National Quantum Initiative Advisory Committee

November 3, 2023

Agenda

Time (pm EST)	Topic
1:00 – 1:05 (5 min)	*Opening Remarks* • Dr. Kathryn Ann Moler and Dr. Charles Tahan, NQIAC Co-Chairs
1:05 – 1:30 (25 min)	*National Quantum Networking Strategy* • Dr. Tanner Crowder, Policy Analyst at the National Quantum Coordination Office, Co-Chair of the SCQIS Interagency Working Group on Quantum Networking
1:30 – 1:50 (20 min)	*Quantum Networking Activities at NIST* • Dr. Jim Kushmerick, Director of the Physical Measurement Laboratory
1:50 – 2:10 (20 min)	*Quantum Networking Activities at NSF* • Dr. Denise Caldwell, Acting Assistant Director of the Directorate for Mathematical and Physical Sciences (MPS)
2:10 – 2:30 (20 min)	*Quantum Networking Activities at DOE* • Dr. Ceren Susut, Associate Director of Science for Advanced Scientific Computing Research (ASCR) in the Office of Science
2:30 – 2:50 (20 min)	*Quantum Networking Activities at DOD* • Dr. John Burke, Principal Director for Quantum Science, Department of Defense
2:50 – 3:00 (10 min)	*Discussion, Next Steps, and Closing Remarks* • Dr. Kathryn Ann Moler and Dr. Charles Tahan, NQIAC Co-Chairs

The National Quantum Initiative and a Coordinated Approach to Quantum Networking

Dr. Tanner Crowder
Senior Policy Advisor, National Quantum Coordination Office
Co-Chair, Quantum Networking -Interagency Working Group
under the NSTC Subcommittee on QIS
Office of Science and Technology Policy

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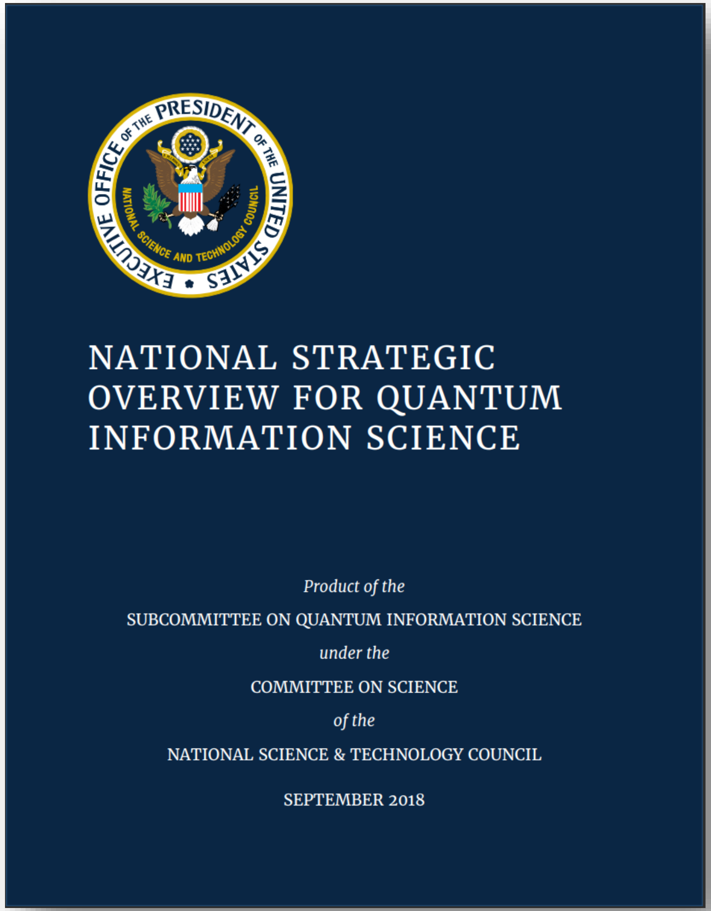
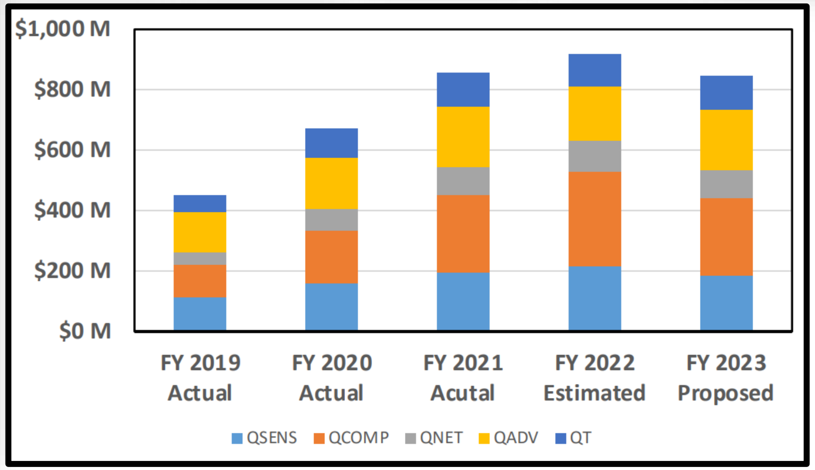
__Office of Science and Technology Policy__
OSTP works to harness the power of science, technology, and innovation to achieve America's greatest aspirations.

QIST is a National Priority

1. Take a **science-first** approach
2. Provide the key **infrastructure**
3. Build a quantum-capable and diverse **workforce**
4. Nurture the nascent quantum **industry**
5. Balance **economic** and **national security**
6. Continue to develop **international collaboration** and cooperation

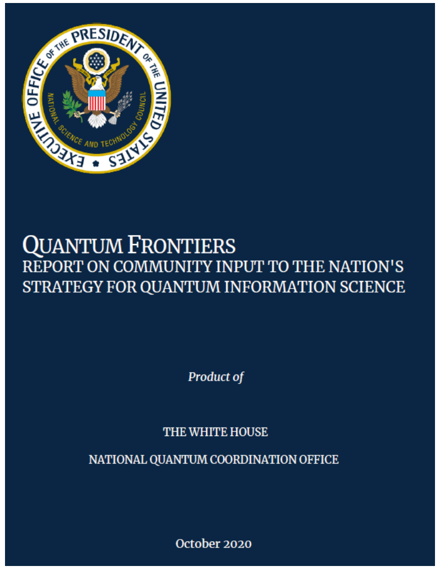




Find all our strategy documents on quantum.gov

Getting the Science Right

1. Expanding Opportunities for Quantum Technologies to Benefit Society
2. Building the Discipline of Quantum Engineering
3. Targeting Materials Science for Quantum Technologies
4. Exploring Quantum Mechanics through Quantum Simulations
5. Harnessing Quantum Information Technology for Precision Measurement
6. Generating and Distributing Quantum Entanglement for New Applications
7. Characterizing and Mitigating Quantum Errors
8. Understanding the Universe through Quantum Information



QUANTUM FRONTIERS
REPORT ON COMMUNITY INPUT TO THE NATION'S STRATEGY FOR QUANTUM INFORMATION SCIENCE

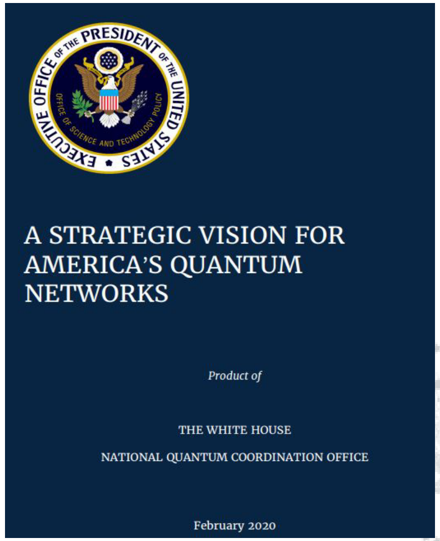
Product of

THE WHITE HOUSE
NATIONAL QUANTUM COORDINATION OFFICE

October 2020

Two goals from Strategic Vision for QNs (published in Jan 2020):

1. Five Years: Demonstrate the foundational science and key technologies to enable quantum networks.
2. Twenty Years: Leverage networked quantum devices to enable new capabilities not possible with classical technology, while advancing our understanding of the role entanglement plays.



A STRATEGIC VISION FOR AMERICA'S QUANTUM NETWORKS

Product of

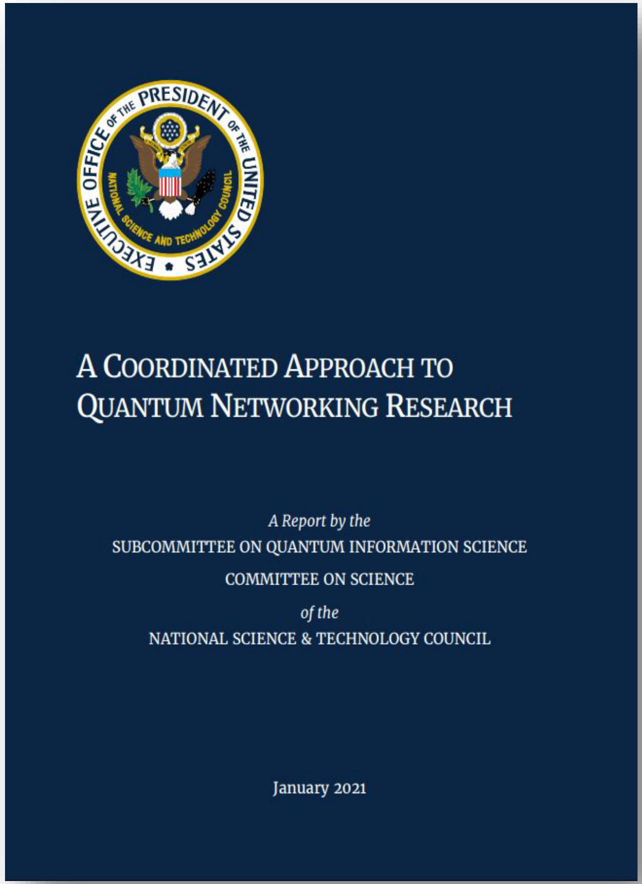
THE WHITE HOUSE
NATIONAL QUANTUM COORDINATION OFFICE

February 2020

A Coordinated Approach to Quantum Networking Research

Builds upon: *National Strategic Overview for QIS*; *Quantum Frontiers*; *A Strategic Vision for America's Quantum Networks*; and agency-led workshops on Quantum Networking

- Technical Recommendations
  1. Continue Research on Use Cases for Quantum Networks
  2. Prioritize Cross-Beneficial Core Components for Quantum Networks
  3. Improve Classical Capabilities to Support Quantum Networks
  4. Leverage "Right-Sized" Quantum Networking Testbeds
- Programmatic Recommendations
  1. Increase Interagency Coordination on Quantum Networking R&D
  2. Establish Timetables for Quantum Networking R&D Infrastructure
  3. Facilitate International Cooperation on Quantum Networking R&D



The QN-IWG of the Subcommittee on QIS, includes representation from:

ARL, ARO, AFOSR, AFRL, DARPA, DOE, ONR, OSTP, NASA, NIST, NRL, NRO, NSA, NSpC, NSF

CHIPS and Science Act

SEC. 10661. Quantum Networking and Comms

Not later than January 1, 2026, the QN-IWG shall submit to Congress a report detailing a plan for the advancement of quantum networking and communications (QNC) technology in the U.S. including:

1) An update to *A Coordinated Approach to Quantum Networking Research*, focusing on a framework for interagency collaboration regarding advancing QNC R&D.
2) A plan for Federal partnership with the private sector and interagency collaboration for international standards in QNC, including a list of Federal priorities for standardization.
3) A proposal for the protection of national security interests relating to the advancement of QNC technology.
4) An assessment of the relative position of the U.S. in the global race to develop, demonstrate, and utilize QNC technology.
5) Recommendations to Congress for legislative action pertaining to (1)-(4) .
6) Other matters the QN-IWG considers necessary to advance the security of communications and network infrastructure, to remain at the forefront of scientific discovery in QIS, and to transition QIS R&D into the emerging quantum technology economy.

CHIPS and Science ACT

SEC. 10661. Quantum Networking and Comms

In June 2023, the NQCO, under the auspices of the QN-IWG & SCQIS, and NASA co-hosted the Quantum Networking Interagency Workshop:

1) Hosted fifteen departments and agencies, along with national labs and QLCIs with quantum networking focuses.
2) Participants discussed the implications of the strategy, along with their institutions' R&D priorities, work being done to advance use-case development, workforce needs, and collaborations.
3) Held five breakout sessions covering:
    a) Domestic cooperation and coordination
    b) Critical components and the supply chain
    c) Near-term applications
    d) International activities and considerations
    e) Interoperability and standardization

QUANTUM NETWORKING
WORKSHOP 2023
Hosted by National Quantum Coordination Office and NASA

Served not only as a retrospective on the two and a half years since the Quantum Networking Strategy was released, but also offered a look toward the future as the QN-IWG prepares to address CHIPS and Science Act responsibilities.

Recent Legislation Related to Quantum Networks:

CHIPS Act Secs. 10104 and 10661 & Consolidated Appropriations Act 2022 and 2023

DOE Quantum Science Network (CHIPS): Carry out an R&D and demonstration program to accelerate innovation in q. network infrastructure:

1) Facilitate the advancement of distributed q. computing systems
2) Improve precision measurements of scientific phenomena and physical imaging technologies
3) Develop secure national q. communications technologies and strategies
4) Utilize DOE Energy Sciences Network User Facilities for q. networking
5) Advance domestic supply chains, manufacturing, and simulations or modeling capabilities

In carrying out this program:

1) Coordinate with NSF, NIST, SCQIS, and ESIX
2) Facilitate new q. infrastructure tech
3) Engage QED-C to transition component tech & establish supply chains
4) Advance basic science in advanced computing
5) Develop experimental tools and testbeds for cross-cutting R&D
6) Consider DOE relevant q. networking infrastructure

Authorized: ~$100M/yr for FY23-27

NIST Quantum Networking and Communication Research and Standardization (CHIPS): Carry out R&D to facilitate the standardization of:

- Q. and post-quantum cryptography
- Q. networking, communications, sensing, and applications
- For q. technologies determined to be at a readiness level for standardization, provide technical assistance to agencies for q. networking infrastructure standards

Authorized: $15M/yr for FY23-27

DOD (CAA):

- Q. networking testbed
- Q. battlefield internet

Appropriated: $17M in ‘22; 10M in ‘23

Office of Science and Technology Policy

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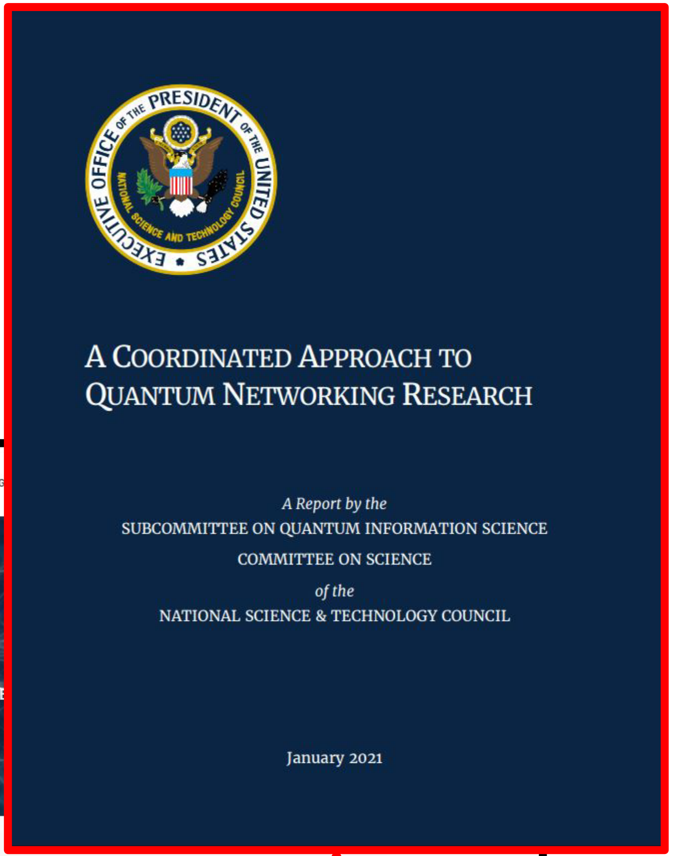

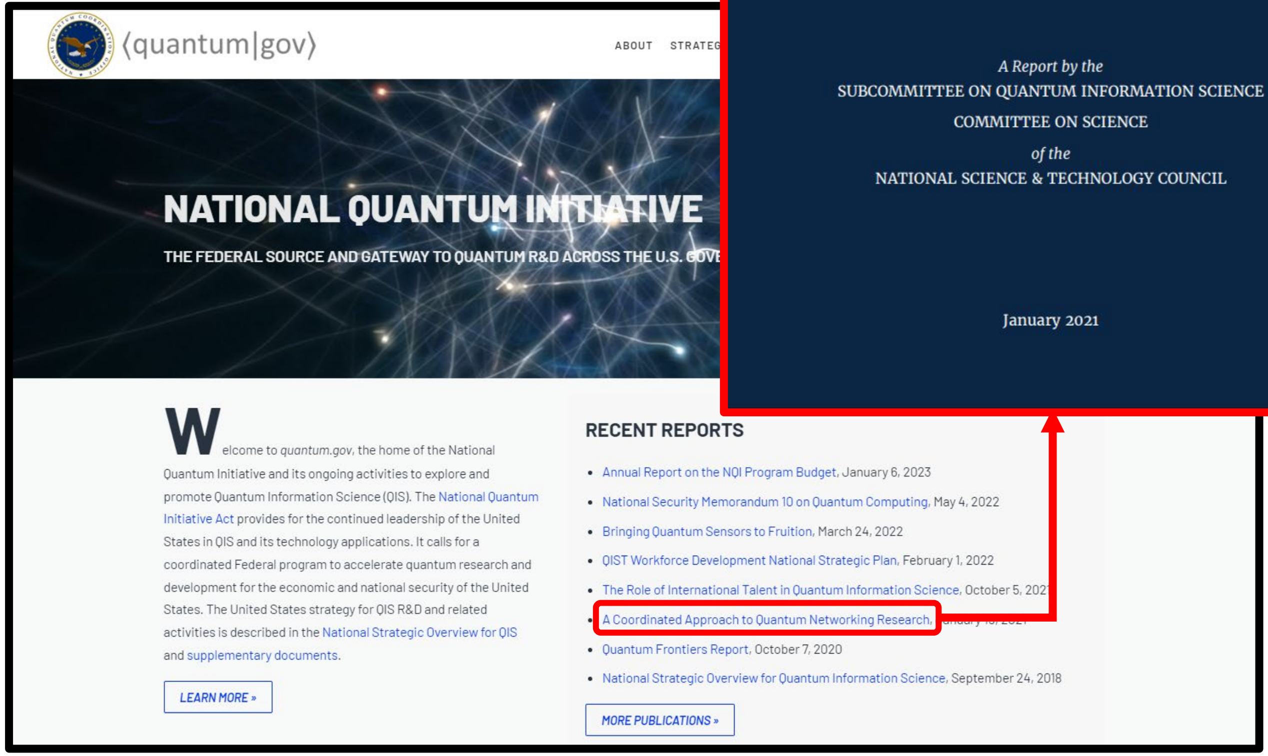

Learn more about all Departments and Agencies working in QIS at https://www.quantum.gov

⟨quantum|gov⟩

SCQIS
Co-Chairs:
Denise Caldwell, NSF
Harriet Kung, DOE
James Kushmerick, NIST
Charles Tahan, OSTP
Executive Secretary:
Alexander Cronin, NSF

ESIX
Co-Chairs:
Barry Barker, NSA
John Burke, DOD
Harriet Kung, DOE
Charles Tahan, OSTP
Executive Secretary:
Corey Stambaugh, NIST

National Quantum Coordination Office (OSTP)
Charles Tahan – Director of NQCO and AD for QIS at OSTP
Gretchen Campbell – Deputy Director for NQCO
Tanner Crowder – Senior Policy Advisor
Thomas Wong – Quantum Liaison

QN-IWG Co-Chairs
Tanner Crowder, OSTP/NQCO
Kathy-Anne Soderberg, DOD/AFRL
Ollie Slattery, NIST

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Quantum Networking at NIST
– Components, Testbeds, and Related Metrology

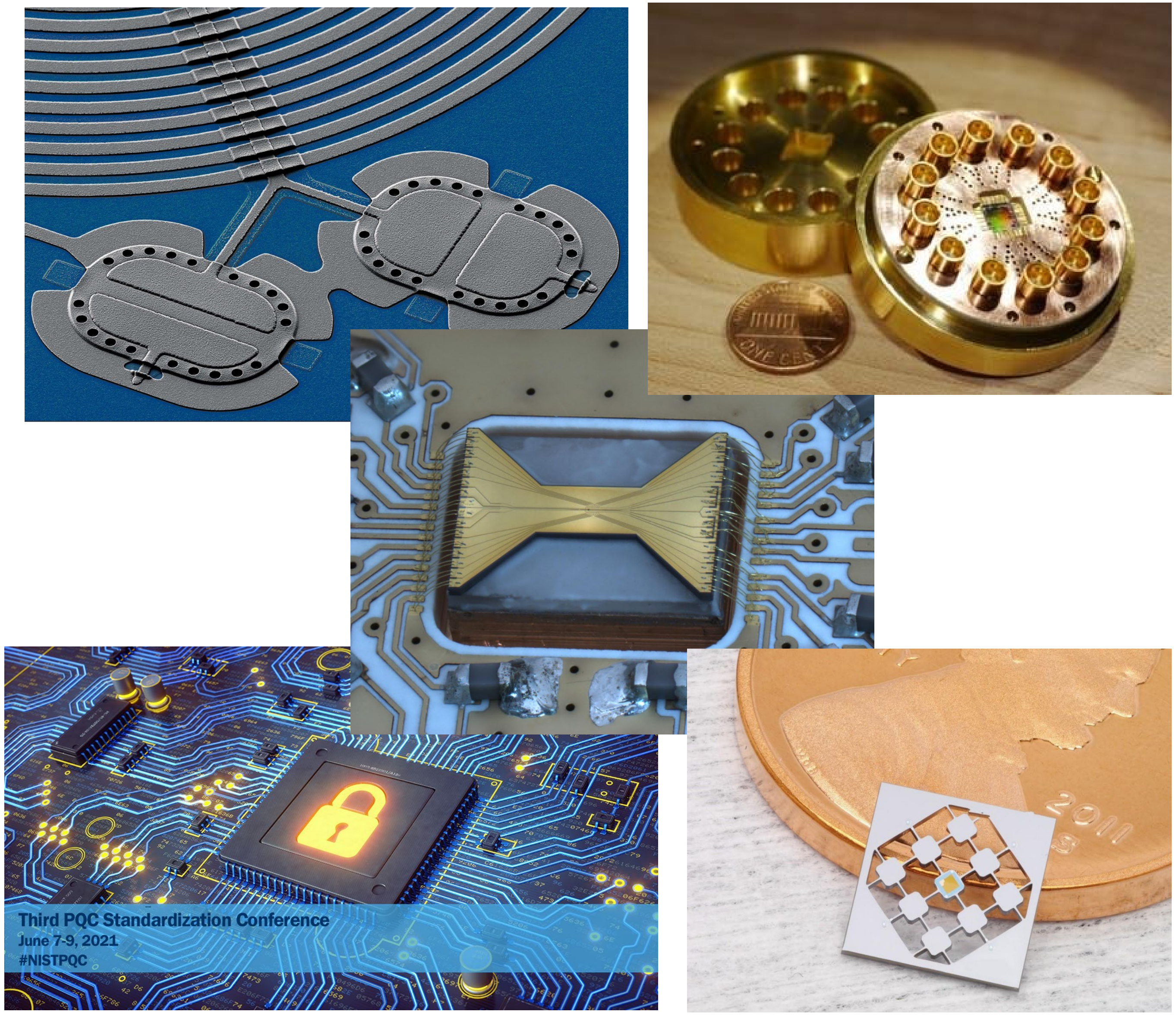
Dr. James Kushmerick
Physical Measurement Laboratory Director

QIST Research @ NIST

NIST

NIST QIST R&D activities span the full NQI Program:

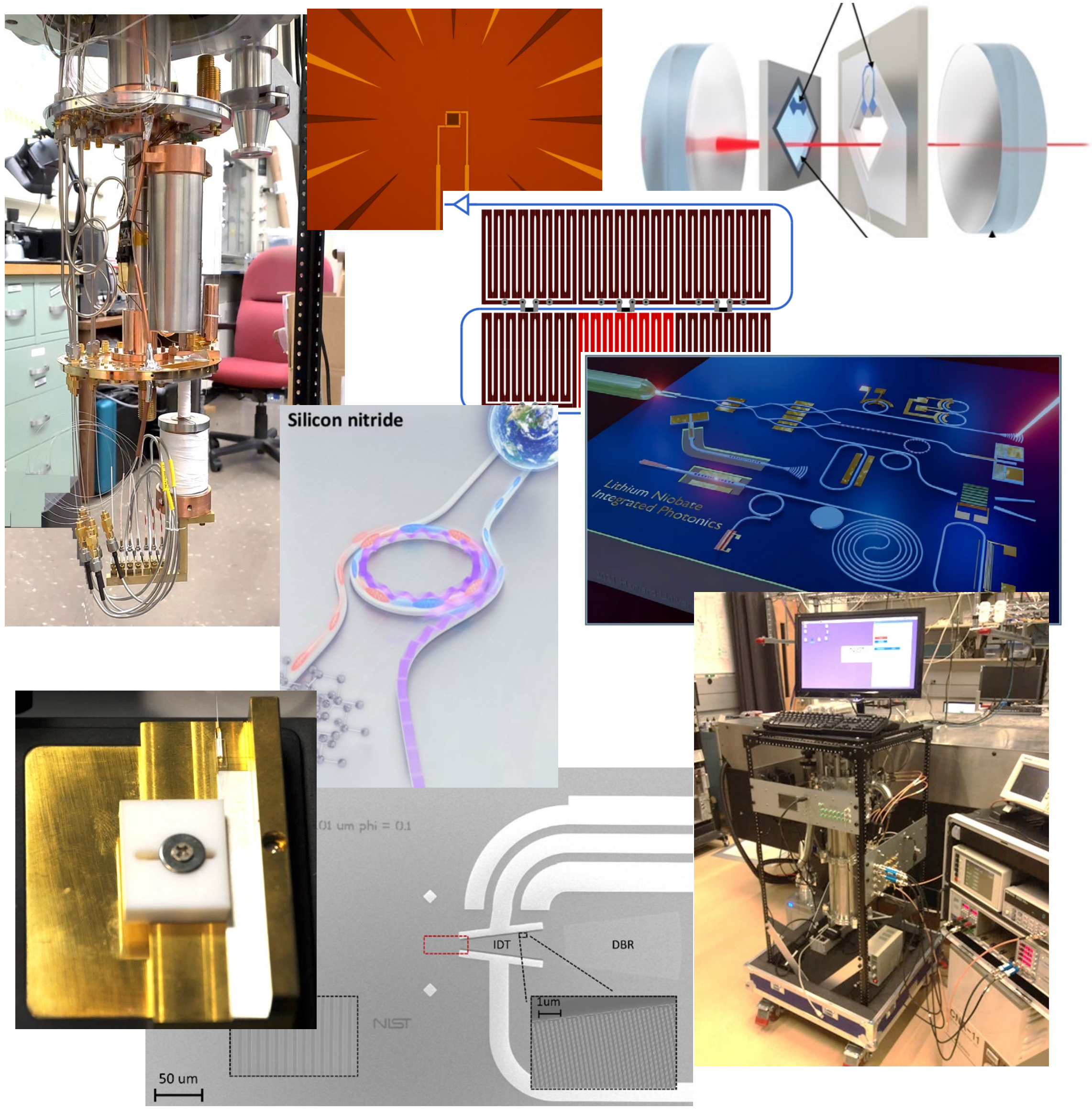
- Quantum Sensing and Precision Measurement e.g. optical atomic clocks (compact and high-performance) for time keeping and navigation, nano-mechanical and opto-mechanical devices, atomic magnetometers, chemical and biological systems.
- Quantum Networking e.g. quantum repeater, quantum transduction, optical networks (both quantum and classical, fiber and free-space), single photon sources and detectors.
- Quantum Computing e.g. improving qubit performance across all major platforms, benchmarking, error correction, new technologies for scaling.
- Fundamental Quantum Science e.g. quantum simulation, understanding complex quantum systems, searches for ‘beyond Standard Model’ physics e.g. dark matter, tests of gravity and quantum mechanics.
- Enabling Technologies e.g. integrated photonics, meta-materials, optical frequency combs, and control electronics.
- Risk Mitigation e.g. post-quantum cryptography.



Quantum Network Components

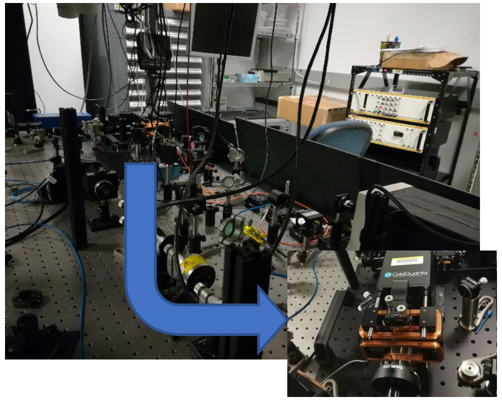
Key Quantum Networking Technologies at NIST

- **Sources of non-classical light**: SPDC, integrated photonics, quantum dots, and atomic sources for generating single photons and entangled photon pairs
- **Single-photon detectors**: superconducting nanowire, transition-edge, semiconductor avalanche photodiodes
- **Repeaters (telecom compatible):** trapped ions and atomic vapor EIT
- **Transducers**: optical to microwave via opto-mechanical, nonlinear optical wavelength conversion
- **High-speed switches**: electro-optic
- **Timing and synchronization**: frequency and phase measurement and stabilization, free-space synchronization and stabilization of optical network links
- **Optical atomic clocks**: optical lattice, tapped ion(s), tweezer array
- **Metrology and calibration**: Pre-standards characterization
- **Network protocols, design, and management**: entanglement distribution and swapping, quantum communication protocols, performance characterization and benchmarking, classical/quantum network coexistence, cryptography, and fundamental architecture considerations, network performance simulation and control, quantum-classical interface
- **Qubits and memory**: trapped ions, ultracold atoms, atomic vapor EIT, superconducting circuits, nano-mechanical, spin qubits in silicon

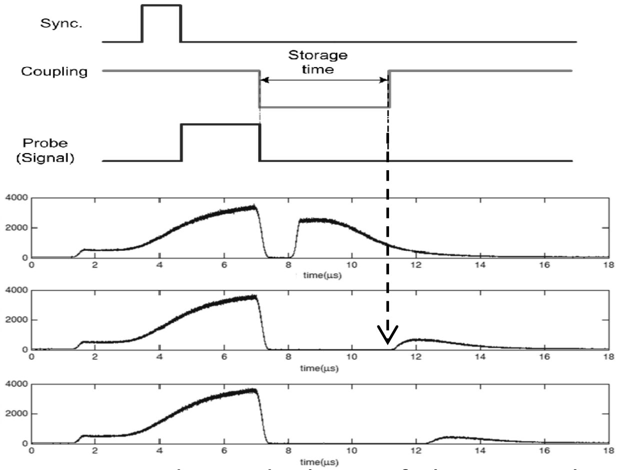


Examples of Quantum Network Components

Quantum Memories

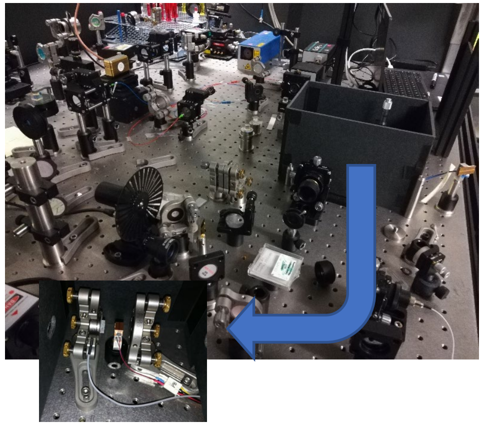


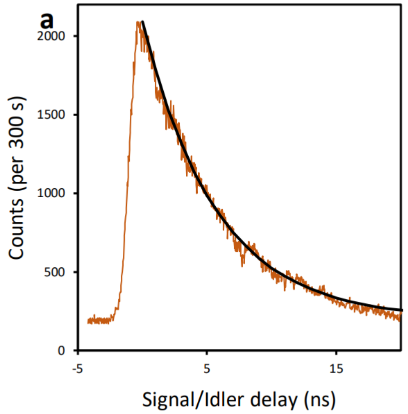
Atomic ensemble (EIT)



Storage + on-demand release of photonic qubits

Narrow linewidth single-photon sources using cavities (PPLN)





Integrated nanophotonics:

Silicon carbide (SiC) for quantum sources and quantum memory

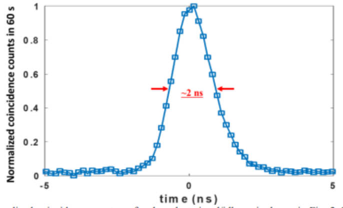
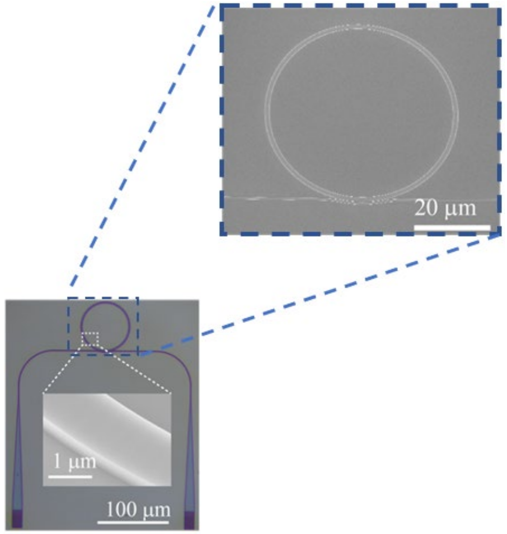
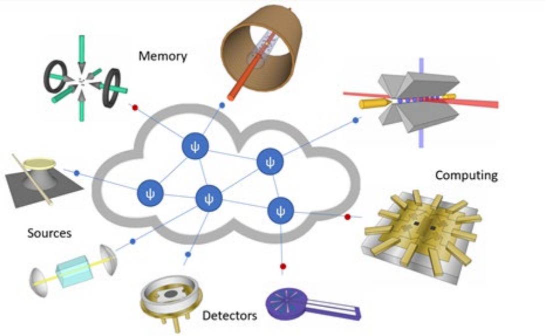


Figure 4: Normalized coincidence spectrum for the select signal/idler pair shown in Fig. 2. The FWHM of the coincidence counts is estimated to be around 2 ns.



Quantum Interfaces

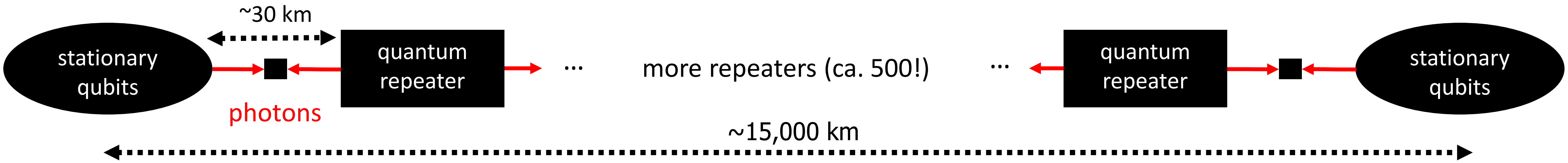


Single Photon Detectors

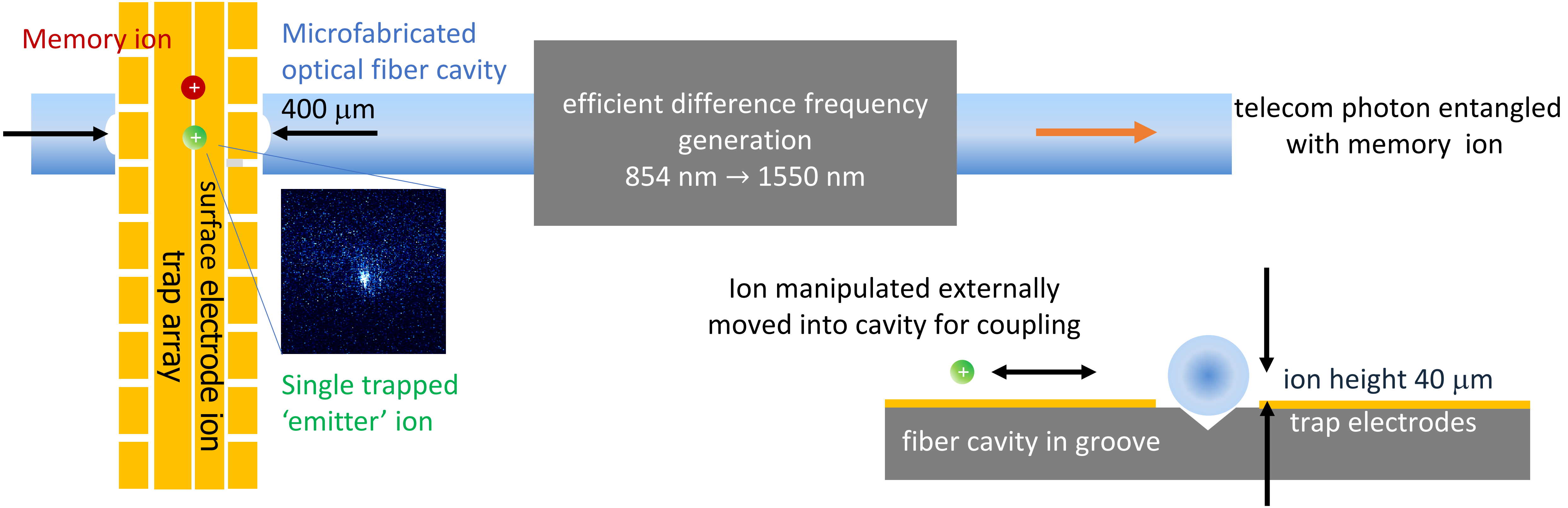
SNSPD Detectors

TES Detectors

Trapped-ion Quantum Repeater



Inside each repeater: efficient ion-photon coupling in *microfabricated* trap array with integrated fiber cavity

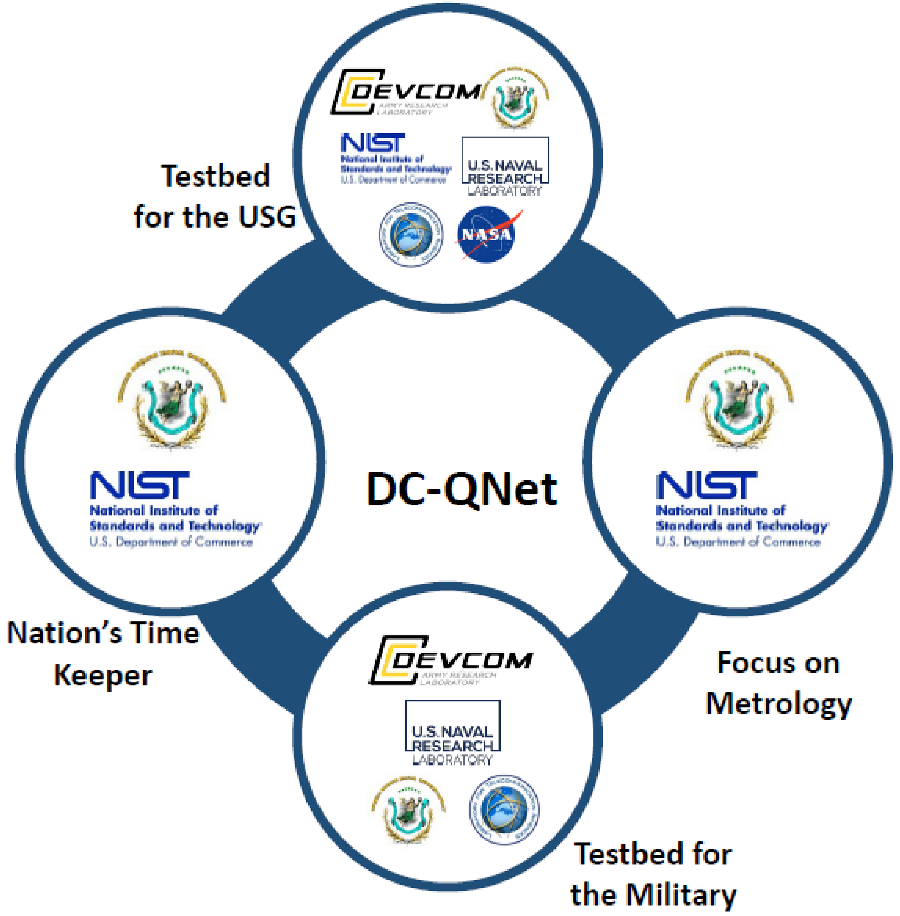


DC-QNET: Washington Metropolitan Quantum Network Research Consortium

A consortium of six metropolitan Washington D.C. USG research laboratories

Objective: Create, develop and demonstrate a regional quantum network testbed

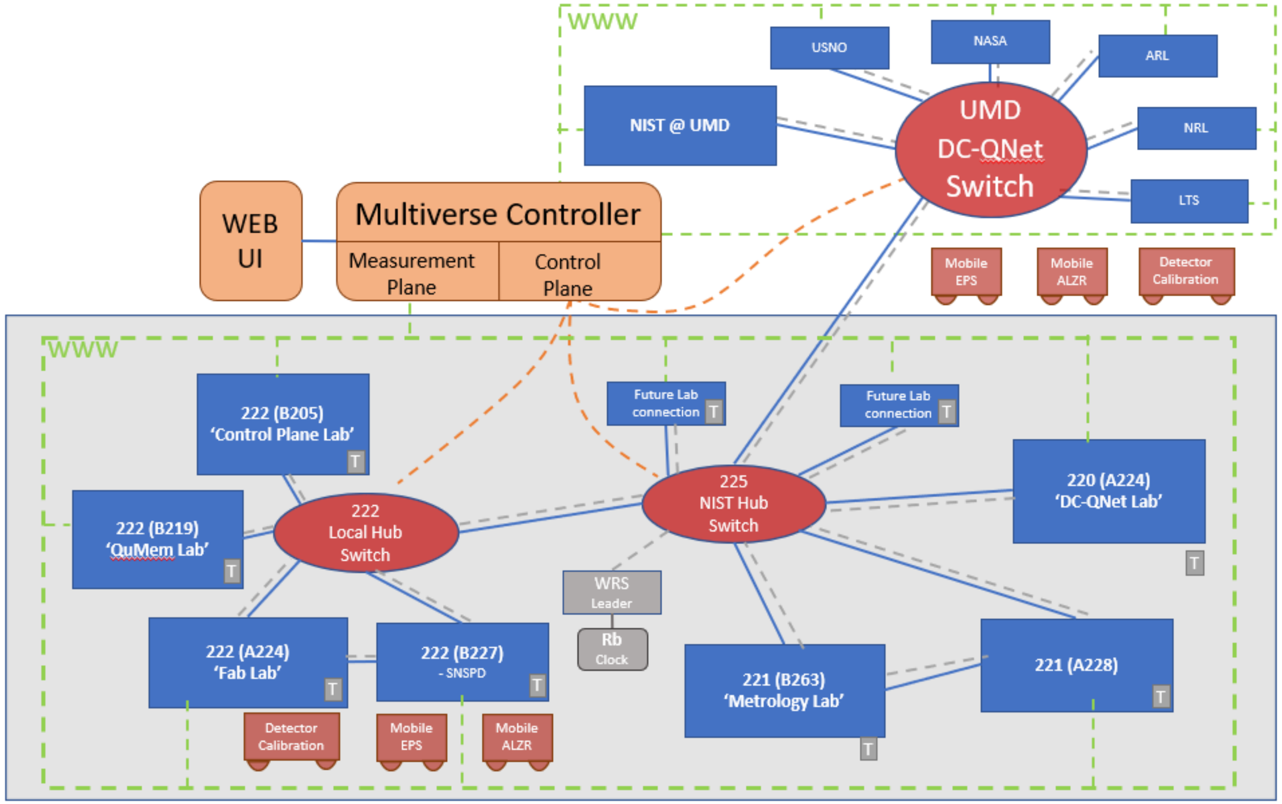
- An open, non-proprietary, environment for test and evaluation of concepts, components, network protocols, architectures and metrology developed both within and eventually beyond the member agencies.
- Enable joint cross-cutting agency synergism in sensor development, secure communications, distributed computing and yet to be discovered use case applications



Gaithersburg QN Testbeds

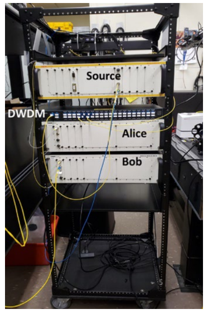
NIST

Testbed environments for test and evaluation of quantum networking concepts, components, protocols and architectures.
A local area quantum network at NIST connected to the regional DC-QNET.



Current quantum network integration activities: Entanglement distribution, synchronization, polarization and phase control, network modeling and management, quantum/classical coexistence, metrology nodes for link characterization, component testing etc.

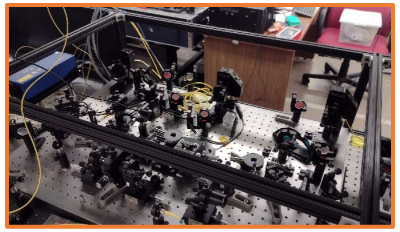
Mobile Grade



Well characterized sources and receivers

- Coincidence measurements.
- Entanglement visibility.
- Local and certain long-distance experiments.

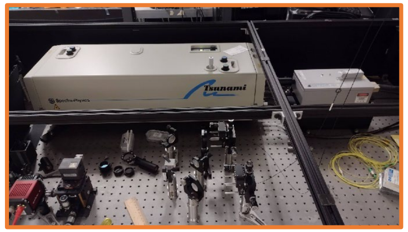
Metrology Grade



'Loop-Hole Free Bell Test' source.

- Hong-Ou-Mandel (HOM) interference experiments.
- Detailed quantum state tomography.
- Entanglement swapping experiments.

Research Grade

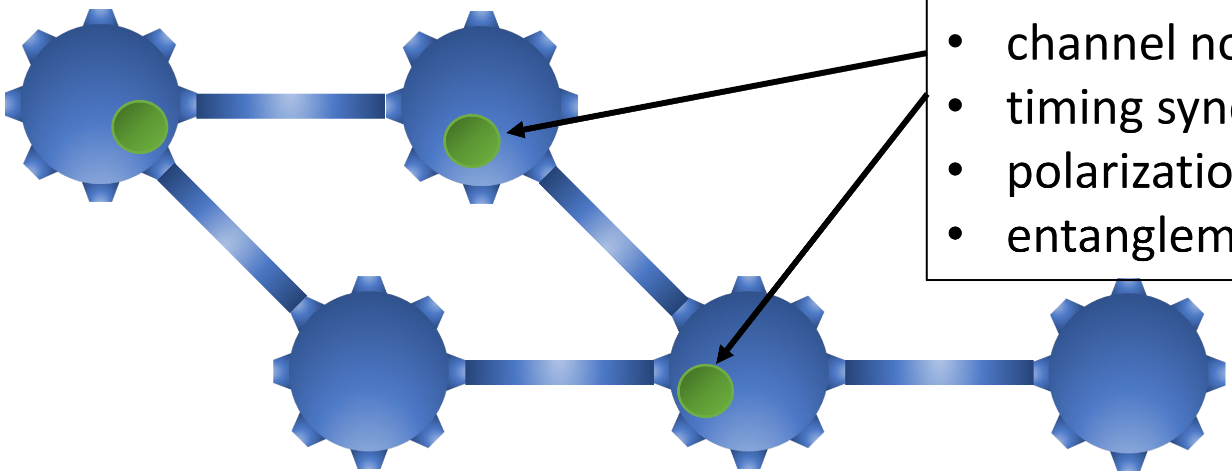


Ultra-low time-bandwidth pump.

- Combined with metrology-grade sources for advanced and long-distance experiments.
- Phase sensitive applications.
- Entanglement swapping.
- Teleportation.

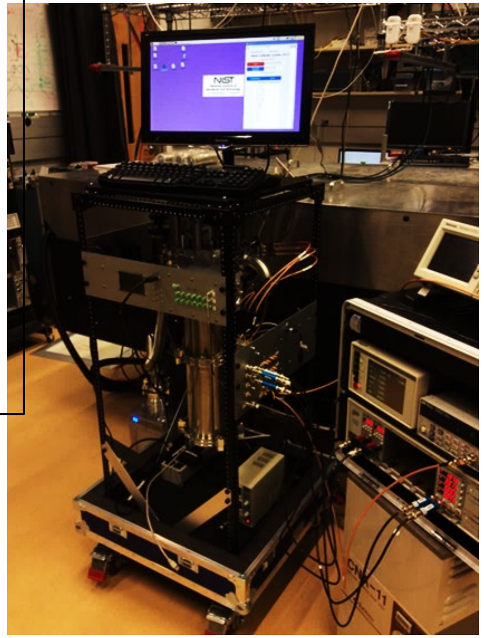
Experimental Complexity

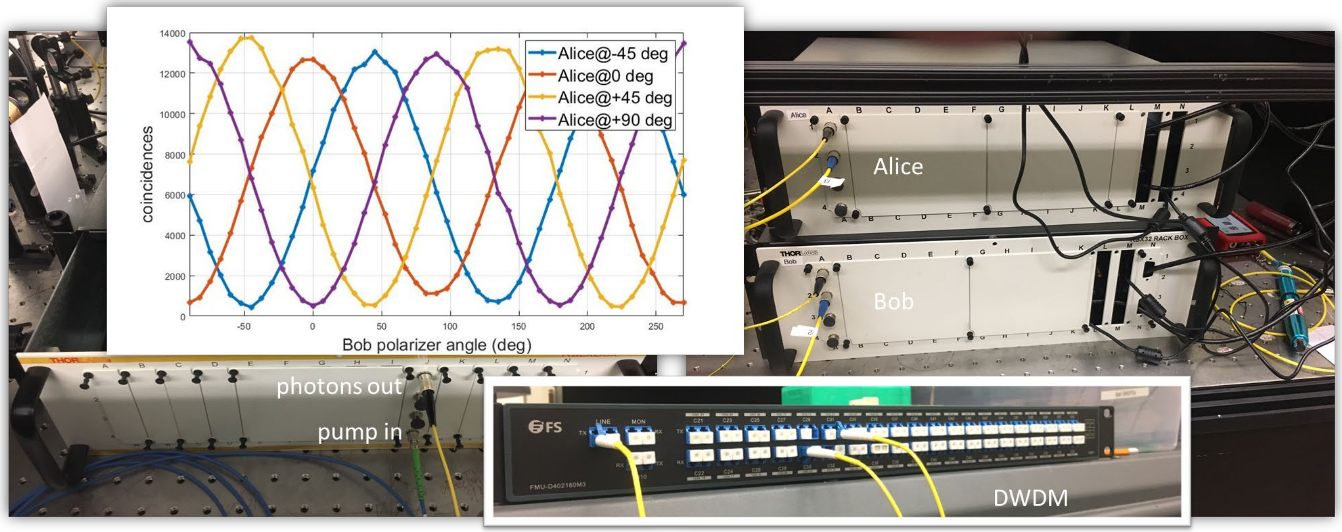
Quantum Network Characterization



Measurement suite:

- state generation and characterization
- beacon source of well-characterized photons
- channel noise & loss measurement
- timing synchronization
- polarization stabilization
- entanglement verification/quality control





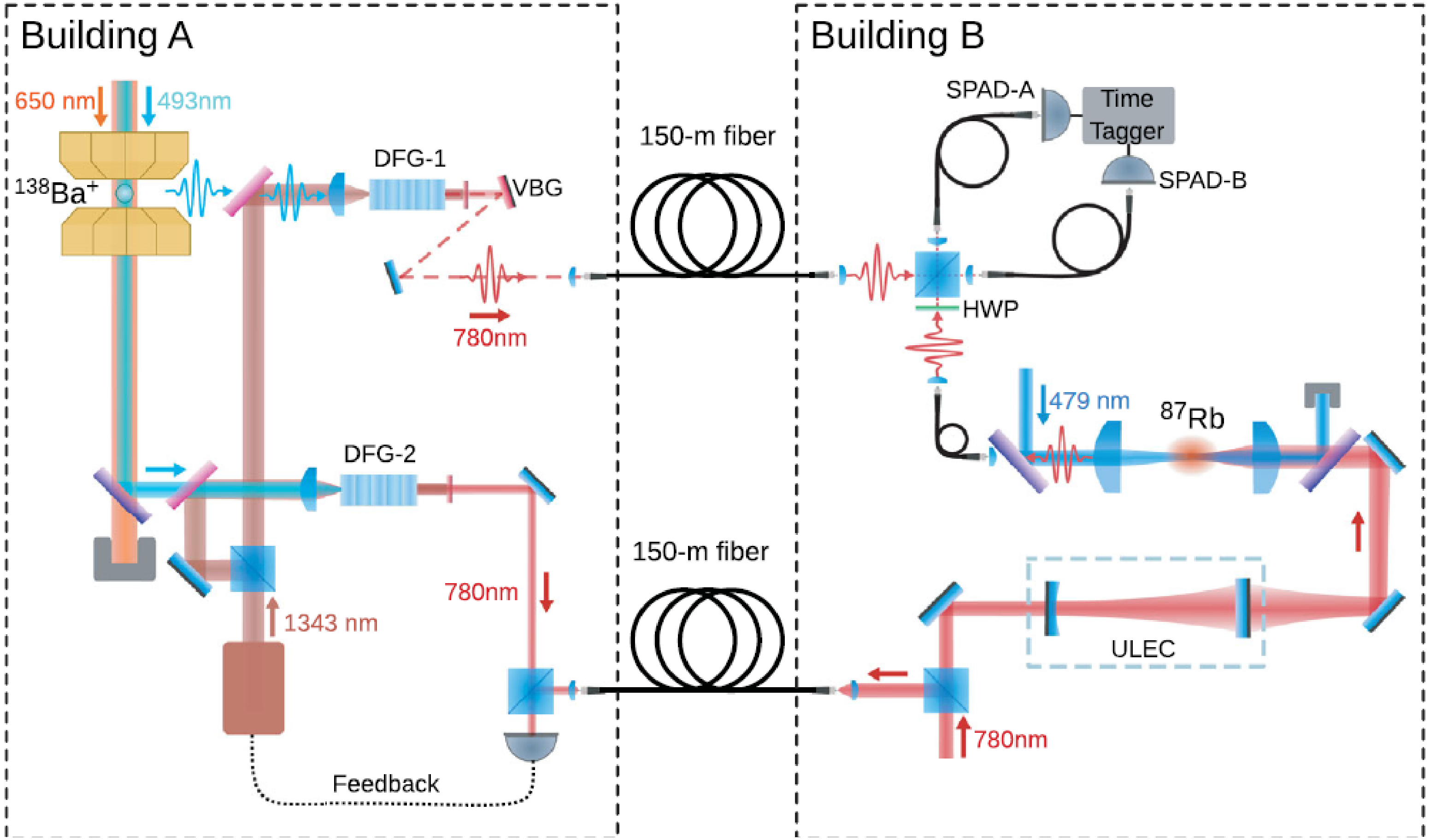
Key enablers:

- Calibrated single-photon detectors
- Calibrated *and deployable* entangled single-photon sources and receivers
- Metrology methods and protocols

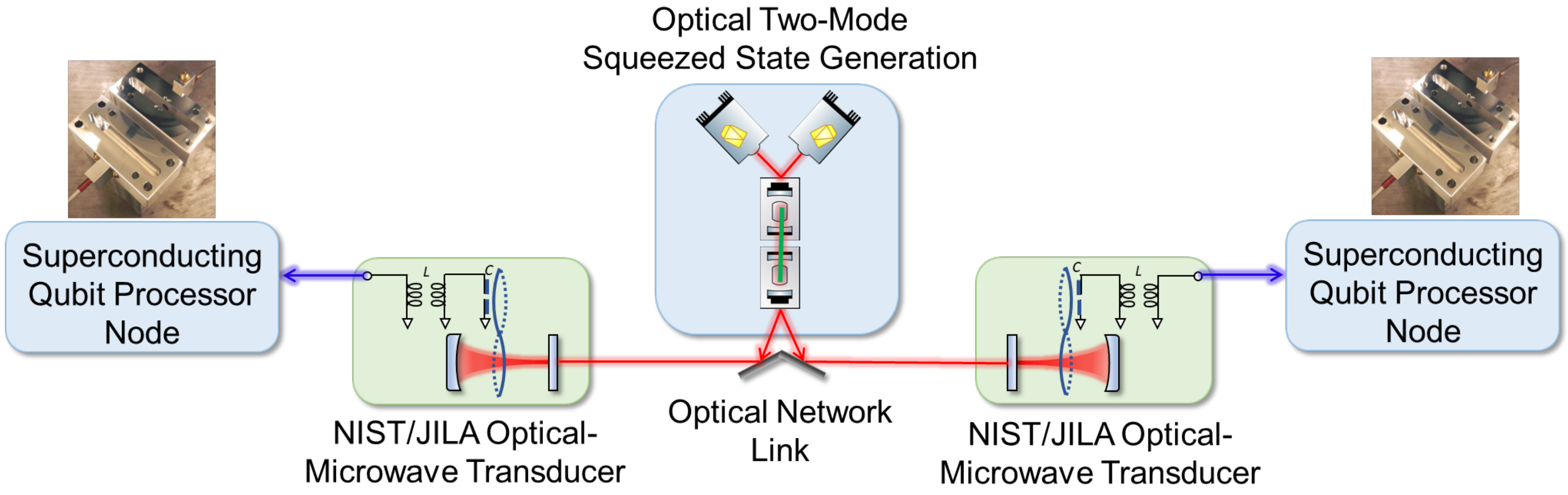
NIST Gaithersburg Testbeds

Hybrid Quantum Networking – NIST/UMD collaboration at JQI

Quantum interference between photons from ultracold atomic ensemble and an atomic ion in separate buildings



Networking Superconducting Qubits



Motivation:
- Quantum processor scaling
- Secure communications
- Sensing and metrology

Network Topology:
- Microwave down conversion of optical two-mode squeezing entanglement

Enabling Technology: Efficient vibrating membrane transducer

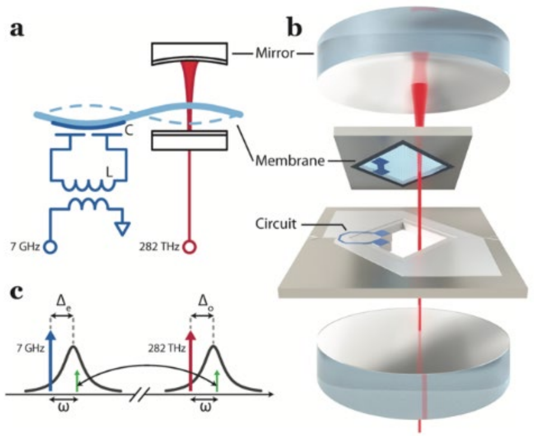


Image: NIST/CU-JILA

Key Approach: continuous squeezing operation overcomes transducer discrete photon added noise.

Our Experimental Goals:
- World's first remote microwave entanglement.
- Transducer generated microwave-optical squeezing.
- Metrology of injected squeezing-cavity interactions.
- Design/fabricate of modular, telecom-ready transducers.
- Develop quantum-enabled networking protocols.

- *Entanglement Thresholds of Doubly Parametric Quantum Transducers*, Phys. Rev. Applied, V17, 2022.
- *Optically distributing remote two-node microwave entanglement using doubly parametric quantum transducers*, Phys. Rev. Applied, 2023.

NIST Boulder QN Testbeds

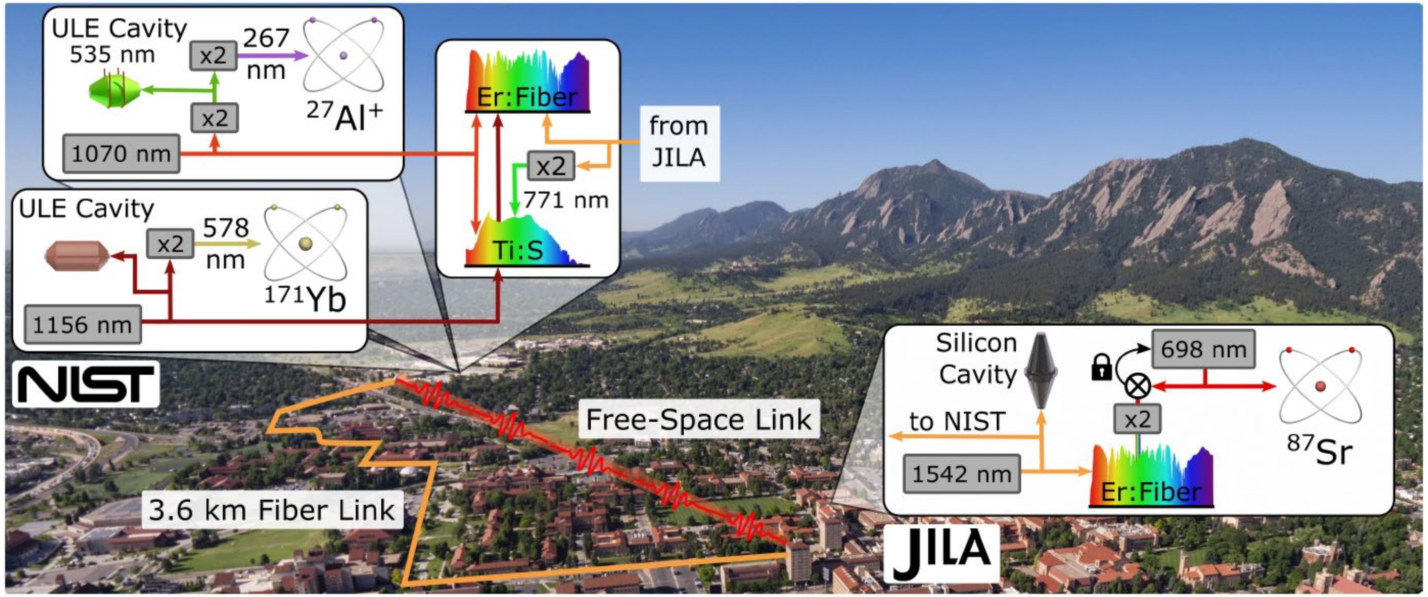
NIST

Optical network (fiber and free-space) with nodes at NIST and CU Boulder

Currently: Developing entanglement swapping scheme using two heralded photon sources (one at NIST and the other at CU Boulder) to establish entanglement across a lossy public channel.

Ultimately: Add quantum information processors at nodes (trapped ion, superconducting, neutral atom). Add quantum repeater (trapped ions).

Optical atomic clock network between NIST and JILA



Comparing optical lattice clocks and trapped ion clock using frequency combs and optical networks (fiber and free-space)

Three record breaking optical clocks: $^{27}Al^{+}$ trapped ion, and ^{171}Yb and ^{87}Sr atoms in optical lattices

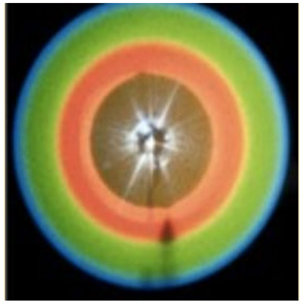
Quantum Economic Development Consortium

QED-C ‘Use Case’ Technical Advisory Committee:

- Has ‘Communications & Security’ subcommittee with >20 industry members, and engagement from several government agencies (DOE, DHS, DIU, NSA, and NIST)
- Conducted a review of approaches to the implementation of an entanglement swapping quantum network, with quantum memory and a quantum repeater.
- Identified the key players and their approaches to developing quantum memory and quantum repeaters
- Addressing the QKD initial authentication problem identified by the NSA.
- Strong interest in Post-Quantum Cryptography (PQC) algorithms and deployment of these.

QED-C Report

Single-Photon Measurement Infrastructure for Quantum Applications:
Needs and Priorities



12/21/2021

Thank you!

NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

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NSF PERSPECTIVES ON QUANTUM NETWORKING RESEARCH

Denise Caldwell
Acting Assistant Director, Mathematical and Physical Sciences
National Science Foundation
November 3, 2023

NSF Priority Goals in QIS

Explore Quantum Frontiers

Discover Principles Overcome Challenges

Support strong NSF centers and programs for science & engineering underpinning QIST

Accelerate Innovation

Pioneer QIST Applications

Foster use-inspired & translational research, end-users, partnerships, co-design, prototypes

Expand Participation

Engage the Full U.S. Complement of Talent

Enable multidisciplinary collaboration, training via research, innovation and advances in EDU

Develop Infrastructure

Ensure Access to Key Facilities & Instruments

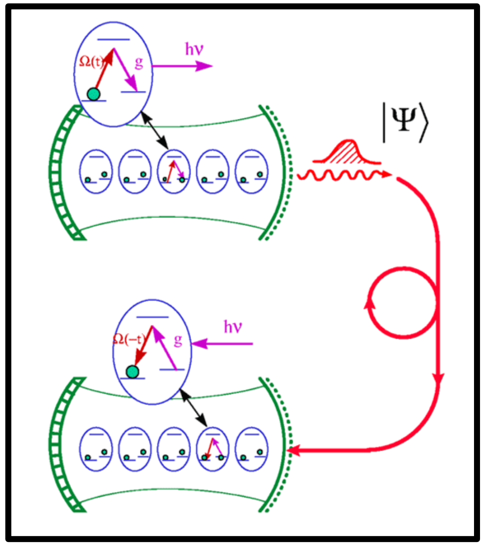
Upgrade & coordinate centers, foundries, and a National Quantum Virtual Laboratory

Learn more at: www.nsf.gov/quantum

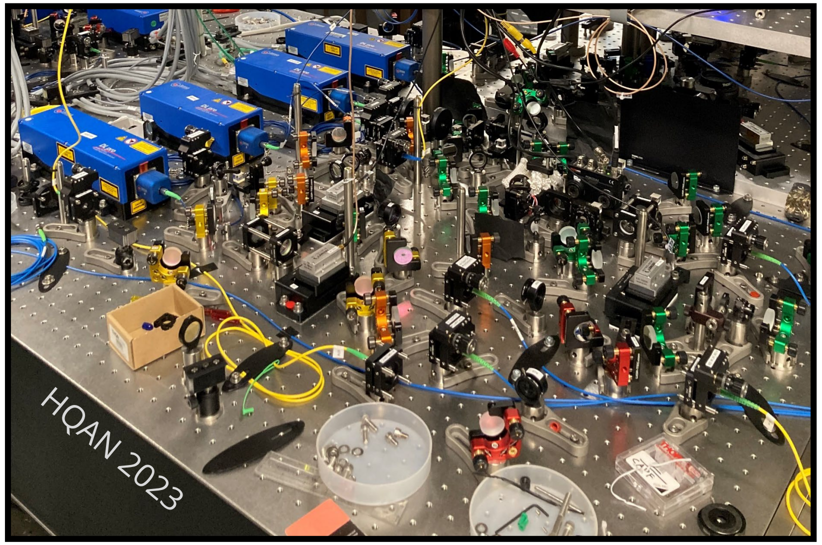
NSF Perspectives on Quantum Networking

Briefing for NQIAC, November 3, 2023

Denise Caldwell, NSF Acting Assistant Director for Mathematical and Physical Sciences



1999 QIS Workshop



Over 570 projects on Qu. Networks

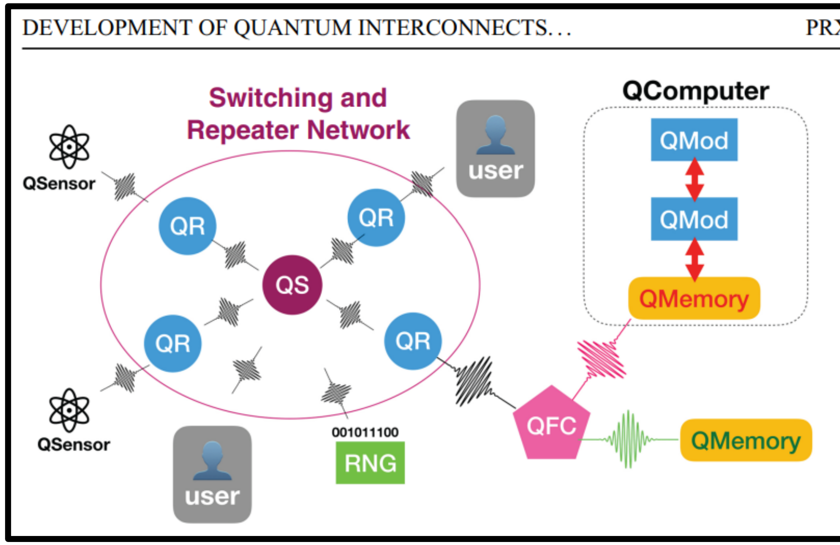


FIG. 1. The broad role of QuICs in quantum information technology. QS, quantum switch; QR, quantum repeater (a device that can relay an entangled state from one set of qubits to a distant set without physically sending an entangled qubit the entire distance); QMod, modular quantum processor; QFC, quantum frequency converter; RNG, random-number generator. The QuICs are indicated by bold red arrows or by wave packets representing photons.

2019 Quantum Interconnects Workshop

Vision → Testbeds → Discoveries

NSF Quantum Networking (QN) Portfolio

Number of Awards with selected QN keywords

192 "quantum network*"
274 "quantum communication"
78 "quantum memory"
40 "quantum internet"
57 "quantum repeat*"

- 570 Awards
- 145 Institutions
- 650 Faculty
- 410 Postdocs
- 2530 Students
- 1340 Publications

Combined: 570 unique Awards ($398M) during 2000 to 2023.
Currently Active: 180 Awards ($170M) started in 2019 to 2023.

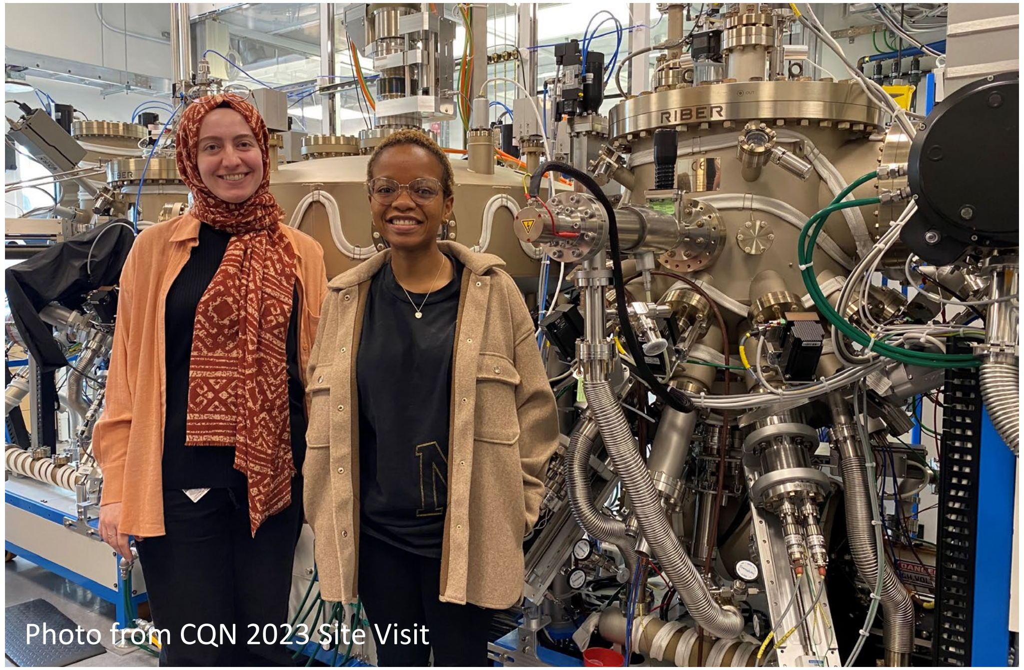


Photo from CQN 2023 Site Visit

Two Examples with QN Testbeds:

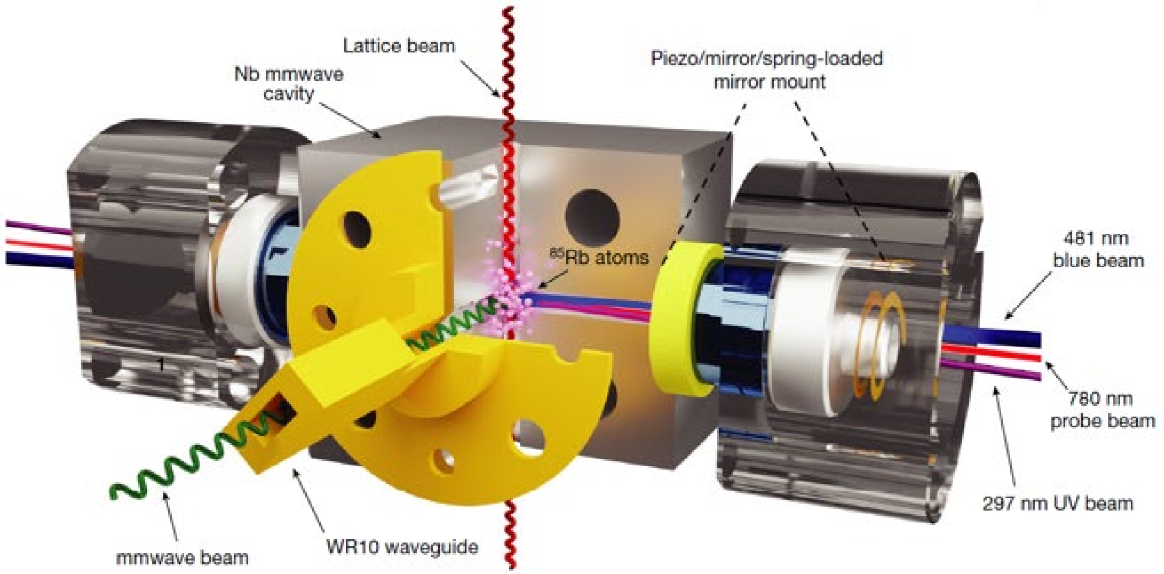
NSF Engineering Research Center for Quantum Networks (CQN); Award #1941583; Lead: U. of Arizona; $20,971,912.
PI: Saikat Guha; Leandros Tassiulas, Marko Loncar, Dirk Englund; Start: 09/01/2020

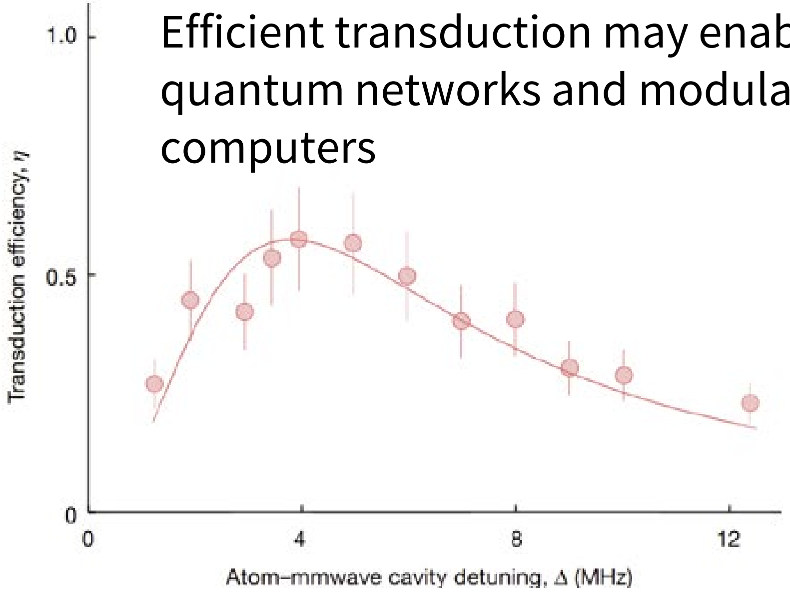
NSF QLCI for Hybrid Quantum Architectures and Networks; Award #2016136; Lead: U. of Illinois; $24,299,419.
PI: Brian DeMarco; Elizabeth Goldschmidt, Paul Kwiat, Hannes Bernien, Mark Saffman; Start: 09/01/2020

NSF

Science Highlight

Microwave to Optical Photon Transduction With Greater Than 50% Efficiency

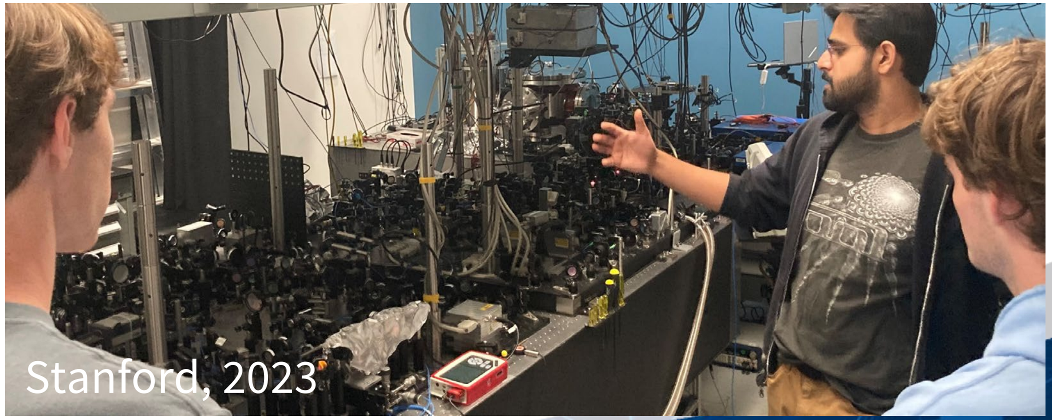




Efficient transduction may enable hybrid quantum networks and modular quantum computers

Demonstrated at U. Chicago and Stanford, with QLCI HQAN. Rydberg atoms in superconducting and optical cavities convert microwave to visible photon states.

Kumar, A., Suleymanzade, A., Stone, M. et al. “Quantum-enabled millimetre wave to optical transduction using neutral atoms.” Nature 615, 614–619 (2023).



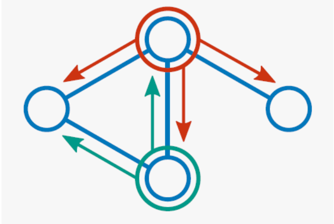
NSF QuIC-TAQS Program

Quantum Interconnect Challenges for Transformative Advances in Quantum Systems

- $25 Million for 10 Awards (2021)
- Interdisciplinary groups of 3 PIs
- Builds upon ENG EFRI-ACQUIRE

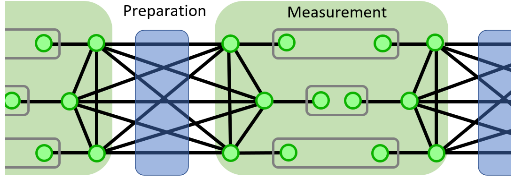
- 2023 QuIC-TAQS Workshop
- EXAMPLES:

Multipartite Entanglement



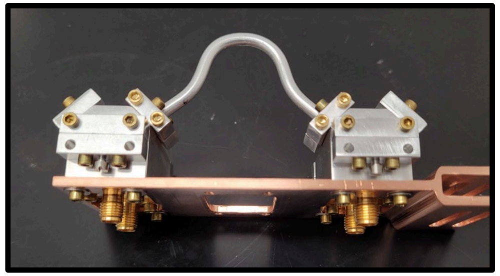
UIUC Mathematics

Uses of Graph States and Cluster States



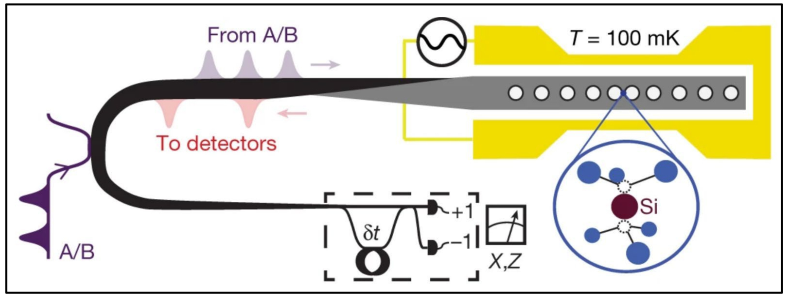
Virginia Tech

Qubit Interconnects



UIUC Physics

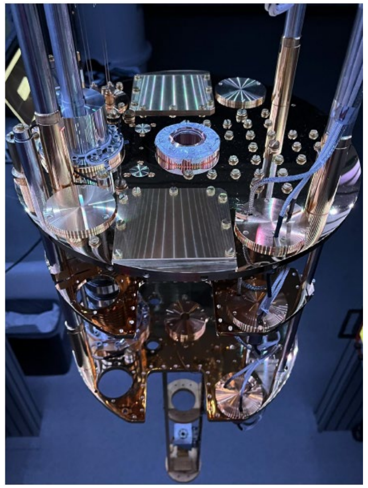
Quantum Memory, Repeaters



Harvard/MIT, Nature 580, 60–64 (2020)

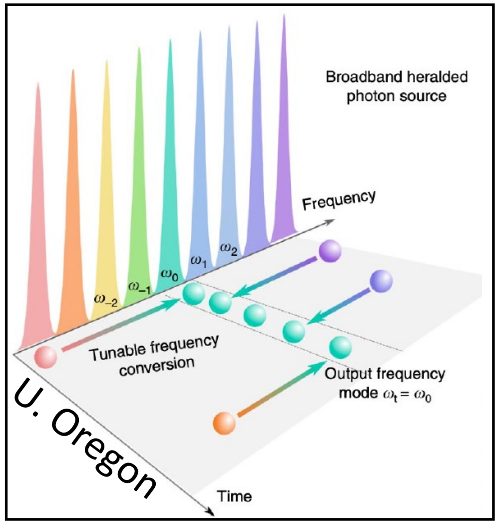
Experimental demonstration of memory-enhanced quantum communication

Defect Qubits

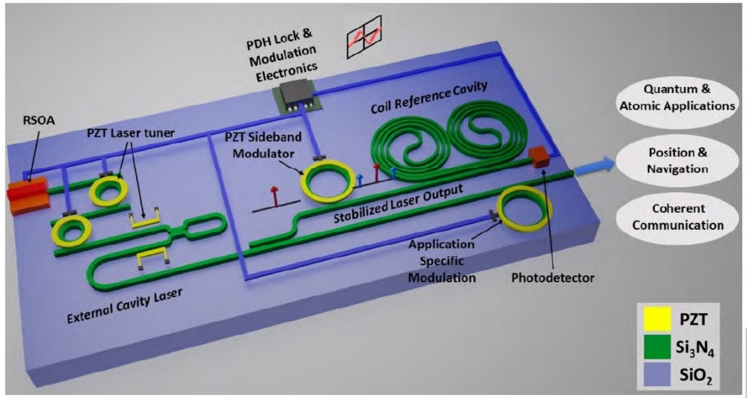


CU Boulder

Heralded Photons



Photonic Integrated Circuits



UCSB, Optics Express 30.18 (2022)

Expanding Capacity in Quantum Information Science & Engineering (Expand-QISE)

To broaden and increase participation in QISE…

Track 1 – nascent activity

Track 2 – with resources connected to QLCI

First cohort, 11 awards ($21.4M)

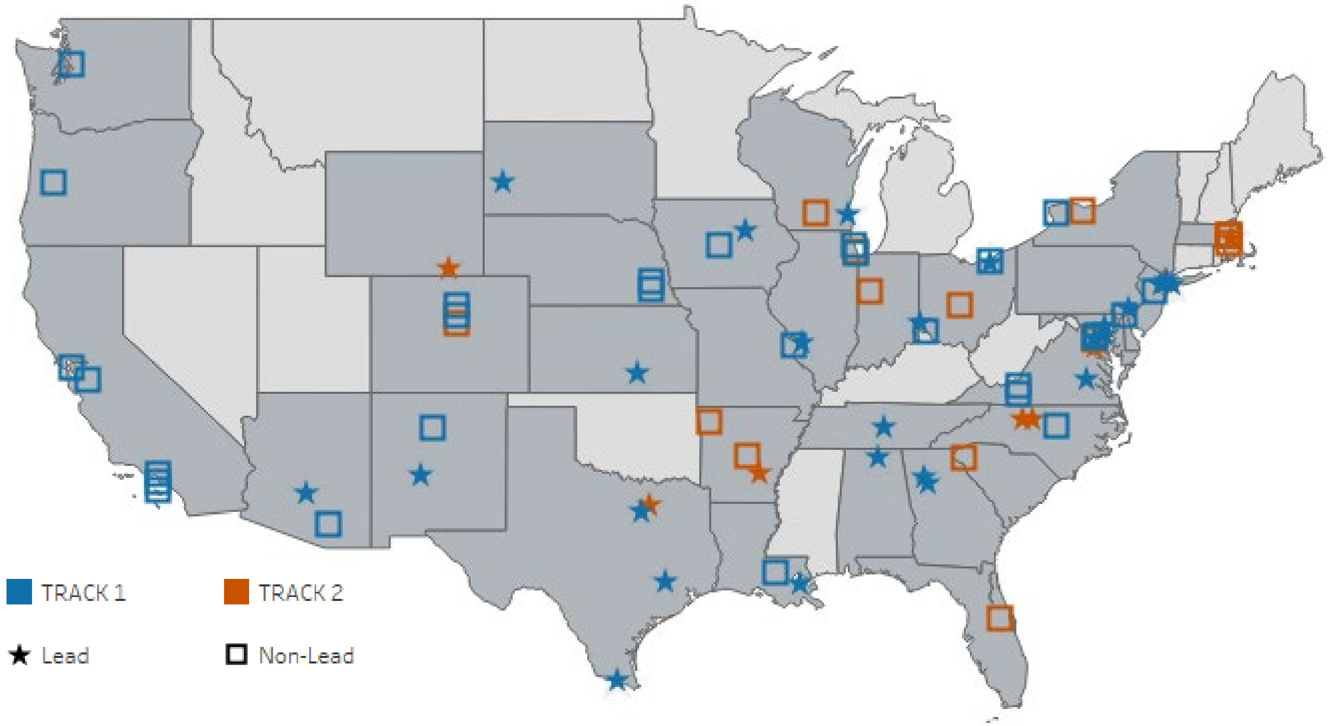
- 3 HBCUs, 3 HSIs, 4 EPSCOR states
- 8 Track 1 awards
- 3 Track 2 awards

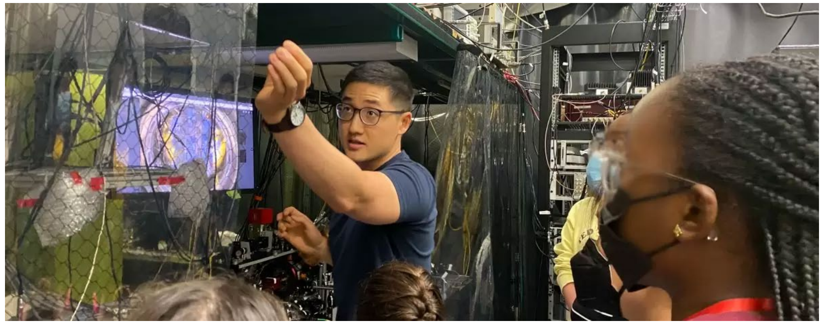
Second cohort, 22 awards ($37.5M)

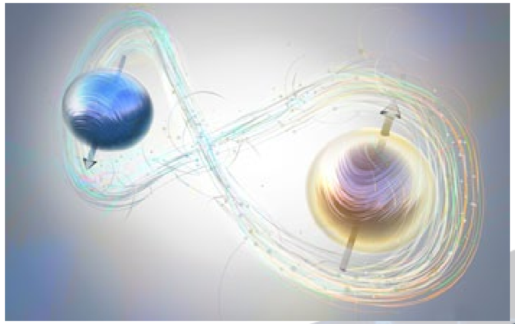
- 6 HBCUs, 3 HSIs, 8 EPSCOR states
- 17 Track 1
- 5 Track 2

Focus Areas:

- Quantum Fundamentals,
- Quantum Metrology and Control
- Co-Design and Quantum Systems
- Education and Workforce Development (ALL)







Press Release:
https://new.nsf.gov/news/more-institutions-participate-quantum-science

NSF National Quantum Virtual Laboratory

2022 Workshop, Accelerating Progress Towards Practical Quantum Advantage: The Quantum Technology Demonstration Project Roadmap“

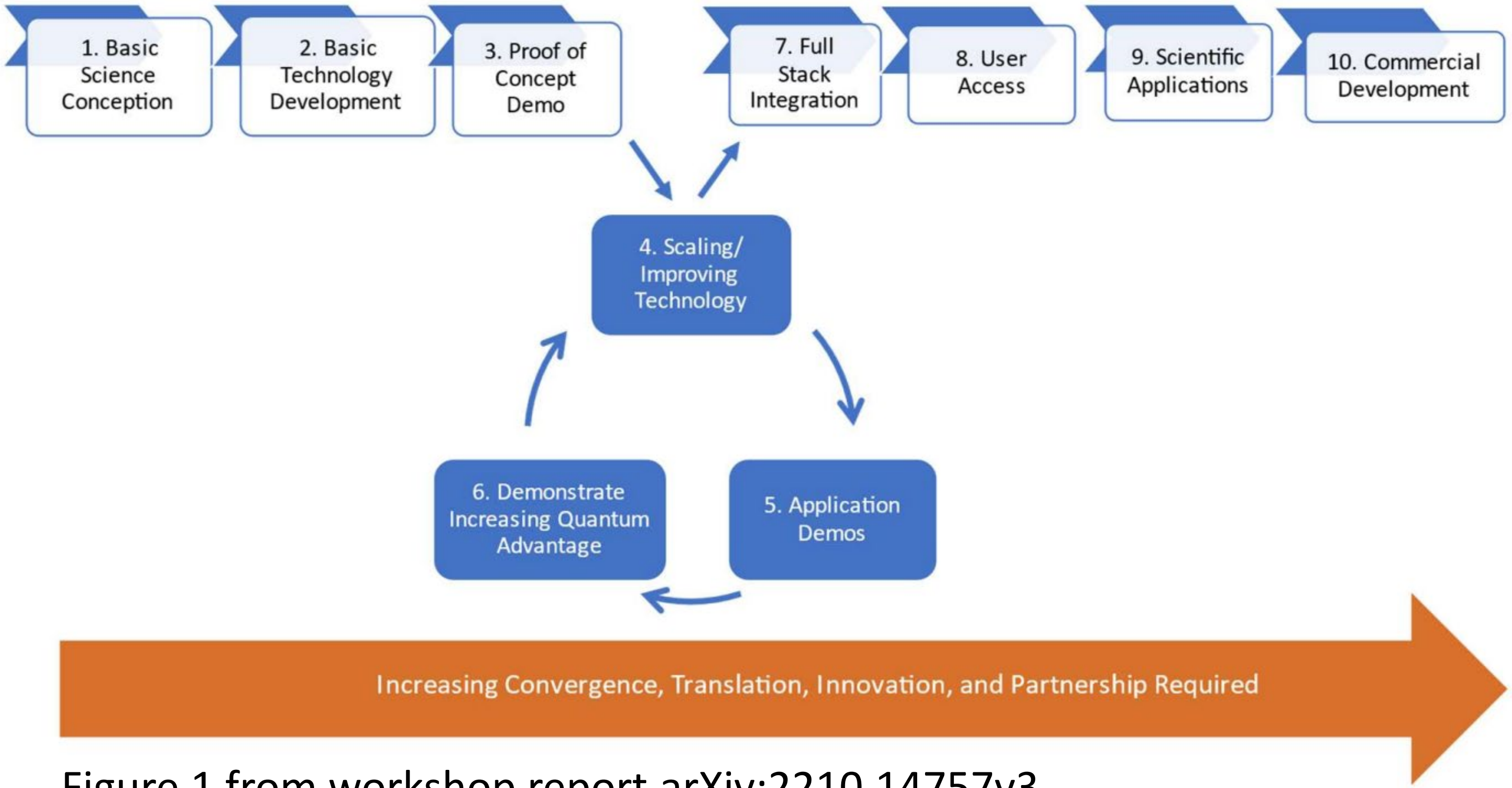


Figure 1 from workshop report arXiv:2210.14757v3

Solicitation NSF 23-604 (7/17/2023)
Webinar (9/8/2023)
Pilot, Design, and Implementation.

Co-design

Integrate end-users into cycles of development with dicoverers, innovators,

Contributors

Across diverse networks of centers, core programs and Expand-QISE teams

Prototypes

Widely available tools and materials lower barriers for QT users to pioneer & test new applications

Thank You – Questions?

Agenda

Time (pm EST)	Topic
1:00 – 1:05 (5 min)	*Opening Remarks* • Dr. Kathryn Ann Moler and Dr. Charles Tahan, NQIAC Co-Chairs
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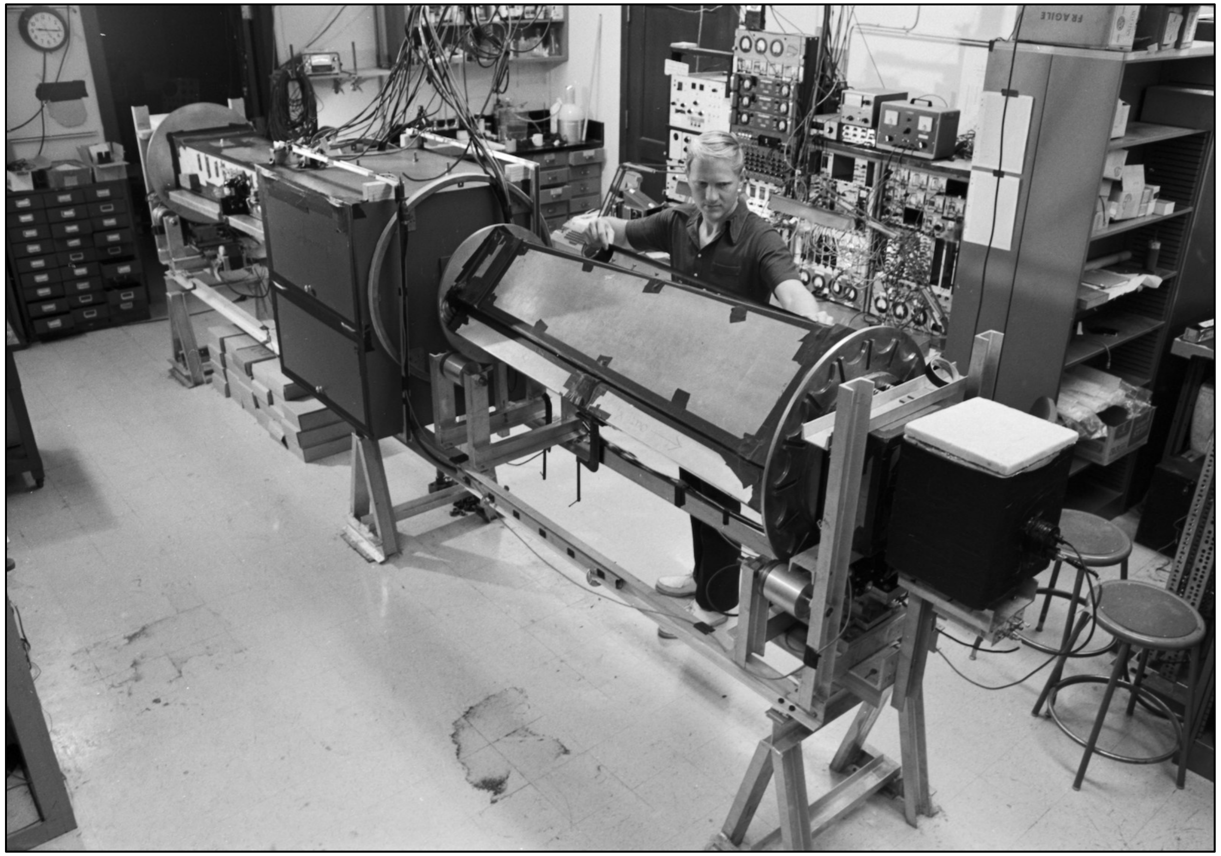
Quantum Networking Activities

Dr. Ceren Susut

Associate Director of Science for Advanced Scientific Computing Research (ASCR)

QIS in DOE is a Long-Term Effort

- DOE investments enabled steady progress on critical fundamental technical fronts.
- QIS is embedded in our core basic research programs.
- DOE's multi-pronged strategy is essential and builds on community input:
  - Core basic research
  - Center-scale efforts that facilitate public-private partnerships
  - Unique infrastructure development
  - Critical supporting technology
  - Workforce development



John Clauser, Nobel Prize in Physics, 2022 for experiments with entangled photons conducted at LBNL in 1972

Quantum Networking across Solicitations

Research and Development

- Supported through multiple QIS funding opportunities, lab calls
- Solicitations issued 2019-2023
- DOE national labs, universities, industry, and centers involved
- Development of prototypes and testbeds supported

Workforce

- Lab scientists, university faculty, postdocs, students
- Small businesses

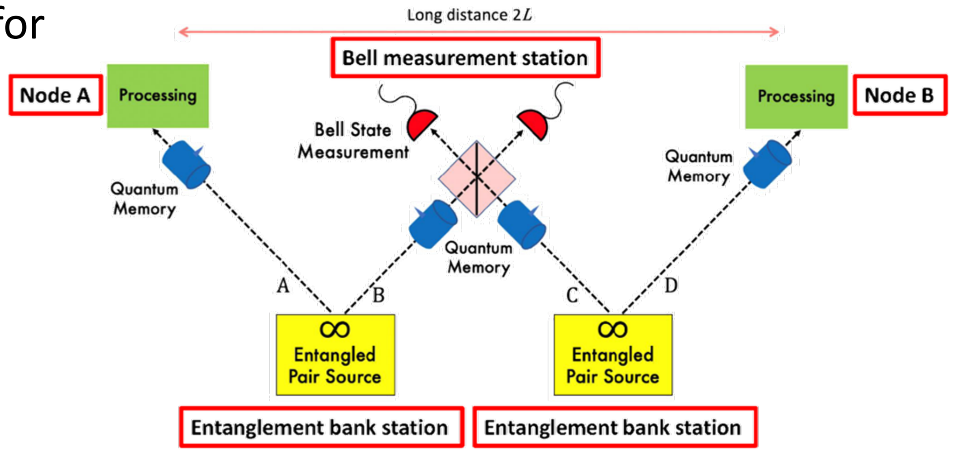
2019	2020	2021	2022	2023
Transparent Optical Quantum Networks for Distributed Science $12M	**National Quantum Information Science Research Centers** $100-620M	**Entanglement Mgmt. & Ctrl. in Transparent Optical Quantum Networks** $2.8M **Quantum Internet to Accelerate Scientific Discovery** $25M	**EXPRESS: Quantum Computing at the Edge** $3.5M	**Scientific Enablers of Scalable Quantum Communications** $24M

https://science.osti.gov/ascr/Research/Quantum-Information-Science-QIS

Quantum Networking R&D

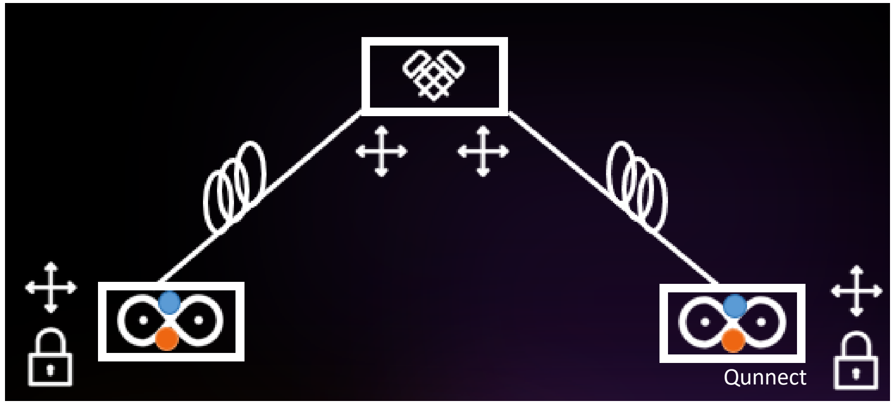
ASCR Vision

- Laboratories and User Facilities exchange quantum information for
  - integrating quantum sensors
  - making distributed quantum computers
  - enabling collaborative experiments



Recent Priorities

- Devices and components to advance repeaters
- Entangled photon generators and detectors
- Entanglement swapping-based network scaling
- Richer interconnecting topologies
- Scalable quantum network architecture, stack, protocols

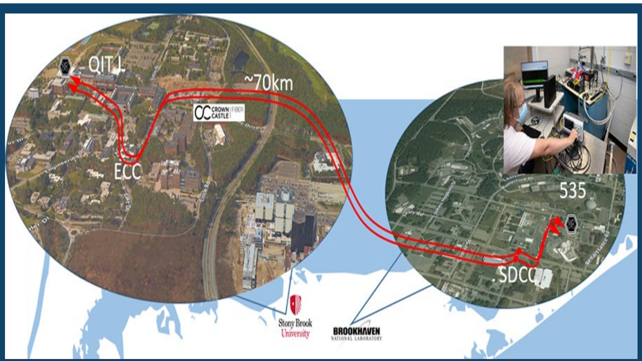


Supported Technical Topic Areas

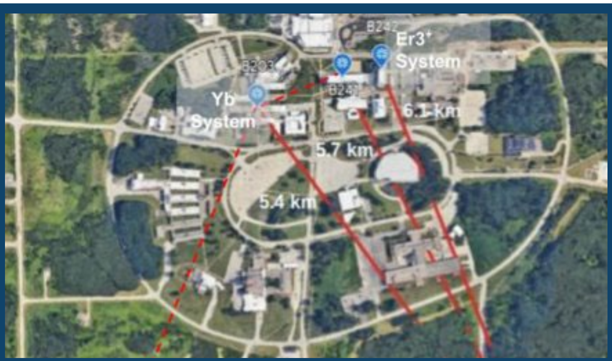
- Entangled qubit generation
- Transduction
- Squeezing
- Teleportation
- Entanglement swapping
- Quantum repeaters
- Quantum switching
- Quantum memories
- High precision time synchronization
- Classical-quantum integration
- Quantum communication over classical channels
- Quantum network architectures
- Quantum internetworking
- Error correction and mitigation in quantum networking

Quantum Network Testbeds

Quantum network demonstration infrastructure is being developed by National laboratories in partnership with universities and industry.

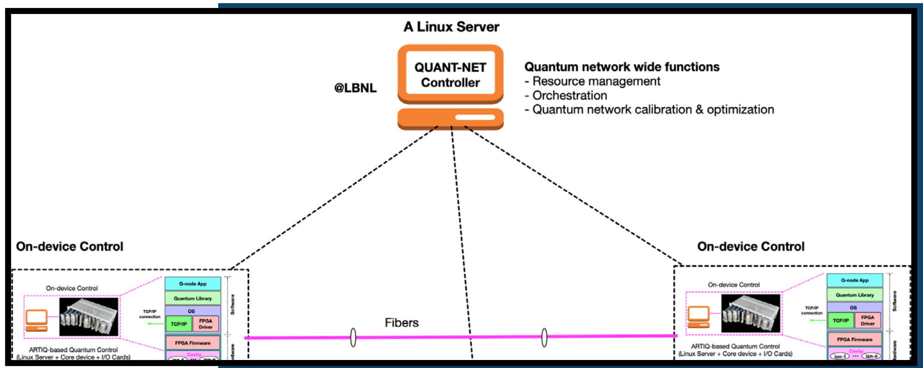


BNL/Stony Brook University

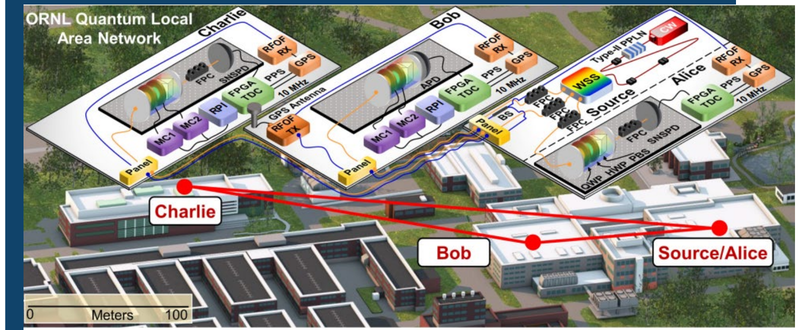


ANL/U Chicago

FNAL/ Caltech



LBNL



ORNL/LANL

Recent ASCR Solicitation LAB-23-3040
"Scientific Enablers for Scalable Quantum Communications"

- **Quantum Repeater Devices:** Development of one or more devices that could become essential components of an entanglement-based quantum network repeater in a scalable quantum network infrastructure.
- **Quantum Error Correction/Mitigation:** Discovery of error correction and mitigation techniques that remain effective as quantum networks are scaled up.
- **Quantum Network Architecture/Protocols:** Advances in scalable quantum network architectures, quantum network stack and associated communication protocols for optimal distributed management and control of quantum communications from local to national scales.

New Projects on Scalable Quantum Networking under LAB 23-3040

Project Title	Participating Institutions
InterQnet: A Heterogeneous Full-stack Approach to Co-designing Scalable Quantum Networks	Argonne National Laboratory (lead) Northwestern University University of Chicago University of Illinois Urbana-Champaign Fermi National Accelerator Laboratory
Advanced Scalable Quantum Networks for Science Discovery	Fermi National Accelerator Laboratory (lead) California Institute of Technology University of Illinois, Urbana-Champaign Northwestern University Argonne National Laboratory
PiQSci -- Performance Integrated Quantum Scalable Internet	Oak Ridge National Laboratory (lead) University of Massachusetts, Amherst University of Arizona Arizona State University

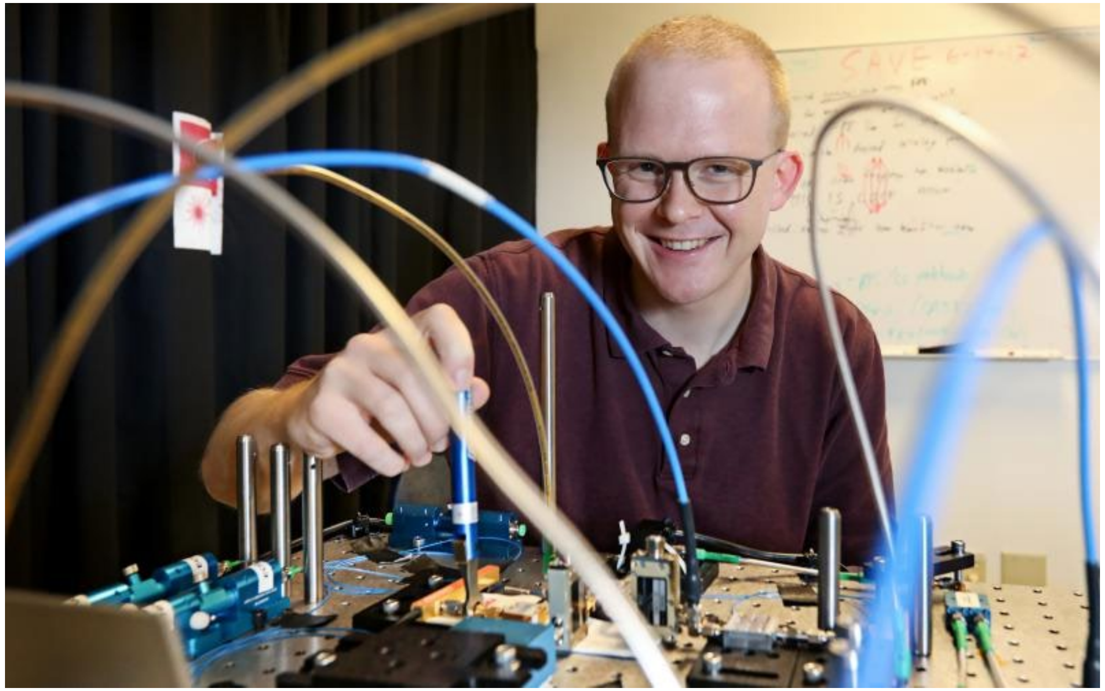
Giant leap toward quantum internet realized with Bell state analyzer

The Science

A multi-institutional team featuring Early Career Awardee Joe Lukens has made strides toward a fully quantum internet by designing and demonstrating the first ever Bell state analyzer for frequency bin coding. Measuring Bell states is critical to performing many of the protocols necessary to perform quantum communication and distribute entanglement across a quantum network. The team's method represents the first Bell state analyzer developed specifically for frequency bin coding, a quantum communications method that harnesses single photons residing in two different frequencies simultaneously.

The Impact

The analyzer was designed with simulations and has experimentally demonstrated 98% fidelity for distinguishing between two distinct frequency bin Bell states. This incredible accuracy is expected to enable new fundamental communication protocols necessary for frequency bins.



Early Career Awardee Joseph Lukens runs experiments in an optics lab. Credit: Jason Richards/ORNL, U.S. Dept. of Energy

Basic Research Needs Workshop

- Workshop was held in Gaithersburg, MD in July 2023
- Research community identified Priority Research Directions (PRD)
- PRD Brochure and Workshop Report are in preparation for release

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USD(R&E)

Defense Research in Distributing Entanglement

Briefing to National Quantum Initiative Advisory Committee

Principal Director: John H. Burke
November 2023

Quantum Science, Technology, and Engineering Areas

Quantum Science
Knowledge-driven

- Processes, Controls & Materials
- Harnessing Entanglement (e.g. quantum networking)
- Quantum Computer Science

Three kinds of research & development To answer **What, How & Why**

Success needs them all plus a workforce (the **Who**)

Quantum Technology
Applications-driven

- Navigation & Timing
- Spectrum, Imaging, & Detection (e.g. electomagnetic sensors)
- Computing

Quantum Engineering
Process-Driven

- Specialized Components
- Integration & Architectures

Using Distributed Entanglement is Challenging Outside of Computers

QUANTUM INTERCONNECT

- Critical path to full scale quantum computing
- Meter scale is sufficient
- Need faster entanglement generation and single photon source (SPS)

QUANTUM SECURE COMMUNICATIONS

- For key distribution: partial security solution only (e.g. doesn't provide means to authenticate)
- Requires special purpose equipment
- Increases cost and insider threat risk
- Validation of security is challenging
- Increases risk of denial of service attack

GEOGRAPHICALLY DISTRIBUTED COMPUTING

- No known application
- Latency and energy loss argue against
- Quantum computers will be special purpose so connections will be difficult to standardize
- Special purpose infrastructure may be expensive
- Q. Information can't be copied or shared, forcing a single user at a time, negating economic "networking effects"

IMAGING WITH ENTANGLEMENT

- Potential trust advantage (watermarking)
- Promise of performance, but only if working in a photon starved context with low channel loss (microscopy) (so no Quantum Radar)
- Advantage to local interferometric sensors/imagers sensing (e.g. LIGO using squeezing)
- Long Baseline Int appears infeasible w/o bright SPS or large quantum memory buffer

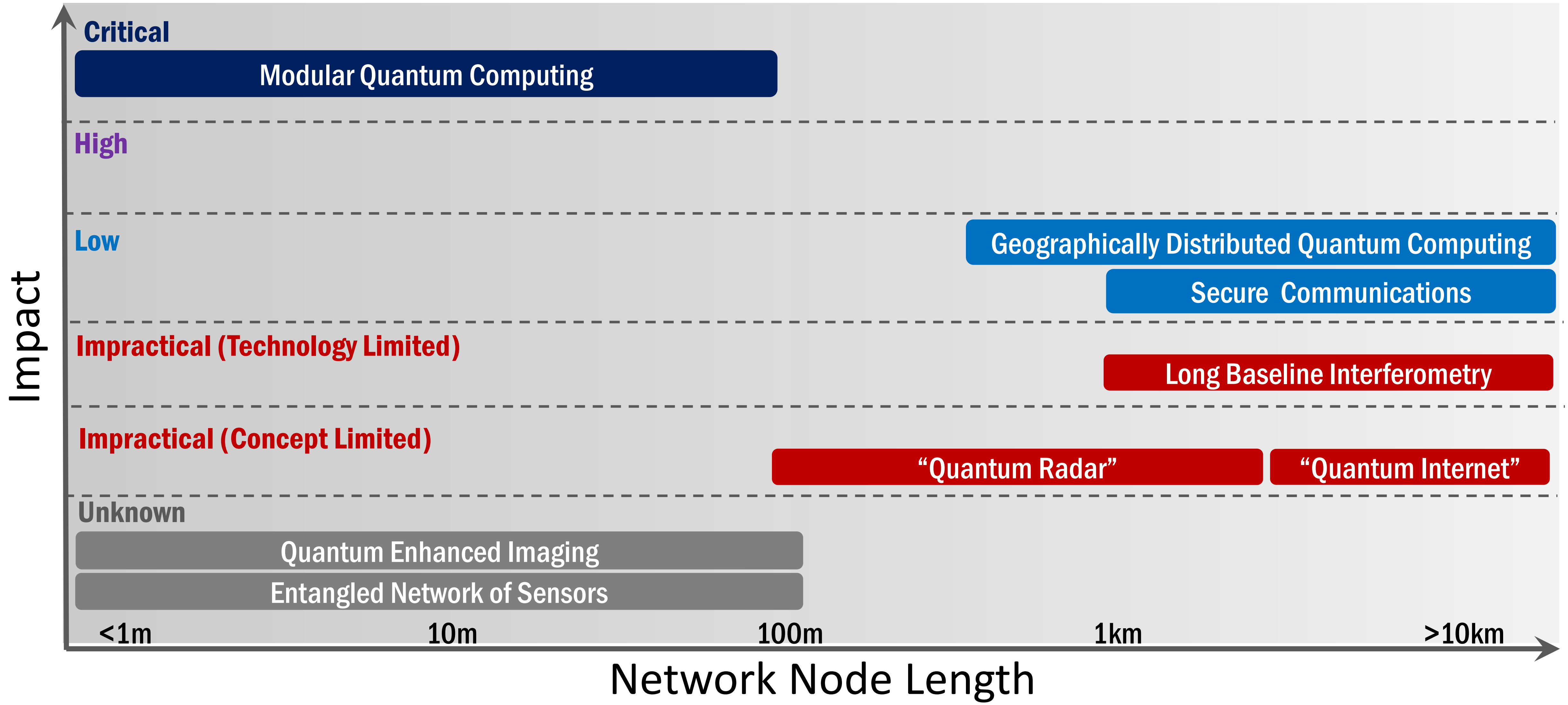
Distributed Entanglement: Current Applications Assessment

Assessment Source: [I]=DoD Funded Independent Study, [A]=Academic Literature [P]=Principal Director

Motivation Area	Application	Concept is relevant to DoD mission	Beneficial given implementation constraints and CONOPS analysis	Performance advantage (in principle)	Technological Feasibility
Compute Scaling	Modular (Building Scale) [A]	Y	Y	Y	Y
	Geographic Scale [P]	?	N	?	N
Metrology/ Imaging	Very Long Baseline Interferometry [I]	Y	Y	Y	N
	Quantum Radar [I]	Y	N	N	N
	Increased Resolution [A]	Y	?	Y	?
	Entangled Satellite Clock Network [A]	Y	?	Y	?
	Entangled Magnetometer Network [A]	Y	?	?	?
Security	Quantum Key Distribution [I]	Y	N	Y	Y
	Blind Computing [A]	?	?	?	?
Increased Utility	Multi-user Quantum Network [P]	N	N	N	N

Further fundamental research needed to discover novel applications and the applicability and practicality of quantum networks to the DoD mission. All assessed concepts are particular proposed approaches.

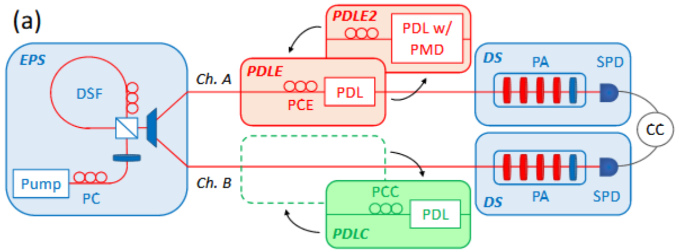
Distributed entanglement :
-Significant science needed to establish applicability of quantum networks
-Quantum interconnects for quantum computing is critical



DEVCOM ARL Quantum Network Activities

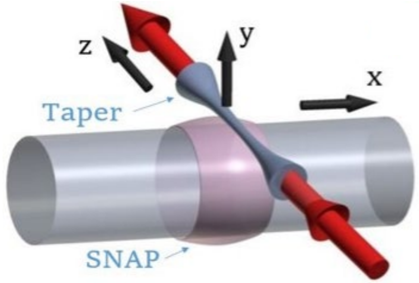
Intramural Efforts focus on 1) physical nodes for high-fidelity quantum memories and 2) protocols and components required for entanglement distribution that is agnostic to eventual use case.

Mitigate Decoherence and Noise



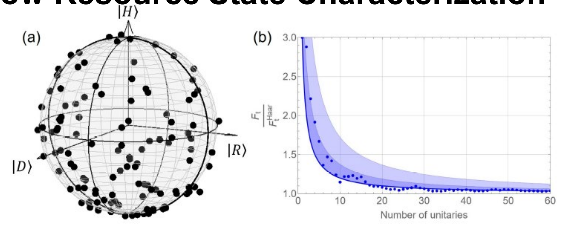
D. E. Jones, et. al., NJP. 22 073037 (2020).

Low-Loss Components

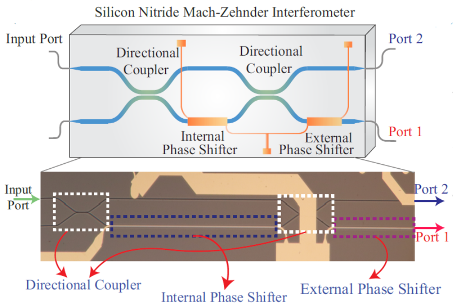


Opt. Exp. 28.18 (2020): 25908-25914.

Low Resource State Characterization

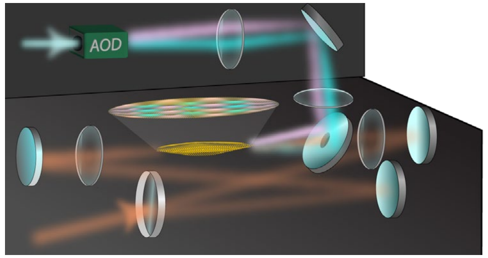


N. Wyderka, et al. Phys. Rev. Lett. 131, 090201 (2023)



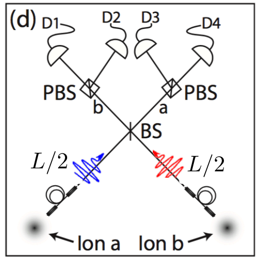
Phys Rev Applied 19.3 (2023): 034001.

Spinwave Quantum Node

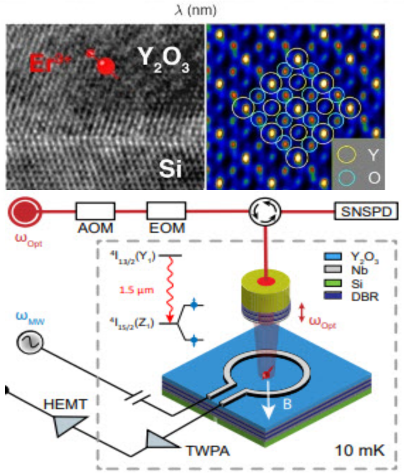


Phys. Rev. Research **4**, 033149 (2022)

Yb+ ion entanglement

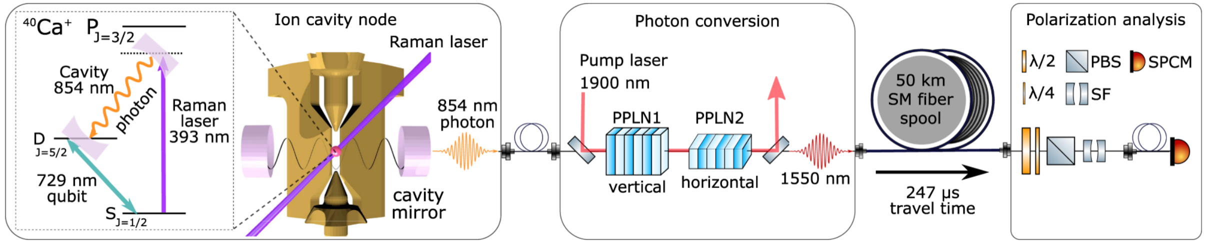


Extramural Efforts have single investigator (SI) projects targeting component development and team projects targeting approaches and use cases for robustly distributing entanglement



***SI Exemplar**: Engineering rare-earth hyperfine qubits*
Exploring new solid-state long lived rare-earth ion qubits doped in epitaxial thin film hosts with telecom optical transitions.
Key Result: Achievement of millisecond coherence times and under a 3 kHz optical dephasing rate with optical and microwave control in a package amenable for scaling. This paves the way for a type of large-scale development of quantum light-matter interfaces for quantum networks.

***Center for Distributed Quantum Information (CDQI) Exemplar**: Scalable Ion Trap Quantum Networks* Elucidating how to realize the simultaneous entanglement of three distributed quantum network nodes and develop and demonstrate a range of techniques that will allow the network to scale and interface with other quantum systems for applications.
Key Result: Demonstration of entanglement between matter and photonic qubits over 50km of optical fiber, two orders of magnitude further than the state of the art (at the time of publication) and a practical distance for quantum networks.



POC: Fredrik Fatemi, fredrik.k.fatemi.civ@army.mil

U.S. NAVAL RESEARCH LABORATORY

Navy Quantum Networking

Basic research on interfaces between stationary and flying qubits:

- Quantum memories
- Single- and entangled-photon sources
- Telecom wavelength transduction
- Deterministic quantum repeater components
- (Theory) Error propagation in quantum networks

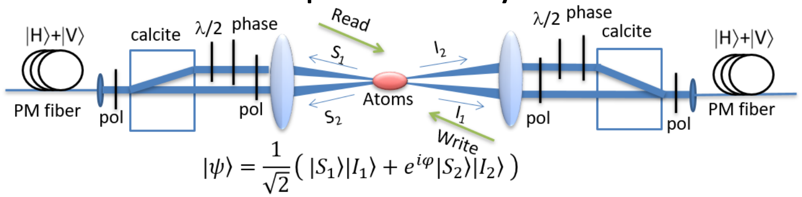
Physical systems:

- Rydberg-coupled cold neutral atoms
- Quantum dots
- Solid-state color centers
- Photonic integrated circuits: microring resonators, photonic crystals

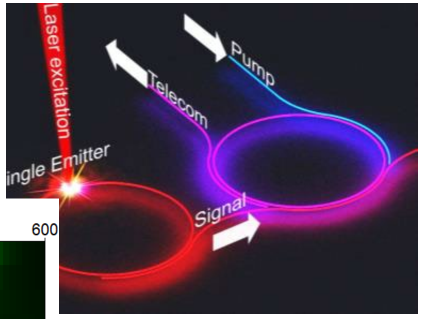
Quantum networking testbed development and demonstration:

- Washington Metro Quantum Network Research Consortium (DC-QNet)
- Planned participation in DARPA QuANET government integration team
- Network node development: telecom switches, entangled photon sources, detectors, synchronization
- Fiber characterization and stabilization (polarization, transit time)
- Related photonics development under DOD ME Commons
- Fundamental research on use cases for distributing entanglement between sensors in a network

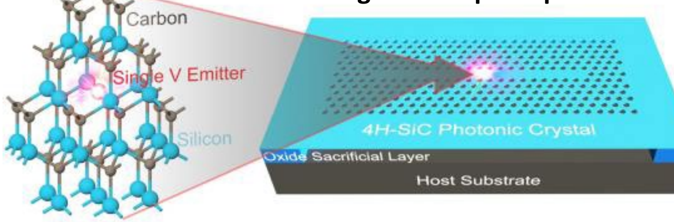
Atomic quantum memory

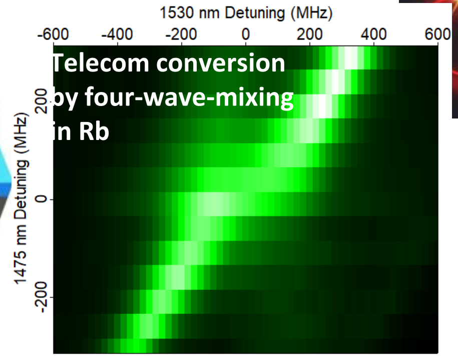


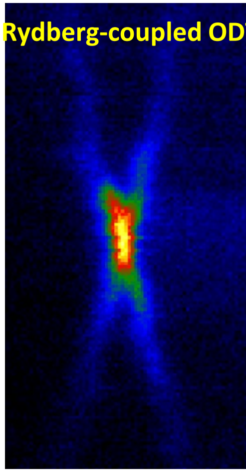
Telecom quantum emitter



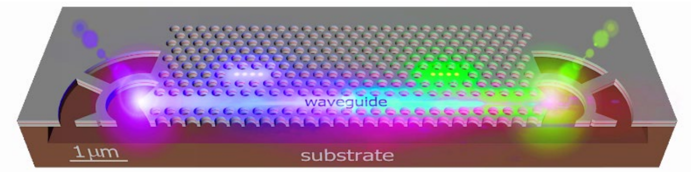
Waveguide-coupled spin defect



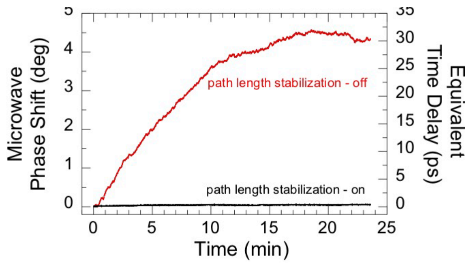




QDs integrated into photonic architecture



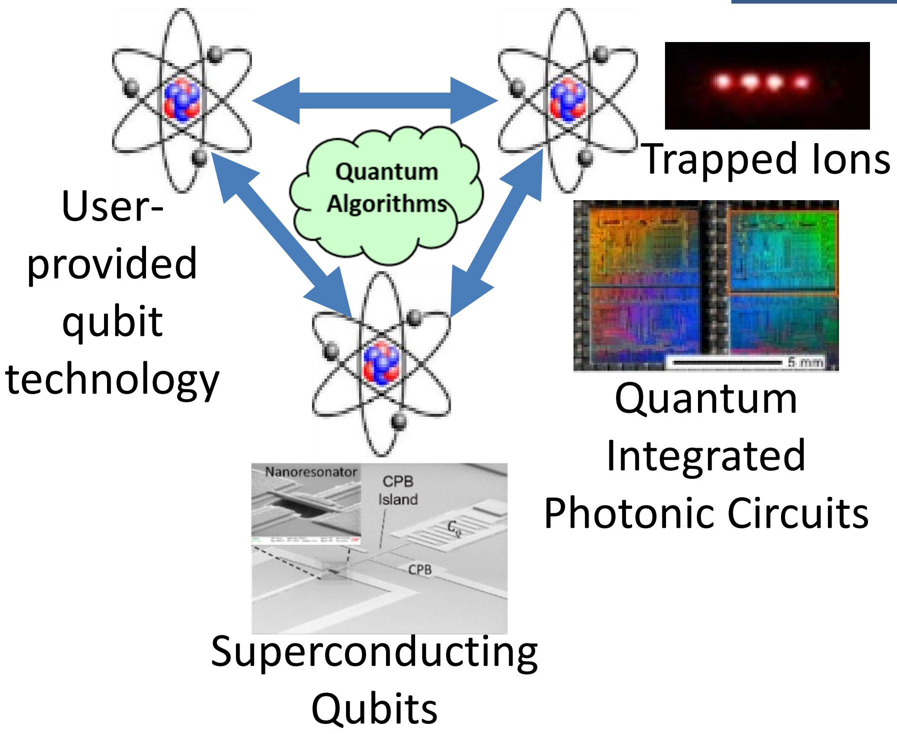
Fiber stabilization



AFRL Quantum Networking Distributed Testbed

Innovare Advancement Center

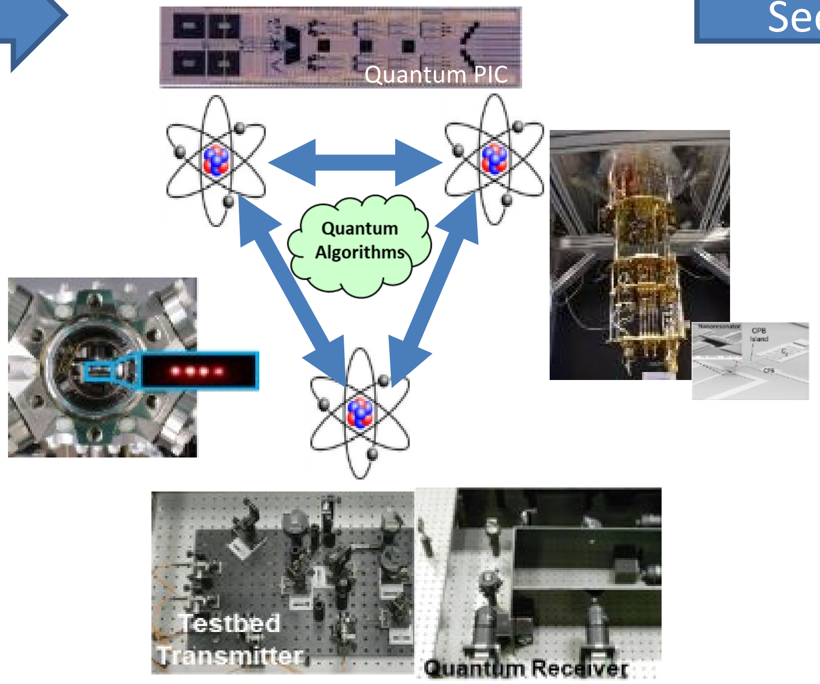
Seed



Basic research focusing on heterogeneous interfaces and preliminary network connections and protocols

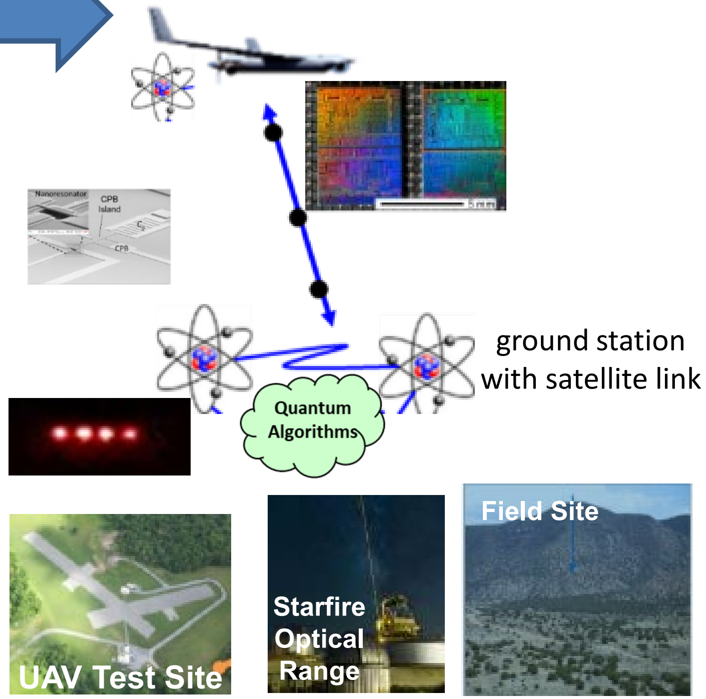
In-House Laboratories

Seed



Applied research focusing on heterogeneous network integration and advanced networking and quantum algorithm protocols

Test Sites



Advanced test demonstrations. Can support ground-ground, ground-air, and ground-space links. Can be host clocks, sensors, distributed computing elements.

Basic — Provides distributed testbed to cross all technology (basic to applied) needs — Applied

Quantum Augmented Network (QuANET)

- **Goal:** develop quantum-augmented networks
  - with novel security and covertness properties inherent in quantum communications
  - Classical non-quantum network infrastructures currently trade security against interoperability

QuANET will develop

- the hardware, protocols and software tools
- required for missions and critical infrastructure,
- enabling the first viable transition strategy to operationalize quantum communications

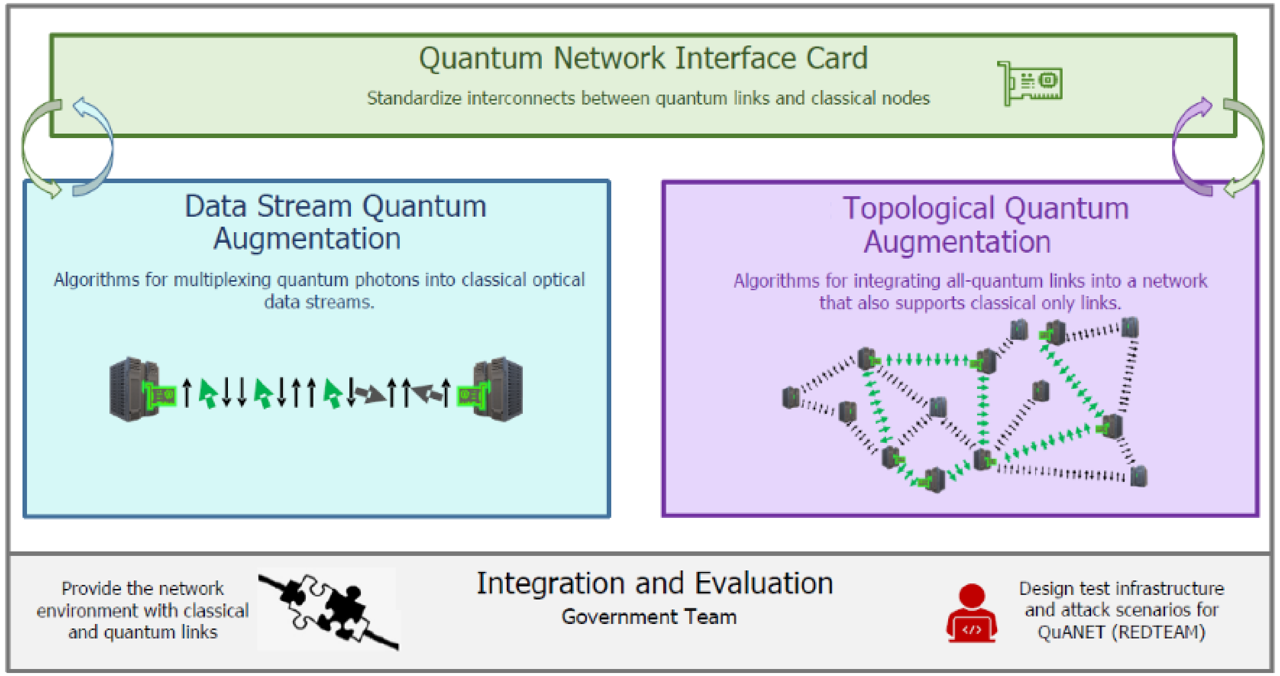


Figure 1: QuANET Program Structure

Source: HR001123S0035, https://sam.gov/opp/60917f7ea74845bf8f6aaa1382813f86/view

Implement the world's first operationally fielded quantum-augmented network

TCP/IP- Transmission Control Protocol/Internet Protocol

Agenda

Time (pm EST)	Topic
1:00 – 1:05 (5 min)	*Opening Remarks* • Dr. Kathryn Ann Moler and Dr. Charles Tahan, NQIAC Co-Chairs
1:05 – 1:30 (25 min)	*National Quantum Networking Strategy* • Dr. Tanner Crowder, Policy Analyst at the National Quantum Coordination Office, Co-Chair of the SCQIS Interagency Working Group on Quantum Networking
1:30 – 1:50 (20 min)	*Quantum Networking Activities at NIST* • Dr. Jim Kushmerick, Director of the Physical Measurement Laboratory
1:50 – 2:10 (20 min)	*Quantum Networking Activities at NSF* • Dr. Denise Caldwell, Acting Assistant Director of the Directorate for Mathematical and Physical Sciences (MPS)
2:10 – 2:30 (20 min)	*Quantum Networking Activities at DOE* • Dr. Ceren Susut, Associate Director of Science for Advanced Scientific Computing Research (ASCR) in the Office of Science
2:30 – 2:50 (20 min)	*Quantum Networking Activities at DOD* • Dr. John Burke, Principal Director for Quantum Science, Department of Defense
2:50 – 3:00 (10 min)	*Discussion, Next Steps, and Closing Remarks* • Dr. Kathryn Ann Moler and Dr. Charles Tahan, NQIAC Co-Chairs

National Quantum Initiative Advisory Committee

November 3, 2023