

Center for  
Quantum Networks

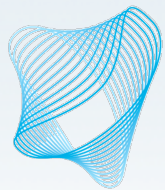
# CQN Innovation Ecosystem

**Stephen Fleming**

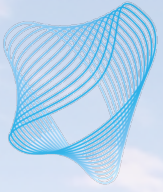
Director of Strategic Partnerships and Innovation  
University of Arizona — [stephenfleming@arizona.edu](mailto:stephenfleming@arizona.edu)



Funded by National Science Foundation Grant #1941583



**WHO AM I?**



# Who Am I?

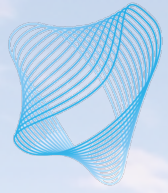
**3 years as Vice President,  
University of Arizona**

*Corporate engagement, Arizona Space  
Business Roundtable, and more...*

**11 years as Vice President,  
Georgia Institute of Technology.**

*Responsible for economic development,  
including commercialization, corporate  
engagement, manufacturing support, incubators,  
accelerators, ecosystem development, and more.  
Helped create and launch NSF I-Corps program.*





# What Did I Do Before?

## 10 years VC experience at General Partner level:

*18 investments as lead investor*

*12 profitable exits (including 4 IPOs, one \$650M acquisition); 47% annualized cash-on-cash IRR*

## 15 years corporate operations:

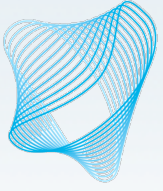
*AT&T Bell Labs*

*Nortel Networks*

*LICOM (venture-backed telecom equipment startup)*

**BS, Physics, Georgia Tech (*Highest Honors*)**





# WHY QUANTUM NETWORKS?

# The Quantum Internet

Fault-tolerant quantum memories are used to build quantum repeaters and switches for high-fidelity high-rate quantum communications over thousands of kilometers.



Secure communications



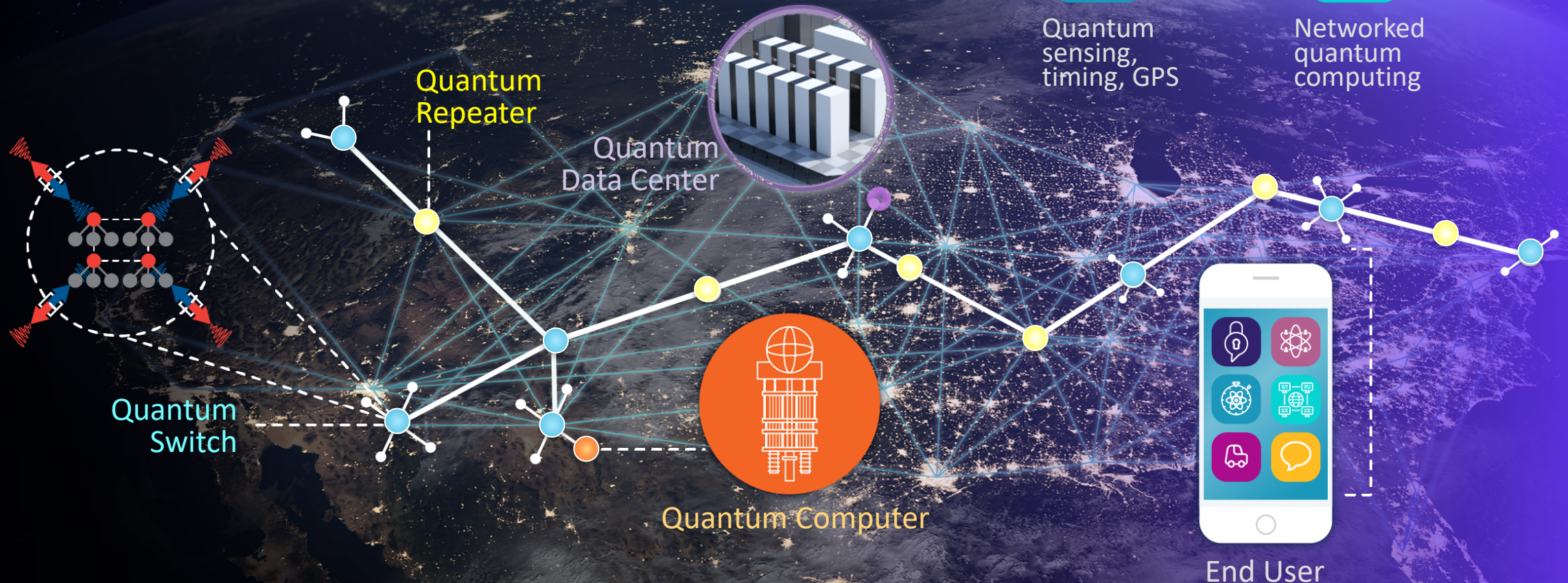
Multi-user quantum applications

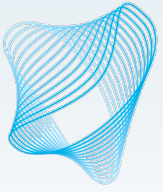


Quantum sensing, timing, GPS



Networked quantum computing



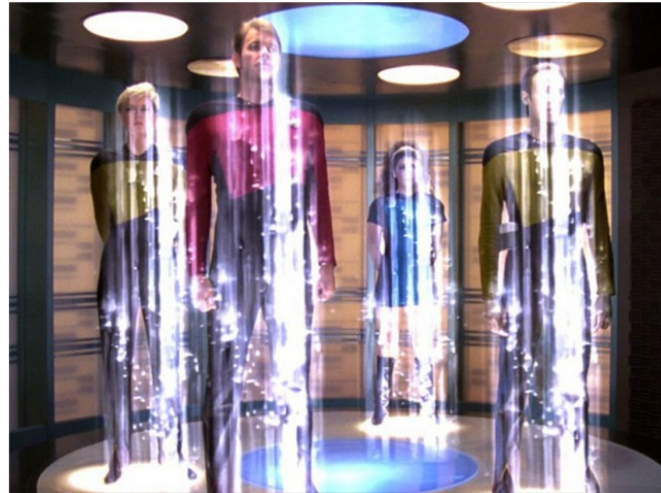


# What Quantum Networks are ***Not!***



Faster-Than-Light  
Communication

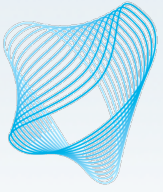
Teleportation



*(Well, not of people)*

Torturing  
Schrödinger's  
Cat





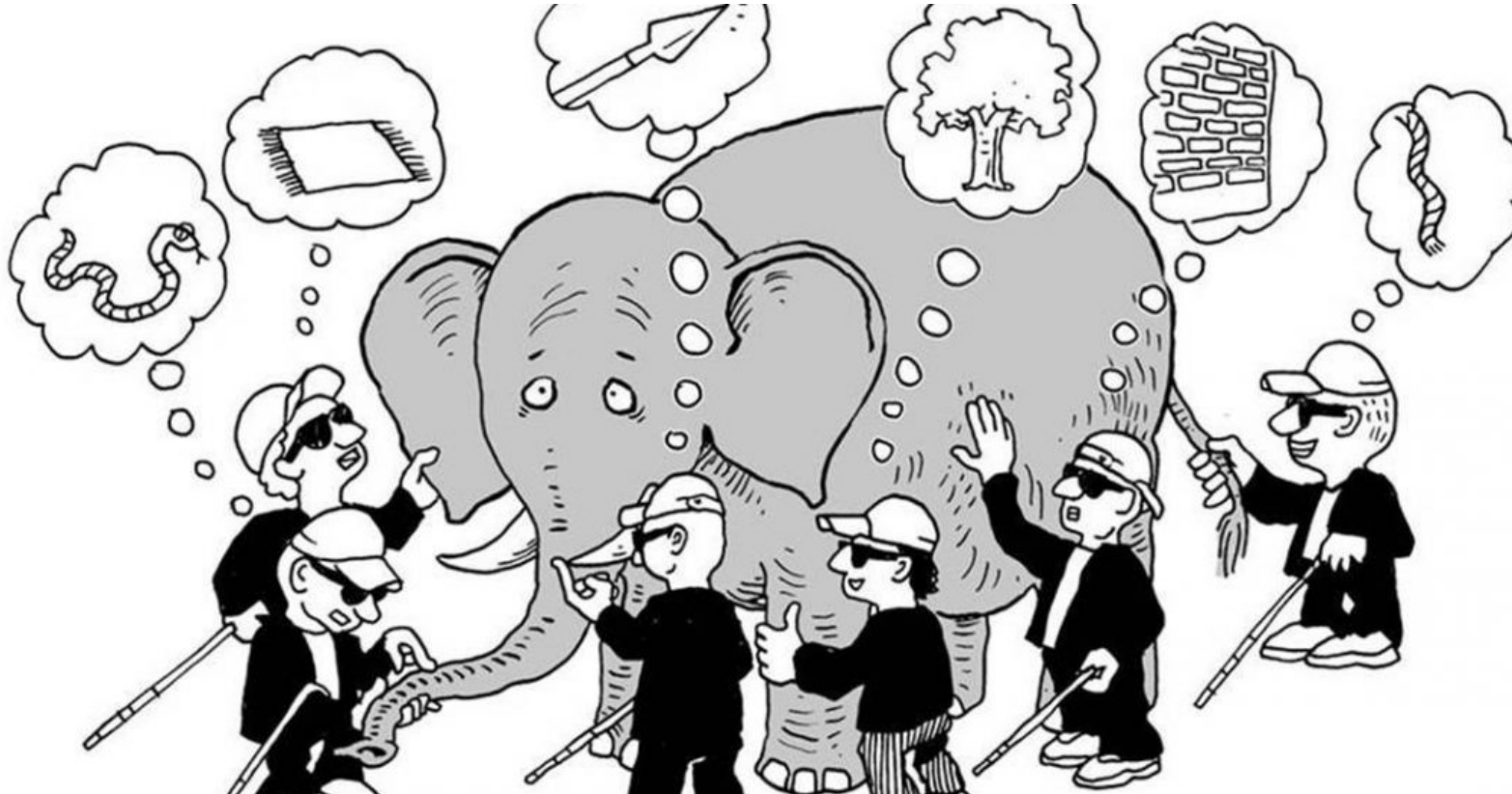
# What Will Quantum Networks Do?

Fundamentally  
powerful  
**computing**

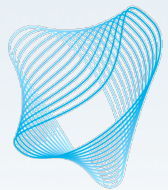
Provably-secure  
**communications**

High-  
resolution  
**sensing**

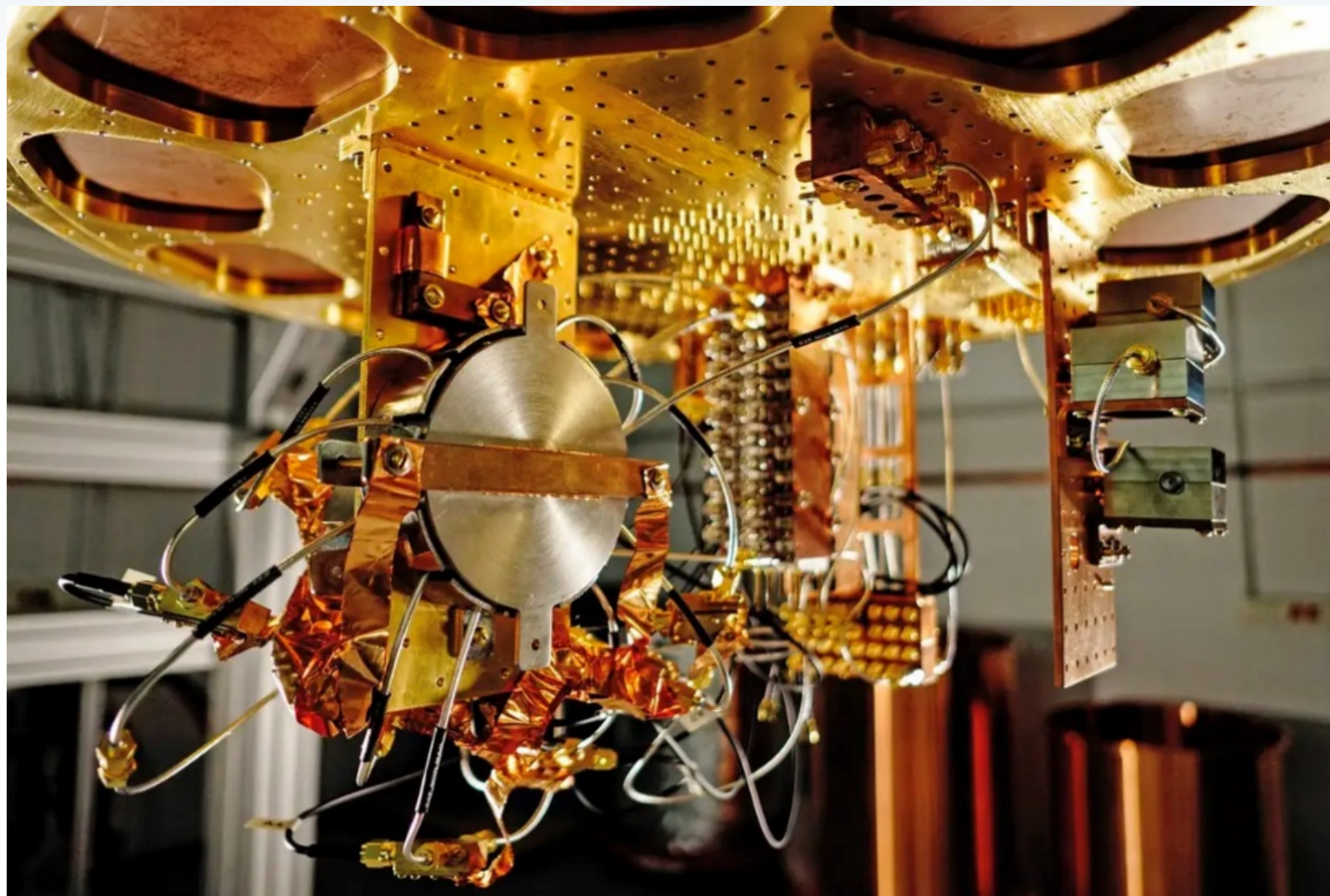
Quantum-  
enabled  
applications  
that we  
cannot  
**imagine**  
today!

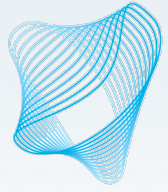




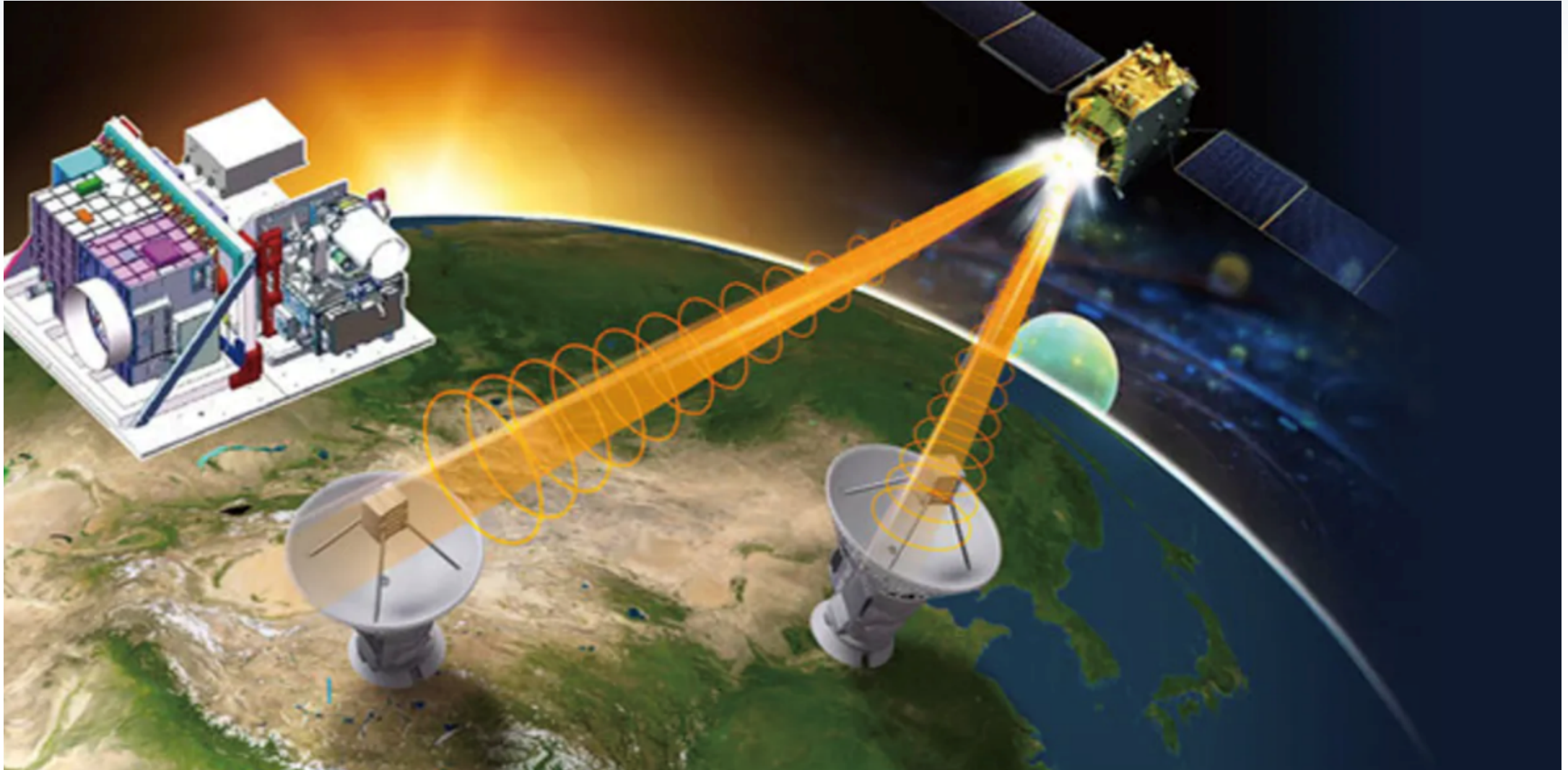


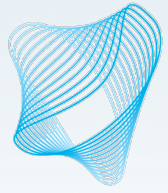
# Fundamentally Powerful Computing





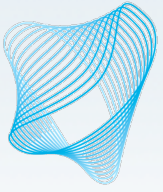
# Provably-Secure Communications



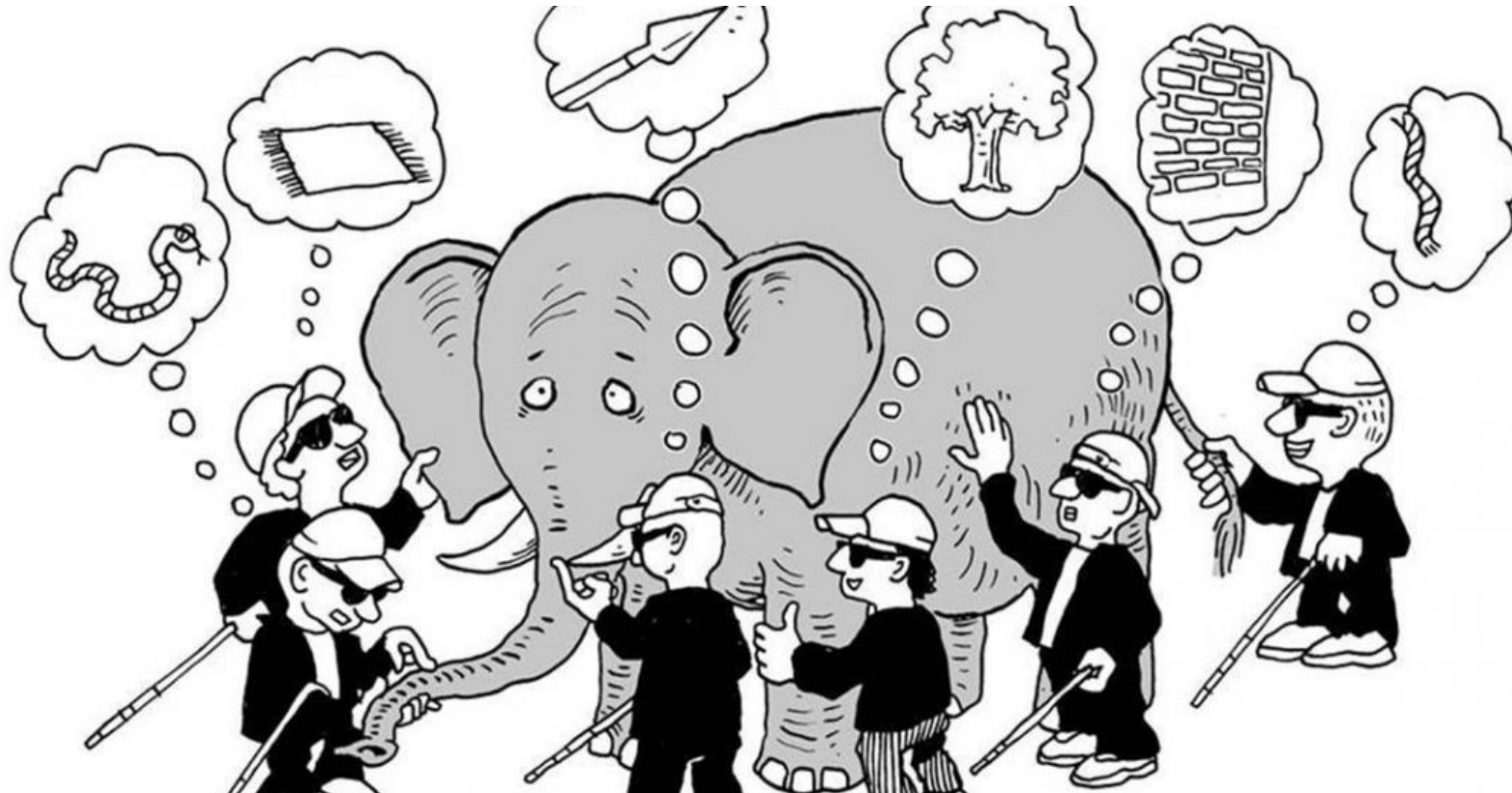


# High-Resolution Sensing

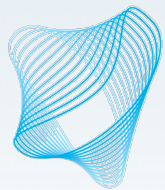




# What Will Quantum Networks Do?

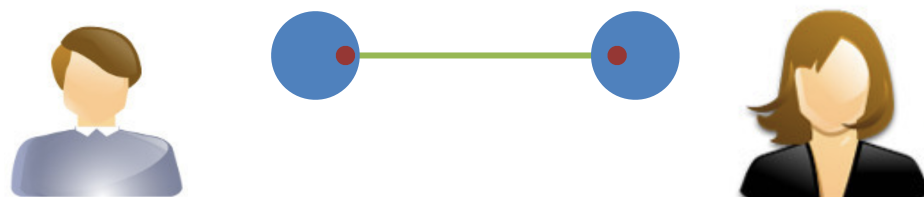


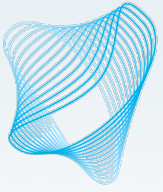
Quantum-  
enabled  
applications  
that we  
cannot  
**imagine**  
today!



# What We Can Do Now

Two-party entanglement across a single point-to-point, loss-limited connection

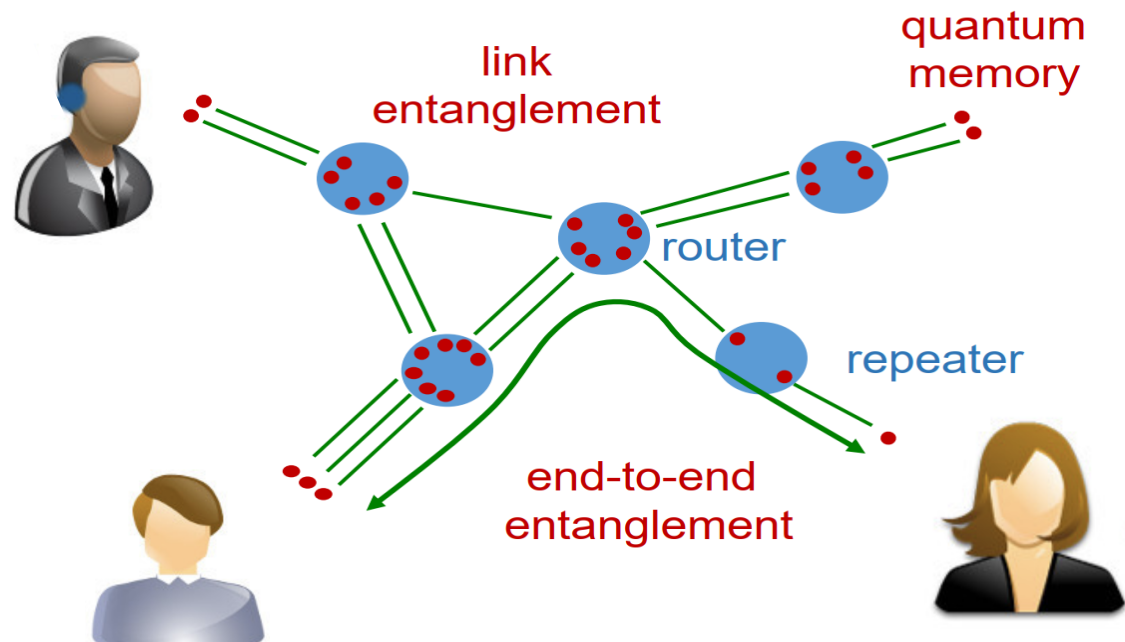


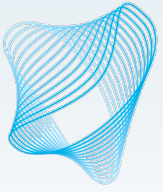


# Quantum Networks We Will Build

Quantum networks that provide shared entanglement

Quantum information transfers among many users that are robust to noise, workload dynamics, eavesdroppers, and failures



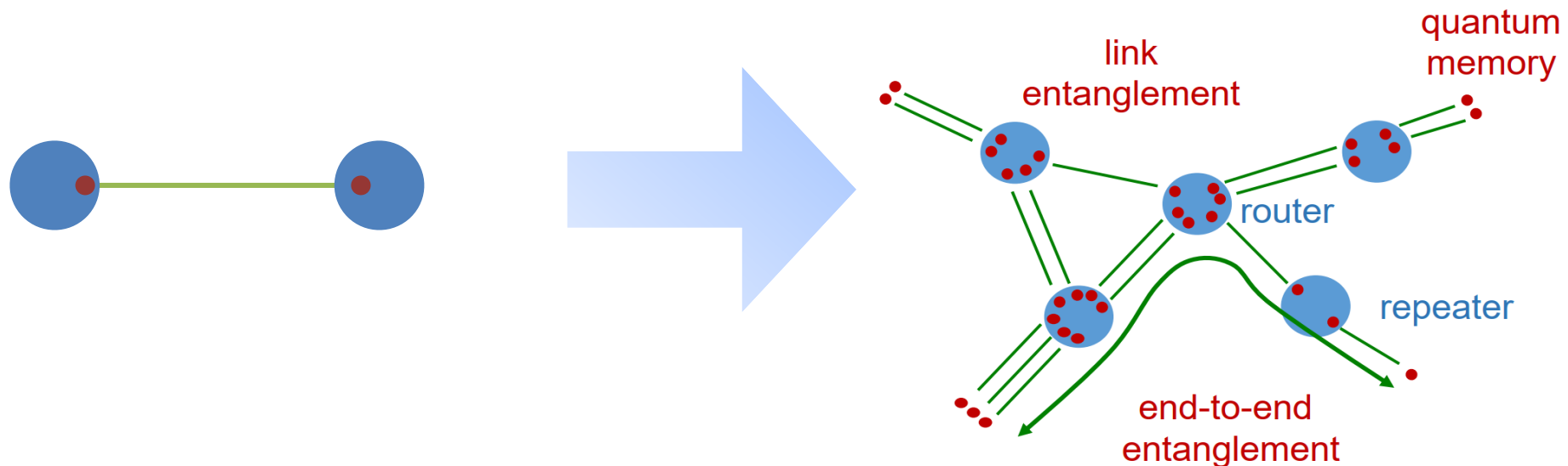


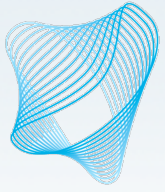
# Challenges

Quantum network design is entirely different from classical counterpart

Loss & noise kill quantum entanglement

Single photons with no equivalent to an amplifier in quantum networks





# Why Quantum Repeaters?

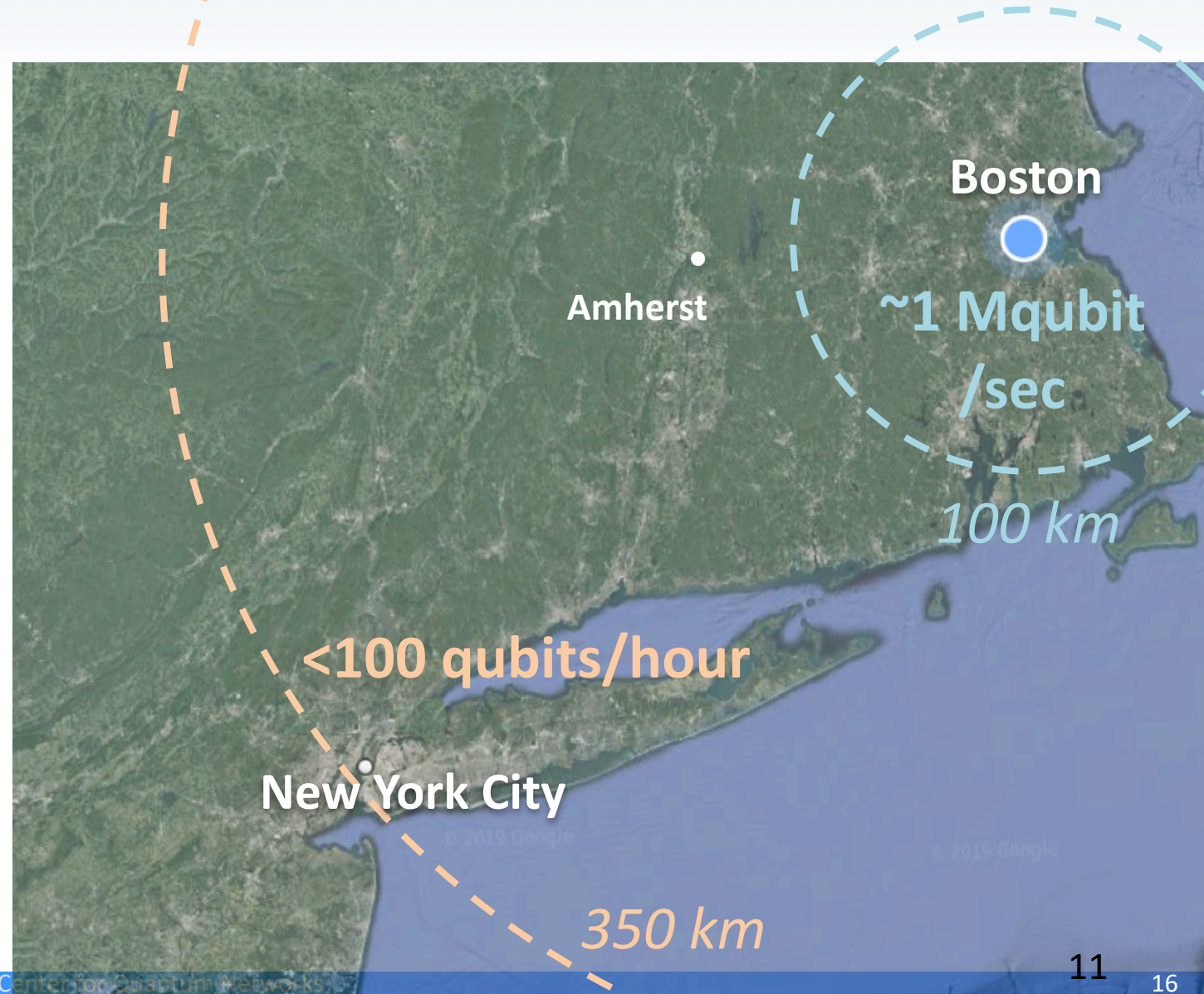
Qubit transmission rate in fiber decays **exponentially** with distance.

Cannot be extended by measure-and-repeat without compromising security.

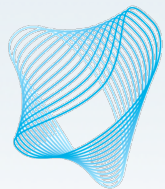
Quantum repeaters:

Intermediate quantum memory nodes

Quantum error correction







## Experimental demonstration of memory-enhanced quantum communication

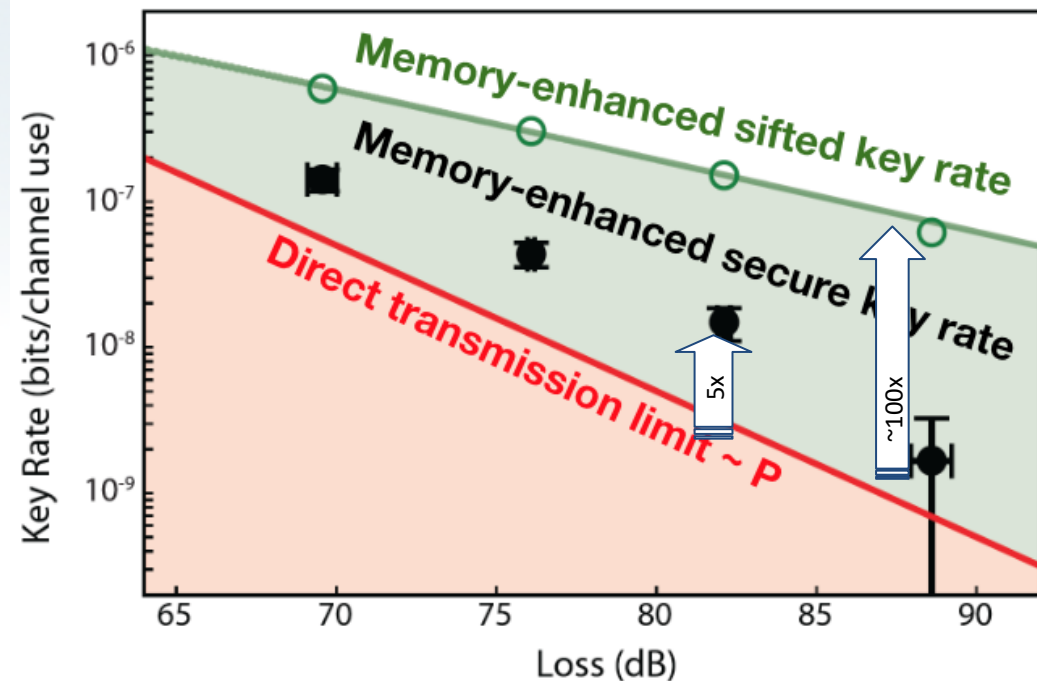
M. K. Bhaskar,<sup>1,\*</sup> R. Riedinger,<sup>1,\*</sup> B. Machielse,<sup>1,\*</sup> D. S. Levonian,<sup>1,\*</sup> C. T. Nguyen,<sup>1,\*</sup>  
E. N. Knall,<sup>2</sup> H. Park,<sup>1,3</sup> D. Englund,<sup>4</sup> M. Lončar,<sup>2</sup> D. D. Sukachev,<sup>1</sup> and M. D. Lukin<sup>1,†</sup>

<sup>1</sup>Department of Physics, Harvard University, Cambridge, MA 02138

<sup>2</sup>John A. Paulson School of Engineering and Applied Sciences, Cambridge, MA 02138

<sup>3</sup>Department of Chemistry and Chemical Biology,  
Harvard University, Cambridge, MA 02138, USA

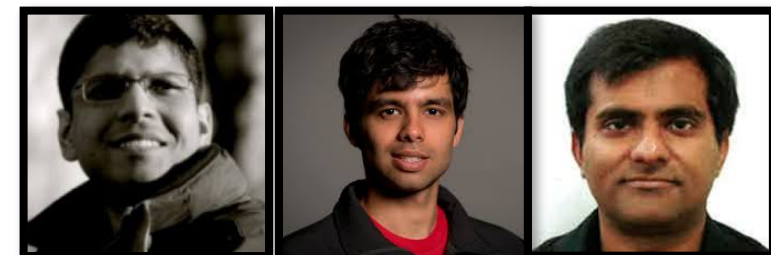
<sup>4</sup>Research Laboratory of Electronics, MIT, Cambridge, MA 02139, USA



npj | Quantum Information

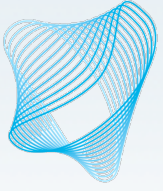
[www.nature.com/npjqi](http://www.nature.com/npjqi)

ARTICLE OPEN

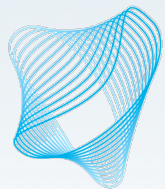


# Routing entanglement in the quantum internet

Mihir Pant<sup>1,2</sup>, Hari Krovi<sup>2</sup>, Don Towsley<sup>3</sup>, Leandros Tassiulas<sup>4</sup>, Liang Jiang<sup>5,6</sup>, Prithwish Basu<sup>7</sup>, Dirk Englund<sup>1</sup> and Saikat Guha<sup>2,8</sup>



# WHY QUANTUM NETWORKS... NOW?



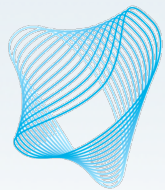
# 2017: “Sputnik Moment” for USA



“Trusted node” repeaters



16 June 2017



# Goal: Reaffirm US Supremacy

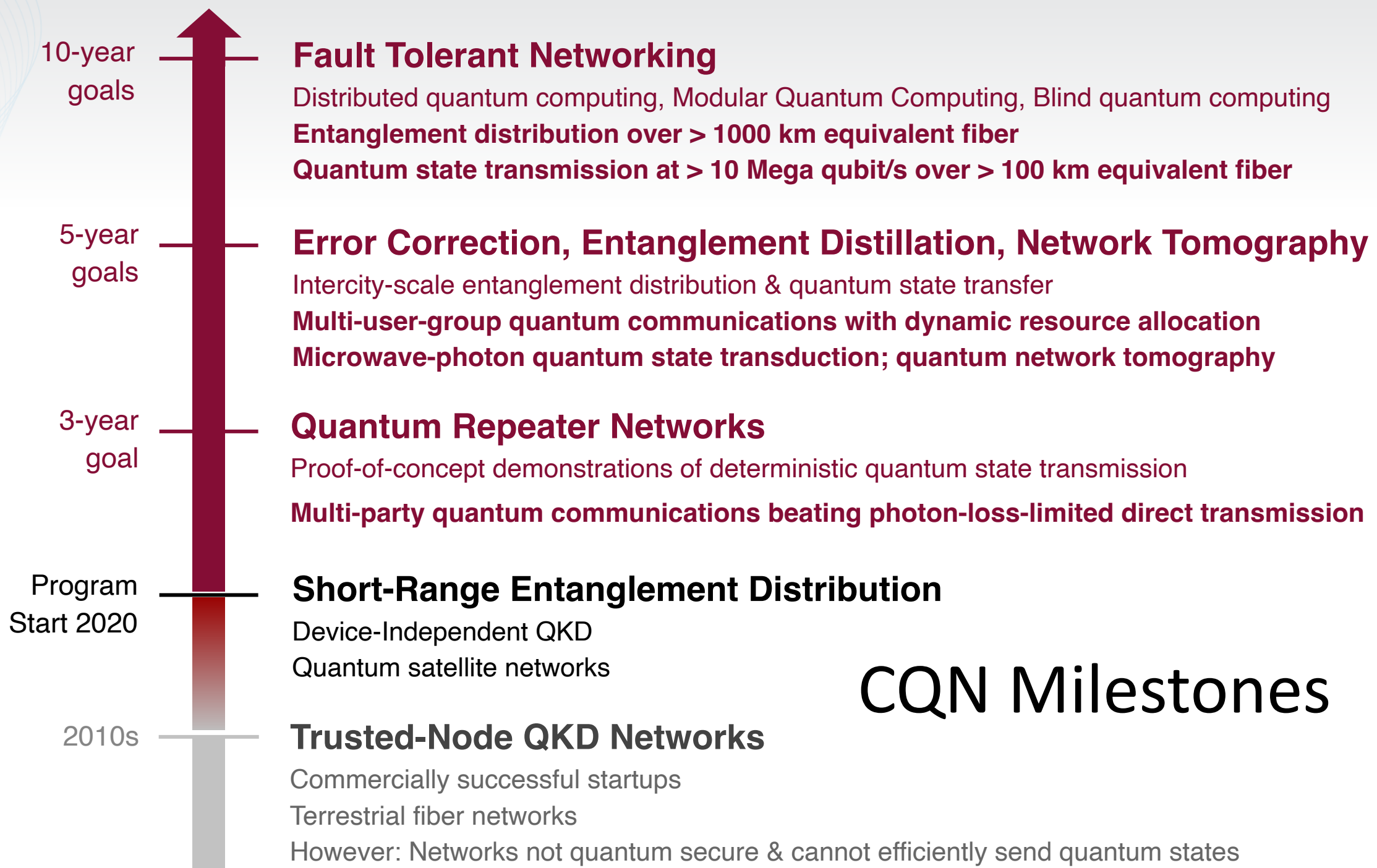
## Full Spectrum of Research Interests

Computer Science  
Mathematics  
Electrical Eng'rg  
Materials Science  
Physics  
Optical Sciences  
Law  
Economics  
Social & Behavioral  
Sciences  
Public Policy  
Business

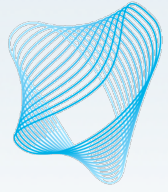
## Highly transdisciplinary and convergent research, spanning:

|  |                             |
|--|-----------------------------|
| Quantum memory development                 | <i>Harvard, MIT</i>         |
| Quantum transduction                       | <i>Yale</i>                 |
| Scalable programmable integrated photonics | <i>UArizona, MIT</i>        |
| Integrated single photon detectors         | <i>MIT</i>                  |
| Quantum error correction theory            | <i>UArizona, Yale</i>       |
| Spin-photon interfaces                     | <i>Harvard</i>              |
| Quantum material research and discovery    | <i>Harvard, NAU, Howard</i> |
| Computer network theory                    | <i>UMass</i>                |
| Societal impacts of the quantum internet   | <i>UArizona, MIT, Yale</i>  |

... and more!



# CQN Milestones



# Quantum Network Capabilities

**Data  
Security  
and  
Privacy**



*Provably secure  
Future-proof*

**Pattern  
Search on  
Distributed  
Data**

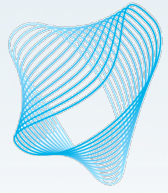


*Capable of dealing with large  
distributed data sets*

**Getting  
Quantum  
Out of  
the Lab**



*Expanded geographical reach*



# Key Societal Impacts

**Data Security and Privacy**



National Security

Medical Records

Personal Finance

Digital Transactions

**Pattern Search on Distributed Data**



Weather Forecasts

Self-Driving Cars

Personalized Medicine

Financial Modeling

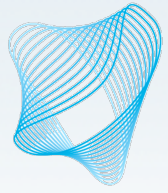
**Getting Quantum Out of the Lab**



Democratized Access

Inter-Organization Collaboration

Shift “from the Mainframe to the PC”

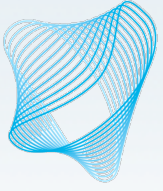


# The Timing is Perfect for Quantum Networks

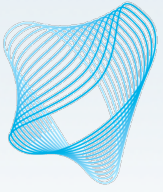
- Right now we have . . .
  - Quantum computers
  - Quantum sensing
  - A very wide range of quantum devices
- Fascinating frontiers in the engineering use of entanglement (e.g. precision timekeeping)
- But we have ***no way*** to interconnect these technologies
- We ***need*** quantum networks!
- Intellectual merit
  - Extremely exciting field
  - Many significant discoveries will occur in the next 5-10 years
    - Ranging from fundamental research to experimental systems
- Broader impact
  - Opens the door to engineering devices and systems we can't imagine today
  - American industry stands to gain tremendously from close collaboration with the CQN team
  - Important area for workforce development

*Slide courtesy of Chip Elliott, Raytheon BBN*





# **NSF ENGINEERING RESEARCH CENTERS**

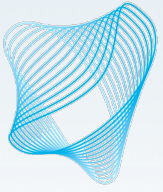


# NSF Engineering Research Centers

The NSF Engineering Research Center (ERC) program supports **convergent research, education, and technology translation** at U.S. universities that will lead to strong societal impacts.

Since the program's start in 1985, NSF has funded 75 ERCs throughout the United States. NSF supports each center for up to 10 years.

- More than 200 spinoff companies,
- More than 850 patents,
- More than 13,500 total bachelors, masters and doctoral degrees to ERC students, and
- Many research outcomes enabling new technologies



# Center for Quantum Networks ERC

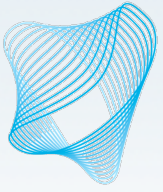
The screenshot shows the NSF Awards website interface. At the top, there is a search bar and navigation links for HOME, RESEARCH AREAS, FUNDING, AWARDS, DOCUMENT LIBRARY, NEWS, and ABOUT NSF. The main content area displays the following information:

|   |
|---|
| Award Abstract #1941583   |
| NSF Org: <a href="#">EEC Div Of Engineering Education and Centers</a>   |
| Initial Amendment Date: August 3, 2020  |
| Latest Amendment Date: August 26, 2020  |
| Award Number: 1941583   |
| Award Instrument: Cooperative Agreement   |
| Program Manager: Nadia El-Masry<br>EEC Div Of Engineering Education and Centers<br>ENG Directorate For Engineering  |
| Start Date: September 1, 2020   |
| End Date: August 31, 2025 (Estimated)   |
| Awarded Amount to Date: \$3,500,000.00  |
| Investigator(s): Saikat Guha saikat@email.arizona.edu (Principal Investigator)<br>Christos Tassiulas (Co-Principal Investigator)<br>Srinivas Aravamudan (Co-Principal Investigator) |

**Initial award: Sept 2020**

**Up to \$26 million over first five years**

**Potential \$25 million renewal for second five years (contingent on milestones)**



# Center for Quantum Networks ERC

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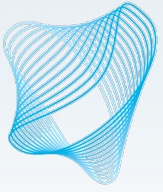
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***Initial award: Sept 2020***

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**Selected as one of four 2020 ERCs from 300+ applicants**



# CQN Mission

To develop the **first quantum network**—

- enabling fully error-corrected, high-speed, and long-range **quantum connectivity** between multiple user groups,
- enabled by **quantum repeaters**,
- **education pathways** for a large and diverse workforce, and
- a roadmap for the **just and equitable deployment** of quantum internet technology and its transformative applications.



## Universities



## Industry

GENERAL DYNAMICS



Raytheon  
BBN Technologies



FT



CORNING



## FFRDCs



## International Partners



Imperial College  
London



## Incubators



THE UNIVERSITY OF ARIZONA  
ELLER COLLEGE OF MANAGEMENT

McGuire Center for  
Entrepreneurship

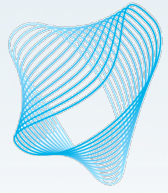


Technology & Entrepreneurship  
Center at Harvard



## Education Partners

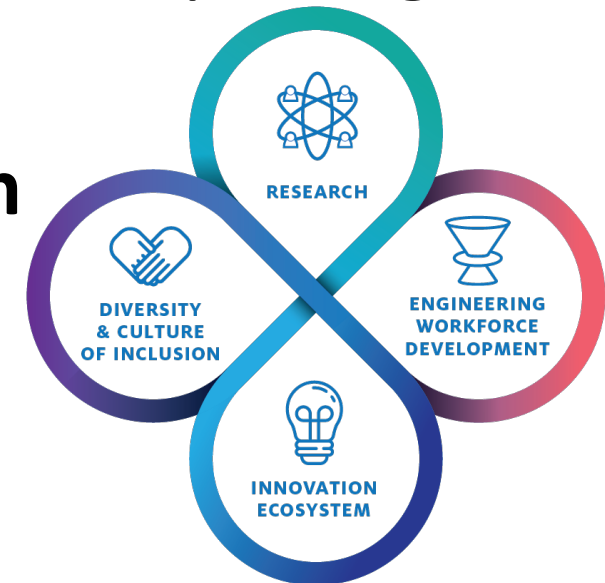


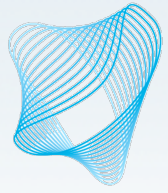


# NSF 4th Generation ERCs

*The Engineering Research Center program supports **convergent research** that will lead to strong societal impact, including*

- **engineering workforce development** at all participant stages,
- a culture of **diversity and inclusion** where all participants gain mutual benefit, and
- value creation within an **innovation ecosystem** that will outlast the lifetime of the ERC.

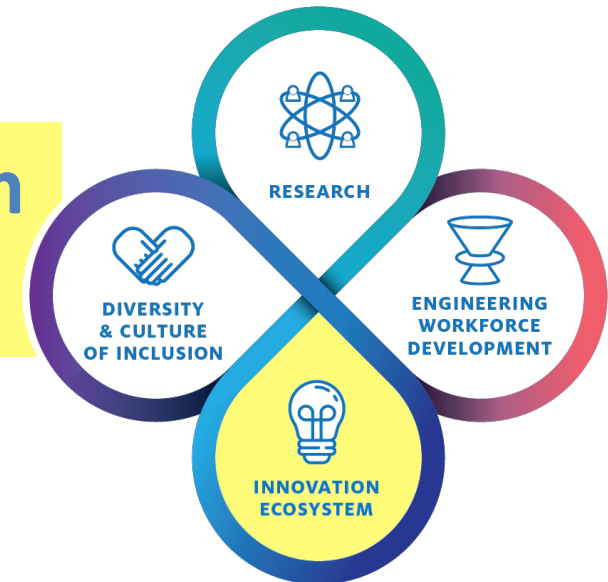




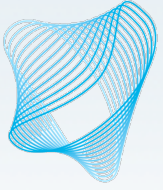
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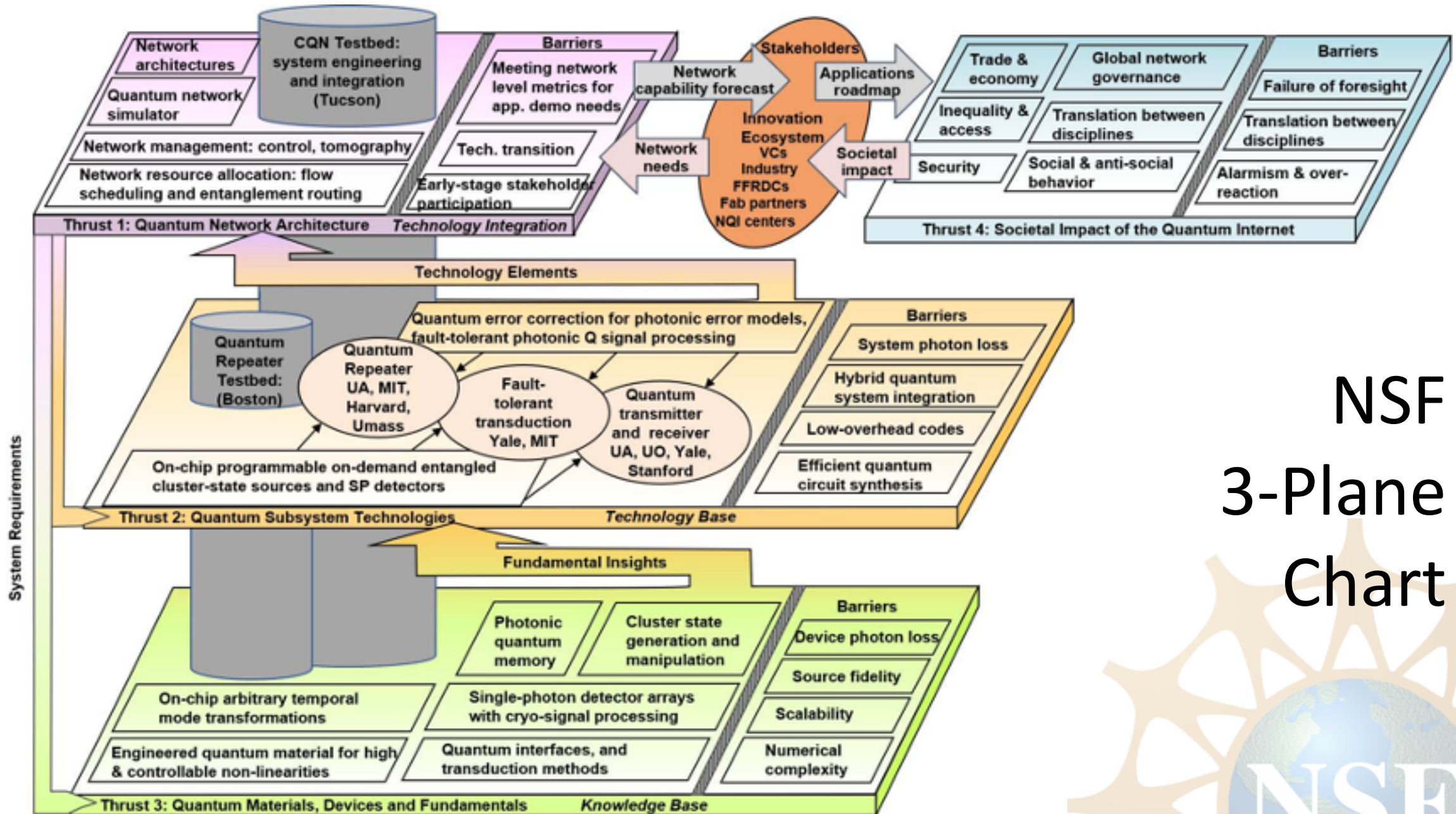
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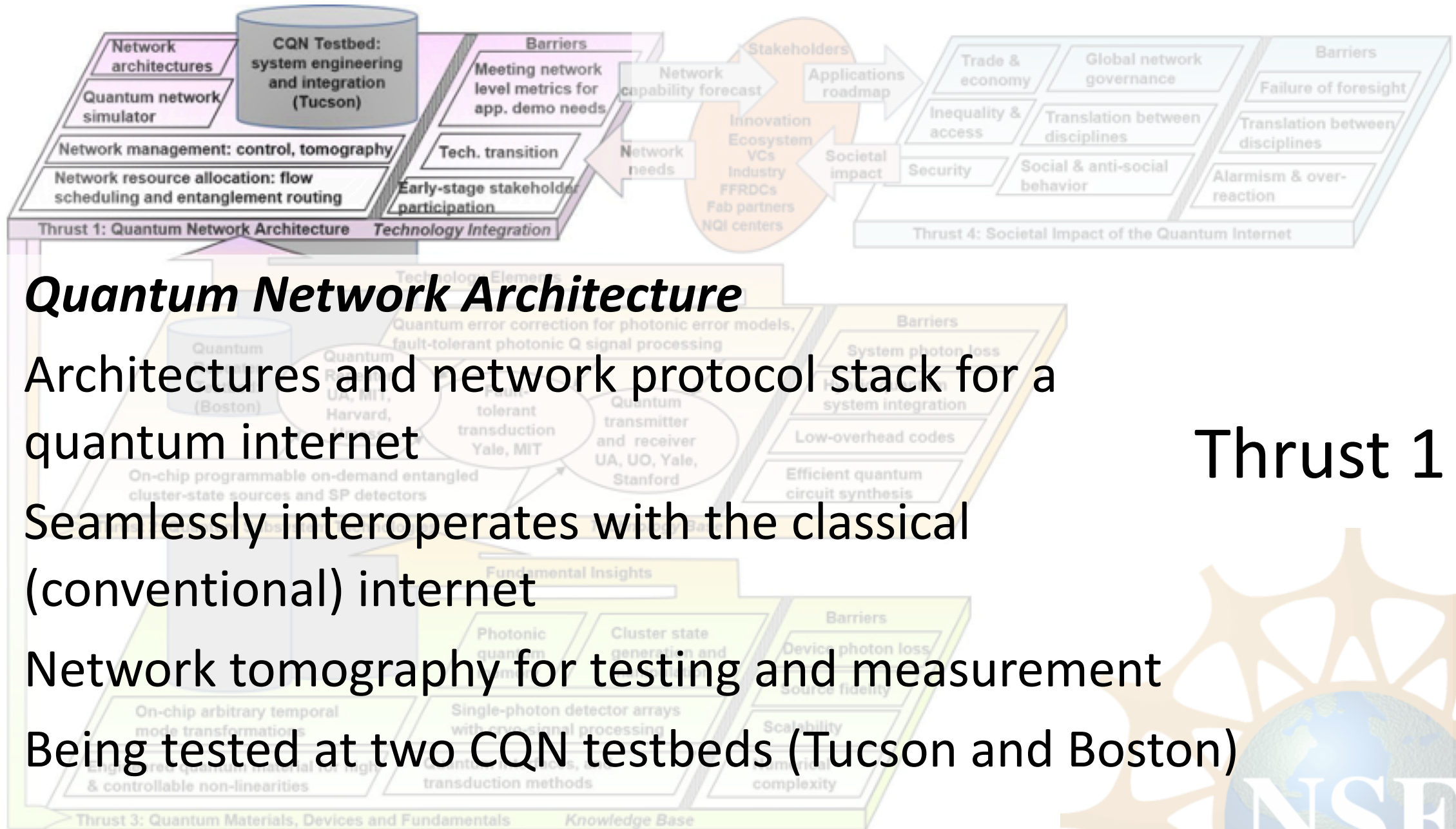


# NSF ERC — CQN STRUCTURE



# NSF 3-Plane Chart





# Quantum Network Architecture

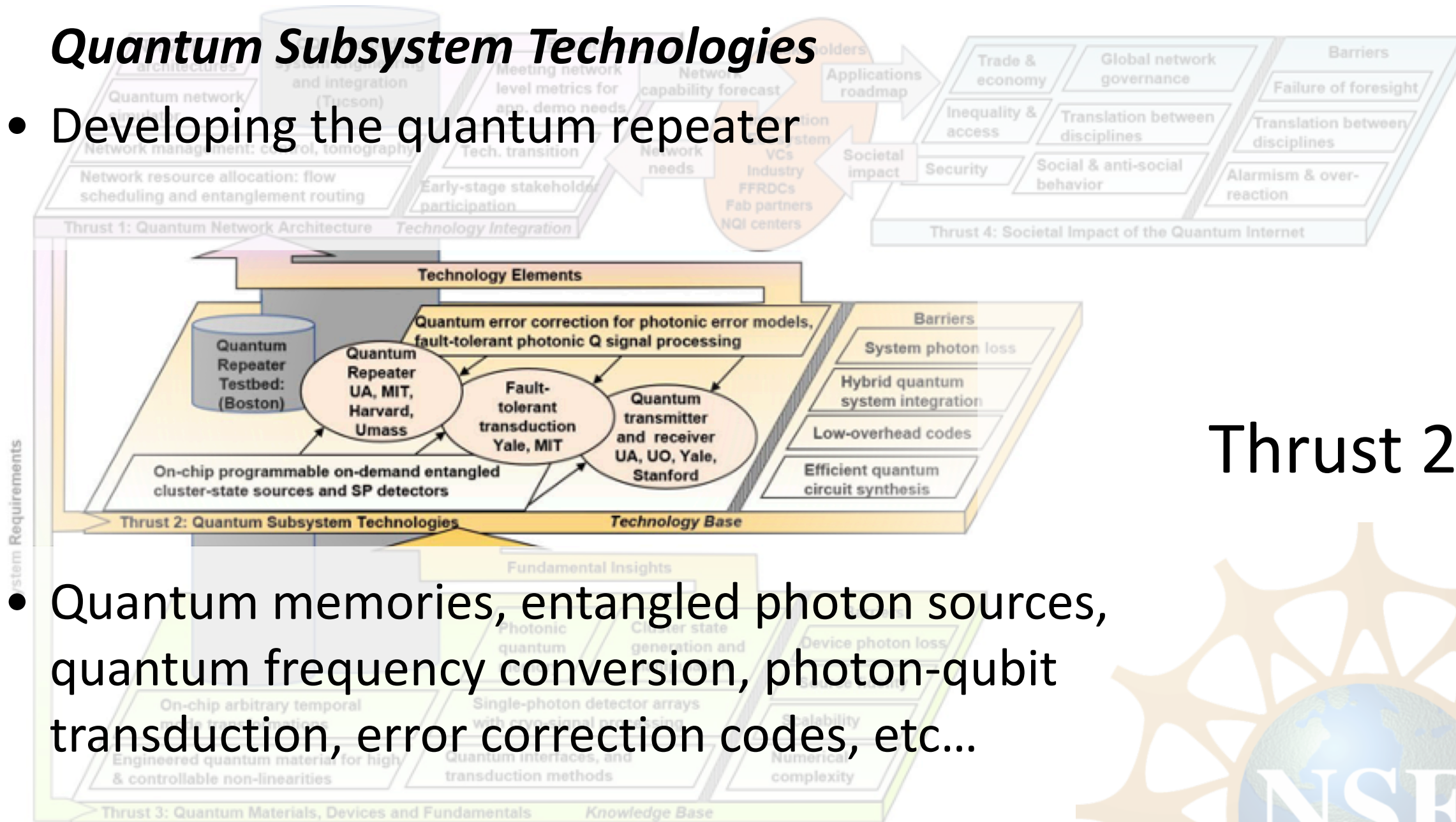
- Architectures and network protocol stack for a quantum internet
- Seamlessly interoperates with the classical (conventional) internet
- Network tomography for testing and measurement
- Being tested at two CQN testbeds (Tucson and Boston)

Thrust 1



# Quantum Subsystem Technologies

- Developing the quantum repeater



## Thrust 2

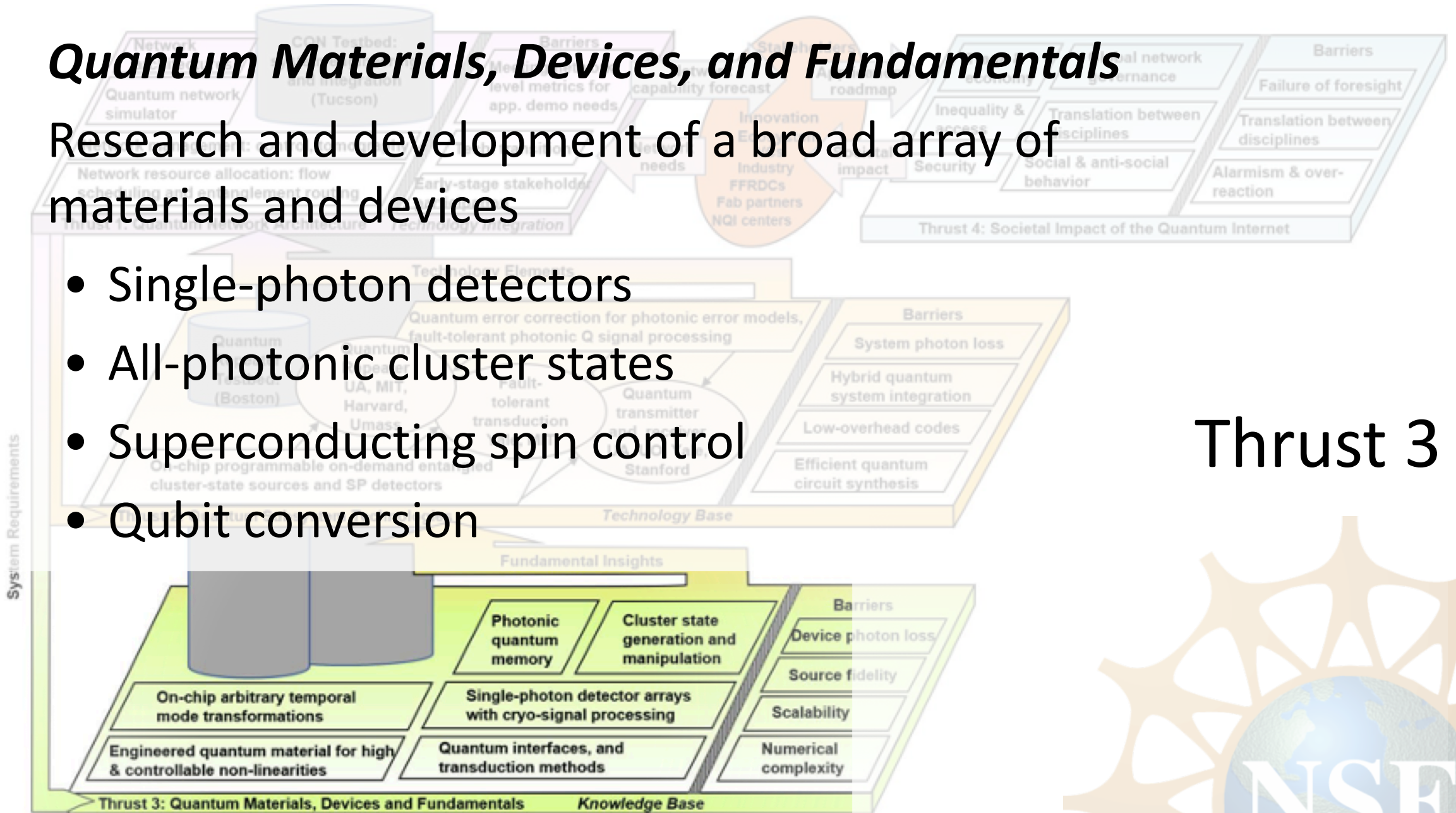
- Quantum memories, entangled photon sources, quantum frequency conversion, photon-qubit transduction, error correction codes, etc...



# Quantum Materials, Devices, and Fundamentals

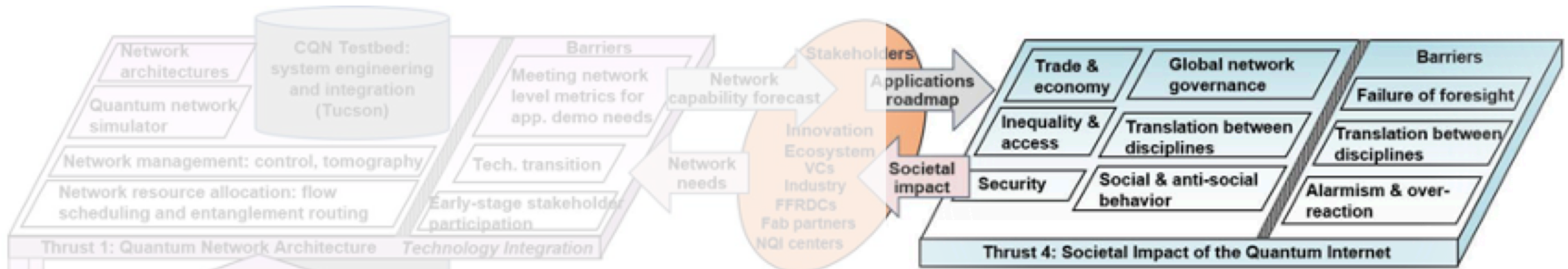
Research and development of a broad array of materials and devices

- Single-photon detectors
- All-photonic cluster states
- Superconducting spin control
- Qubit conversion



## Thrust 3



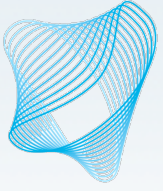


## ***Societal Impact of the Quantum Internet***

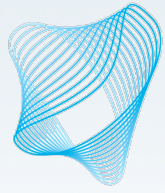
- Legal and social issues versus classical networks
- Applications and market adoption
- Post-quantum communications and encryption
- Developing a “mixnet” to reduce info leakage
- Preparing for and reducing disparities in access to quantum-based medical innovations

Thrust 4





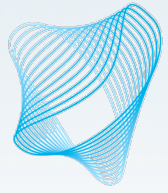
# CQN INNOVATION ECOSYSTEM



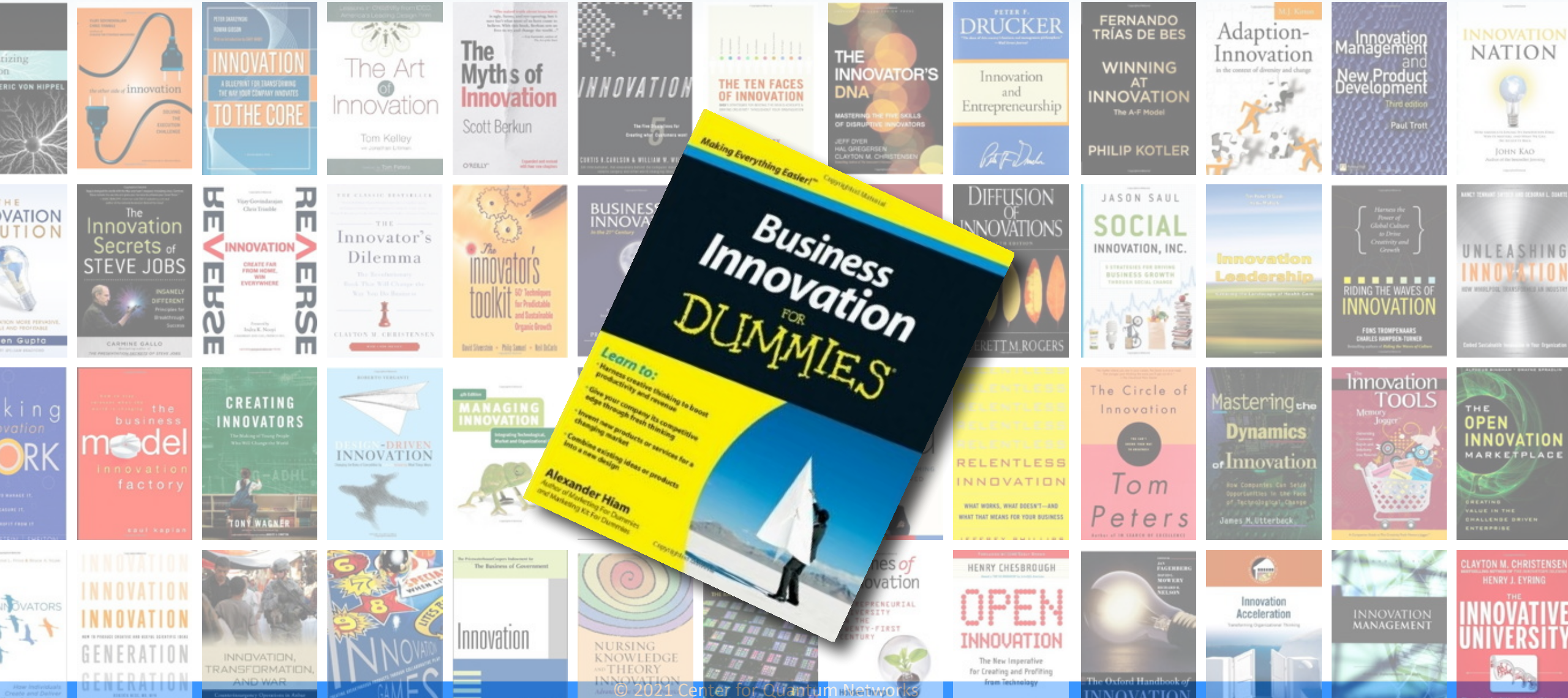
# Innovation...

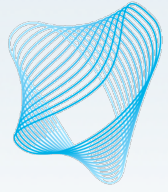






# Innovation...

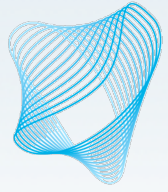




# Role of the University

Three distinct stages of university evolution:

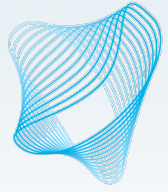
**Reference:** Jan Youtie & Philip Shapira, *Building an Innovation Hub: A Case Study of the Transformation of University Roles in Regional Technological and Economic Development*, 2006



# Role of the University

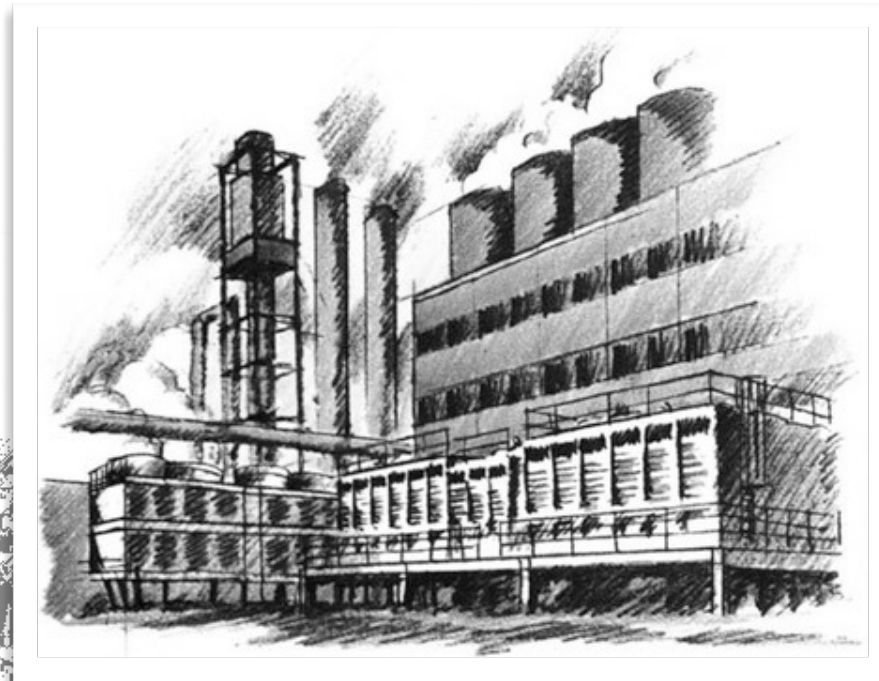
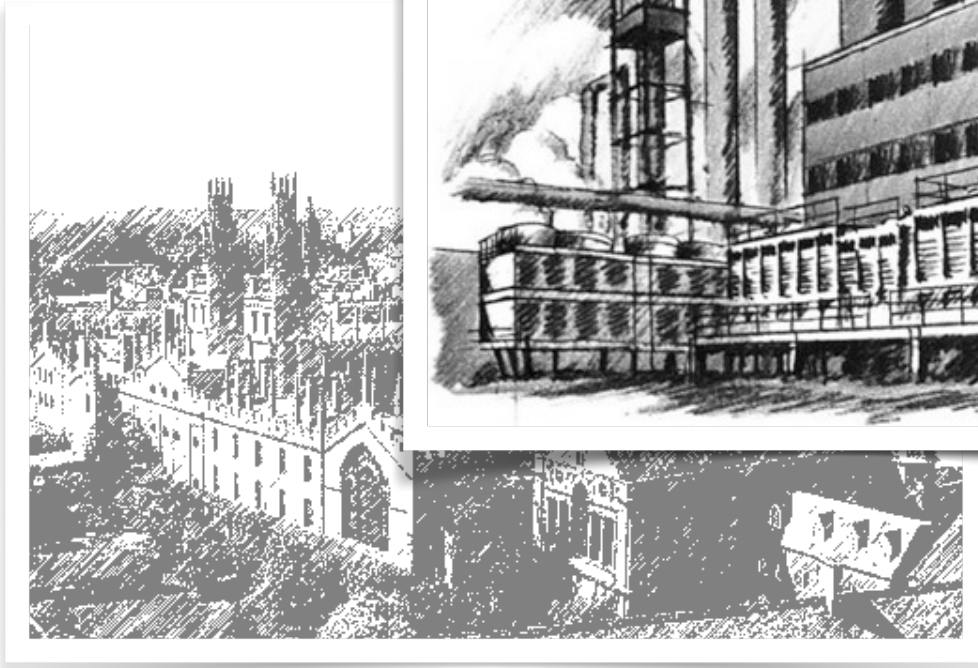
*1200 AD: Scholarly storehouse*

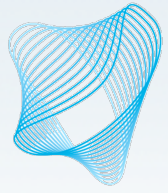




# Role of the University

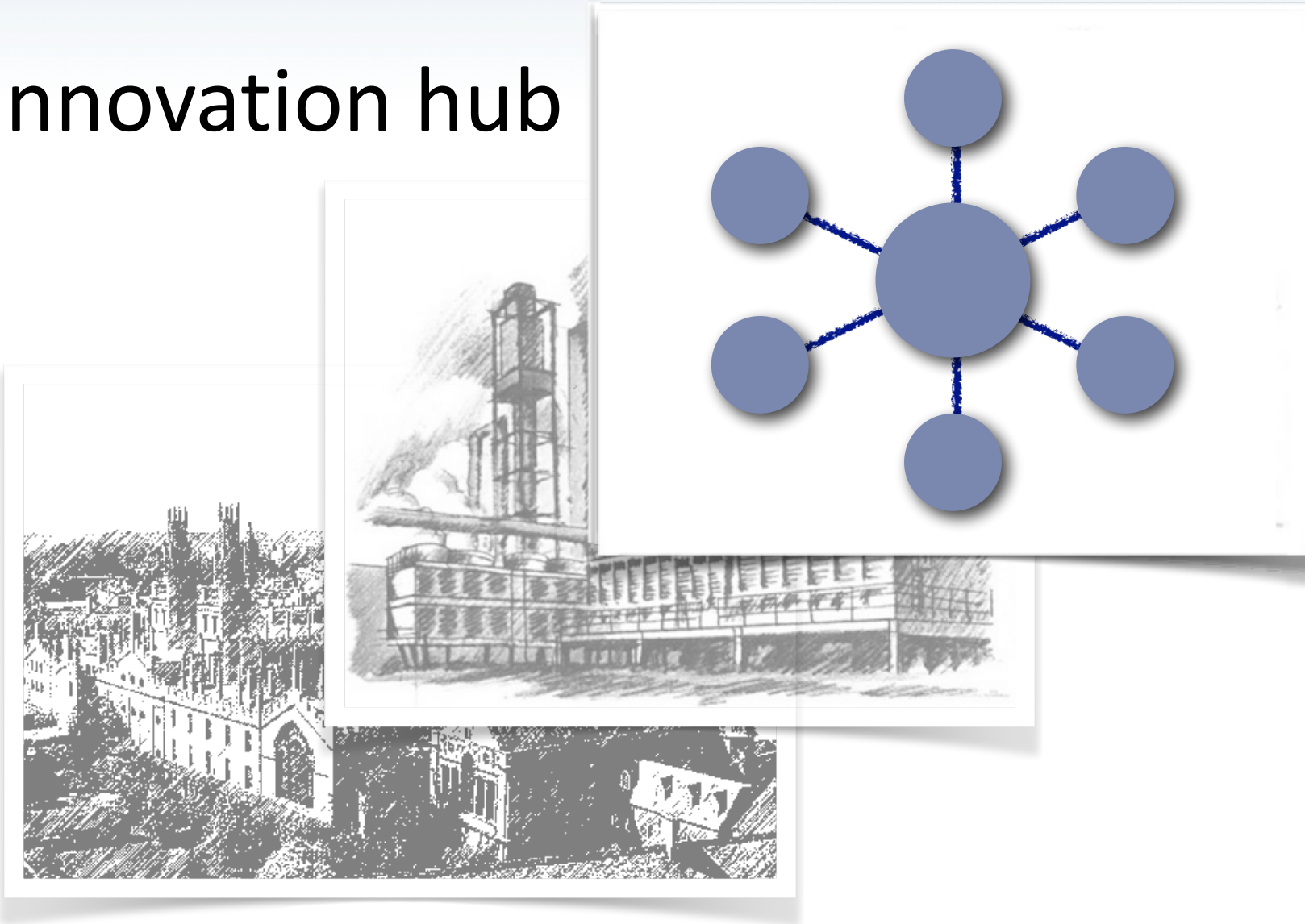
*1880s: Competence factory*

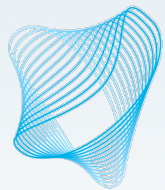




# Role of the University

*Now:* Innovation hub



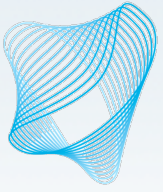


# What is Innovation?

*Research is the transformation  
of money into knowledge.*

*Innovation is the transformation  
of knowledge into money.*

*—Dr. Geoffrey Nicholson, 3M  
(inventor of the Post-it note)*



# CQN as an Innovation Hub

**Core Academic Partners**



**Spinout / Startup Companies**

**Venture Capital Investors**

**Incubators**

**US Industry**

**FFRDCs /  
Federal  
Agencies**



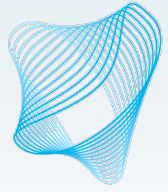
**CQN**

**Other Academic Partners**

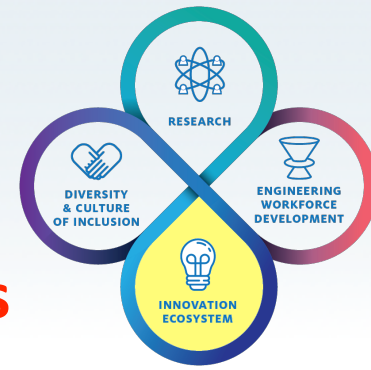


**International  
Partners**

**K-12 Education  
Partners**



# CQN Industrial Partners Program



Core Academic Partners

Spinout / Startup Companies



Venture Capital Investors

Incubators

US Industry

# CQN

Other Academic Partners

FFRDCs /  
Federal  
Agencies

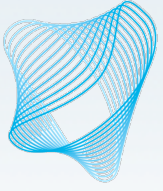


International  
Partners

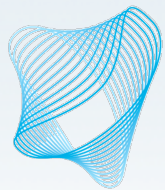
K-12 Education  
Partners



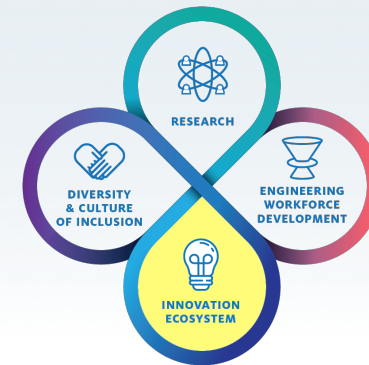




# **INDUSTRIAL PARTNERS PROGRAM**

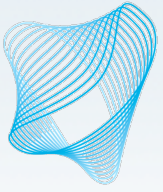


# Industrial Partners Program (IPP)



| IPP Membership Level  | Associate | Collaborator | Partner   |
|---|-----------|--------------|-----------|
| Annual Contribution ‡   | \$10,000  | \$40,000     | \$150,000 |
| Early Access to Research Results                                  | ✓         | ✓            | ✓         |
| Technical Collaboration   |           | ✓            | ✓         |
| Industry Advisory Board (IAB)                                     |           | 1 seat       | 2 seats   |
| Access to Facilities, Seminars, Recruiting of Students & Postdocs |           | ✓            | ✓         |
| Ability to Sponsor Research                                       |           | ✓            | ✓         |
| Customized Research Opportunities                                 |           |              | ✓         |
| Early Access to Intellectual Property                             |           |              | ✓         |
| Partial Patent Costs Reimbursement                                |           |              | ✓         |
| Priority Option for IP Licensing                                  |           |              | ✓         |

‡ All Members may adjust cash, in-kind, and IP license credits with the approval of the Center Director.

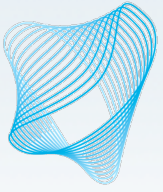


# IPP: Associate-Level Membership



## *Associate-Level Member benefits:*

- **Research findings.** Pre-publication access to research findings (subject to confidentiality), and industry trends.
- **Awareness** of R&D technology transfer, policy, and environmental aspects through bi-annual meetings, webinars, and quarterly newsletters.

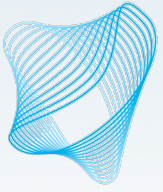


# IPP: Collaborator-Level Membership



Associate-Level Member benefits *plus*:

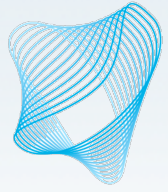
- **Involvement.** Invitation to attend technical reviews, Innovation Ecosystem meetings, and to interact with CQN management and research teams.
- **Collaboration.** Ability to collaborate with CQN faculty/staff/students on CQN research projects.
- **Facilities.** Access to CQN facilities and instrumentation as part of CQN research.



## IPP: Collaborator-Level (2)



- **Education.** On-location seminars and short courses to be provided by CQN at nominal fees (to recover costs).
- **Recruitment.** Early access to CQN recruitment events for industry-ready undergraduates, graduate students, and post-doctoral researchers.
- **Sponsored Research.** Ability to sponsor additional focused research projects (with negotiated IP terms).
- **IAB.** One voting seat on the CQN Industry Advisory Board.

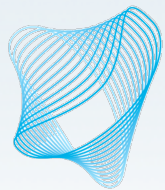


# IPP: Partner-Level Membership



Collaborator-Level Member benefits *plus*:

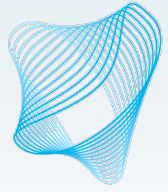
- **Customized Research Opportunities.** Ability to direct up to \$50K/year of membership fees towards targeted CQN research projects. (Results to be treated as CQN IP.)
- **Research NERF.** Automatic non-exclusive royalty-free IP license for internal research use.
- **Commercial Licenses.** 90-day priority window to option CQN IP for co-exclusive royalty-bearing commercial licenses (shared only among Partner-Level Members who exercise the option).



## IPP: Partner-Level (2)



- **Patent Costs.** Portion of patent costs for commercially-licensed IP to be reimbursed from membership fee.
- **IAB.** Two voting seats on the CQN Industry Advisory Board.

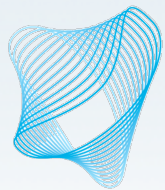


# Industrial Partners Program (IPP)

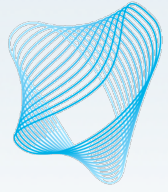
## *Special cases:*

- Founding Members (pre-award support) receive 20% discount
- Small Business Concerns (by NSF definition: < 500 employees) receive 75% discount
  - *Discounts may be concatenated*
- Spinouts based on CQN University research get Partner-Level Membership (*nonvoting*) benefits for any level of Membership
- Up to \$10,000/year of CQN University licensing fees may be applied to Membership annual contribution





# INDUSTRY ADVISORY BOARD



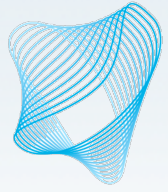
# Innovation Convergence

*Workforce Development/DCI/Societal Impacts/Research*



Industrial Advisory Board (IAB) will have a significant role in CQN:

- Provide **guidance to CQN research**; proprietary programs can be funded adjacent to CQN
- Shape **workforce development** programs
- Select and develop **course content** for post-college short courses as well as new Master's program in QISE
- Mentor **diverse population** of CQN students
- Develop and maintain CQN Sci & Tech **Application Roadmap**
- Flag **potential regulatory issues** associated with evolving technology

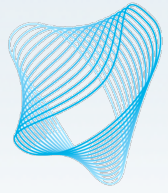


# Industry Advisory Board



*The IAB advises CQN on research directions, industry engagements, and strategic investments from the perspectives of corporate partners, entrepreneurs, and venture capital.*

- Provides **guidance** to CQN executive leadership.
- Participates in NSF annual **site visit**.
- Assists in development and maintenance of a comprehensive **application roadmap** for quantum information science and technology.

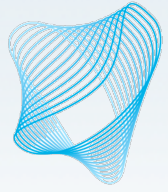


# Industry Advisory Board



## Guidance in four areas:

- Creating and demonstrating the scientific and technological **feasibility** of innovative methodologies and systems governing quantum communication networks,
- Assisting in the **transfer** of research discoveries and observations from university to industry and vice versa,
- Developing an interdisciplinary **education** program for quantum information science and technology, including workshops, short courses, certificates, and accredited degrees, including QISE Masters program, and
- Navigating **regulatory** issues and **public policy** challenges in the U.S. and abroad.

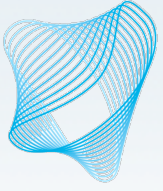


# Industry Advisory Board

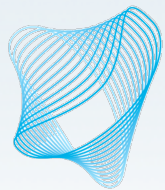


## IAB membership and voting:

- Partner-Level Members have two voting seats.
- Collaborator-Level Members have one voting seat.
- Under certain circumstances, venture capital firms and university spinout companies may have non-voting observation rights.
- IAB Chair to be elected from voting membership for a two-year term.
- Two IAB meetings per year, one as part of NSF site visit.
  - *Each full IAB meeting is expected to include a recruiting event.*
  - *Interim conference-call meetings as required.*



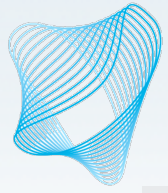
# **STRATEGIC PARTNERSHIPS AND INNOVATION**



# IPP Membership — January 2022

| Associate                        | Collaborator                | Partner          |
|----------------------------------|-----------------------------|------------------|
| Aliro Quantum Networks           | Lockheed Martin             | Cisco Systems    |
| Anametric                        | Raytheon Technologies       | Corning          |
| General Dynamics Mission Systems | L3Harris ( <i>pending</i> ) | Juniper Networks |
| Teledyne ( <i>pending</i> )      |                             |                  |

| Venture Associate         | FFRDC/Agencies                       |
|---------------------------|--------------------------------------|
| Flybridge Capital         | NASA                                 |
| Osage University Partners | NIST                                 |
|                           | Sandia National Laboratories         |
|                           | ( <i>Not formal members of IPP</i> ) |

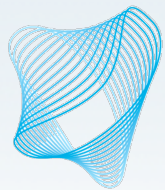


# Partners in CQN Value Chain



Companies on this page have joined or committed to join the CQN IPP.





# Startup Company Framework

CQN ERC will incorporate **entrepreneurship training** for faculty and students to instill an innovative and inclusive culture

- Regular training for center scientists, engineers, and students
- NSF I-Corps program will be integrated into ERC innovation program (MIT/UA)
- Diversity and a culture of inclusion (DCI) will be emphasized in training



CQN may develop discoveries which all partners agree would be useful to spin off as **startup companies**. Pieces of IP would be:

- Vetted through the tech transfer process with the partner schools (I-Corps)
- Catalyzed within the relevant ecosystems partner(s)
- Facilitated (and possibly invested in) by CQN venture affiliate partners



THE UNIVERSITY OF ARIZONA  
ELLER COLLEGE OF MANAGEMENT

**McGuire Center for  
Entrepreneurship**



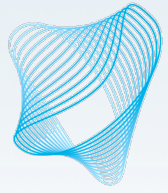
MARTIN TRUST  
CENTER FOR MIT  
ENTREPRENEURSHIP



**Yale** Center for Business  
and the Environment

Technology & Entrepreneurship  
Center at Harvard





# Protection of Complex Center Relationships

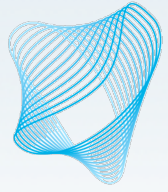
The key to any major public-private partnership

An Intellectual Property Management Plan has been negotiated between UArizona, Harvard, MIT, and Yale.

Led by UArizona, core partner institutions will coordinate to develop:

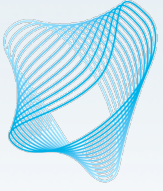
- IP protection plan
- IP licensing process
- Patent prosecution
- Ownership
- Startup candidates
- Fees for membership
- Rights in research results





# Activities and Milestones

|                           | Year 1  | Year 2 | Year 3 | Year 4 | Year 5 | Milestone Based |
|---------------------------|---------|--------|--------|--------|--------|-----------------|
| Trade Show Recruiting     | COVID   | ✓      | ✓      | ✓      | ✓      |                 |
| Annual Innovation Meeting | Virtual | ✓      | ✓      | ✓      | ✓      |                 |
| Advisory Board Meeting    | ✓       | ✓      | ✓      | ✓      | ✓      |                 |
| Entrepreneurship Training | ✓       | ✓      | ✓      | ✓      | ✓      |                 |
| S&T Roadmap / Refresh     | ✓       |        | ✓      |        | ✓      |                 |
| Invention Disclosures     |         |        |        |        |        | ✓               |
| Technology Licenses       |         |        |        |        |        | ✓               |
| Startup Formation         |         |        |        |        |        | ✓               |



# QUESTIONS?

## Stephen Fleming

Director of Strategic Partnerships and Innovation  
University of Arizona — [stephenfleming@arizona.edu](mailto:stephenfleming@arizona.edu)