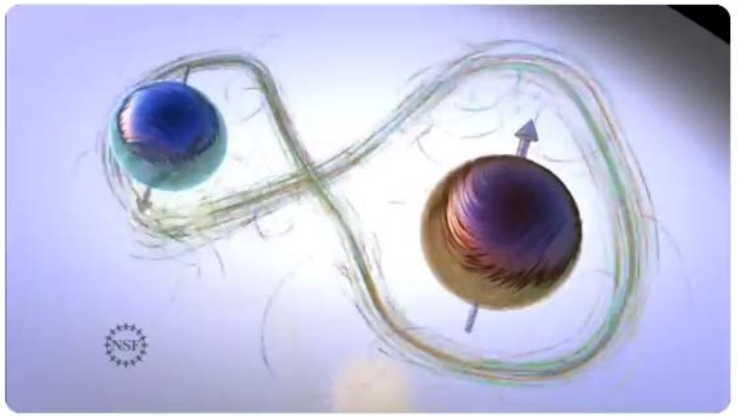
UPDATE: NSF Big Idea - Quantum Leap

May 3, 2019

MPS

Advisory Committee



Denise Caldwell & Henry Warchall

QIS @ NSF goes back a long time

Wootters & Zurek (1982) "**A single quantum cannot be cloned"** *Nature*, ***299***, 802
acknowledged NSF Award 7826592 [PI: John A. Wheeler, UT Austin]

No Cloning Theorem

C. Caves (1981) "**Quantum Mechanical noise in an interferometer**" *PRD*, **23**,1693
acknowledged NSF Award 7922012 [PI: Kip Thorne, Caltech]

Squeezing for Metrology

Information Mechanics (Computer and Information Science)
NSF Award 8618002; PI: Tommaso Toffoli, MIT

Toffoli Gate

Quantum Statistics of Nonclassical, Pulsed Light Fields
NSF Award 9224779; PI: Michael Raymer, U. Oregon

Quantum Tomography

Research on Randomized Algorithms, Complexity Theory, and Quantum Computers
NSF Award 9310214; PI: Umesh Vazirani, UC-Berkeley

Q. Fourier Transform

QIS @ NSF goes back a long time

Complexity Studies in Communications and Quantum Computations
NSF Award 9627819; PI: Andrew Yao, Princeton

QC Complexity; Cryptography

Quantum Logic, Quantum Information and Quantum Computation
NSF Award 9601997; PI: David MacCallum, Carleton College

Quantum Logic

Physics of Quantum Computing
NSF Award 9802413; PI: Julio Gea-Banacloche, U Arkansas

Photonic Q. Computing

Quantum Foundations and Information Theory Using Consistent Histories
NSF Award 9900755; PI: Robert Griffiths, Carnegie-Mellon U

Foundations; Eavesdropping

QIS @ NSF goes back a long time

ITR: Institute for Quantum Information
NSF Award 0086038; PI: John Preskill; Co-PI:John Doyle, Leonard Schulman, Axel Scherer, Alexei Kitaev, CalTech

Q. Error Correction; Topological QC

Quantum Information Theory
NSF Award 0074566; PI: Mary Beth Ruskai, U Mass Lowell

Quantum Entropy (subadditivity)

MRI: Acquisition of Equipment for Quantum Information Processing
NSF Award 0079842; PI: Eli Yablonovitch, UCLA

Quantum Memory Hybrid Q. Systems

and many more…

See NSF Award Search for over 2078 Awards with “quantum information” or “quantum comput*” in Title or Abstract. From over 1218 unique PIs.

QIS Efforts Cross the Foundation

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Director

F. Fleming Crim
Chief Operating Officer

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- EFRI ✓

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- DIVISION OF BEHAVIORAL & COGNITIVE SCIENCES (BCS) — Amber Story, Acting Division Director, 703.292.8740
- SES ✓
- NATIONAL CENTER FOR SCIENCE AND ENGINEERING STATISTICS (NCSES) — John Gawalt, Division Director, 703.292.8780

From all NSF programs combined:

Over 2000 QIS-related Awards (✓). 269 of these QIS-related Awards were in FY 2018.

"The Quantum Leap": Why Now?

- Advances in <u>science</u> & technology are enabling new opportunities for rapid advances
- International <u>competition</u> is extremely high. Success has implications for U.S. *economic competitiveness* and *national security.*
- Strong <u>industrial and government interest globally</u>.

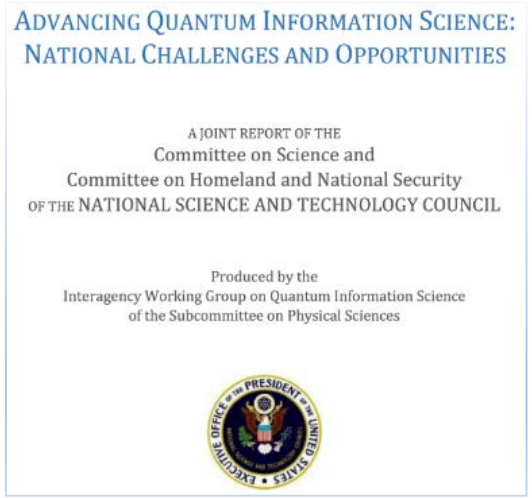
IBM

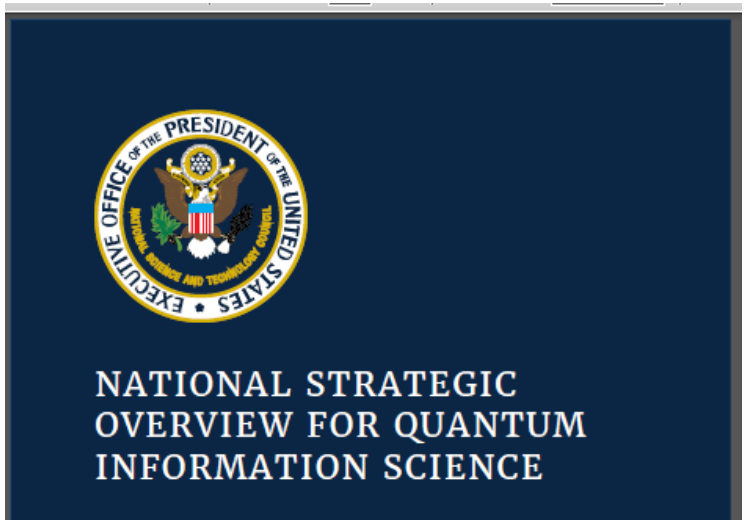
Google

GORDON AND BETTY MOORE FOUNDATION

AO Sense
Cold Quanta
Zapata
Ion Q, etc…

Honeywell
Microsoft
HRL Labs
Lockheed





National Quantum Initiative

*Subcommittee on Quantum Information Science

Establishes SCQIS* (NSF, NIST, DOE Co-chairs)

Establishes National Quantum Coordination Office

Jake Taylor, Director

Alex Cronin, NSF, detailee

TITLE I—NATIONAL QUANTUM INITIATIVE

SEC. 101. NATIONAL QUANTUM INITIATIVE PROGRAM.

(a) IN GENERAL.—The President shall implement a National Quantum Initiative Program.

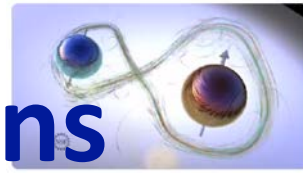
(b) REQUIREMENTS.—In carrying out the Program, the President, acting through Federal agencies, councils, working groups, subcommittees, and the Coordination Office, as the President considers appropriate, shall—

(1) establish the goals, priorities, and metrics for a 10-year plan to accelerate development of quantum information science and technology applications in the United States;

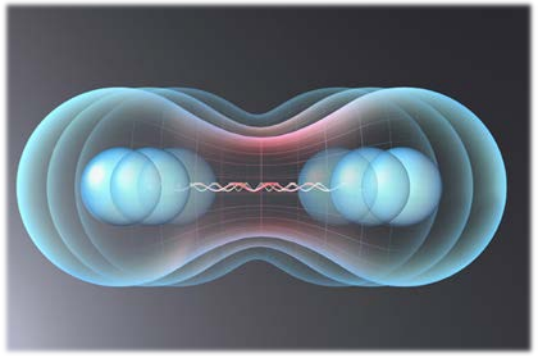
(2) invest in fundamental Federal quantum information science and technology research, development, demonstration, and other activities to achieve the goals established under paragraph (1);

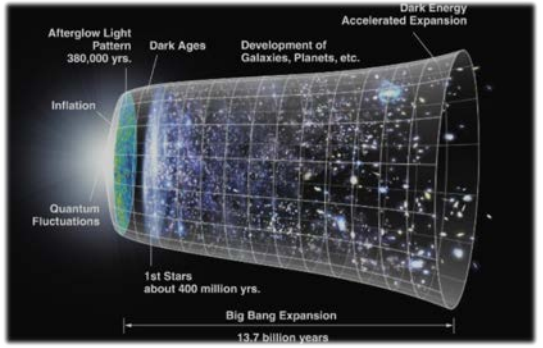
(3) invest in activities to develop a quantum information science and technology workforce pipeline;

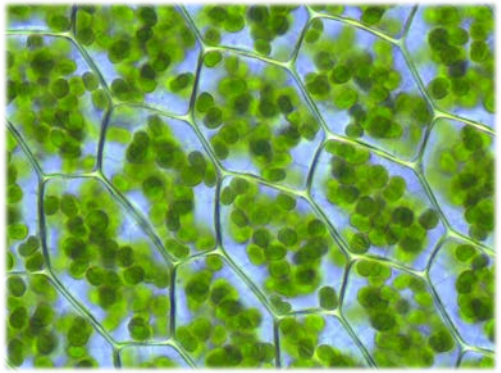
Quantum Leap : Asking Ambitious Questions



Q1: Are there fundamental limits to how far we can push the **entanglement and coherence** frontiers for quantum states?

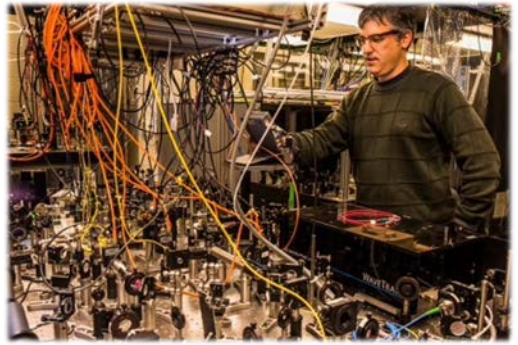






Q2: What can we learn from quantum phenomena in **naturally-occurring and engineered quantum systems**?

Q3: How do we galvanize the science and engineering **community** to enable quantum devices, systems, and technologies that **surpass classical** capabilities?



Our NSF Approach

The 3 C's

Physics
Chemistry
Astronomy
Mathematics
Materials

Electrical, Communications and Cyber Systems

Industrial Innovation & Partnerships

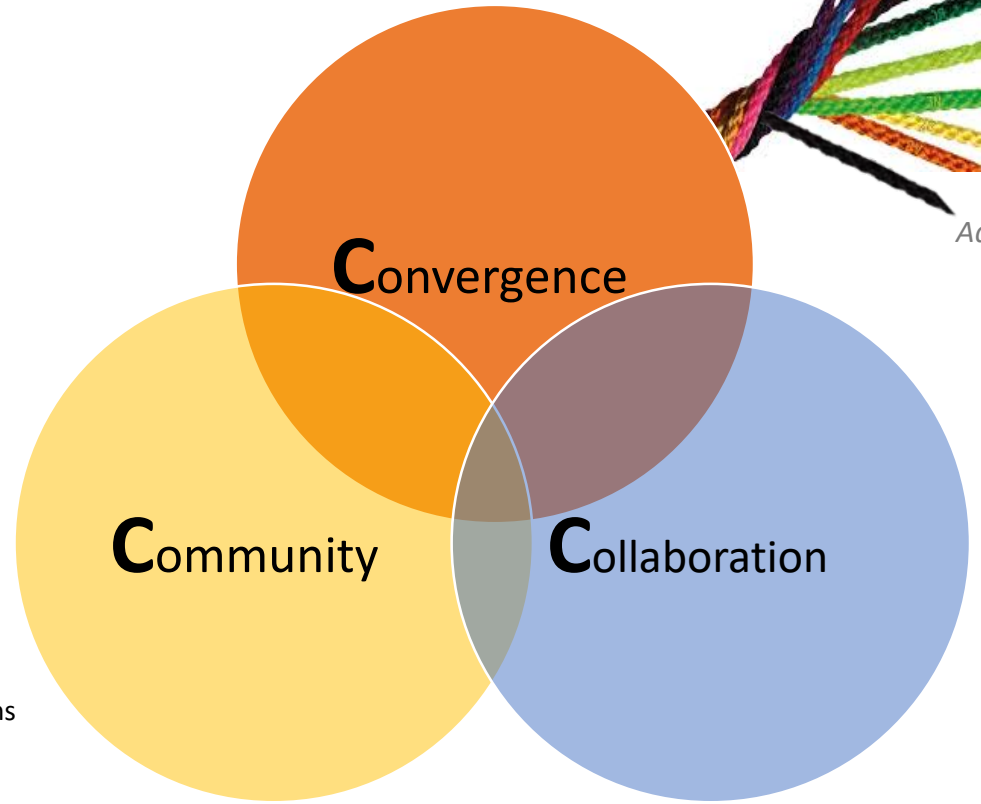
Education and Workforce

Information and Intelligent Systems

Computing and Communication Foundations

Computer and Networked Systems

Advanced Cyberinfrastructure



$$|\text{Quantum Workforce}\rangle = c_1|\text{Materials Researchers \& Chemists}\rangle + c_2|\text{Engineers}\rangle + c_3|\text{Physicists}\rangle + c_4|\text{Mathematicians \& Computer Scientists}\rangle$$

Enabling the Quantum Leap (FY16-18)

DCL-RAISE-EQuIP: Engineering Quantum Integrated Platforms for Quantum Communication

DCL-RAISE-TAQS: Transformational Advances in Quantum Systems

Ideas Lab: Practical Fully-Connected Quantum Computer Challenge (PFCQC)

Enabling Practical-scale Quantum Computing: *Expeditions in Computing*

DCL: Achieving Room-temperature quantum logic through improved low-dimensional materials

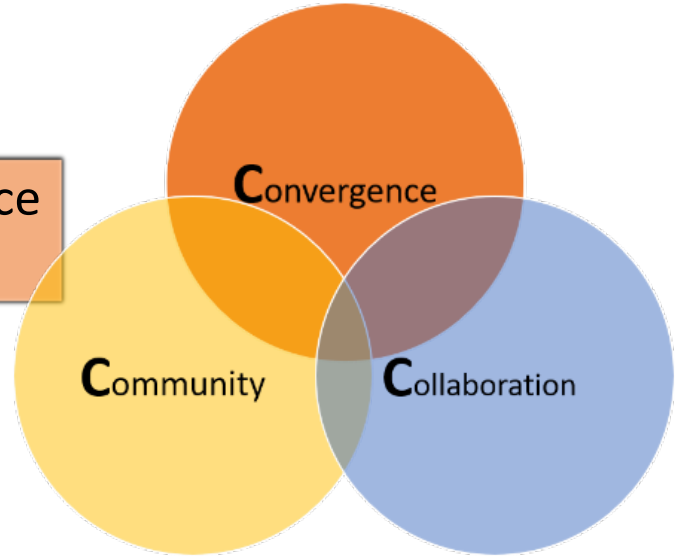
DCL: A Quantum Leap Demonstration of Topological Quantum Computing

DCL: Quantum Leap in Chemistry: molecular approaches

QISE-Net: Quantum Information Science and Engineering Network – "TRIPLETS"

NSF/DOE/AFOSR: Quantum Science Summer School; 2017-2020

EFRI-ACQUIRE (2016): Advancing Communication Quantum Information Research in Engineering

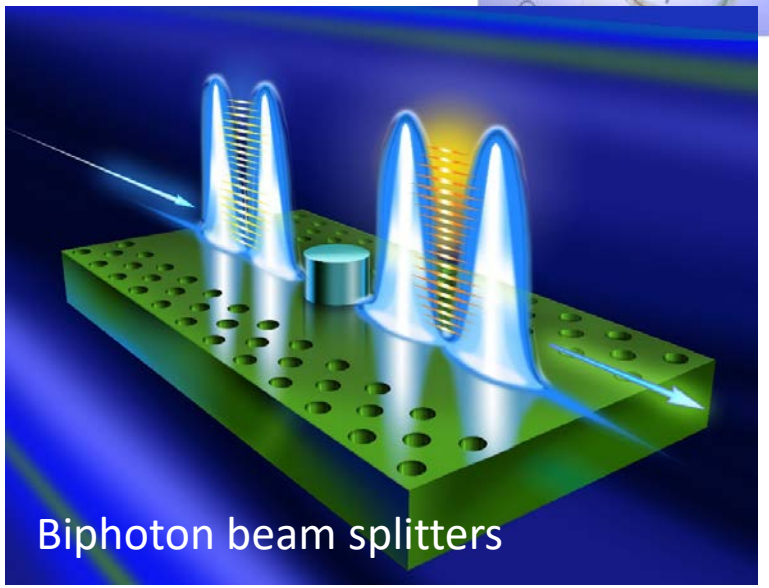


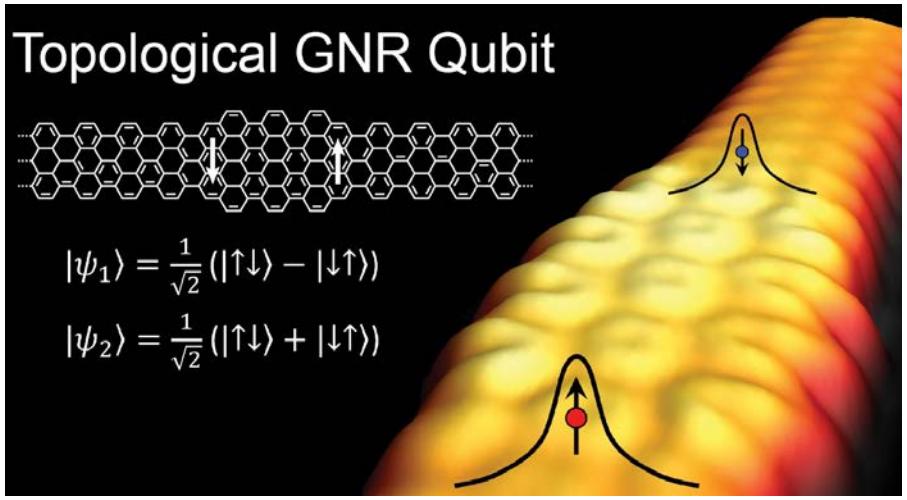
Transformational Advances in Quantum Systems (RAISE-TAQS)

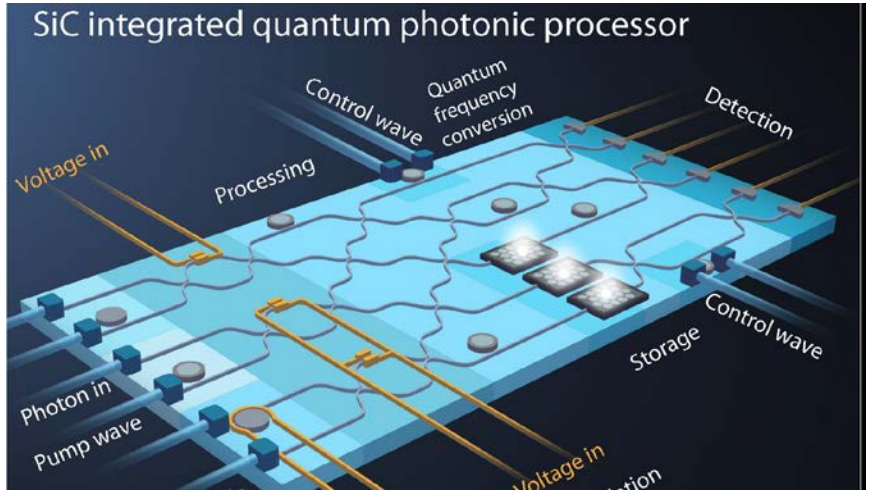
Innovative proposals from Teams of 3 or more PIs

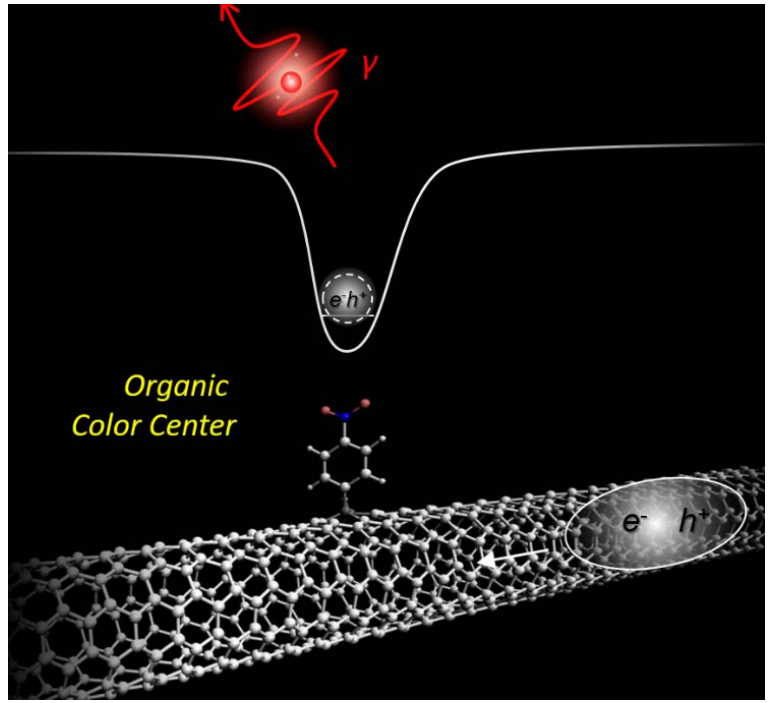
- Expertise in several technical disciplines
- Focus on quantum functionality
- Experimental demonstrations that advance fundamental concepts and applications

FY 2018:
25 awards
totaling $25M





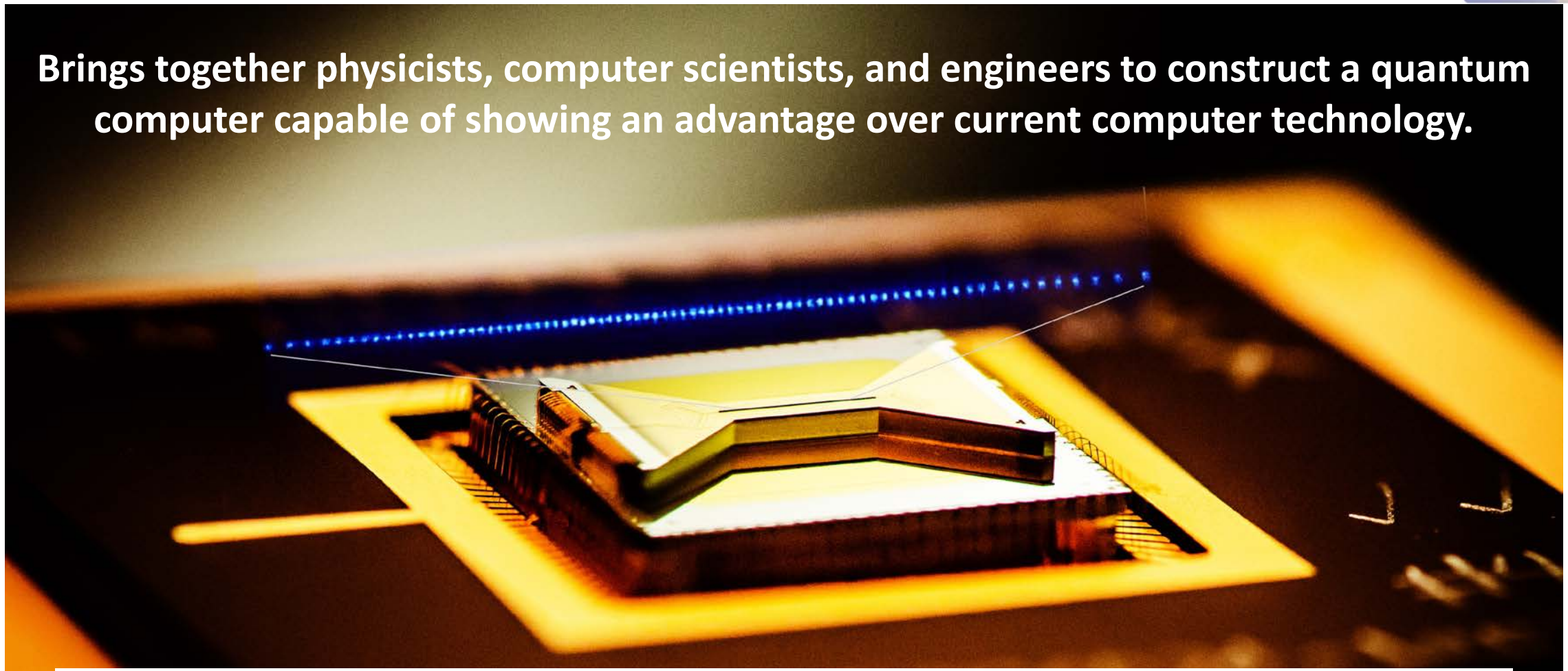




NSF 18-035

Ideas Lab: Practical Fully-Connected Quantum Computer (PFCQC)

Brings together physicists, computer scientists, and engineers to construct a quantum computer capable of showing an advantage over current computer technology.



NSF Award 1818914 PFCQC: STAQ: Software-Tailored Architecture for Quantum co-design

$15 million grant for a multi-institution quantum research collaboration.

Trapped ions (superimposed) above a fabricated trap to capture and control ion qubits (quantum bits).

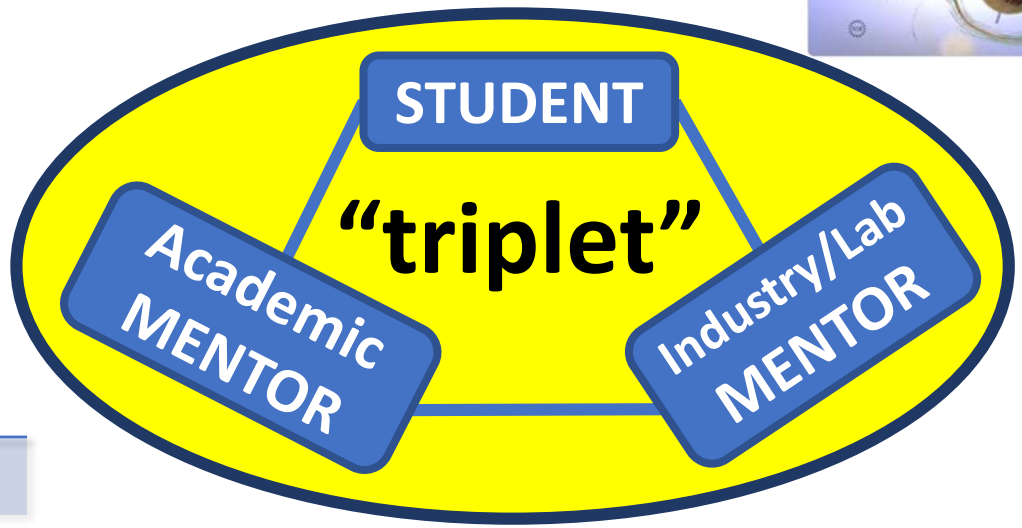
Image Credit: *K. Hudek, Ion Q&E / E. Edwards, JQI*

NSF 17-548

Quantum Leap Triplets

Quantum Information Science and Engineering Network (QISE-NET)

Building "Triplets" to Bridge Academia and Industry



University	*Partner*
Columbia U	Raytheon BBN
Georgia Tech	IBM Watson
MIT	Sandia Labs
U. Maryland	IonQ Inc.
MIT	Google
U. Maryland	IBM Watson
UW-Madison	Google
Georgetown	IBM Almaden
Georgia Tech	IBM
Dartmouth	Google

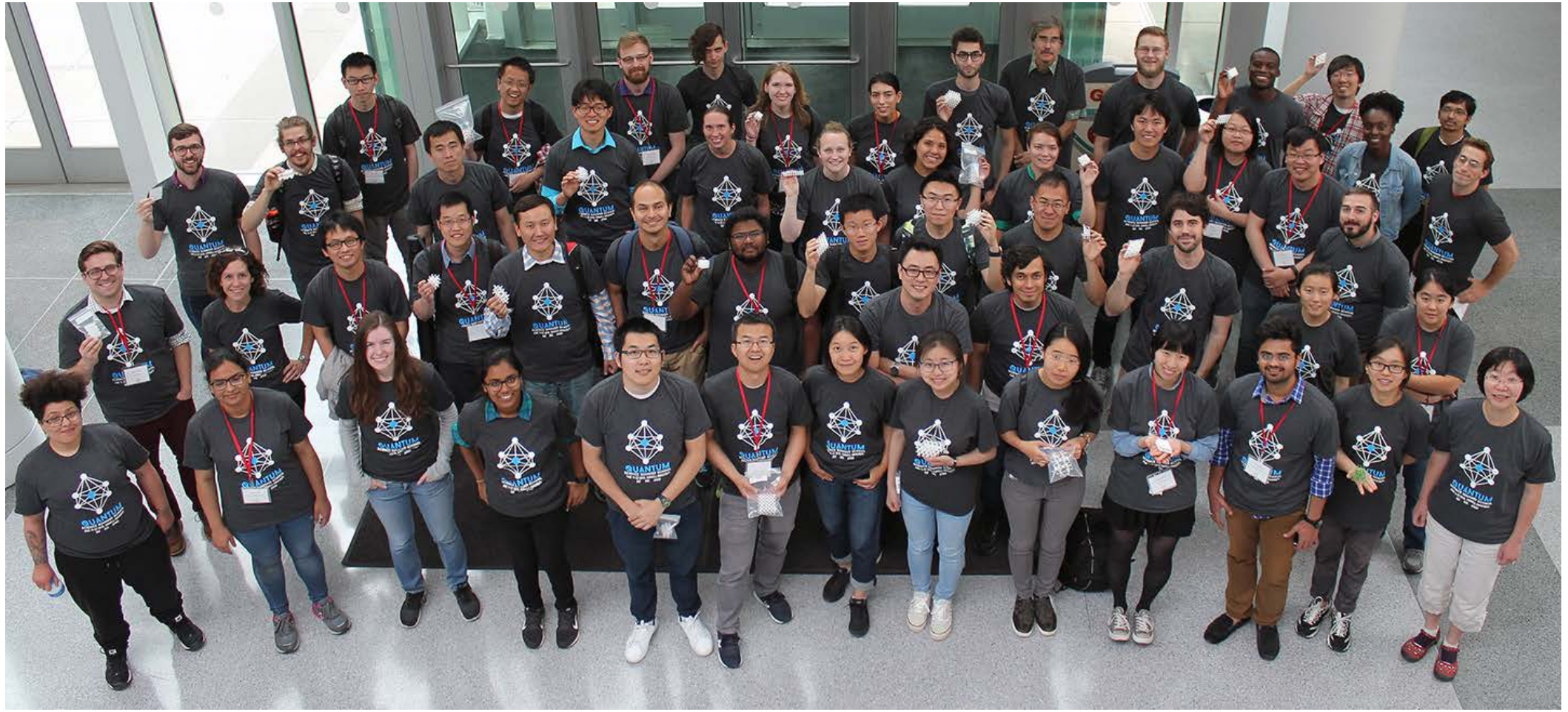
University	*Partner*
U. Chicago	IBM
UCSC	Argonne
UT Austin	NIST
Caltech	IBM
Caltech	Google
U. Pitt.	IBM
U. Illinois	NIST
Vanderbilt	ORNL
Sony Brook U.	BNL
UW Madison	Adamas Nano.
MT State	MT Instruments

Groups of students, faculty, industry partners working on Quantum Leap challenges

NSF Award 1747426
(9 participating NSF Divisions)

Quantum Science Summer School

Held at: JHU 2017, Cornell 2018, PSU 2019



Jointly Funded with DOE

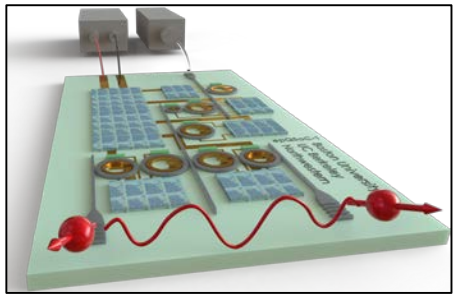
and AFOSR

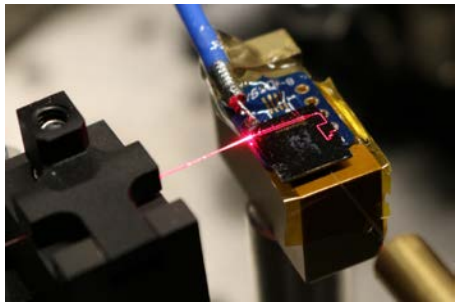
2019 QS³ will be at Penn State, June 3-14

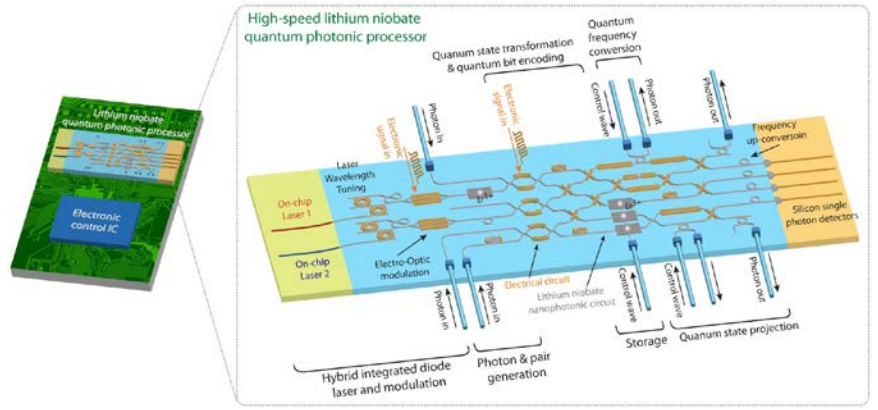
NSF Award #1743059

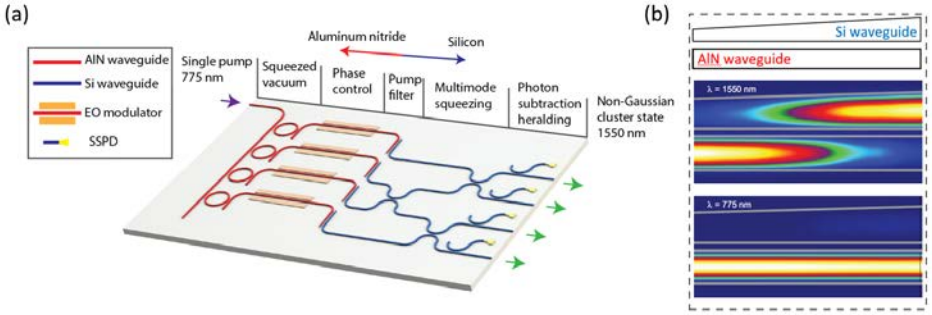
Engineering Quantum Integrated Platforms for Quantum Communication (RAISE-EQuIP)

- **Engineering-led interdisciplinary research for advancing quantum communication**
- **Innovations in key components:**
  - Transmitter or emitter of quantum information
  - Channel for propagation/storage of quantum information
  - Receiver or detector of quantum information
- **Address problems from two perspectives:**
  - Device-level challenges
  - Signal-processing and communication-protocol challenges
- **Lead to a prototype system**
- **NSF 18-062**
- **8 awards** totaling **$6M**



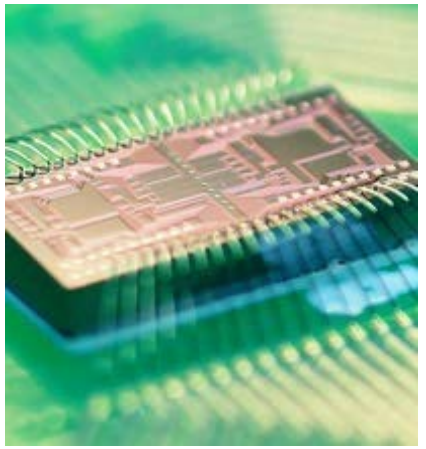






EFRI-ACQUIRE (2016-2017)

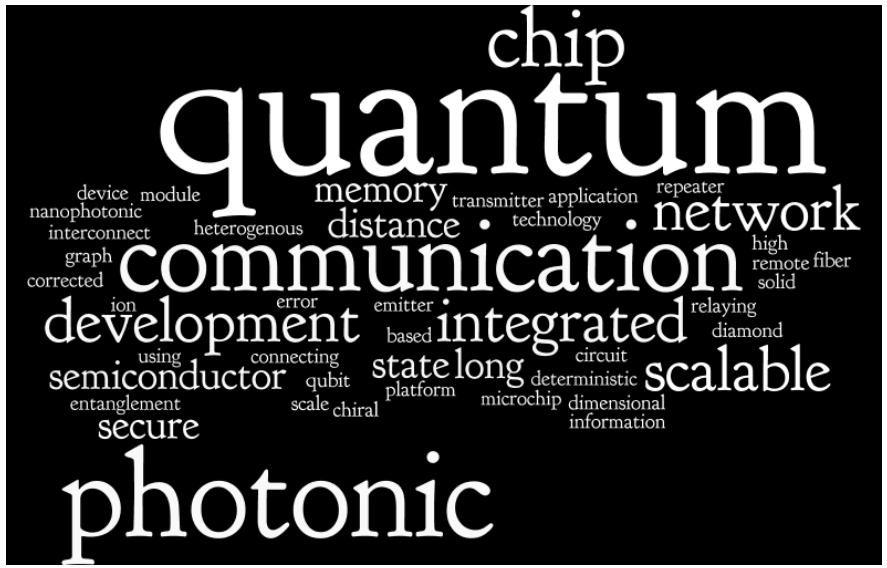
Advancing Communication
Quantum Information Research in Engineering



$18M
9 awards

- **Goals**
  - **Engineering** of deployable quantum communication systems
  - Development of a new workforce – **Quantum Engineers** – through training in quantum technology

- **Expected Outcomes**
  - Address challenges of quantum communication network engineering
  - **Target: Operation at/near room temperature with low energy in a secure communication network**



NSF 16-502 & 16-612

Taking the Leap (FY 19 and Beyond)

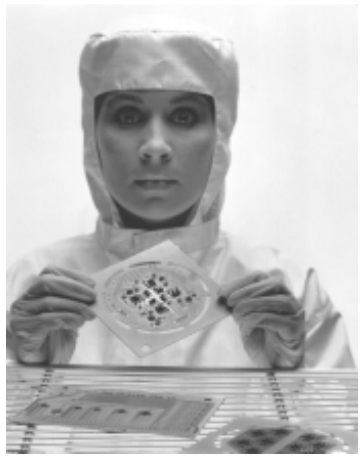
QLCI: Quantum Leap Challenge Institutes; 20-25 Conceptualization Grants and (up to) 5 Challenge Institutes; $94 M over 5 years; released Feb. 19, 2019. (NSF 19-559)

QII-TAQS: Quantum Idea Incubator for Transformational Advances in Quantum Systems; $26 M over 3-5 years; released Nov. 20, 2018. (NSF 19-532)

QCIS-FF: NSF Quantum Computing & Information Science Faculty Fellows; $6.75 M over 3 years; released Oct 22, 2018. (NSF 19-507)

Q-AMASE-i: Convergent Accelerated Discovery Foundries for Quantum Materials Science, Engineering and Information; $20-25 M over 5 years; released Aug. 2, 2018. (NSF 18-578)

Q-AMASE-i: Quantum Foundries



- Enabling Quantum Leap: Convergent Accelerated Discovery Foundries for Quantum Materials Science, Engineering, and Information (Q-AMASE-i) – NSF 18-578
- Private Sector Participation Required – Industrial partner expectations:
  - Be actively involved in proposing and executing research directions with the best chance of translation;
  - Participate in the Foundry's advisory board, research and curriculum collaborations, and entrepreneurship;
  - Provide internships to students
- Full proposals under evaluation

NSF 18-578
Anticipated 1-5 awards
Total: $20-25M per award / 6 yrs

QCIS-FF: Quantum Computing & Information Science Faculty Fellows

NSF QCIS-FF

The QCIS-FF program is intended to add to the existing academic workforce in quantum computing and communication.

- NSF funding will support the entire academic year salary and benefits of a single tenure-track or tenured faculty member.
- Total Budget per proposal: **$750K (for 3 years)**
- Anticipated Funding: **$6.75M**
- Anticipated number of awards: **9**

NSF 19-507

QII-TAQS – Quantum Incubators

Quantum Idea Incubator for Transformational Advances in Quantum Systems

- ***Goal:*** Innovative interdisciplinary research for incubating new ideas, concepts, and technologies
  - **focus on quantum functionality**
  - **result in experimental demonstrations and/or proof-of-concept validations**
- ***How:*** **Interdisciplinary team efforts. Research topic goals open.**
- ***Why:*** **Building and growing a community of cross-disciplinary QL research teams**
  - Broadly distributed, yet feasible, cross-disciplinary teams
  - Education/training of next generation QIS engineers and scientists
  - Enhancing connection between distinct disciplines
  - Growing less-mature communities

NSF 19-532
Anticipated 18-22 awards
Total: $26M

Quantum Leap Challenge Institutes (QLCI)

- Large-scale projects driven by a **cross-disciplinary** challenge research theme for advancing QIS frontiers
- Conceptualize, develop, and implement revolutionary new approaches and technologies for quantum information processing
- Projects with clear and compelling science-, algorithm-, and engineering-driven goals, with specific target milestones for a five-year period of performance
- Research in focus areas of **quantum computation**, **quantum communication**, **quantum simulation, or quantum sensing**

Related documents:

- ***National Strategic Overview for Quantum Information Science***, National Science and Technology Council, September 2018
- ***National Quantum Initiative* Act**, H.R. 6227, December 21, 2018

Quantum Leap Challenge Institutes (QLCI)
(continued)

- Activities:
  - **Cross-Disciplinary Research**
  - **Education, Training, and Workforce Development**
  - **Research Coordination and Community Engagement**
  - **Synergistic Partnerships and Infrastructure Development**
- Two types of awards:
  - **Conceptualization Grants** funded at a level of $100,000-$150,000 for 12 months
  - **Challenge Institute awards** funded at a level of up to $5,000,000/year for 5 years

- Two rounds of competition:

Round I:
  - **Conceptualization Grant** proposals from groups undertaking planning activities
  - **Challenge Institute** proposals from groups ready to apply

Round II:
  - **Challenge Institute** proposals only

NSF 19-559

Anticipated:

15 to 25 Conceptualization Grants

1 to 3 Challenge Institutes in each round

Total: $94M / 5 yrs

THANK YOU

Contact details:

- Denise Caldwell
  - Quantum Leap Steering Committee Co-Chair
  - Division of Physics
- Henry Warchall
  - Quantum Leap Working Group Co-Chair
  - Division of Mathematical Sciences

Enabling the Quantum Leap

- NSF 16-502 EFRI ACQUIRE. Quantum Communication and Networking; $18M; 9 awds
- NSF 17-548 Ideas Lab: Practical Fully-Connected Quantum Computer; $15M / 5 yrs
- NSF Award 1730449 “EPiQC: Enabling Practical-scale Quantum Computing”; $10M / 5 yrs
  Expeditions in Computing program in CISE/CCF; See NSF news release 18-011
- NSF Award 1743059 (NSF, DOE, & AFOSR): Quantum Science Summer School (QS^3)
- NSF Award 1747426 “Triplets” QISE-Net Workshop Series: Cross-Sector Connections; $2.5M
- NSF 17-053 DCL: EAGER: BRAIDING Awards for Demonstrating Topological QC
- NSF 18-035 DCL: TAQS - Transformational Advances in Quantum Systems; $25M; 25 awds
- NSF 18-051 DCL: Enabling Quantum Leap in Chemistry; $6.4M in FY 2018
- NSF 18-046 DCL: Room-Temperature Q. Logic through Improved Low-D Materials
- NSF 18-062 DCL: EQuIP - Engineering Q. Integrated Platforms for Q. Comm.; $6M; 8 awds
- NSF 18-578 QAMASEi: Foundries for Q. Materials Science, Engineering, and Info. $20M - $25M
- NSF 19-507 QCIS Faculty Fellows; FY 2019 and FY 2020; $6.7M
- NSF 19-532 QII-TAQS Transformational Advances in Quantum Systems; $26M in FY 2019 - 2020
- NSF 19-559 QLCI Quantum Leap Challenge Institutes; $5M/year for each center; $94M / 5 yrs