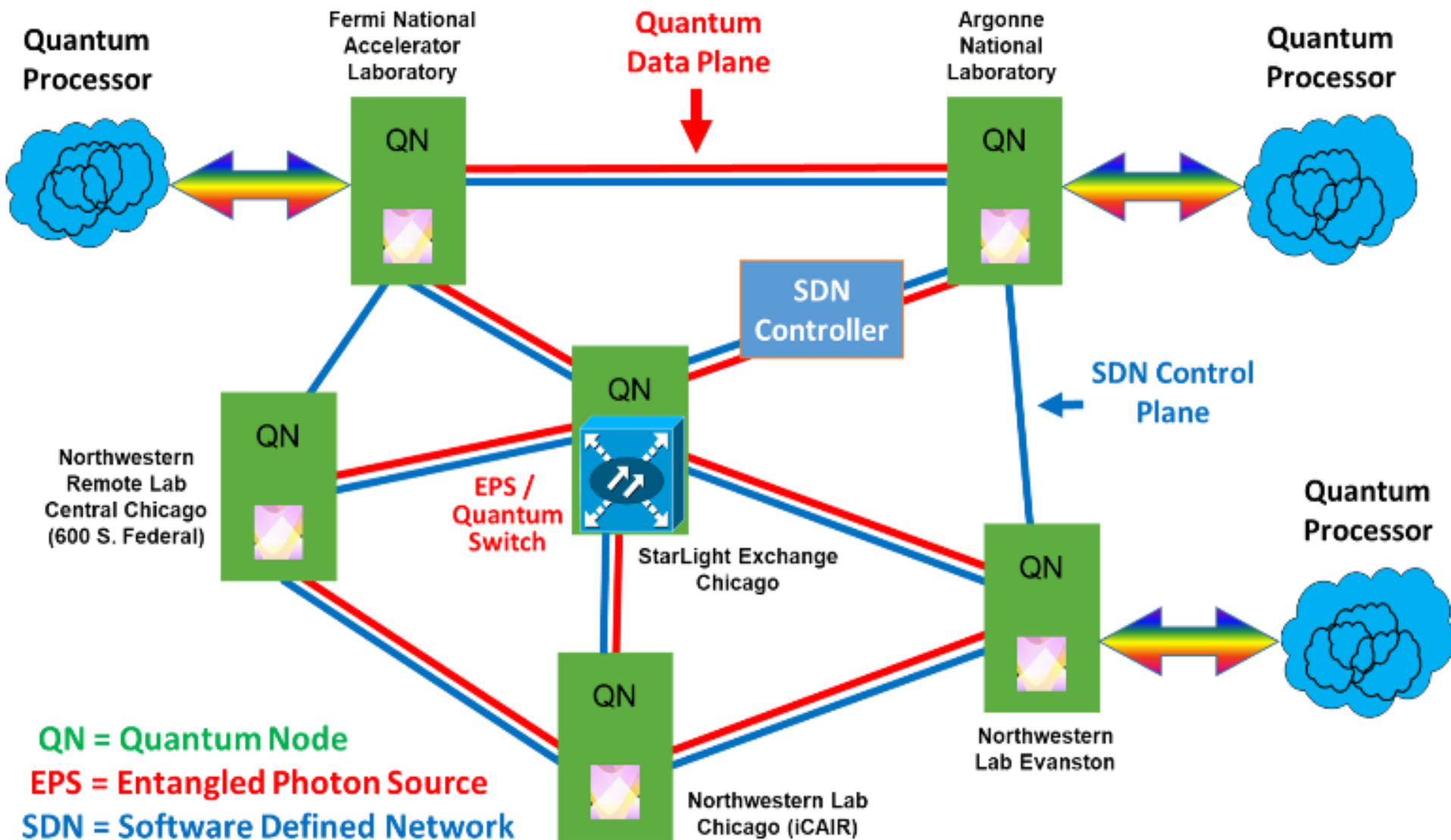
STARLIGHT<sup>SM</sup>



# Quantum Testbed Design Architecture



# IEQnet Quantum Networking Testbed



# Argonne National Laboratory QILab Testbed Architecture

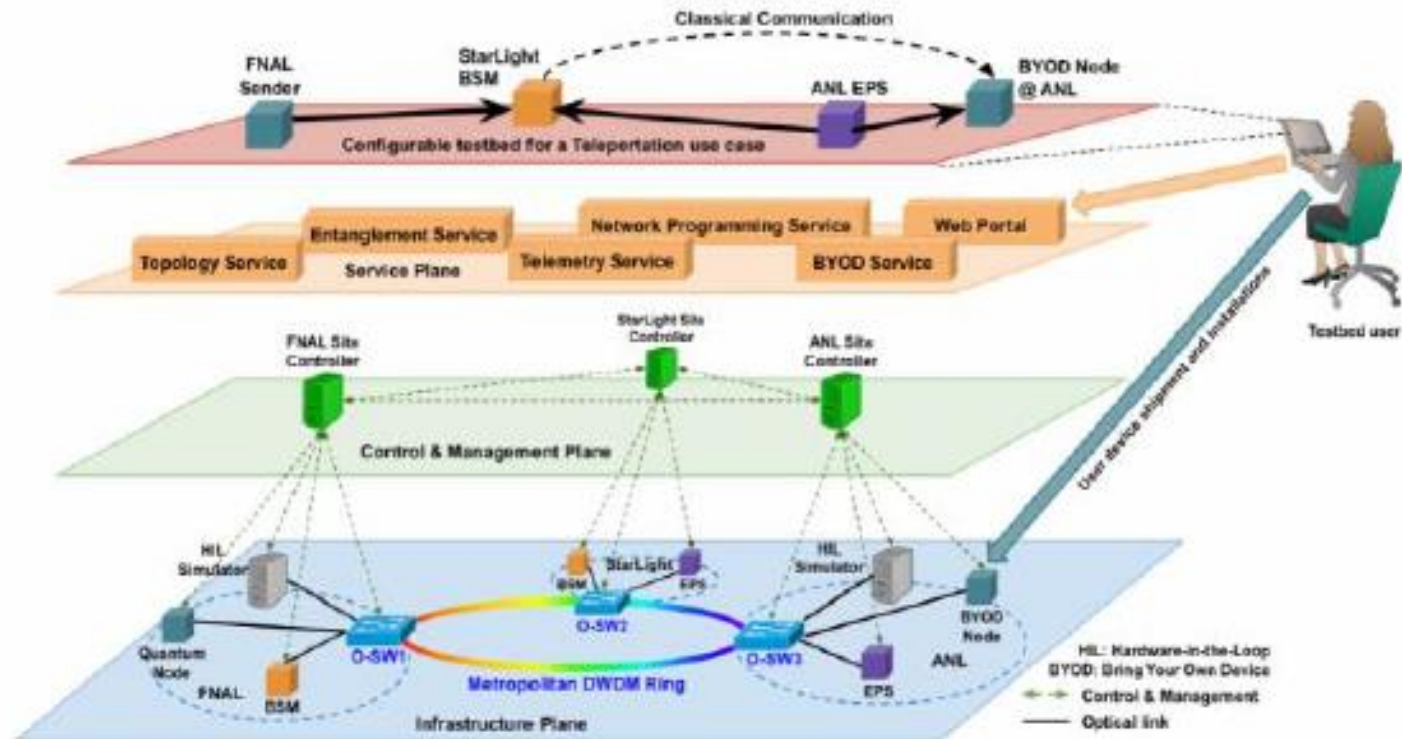
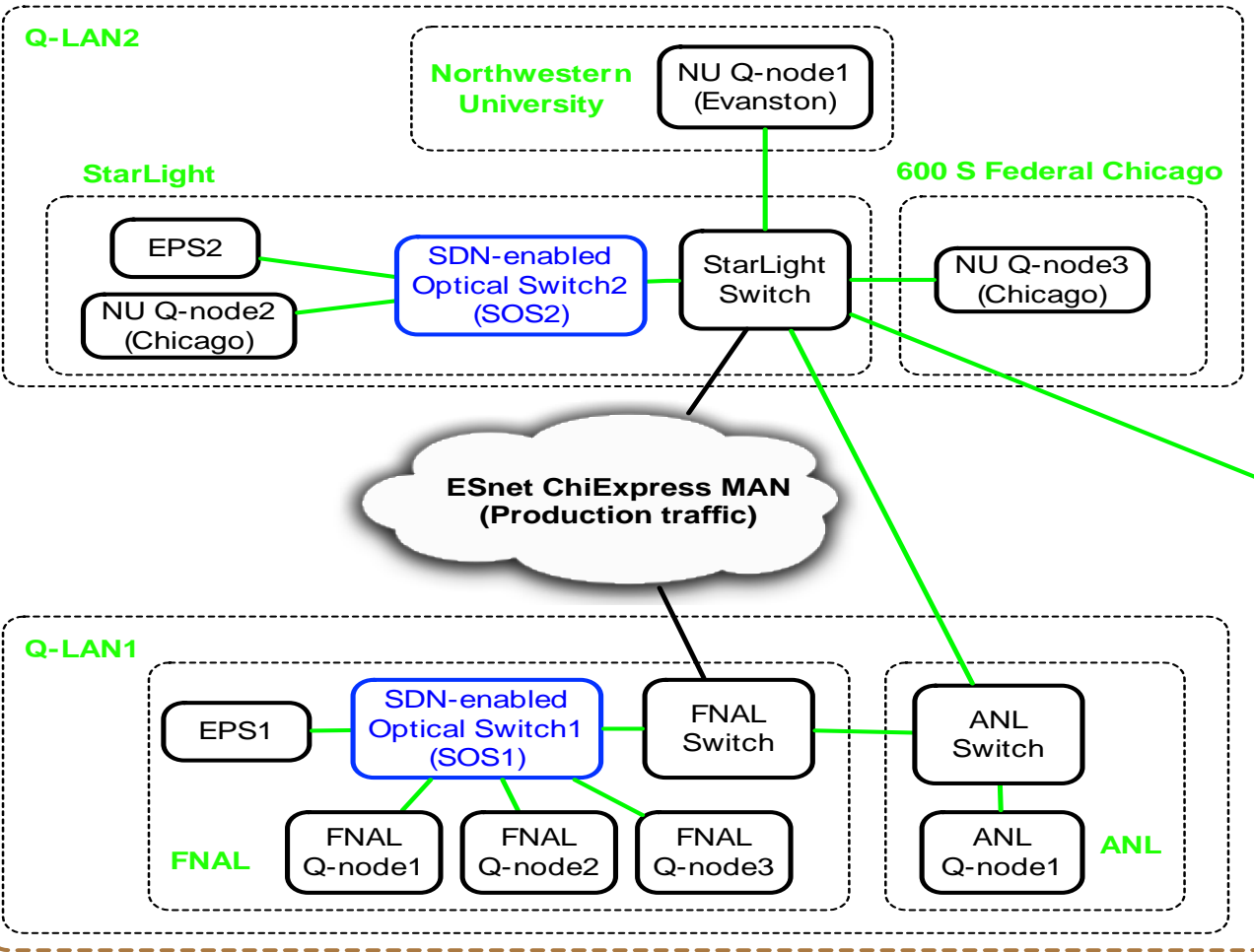


Figure 1: QILab architecture, showing an example reconfigurable testbed (top) using capabilities from the reconfigurable and adaptable service, control/management, and infrastructure planes.

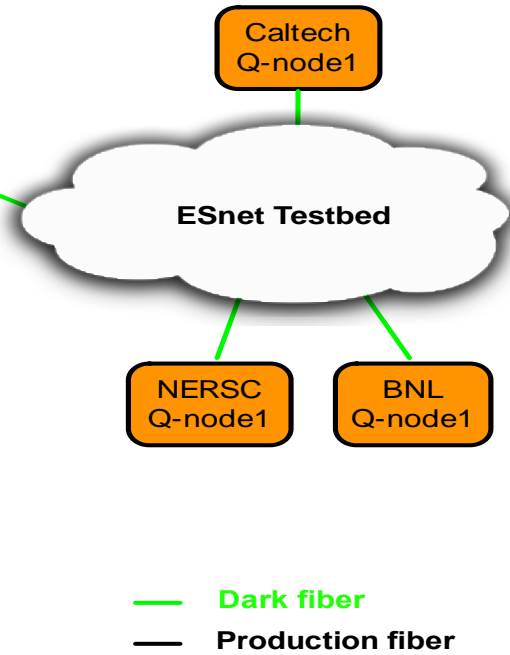
# Illinois Express Quantum Network

## Q-MAN: Illinois-Express Quantum Network (IEQNET)



## Q-WAN

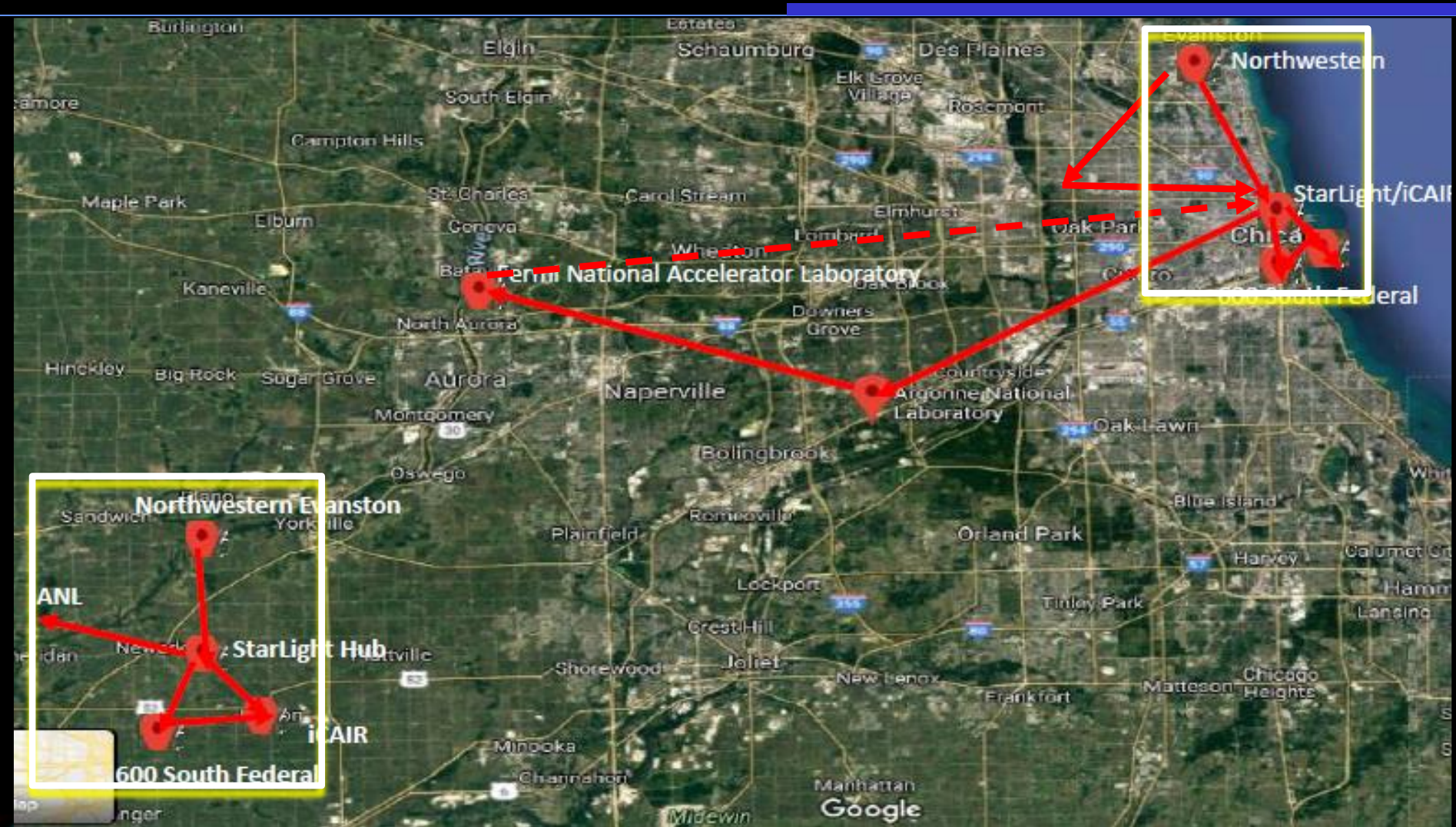
### Future



Source: Wenji Wu, ESnet



# IEQnet Testbed Topology



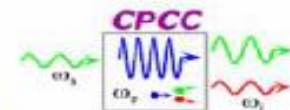
**BOUGHTON ROAD  
TOLL PLAZA**



**Argonne**   
NATIONAL LABORATORY



# Optimization of Classical $\lambda$ Coexisting with C-band Q. Networks (paper Tu3H.3)



## 1. Time Synchronization

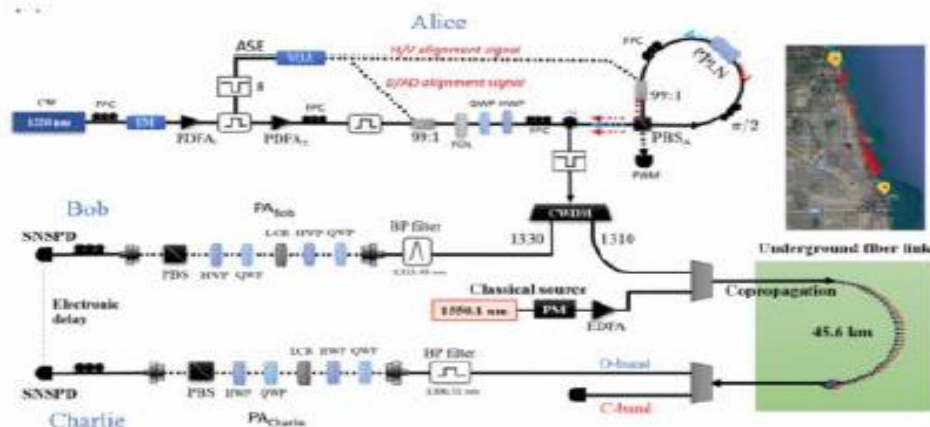
1310 nm classical clock light coexisting with 1536 nm photon pairs for picosecond synchronization over 59 km



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

## 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



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

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

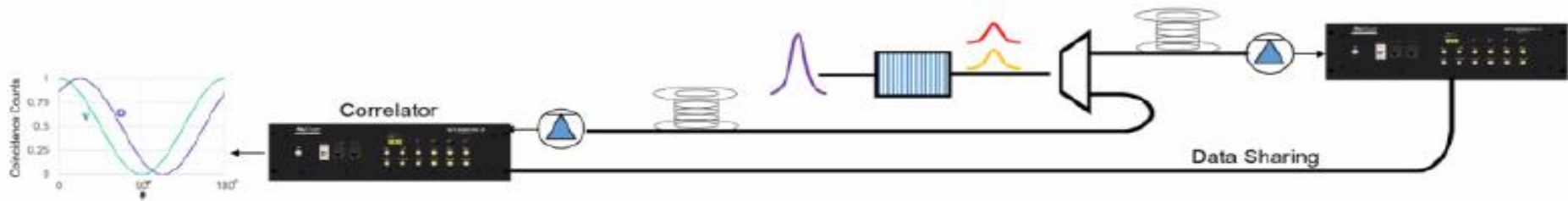


Entanglement Distribution in Installed Fiber with Coexisting Classical Light for Quantum Network Applications

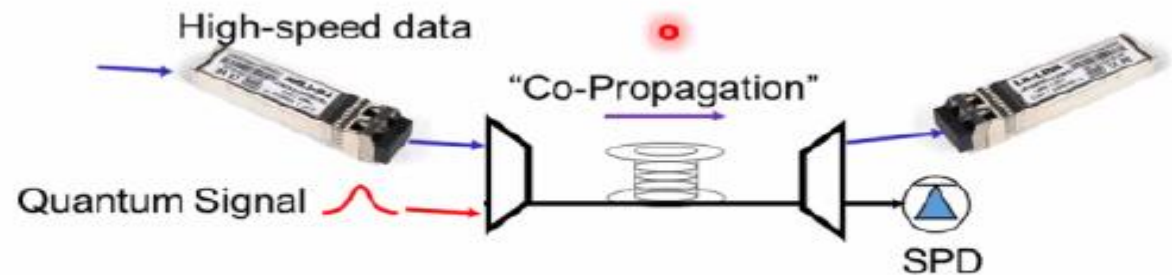
Jordan M. Thomas, Gregory S. Kanter, Ely M. Eastman, Kim F. Lee, and Prem Kumar



1. **Generation of entangled photons (distributed over fiber)**
2. **Data communication between distant Quantum Nodes**



### 3. Co-Propagation of quantum and classical data

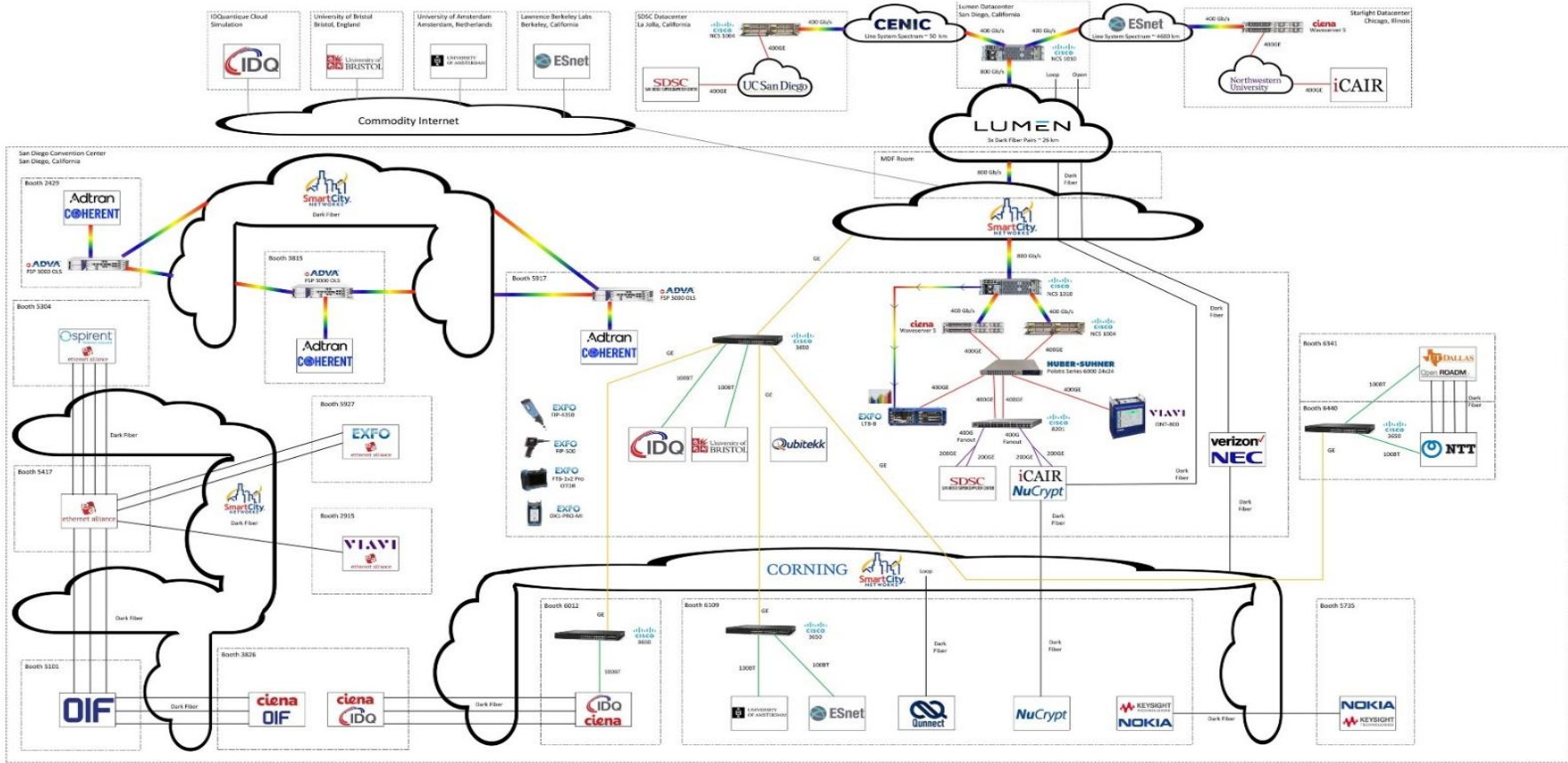




**Demo Lead Partner - NuCrypt (1) - Distribution of Quantum Entanglement Through Fiber With Co-Propagating Classical Data**

**(1) Spin Off From Northwestern University's Center for Photonic Communications and Computing, Which Was Also A Partner for the OFC 2023 Demonstrations (Prem Kumar, Director)**

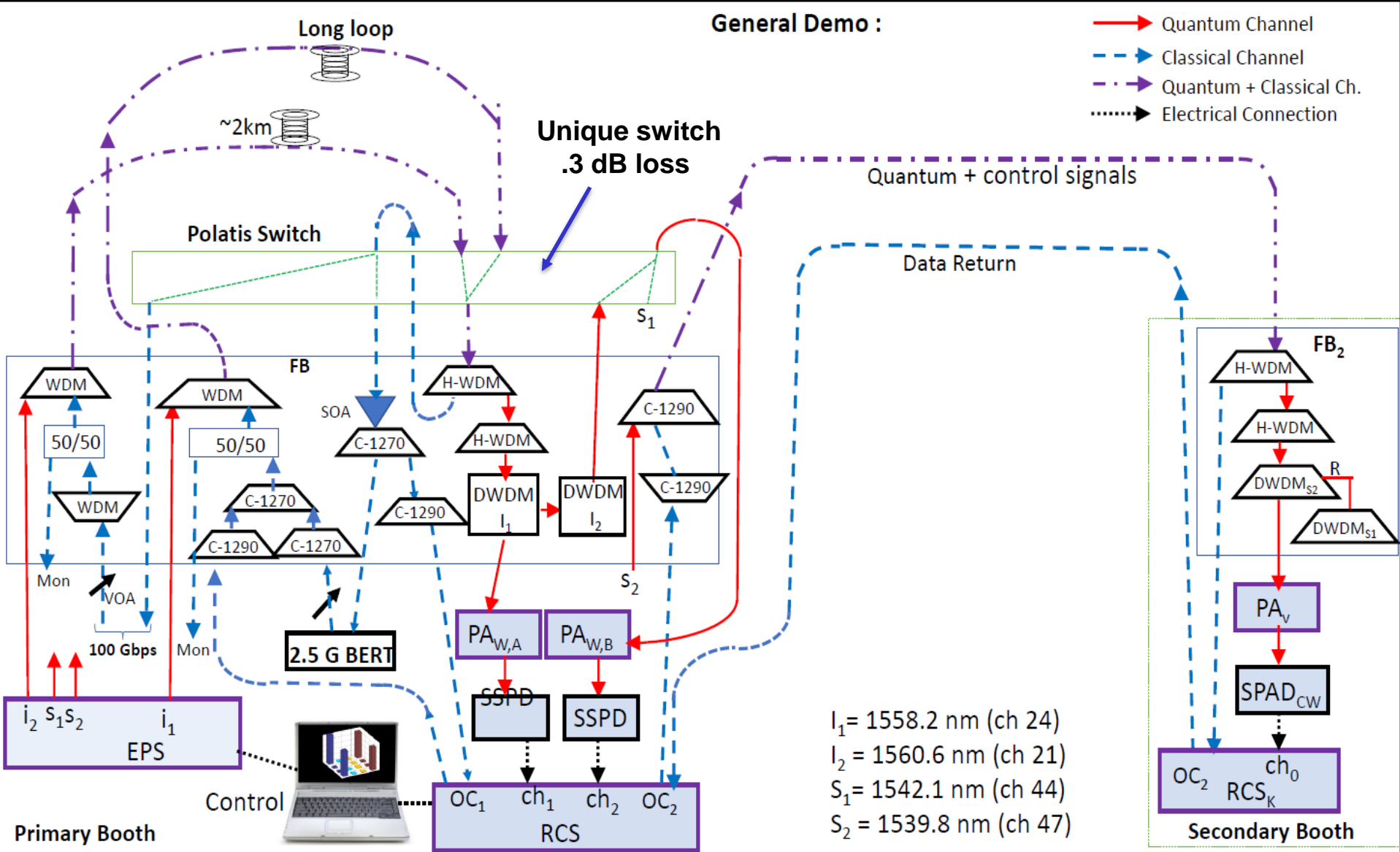




## OFC 2023 – OFCnet Architecture Diagram

## Distribution of Quantum Entanglement Through Fiber With Co-Propagating Classical Data

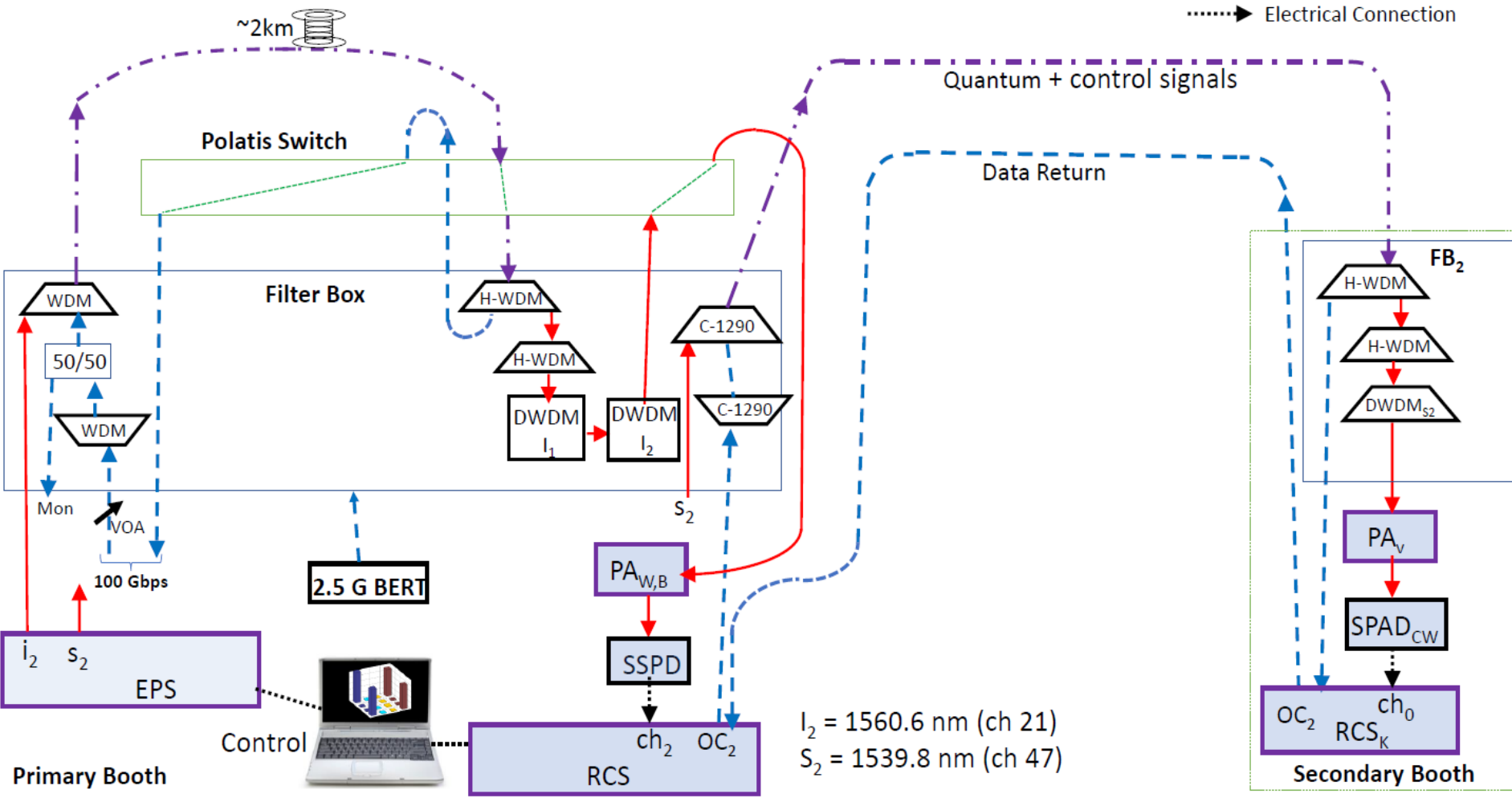
- A complete system for distributing and measuring quantum entangled signals over fiber was demonstrated. Distributed measurements were collected and controlled from a single location using an embedded optical data link. An optical switch was programmed to send different quantum entangled wavelengths to spatially separated users. The demonstration centered around the use of commercially available components that interface to multiple types of single photon detectors. The demonstrations of coordinated control of quantum photonic instruments at multiple sites highlights the capability for robust operation of commercially available quantum optical equipment over existing fiber optic infrastructure.





# 100G Demo :

- Quantum Channel
- - - - - Classical Channel
- - - - - Quantum + Classical Ch.
- - - - - Electrical Connection



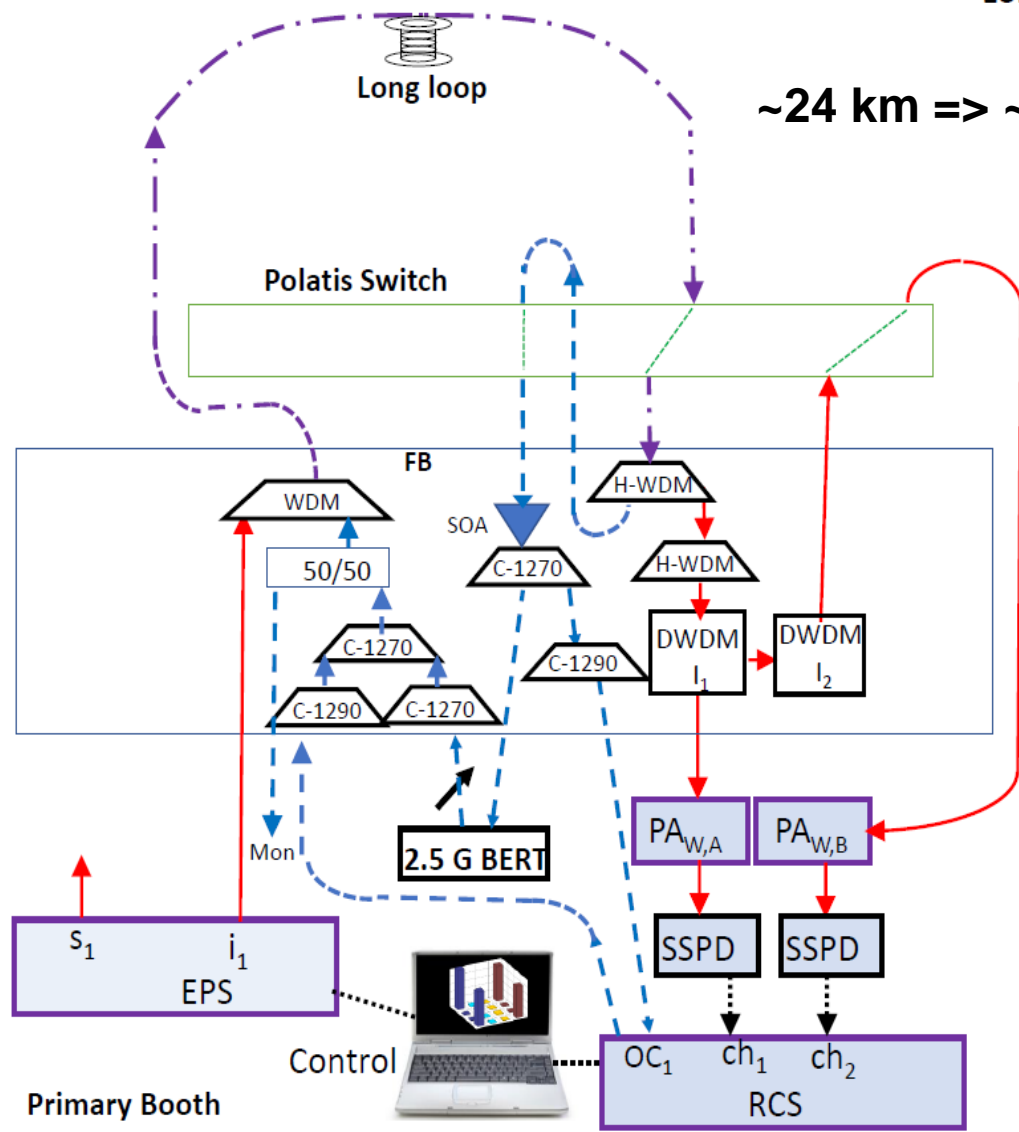
94% Fidelity

STARLIGHT<sup>SM</sup>

Long Distance Demo :

- Quantum Channel
- Classical Channel
- Quantum + Classical Ch.
- Electrical Connection

~24 km => ~12 km each direction



$I_1 = 1558.2 \text{ nm (ch 24)}$   
 $S_1 = 1542.1 \text{ nm (ch 44)}$

91% Fidelity

### Entangled Photon Analyzer

version 2.18 NuCrypt 2020

Devices:

light  dark 53.275  H  V

FX:

1:

2:

CPDS:

3:

resolution: 40 Mhz = 400 ns

display:

Dark Counts:

Alignment:  use factory calibration  set # 0 when native

align H sig  align V corr

semi alignment:

Tomography:  Kelly  new method  smex  coherent

Two Photon Interference:    sweep PA 1   minus det

taking tomographic measurements  
writing ..\log\d230107\tom012.txt

run 1 measurement dur 16.061s  
overhead 2.161s = 13.3%

maximum likelihood analysis...

new alignment settings:  
pa1: 21.0 97.1 54.1  
pa2: 49.3 10.4 -45.8

time to analyze and plot 6470.4 ms  
setting both channels to H basis

### Figure 1: quantum state density matrix

File: ..\log\d230107\tom012.txt

dark-subtracted state

polarization tomography

num\_detectors 2  
num\_runs 35  
gates 408  
color\_map 121  
dark\_rates 4.5e-5 4.3e-7 4.5e-5 6.3e-7  
exp\_per 6  
clocking 800.000 MHz

figures of merit	num	den	ratio
fidelity	0.908	0.956	0.917
concis	0.968	0.961	0.726
lin_entropy	0.028	0.107	0.262
concurrence	0.984	0.928	0.952
purity	0.972	0.920	0.949

Project Summary

Overview

Settings: [edit](#)

Project name: ber  
Project location: C:\reilly\proj\ofc\bert\_v2  
Product family: Zynq-7000



### Entangled Photon Analyzer

version 2.10 NuCrypt 2022

DEVICES: identity ip addr SPI = iab1 COMB0 reset

Topology: 'ent\_100g'

FA: wave 1580.51 nm ch 21  
wave 1538.77 nm ch 47

CPDS: res0001-ws 2 cond  
res0001-nc 4 cond  
res0001-gnd  
res0001-unassigned

readout: 40 NCYC = 400 ns  
display: counts  
fsamp: 500 MHz

Dark Counts: measure 1811 A  
clear 0

Alignment: align H33 steps use factory calibration  
align H ring align D ring

tomographic: align master 80 Mjyc = 800 yes

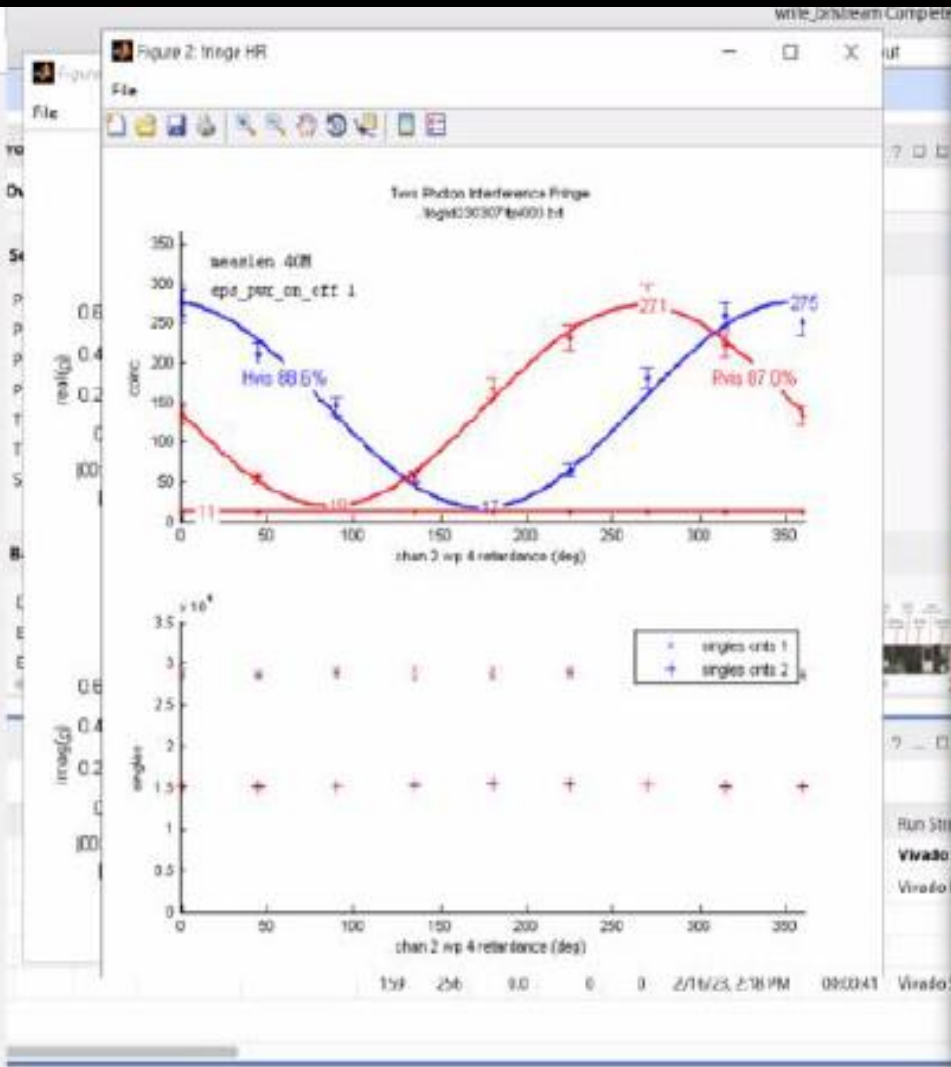
Tomography: run 10 avg window 1  
density max likelihood  
spheres save as tom007.txt

Two Photon Interference: step 45 runs 1  
twos FA 1  
bias +15.8  
set ps save as tp04.txt start

```

writing ...log\4226307\tps003.txt
setting both channels to H basis
run 1
fringe II
30% of Singles 1: 1.04
30% of Singles 2: 1.24
retardance_at_max = 354.1 deg
vix = 99.4%
est_raw_fidelity 01.0%
gber = 3.7%
fringe I
30% of Singles 1: 0.84
30% of Singles 2: 2.44
retardance_at_max = 266.2 deg
vix = 97.0%
est_raw_fidelity 00.2%
gber = 4.4%
wrote ...log\4226307\tps003.txt

```





**Co-Propagation  
And 400 Gbps WAN  
Demonstrations  
OFCnet Booth  
March 2023**

**STARLIGHT<sup>SM</sup>**



# IQUIST Quantum Network Testbed: QUIUC-NET

## IQUIST Quantum Network Development: QUIUC-NET

- Interdisciplinary (ECE, Math, Physics,...) quantum network research
- Resource development: (Hyper)entangled sources, photon detectors, quantum memories, processing nodes
- Partnerships UW, UC, ANL
- Industrial partners (Qubbitex, Quantum Opus, PSICorp, AdvR): accelerate R&D cycle
- Discover new networking applications and protocols, e.g., distributed processing and sensing, network verification...

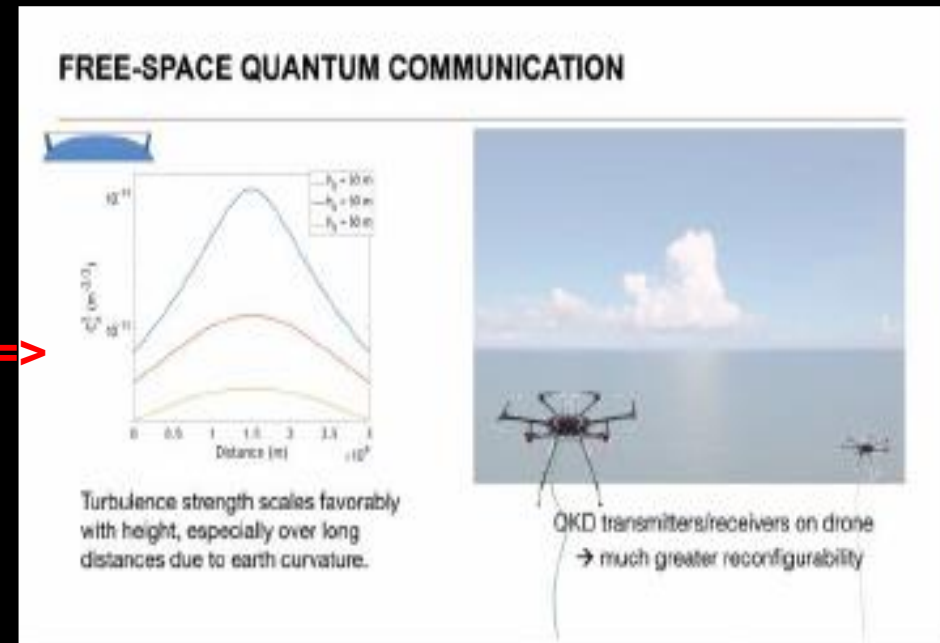


StarLight

Urbana ⇔ 30km 6-8.5 dB ⇔ Rantoul ⇔ 97km 19-22dB ⇔ Kankakee ⇔ 96km 19-23 dB ⇔ Chicago

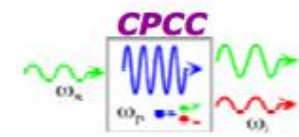
# IQUIST Quantum Network Testbed: QUIUC-NET

(Hyper)Entangled Sources  
Photon Detectors  
Quantum Memories  
Processing Nodes  
Net Aps  
Protocols  
Distributed Processing  
Sensing Net Verification  
Repeater Enhanced Quantum Links  
Free Space Quantum Communications ⇒



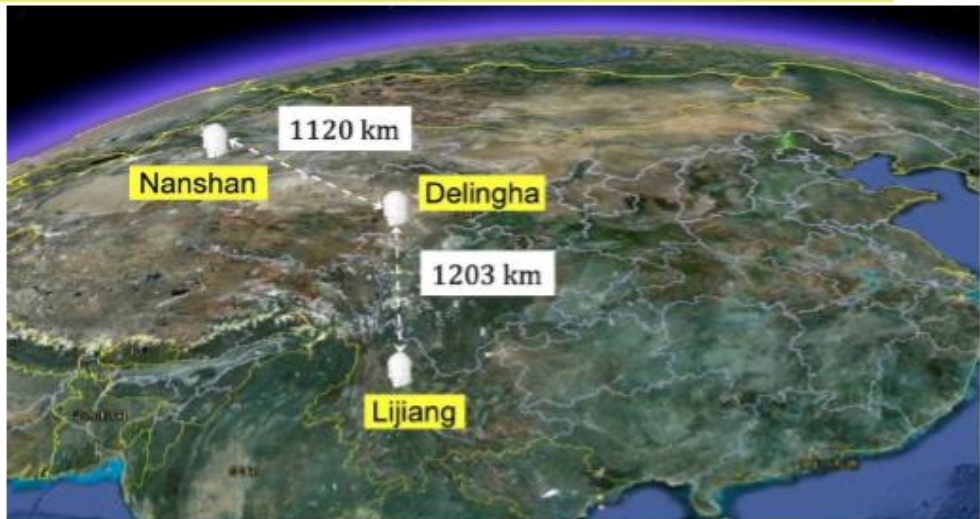
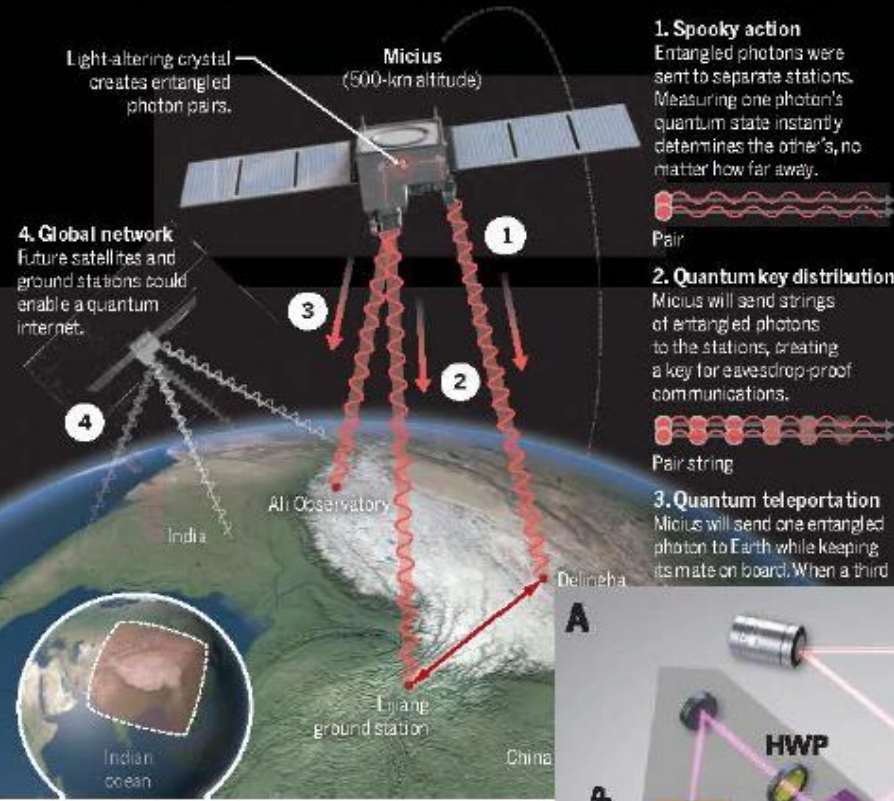
Source: Paul Kwiat, Director,  
IQUIST

# Source Aboard Satellite Micius Entanglement Distribution over 1200 km



## Quantum leaps

China's Micius satellite, launched in August 2016, has now validated across a record 1200 kilometers the "spooky action" that Albert Einstein abhorred (1). The team is planning other quantum tricks (2-4).

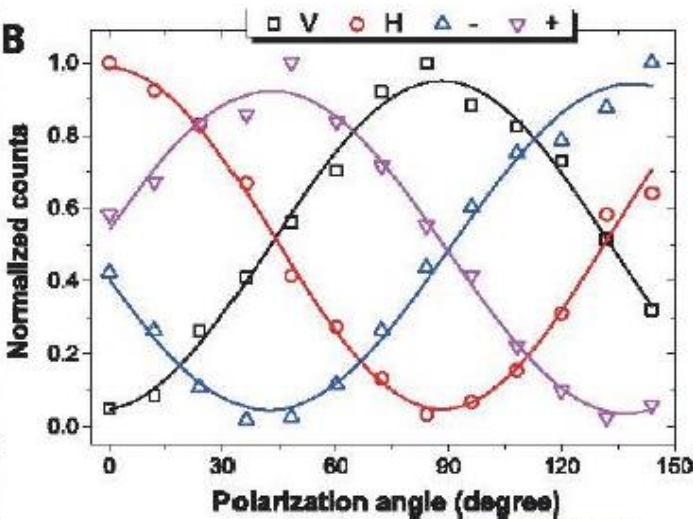
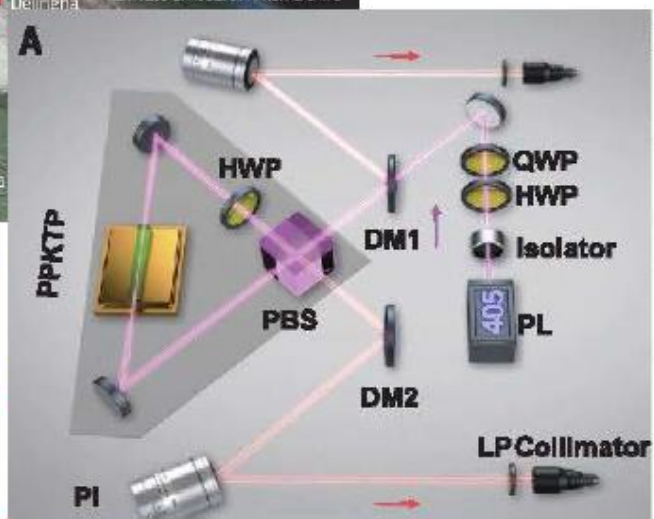


F. N. C. Wong *et al.*, Phys. Rev. A 73, 012316 (2006)

## 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





# Future Directions

- **Additional Testbeds, Experiments, and Prototypes Are Being Planned To Support Multiple Quantum Scenarios**
- **For Example, Enhancements Of Techniques For O-band/C-band Quantum/Classical Wavelength Allocation With Temporal and Spectral Filtering in Coincidence Detection As Useful Noise Mitigation Methods For Coexistence Scenarios In Fiber-Optic Quantum Networking. (O-band Classical Alignment Signal Is Built Into the Entanglement Source To Align Each Node in a Polarization Entanglement Network To the Same Polarization Reference Frame.)**
- **Projects Are Developing And Validating Viable Platforms for Quantum Network Testbeds For Rapid Prototyping, System Characterization And Optimization**
- **New Comprehensive System Designs Are Being Created For Quantum Communications And Networking, Including Advanced Programming Paradigms For Service Creation And Implementation**
- **Specific Customized Properties Enable Information To Be Exchanged Among And Across Quantum-Classical Boundaries**



A STRATEGIC VISION FOR  
AMERICA'S QUANTUM  
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Product of

THE WHITE HOUSE  
NATIONAL QUANTUM COORDINATION OFFICE

February 2020

# National Policy Report On Quantum Networks

# ESnet Quantum Internet Initiative

Report of the DOE  
Quantum Internet  
Blueprint Workshop

From Long-distance Entanglement to  
**Building a Nationwide Quantum Internet**

February 5-6, 2020

Report of the DOE Quantum Internet  
Blueprint Workshop: From Long-Distance  
Entanglement To Building a Quantum Internet

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23 eScience

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IEEE eScience 2023 brings together leading interdisciplinary research communities, developers and users of eScience applications and enabling IT technologies. The objective of the eScience Conference is to promote and encourage all aspects of eScience and its associated technologies, applications, algorithms and tools with a strong focus on practical solutions and challenges. eScience 2023 interprets eScience in its broadest meaning that enables and improves innovation in data- and compute-intensive research across all domain sciences ranging from traditional areas in physics and earth sciences to more recent fields such as social sciences, arts and humanities, and artificial intelligence for a wide variety of target architectures including

### Important Dates

~~February 10, 2023~~ **Friday, February 24, 2023**  
Workshop Submissions

~~February 24, 2023~~ **Friday, March 10, 2023**  
Workshop Acceptance Notification

**Friday, May 26, 2023**  
Paper Submissions

**Friday, June 30, 2023**  
Notification of Paper Acceptance



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Thanks to the NSF, DOE, NASA,  
NIH, DARPA  
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International & Industrial  
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and Other Supporters

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