Quantum Science and Technology at Fermilab

Farah Fahim

53rd Annual Users Meeting

11 Aug 2020

Quantum Science and Technology

- **Quantum computing:** processors that manipulate entangled qubits (or more generally qudits) coherently
- **Quantum algorithms:** mapping pieces of HEP problems to quantum computers/simulators
- **Quantum sensors:** using quantum devices as sensors, exploiting quantum properties such as entanglement, squeezing, and quantum non-demolition measurements
- **Quantum communications:** moving quantum information over macroscopic distances coherently, with applications such as networking of quantum computers or sensors

Fermilab Quantum Science and Technology Program

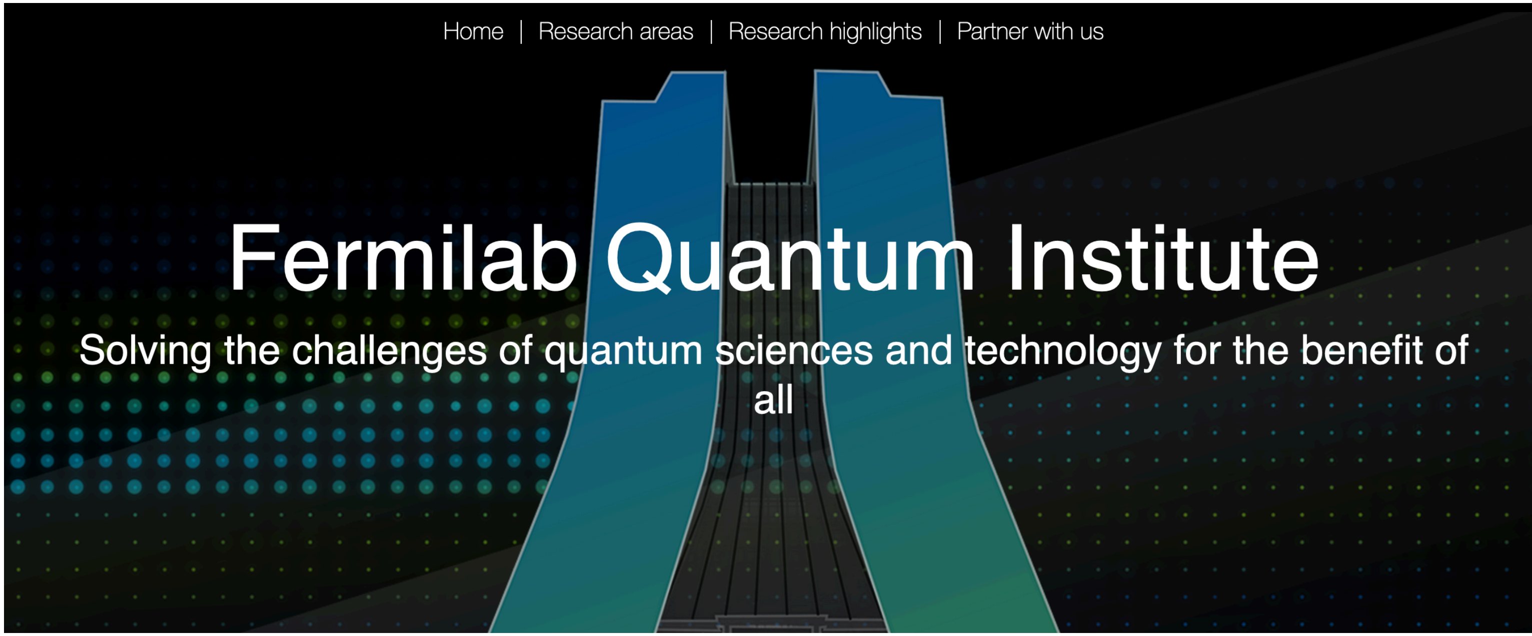
- **Goal:** Produce high impact quantum science and technology results in the near term, while building capacity for HEP needs in the long term
- **Fermilab is engaging with the National Quantum Initiative in ways appropriate to our role as the main HEP lab:**

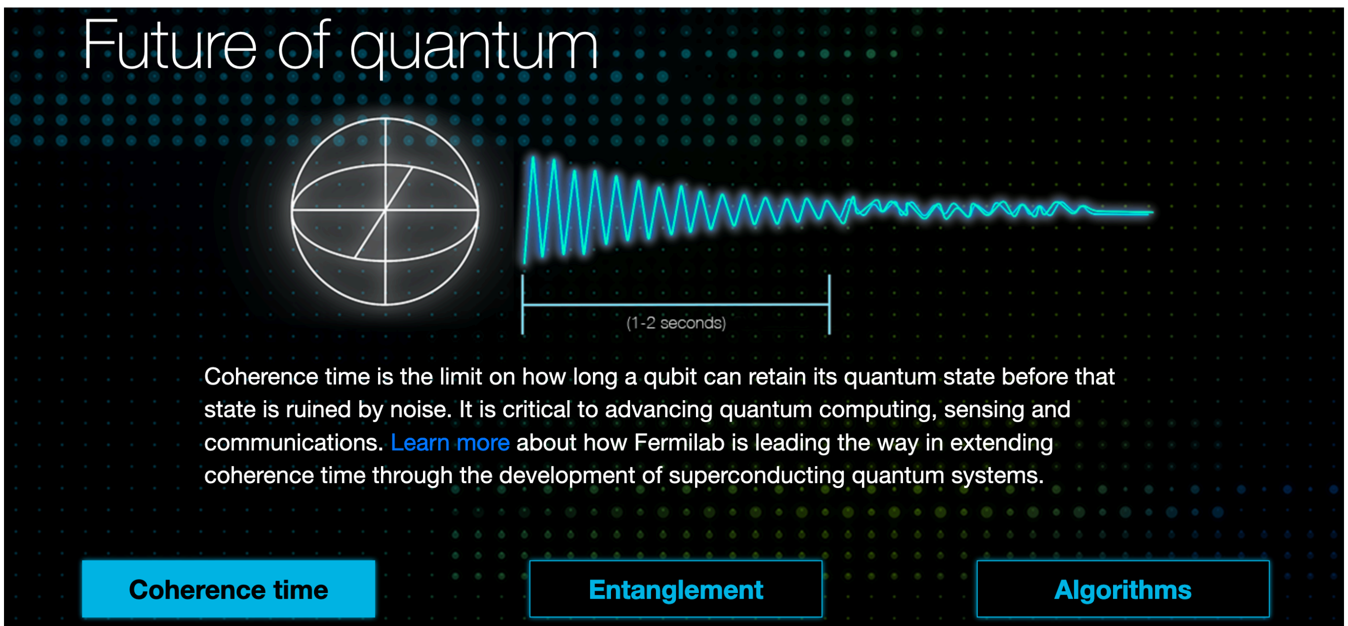
• • • • • •

- Focus on the science
- Exploit existing Fermilab expertise and infrastructure
- Keep Fermilab activities aligned to HEP program needs
- Engage partners who already have leading quantum expertise
- Find out where HEP can have impact on QIS, including tech transfer
- Act as a gateway and hub for the larger HEP community to engage with quantum science and technology

FY20 DOE QuantISED funding consolidates the core quantum research program hosted at Fermilab

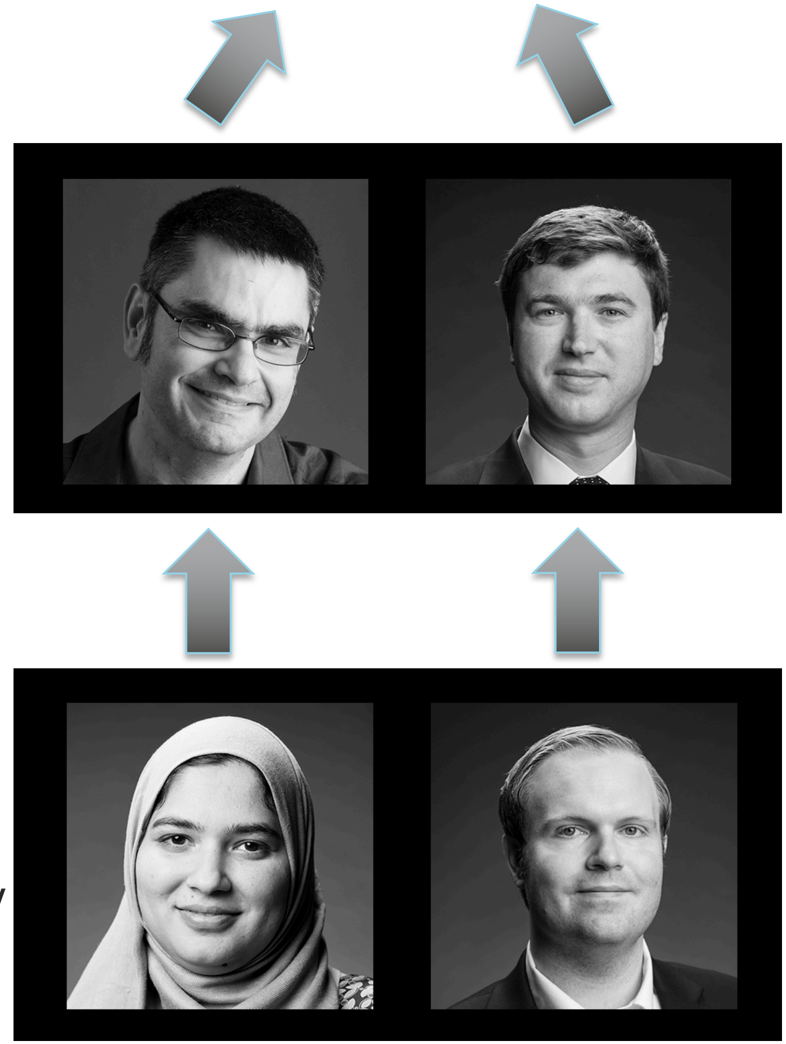
- Task 1: QIS and HEP Theory (Marcela Carena PI)
  Collaborating institutions: Caltech, MIT, U. Wash, UIUC, Purdue
- Task 2: Quantum Networks and Analysis (Gabe Perdue PI)
  Collaborating institutions: Caltech
- Task 3: SRF-based Quantum Technology and Sensing (Alex Romanenko PI)
  Collaborating institutions: Northwestern, U. Colorado/NIST, U. Wisc.
- Task 4: Quantum Sensors for Dark Matter (Aaron Chou PI)
  Collaborating institutions: Caltech/JPL, MIT, LBNL, U. Chicago, U. Colorado/NIST, Yale, U. Wisc.


Home | Research areas | Research highlights | Partner with us
Fermilab Quantum Institute
Solving the challenges of quantum sciences and technology for the benefit of all


Future of quantum
(1-2 seconds)
Coherence time is the limit on how long a qubit can retain its quantum state before that state is ruined by noise. It is critical to advancing quantum computing, sensing and communications. Learn more about how Fermilab is leading the way in extending coherence time through the development of superconducting quantum systems.
Coherence time
Entanglement
Algorithms

Nigel Lockyer, FNAL Director
Joe Lykken, Deputy Director for Research

FQI organization



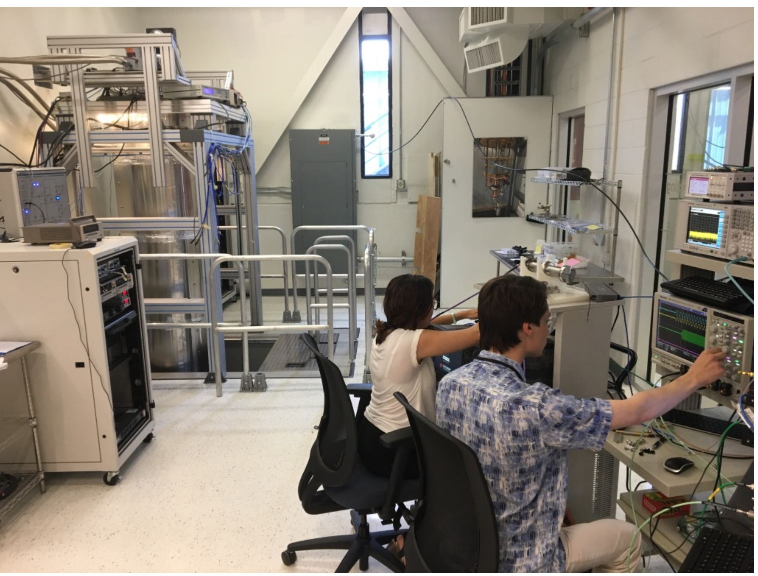
Panagiotis Spentzouris
FQI Head of Quantum Science
Alex Romanenko
FQI Head of Quantum Technology

Farah Fahim
FQI Deputy Head of Quantum Science
Eric Holland
FQI Deputy Head of Quantum Technology

Most FQI members are matrixed from the Fermilab divisions

Fermilab lab for SRF-based quantum systems

Now expanding to a second test stand, and a microwave channel connecting the test stands



Fermilab

THE UNIVERSITY of WISCONSIN MADISON

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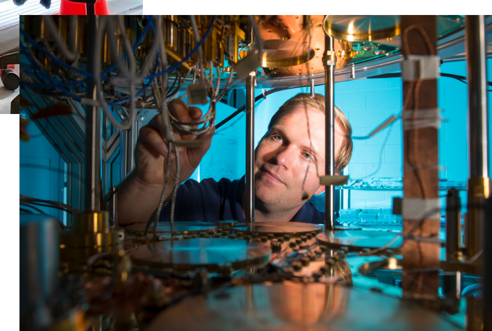
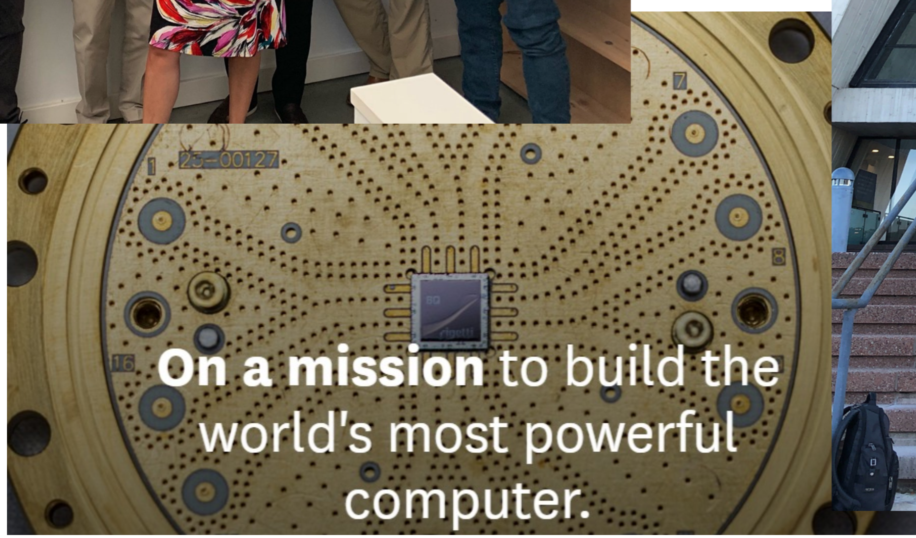


Fermilab @ rigetti

Aug 22-23 2019

rigetti @ Fermilab

Sept 16-17 2019



MAGIS-100 experiment moving forward

The MAGIS-100 experiment has been funded by the DOE QuantISED program and by the Moore Foundation

- This is the first experiment funded by QuantISED, with first results expected in three years
- We will be hosting the world's largest cold atom interferometer system, sensitive to both ultralight dark matter and gravity waves
- The collaboration includes Stanford, Northwestern, NIU, Johns Hopkins, Univ. of Liverpool, and Cambridge U.

Jason Hogan PI
(Stanford)

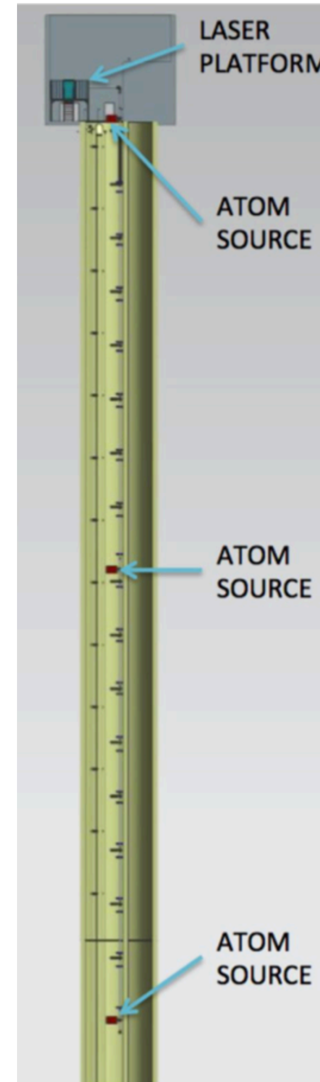
GORDON AND BETTY MOORE FOUNDATION

JOHNS HOPKINS UNIVERSITY

Fermilab

NIU

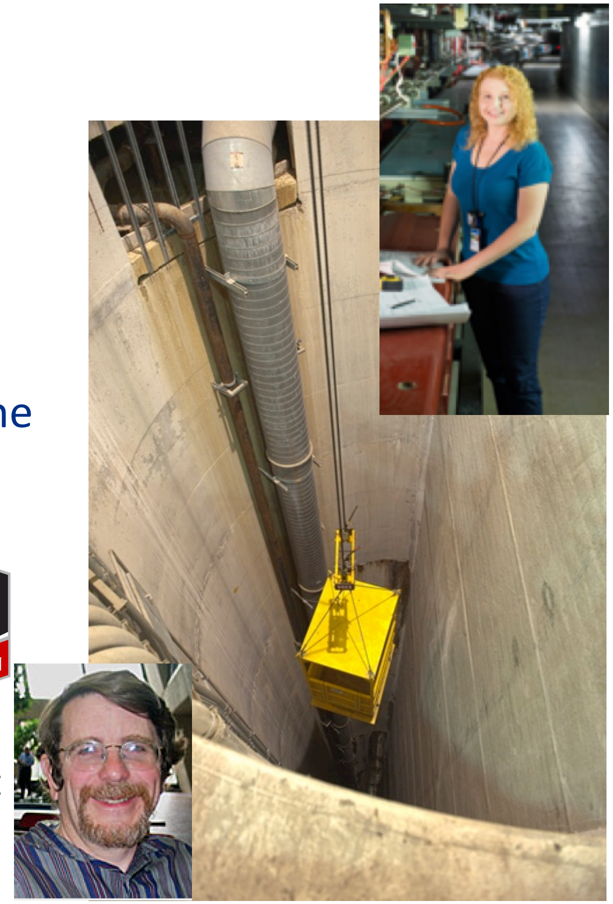
UNIVERSITY OF LIVERPOOL



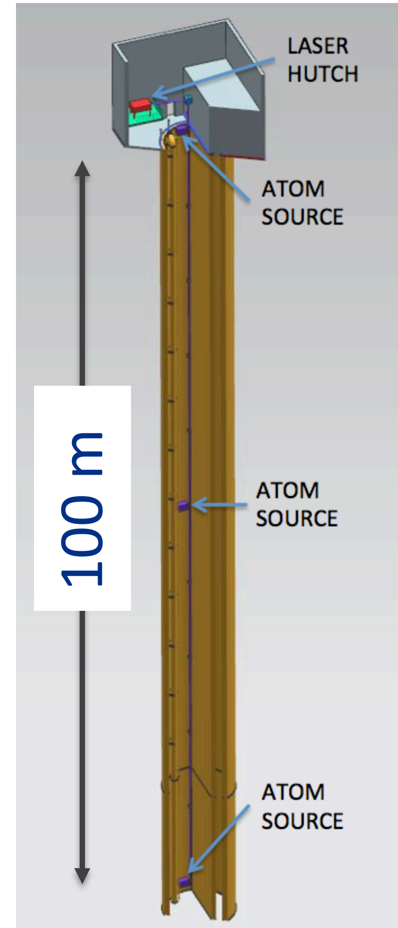
MAGIS-100 recent progress

Finalized the configuration and lens geometry design of the in-vacuum telescope for the interferometry laser beams.
Laser vendor can test frequency stabilization and control in house.
Progress on laser transport system vibration analysis, design details for the laser transport system,

Linda Valerio



Rob Plunkett



supported by the DOE HEP QuantISED program

Nine recent quantum papers from Fermilab

FERMILAB-PUB-20-198-T

Gluon Field Digitization via Group Space Decimation for Quantum Computers

Yao Ji,[1,2,*] Henry Lamm,[3,†] and Shuchen Zhu[4,‡]
(NuQS Collaboration)
[1] *Theoretische Physik 1, Naturwissenschaftlich-Technische Fakultät, Universität Siegen, D-57068 Siegen, Germany*
[2] *Institut für Theoretische Physik, Universität Regensburg, D-93040 Regensburg, Germany*
[3] *Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*
[4] *Department of Computer Science, Georgetown University, Washington, DC 20057, USA*
(Dated: June 2, 2020)

FERMILAB-PUB-20-184-QIS

Quantum Machine Learning in High Energy Physics

Wen Guan, Gabriel Perdue, Arthur Pesah, Maria Schuld, Koji Terashi, Sofia Vallecorsa, Jean-Roch Vlimant
E-mail: jvlimant@caltech.edu
May 2020

FERMILAB-PUB-19-546-QIS-SCD

Restricted Boltzmann Machines for galaxy morphology classification with a quantum annealer

João Caldeira,[1,*] Joshua Job,[2,*] Steven H. Adachi,[2] Brian Nord,[1,3,4] and Gabriel N. Perdue[1]
[1] *Fermi National Accelerator Laboratory, Batavia, IL 60510*
[2] *Lockheed Martin Advanced Technology Center, Sunnyvale, CA 94089*
[3] *Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637*
[4] *Department of Astronomy and Astrophysics, University of Chicago, Chicago, IL 60637*
(Dated: February 17, 2020)

FERMILAB-PUB-20

Suppressing Coherent Gauge Drift in Quantum Simulations

Henry Lamm,[1,*] Scott Lawrence,[2,†] and Yukari Yamauchi[2,‡]
(NuQS Collaboration)
[1] *Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*
[2] *Department of Physics, University of Maryland, College Park, MD 20742, USA*

Three-Dimensional Superconducting Resonators at $T < 20$ mK with Photon Lifetimes up to $\tau = 2$ s

A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Belomestnykh, S. Posen, and A. Grassellino
Phys. Rev. Applied **13**, 034032 – Published 12 March 2020

Quantum Computing for Neutrino-nucleus Scattering

Alessandro Roggero,[1,*] Andy C. Y. Li,[2,†] Joseph Carlson,[3,‡] Rajan Gupta,[3,§] and Gabriel N. Perdue
[1] *Institute for Nuclear Theory, University of Washington, Seattle, WA 98195, USA*
[2] *Fermi National Accelerator Laboratory, Batavia, IL 60510*
[3] *Los Alamos National Laboratory, Theoretical Division T-2, Los Alamos, NM 87545, USA*
(Dated: November 18, 2019)

Overlap junctions for superconducting quantum electronics and amplifiers

Mustafa Bal,[1,2,a)] Junling Long,[1,2] Ruichen Zhao,[1,2] Haozhi Wang,[1,2] Sungoh Park,[1,2] Corey Rae Harrington McRae,[1,2] Tongyu Zhao,[1,2] Russell E. Lake,[1,2] Daniil Frolov,[3] Roman Pilipenko,[3] Silvia Zorzetti,[3] Alexander Romanenko,[3] and David P. Pappas[1,b)]
[1)] *National Institute of Standards and Technology, Boulder, Colorado 80305, USA*
[2)] *Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*
[3)] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*
(Dated: 25 May 2020)

FERMILAB-PUB-19-537-T

Back-action evading impulse measurement with mechanical quantum sensors

Sohitri Ghosh[a,b,*] Daniel Carney[a,b,d,†] Peter Shawhan[b,c,‡] and Jacob M. Taylor[a,b§]
[a] *Joint Quantum Institute/Joint Center for Quantum Information and Computer Science, University of Maryland, College Park/National Institute of Standards and Technology, Gaithersburg, MD, USA*
[b] *Department of Physics, University of Maryland, College Park, MD, USA*
[c] *Joint Space-Science Institute, University of Maryland, College Park/NASA Goddard Space Flight Center, Greenbelt, MD, USA and*
[d] *Fermi National Accelerator Laboratory, Batavia, IL, USA*

FERMILAB-PUB-20-045

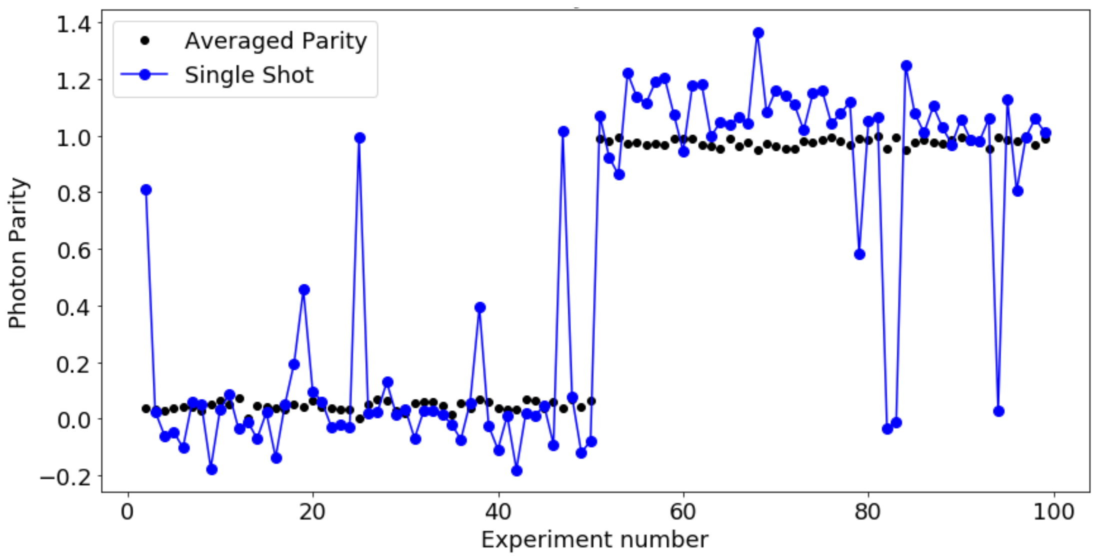
Quantum Simulation of Field Theories Without State Preparation

Siddhartha Harmalkar,[1,*] Henry Lamm,[2,†] and Scott Lawrence[1,‡]
(NuQS Collaboration)
[1] *Department of Physics, University of Maryland, College Park, MD 20742, USA*
[2] *Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*
(Dated: January 31, 2020)

Quantum non-demolition measurements of single, signal photons

Akash Dixit, Aaron Chou, David Schuster

In a dark matter experiment, repeatedly measure the qubit clock frequency to determine whether the cavity contains 0 or 1 signal photons:



Many QND measurements agree that the cold cavity contains 0 photons

Start injecting mock signal photons

Many QND measurements of the single photons. **Averaging improves fidelity.**

Fermilab

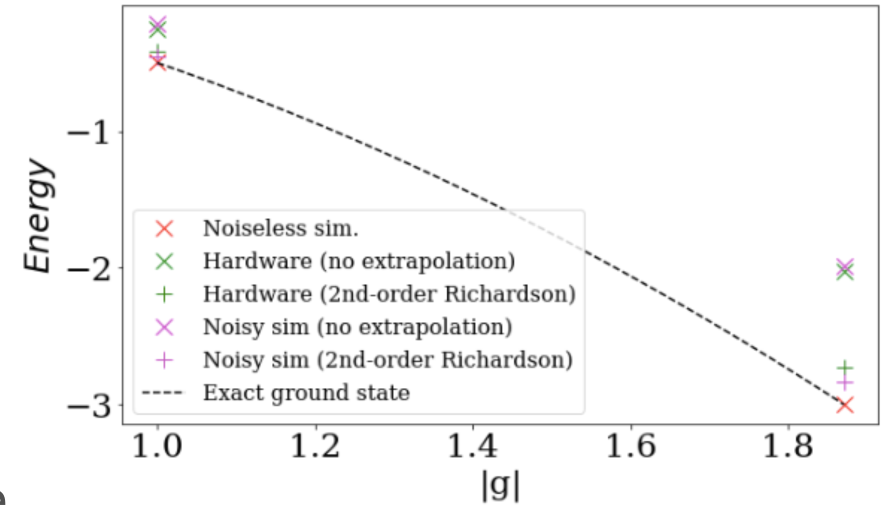
THE UNIVERSITY OF CHICAGO

HEISING-SIMONS FOUNDATION

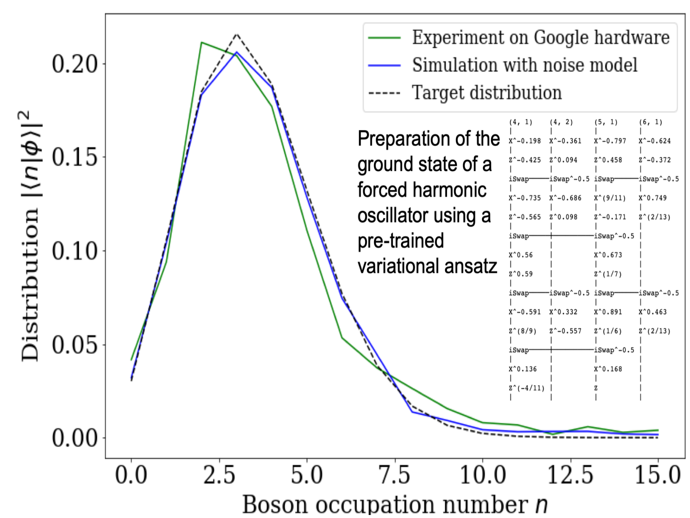
DOE HEP QuantISED

From Quantum Supremacy to Quantum Advantage

Fermilab is working with Google to explore physics problems where NISQ era quantum computers might show the possibility of a quantum advantage

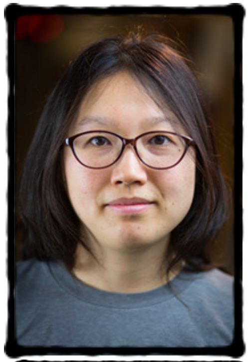


Running on Google: Variational Quantum Eigensolvers (VQE) for **non-relativistic fermion-boson systems**, in a **codesign activity**



Quantum Computing as a High School Module

arXiv:2004.07206 , arXiv:1905.00282



Ranbel Sun

Anastasia Perry

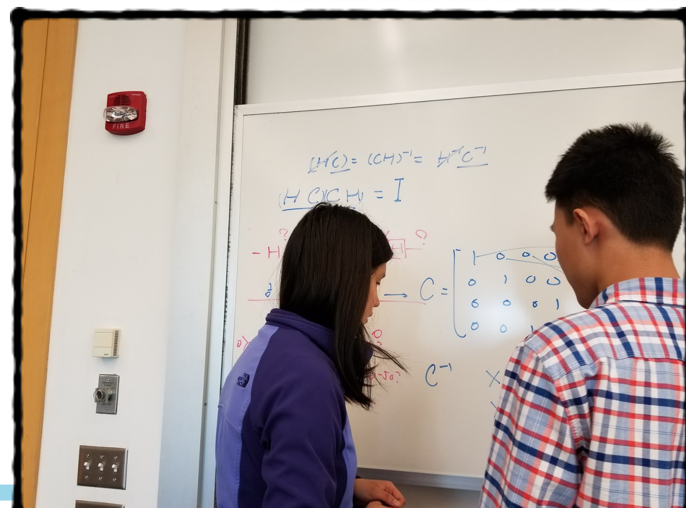
High School Teachers

Ciaran Hughes

Joshua Isaacson

Jessica Turner

Fermilab Scientists



Students Learning Quantum Computing from our course. Left: Quantum Teleportation. Right: C-not gate.

Quantum Computing as a High School Module

[arXiv:2004.07206](https://arxiv.org/abs/2004.07206) , [arXiv:1905.00282](https://arxiv.org/abs/1905.00282)

Paul Dabbar @ScienceUnderSec · Jun 15

This is an excellent quantum computing course for high schoolers. All, please RT to spread awareness to teachers across the country about this course material.

> **Fermilab** @Fermilab · Jun 14
>
> Fermilab scientists publish quantum computing course for high school students:
> news.fnal.gov/2020/06/fermil...

Students Learning Quantum Computing from our course. Left: Quantum Teleportation. Right: C-not gate.

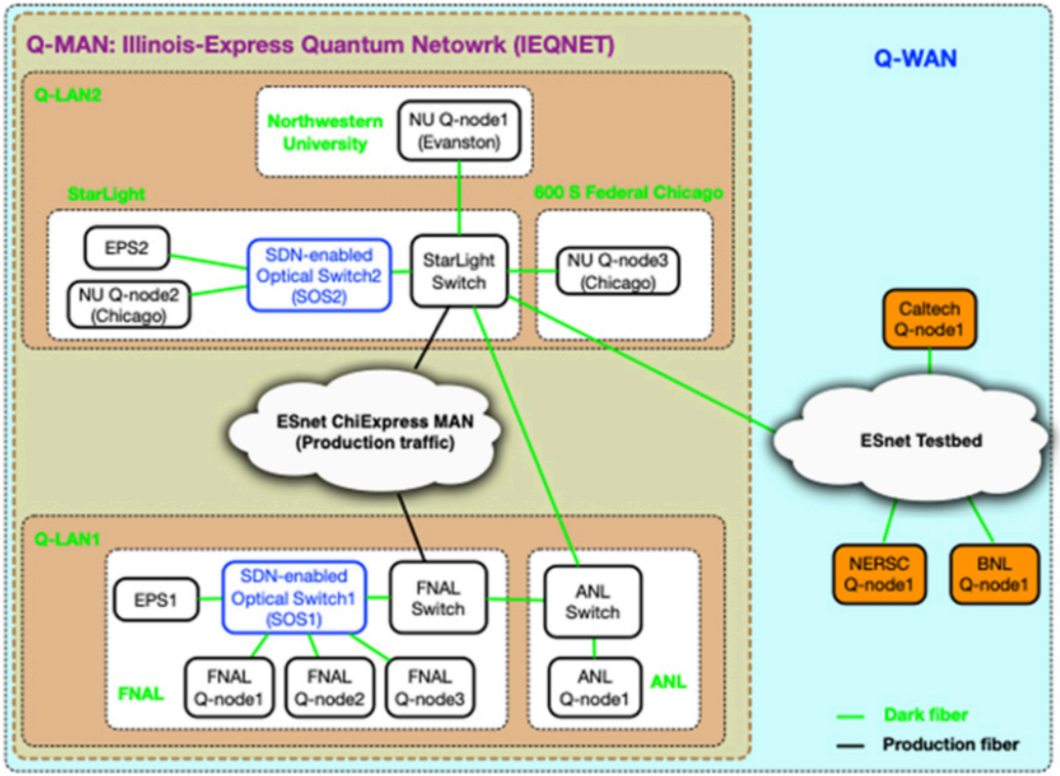
From Long-distance Entanglement to Building a Nationwide Quantum Internet

Report of the DOE Quantum Internet Blueprint Workshop

February 5-6, 2020

5.2. Milestone I: Repeaterless Metropolitan-scale Testbeds

Like the Internet, quantum networks are expected to undergo different stages of research and development until they reach their full functionality. Fermilab, Argonne National Laboratory, California Institute of Technology, Northwestern University, NuCrypt, and HYPERLIGHT are working collaboratively on such an early-stage project, funded by DOE-ASCR's Illinois-Express Quantum Network (IEQNET) project. The project's goal is to build a metropolitan-scale quantum network testbed that supports the investigation and demonstration of essential quantum network functionality and capabilities.

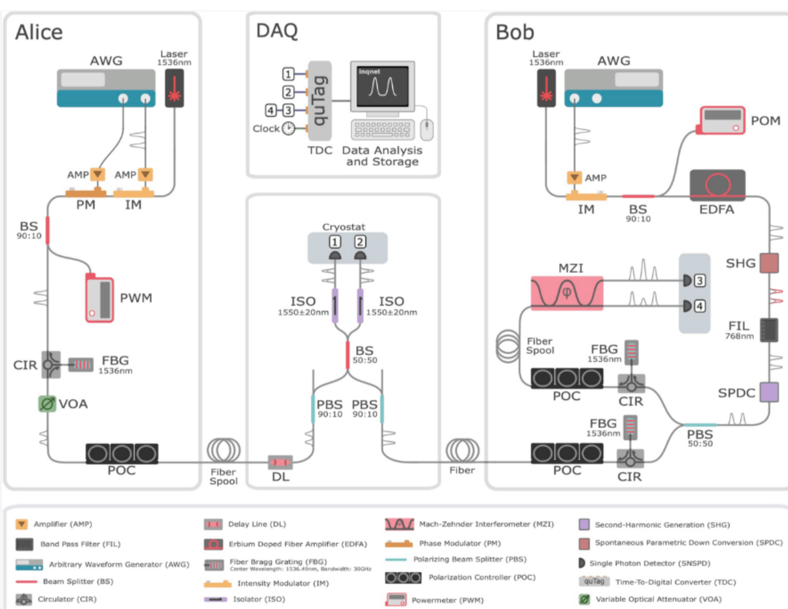


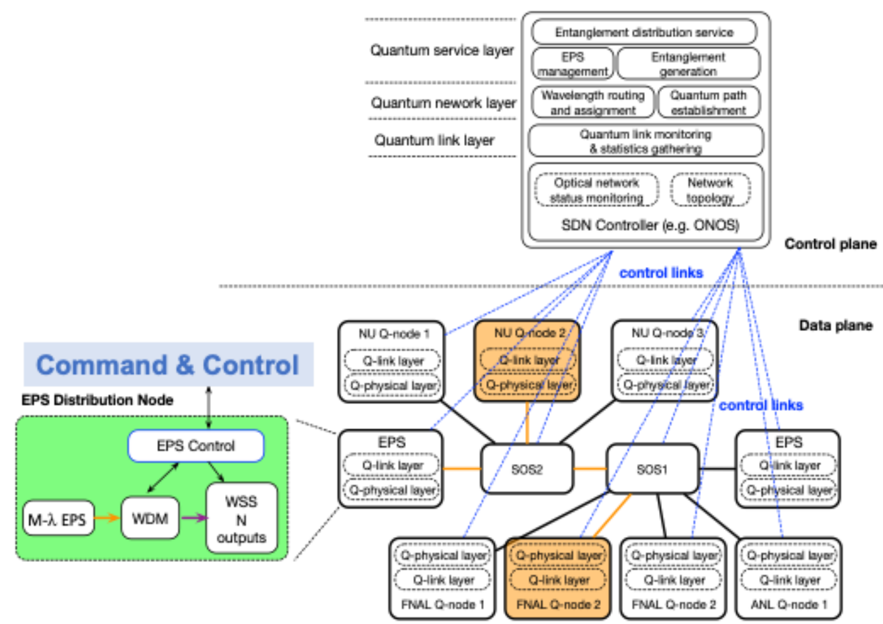
Illinois Quantum Express Network (IEQNET)

- Collaboration of Fermilab, Northwestern, Caltech, and Argonne to demonstrate a quantum network connecting Fermilab to the Northwestern campuses in Chicago and Evanston using existing fiber links
- A 4-year project funded by DOE ASCR with Panagiotis Spentzouris PI
- Leverages off the technology developed for FQNET

The IEQNET testbed

- Built leveraging deployment and R&D at the FQNET and CQNET teleportation experiments
  - Optical photonic qubits over telecom fiber, cutting edge single photon detectors (SNSPD), electronics and control systems developed for HEP experiments
  - Achieving excellent teleportation fidelity and stability of operations
- IEQNET incorporate transparent optical switches and SDN technology for multi-user network use cases





Teleportation System Towards a Quantum Internet*

Raju Valivarthi,[1,2] Samantha Davis,[1,2] Cristián Peña,[1,2,3] Si Xie,[1,2] Nikolai Lauk,[1,2] Neil Sinclair,[1,2,4] Lautaro Narváez,[1,2] Jason P. Allmaras,[5] Andrew D. Beyer,[5] Yewon Gim,[2,6] Meraj Hussein,[2] George Iskander,[1] Hyunseong Linus Kim,[1,2] Boris Korzh,[5] Andrew Mueller,[1] Daniel Oblak,[7] Mandy Rominsky,[3] Matthew Shaw,[5] Christoph Simon,[1] Panagiotis Spentzouris,[3] Dawn Tang,[1,2] Emma E. Wollman,[5] and Maria Spiropulu[1,2]

[1] *Division of Physics, Mathematics and Astronomy, California Institute of Technology, Pasadena, CA 91125, USA*
[2] *Alliance for Quantum Technologies (AQT), California Institute of Technology, Pasadena, CA 91125, USA*
[3] *Fermi National Accelerator Laboratory, Batavia, IL 60510, USA*
[4] *John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA*
[5] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA*
[6] *AT&T Foundry, Palo Alto, CA 94301, USA*
[7] *Institute for Quantum Science and Technology, and Department of Physics & Astronomy, University of Calgary, Calgary, AB T2N 1N4, Canada*

(Dated: June 29, 2020)

Quantum teleportation is essential for many quantum information technologies including long-distance quantum networks. Using fiber-coupled devices, including off-the-shelf optics and state-of-the-art low-noise superconducting nanowire single photon detectors, we achieve quantum teleportation of time-bin qubits at the telecommunication wavelength of 1536.5 nm. We measure teleportation fidelities of $\geq 90\%$ that are consistent with an analytical model of our system, which includes realistic imperfections. To demonstrate the compatibility of our setup with deployed quantum networks, we teleport qubits over 22 km of single-mode fiber while transmitting qubits over an additional 22 km of fiber. Our system, which is compatible with emerging solid-state quantum devices, is a foundation for a high-fidelity quantum internet with practical devices.

Caltech

inqnet ALLIANCE FOR QUANTUM TECHNOLOGIES

In partnership with:

JPL

Teleportation System Towards a Quantum Internet*

Raju Valivarthi,[1,2] Samantha Davis,[1,2] Cristián Peña,[1,2,3] Si Xie,[1,2] Nikolai Lauk,[1,2] Neil Sinclair,[1,2,4] Lautaro Narváez,[1,2] Jason P. Allmaras,[5] Andrew D. Beyer,[5] Yewon Gim,[2,6] Meraj Hussein,[2] George Iskander,[1] Hyunseong Linus Kim,[1,2] Boris Korzh,[5] Andrew Mueller,[1] Daniel Oblak,[7] Mandy Rominsky,[3] Matthew Shaw,[5] Christoph Simon,[1] Panagiotis Spentzouris,[3] Dawn Tang,[1,2] Emma E. Wollman,[5] and Maria Spiropulu[1,2]

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[4]*John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, MA 02138, USA*
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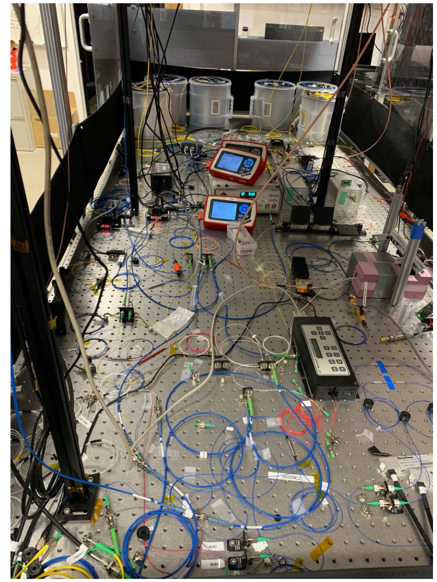
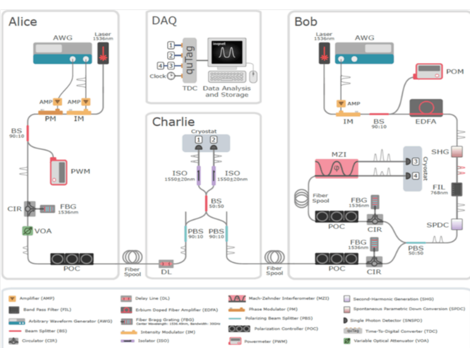
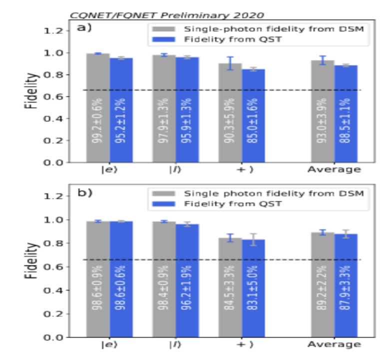




- Quantum teleportation technology ready to move from labs to **real networks.**
- **Record fidelities** achieved for time-bin qubit teleportation.
- First complete **theoretical model** of the experiment.
- Advanced **data acquisition** techniques.



DOE SC National Quantum Information Science Research Centers

Fermilab leading on one proposal and is a core partner on another

- $25M/yr for 5+5 years to multi-disciplinary consortia of labs, universities, and industry
- Sponsored by DOE BES, ASCR, and HEP
- Expect up to five Centers to be funded in FY20

DEPARTMENT OF ENERGY
OFFICE OF SCIENCE

NATIONAL QUANTUM INFORMATION SCIENCE
RESEARCH CENTERS

FUNDING OPPORTUNITY ANNOUNCEMENT (FOA) NUMBER:
DE-FOA-0002253

- Must be transformative value added to the quantum core program
- Must contain both fundamental science and technology development