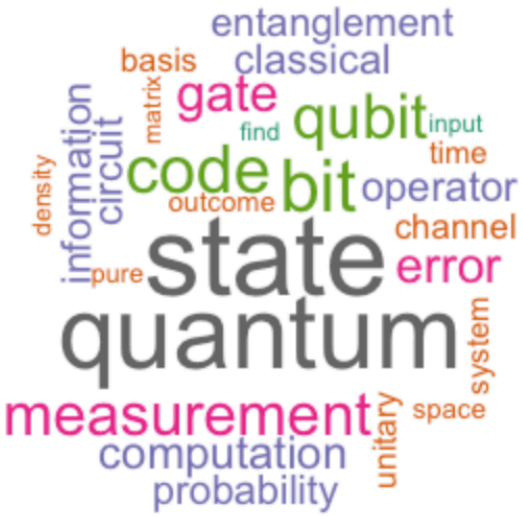
Status of Quantum Science an Technology at Fermilab

Joe Lykken

Fermilab PAC Meeting

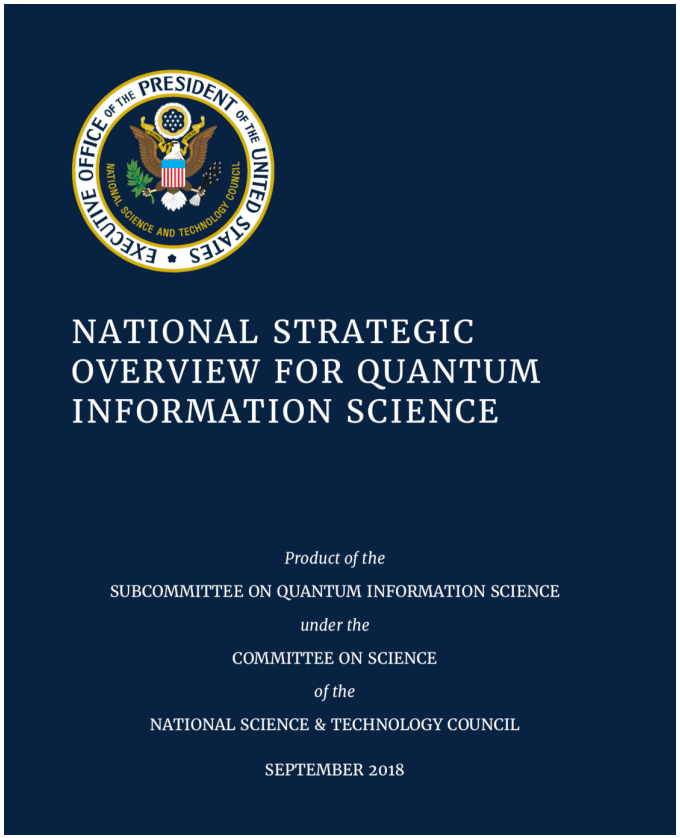
January 14, 2020



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

National Quantum Initiative



DEPARTMENT OF ENERGY
OFFICE OF SCIENCE

NATIONAL QUANTUM INFORMATION SCIENCE
RESEARCH CENTERS

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

The FOA to establish up to 5 DOE NQI centers was released last Friday

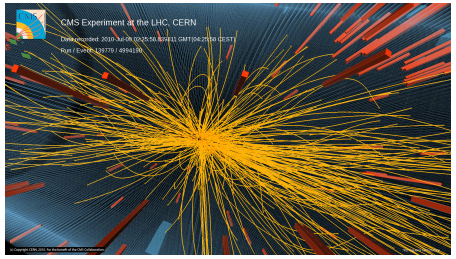
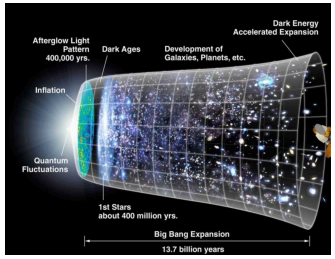
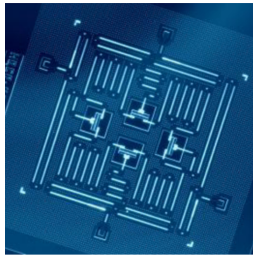
Fermilab Quantum Science Program

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

Intersecting Quantum Frontiers

Energy and Intensity	Cosmic	Quantum Information
		
Higgs boson: quantum vacuum	Dark energy: quantum vacuum	Quantum entanglement
Neutrinos: quantum superposition and mixing	Dark matter: interactions and identity	Quantum coherence
Muon g-2: detecting virtual quantum effects	Cosmic inflation and cosmic singularities	Quantum simulation
Quantum gravity	Gravitational waves	Spacetime emergent from quantum information

Fermilab quantum research funded by DOE:

1. Ultra-high coherence superconducting quantum systems: Alex Romanenko PI
2. FQNET quantum communications and teleportation: Maria Spiropulu (Caltech) PI, additional support from AT&T
3. Quantum metrology for axion dark matter detection: Aaron Chou PI, additional support from the Heising-Simons Foundation
4. Dark photon search with superconducting cavities: Anna Grassellino, PI
5. Solving HEP problems on NISQ quantum processors: Marcela Carena PI
6. HEP machine learning and optimization: Gabe Perdue PI
7. Cold electronics for QIS: Davide Braga PI
8. Quantum machine learning for HEP: Maria Spiropulu (Caltech) PI
10. MAGIS-100 cold atom gradiometer, Jason Hogan (Stanford) PI, **new in FY19,** additional support from the Moore Foundation
11. RF readout and controls for quantum systems, Gustavo Cancelo PI **new in FY19**
12. Large scale simulation of quantum systems, Adam Lyon PI **new in FY19**
13. Microwave Single-Photon Sensors for Dark Matter Searches and Precision Neutrino Measurements, Daniel Bowring, DOE Early Career Award
14. Skipper CCD single photon detector for quantum imaging: Juan Estrada PI
15. Quantum computing for neutrino-nucleus dynamics: Rajan Gupta (LANL) PI
16. Illinois Express Quantum Network: Panagiotis Spentzouris PI, ASCR funded, **new in FY19**

New for FY20: consolidation of the base quantum research program hosted at Fermilab

- For FY20 Fermilab was invited by DOE HEP to submit consortia proposals for 3+2 years of support in 4 Task Areas
- This is an evolution towards the more usual mechanisms of base program support
- As part of this process, Fermilab reached out to several university PIs who had been supported by pilot funding from DOE QuantISED
- These consolidated renewal proposals are being peer-reviewed this month

New for FY20: consolidation of the base quantum research program hosted at Fermilab

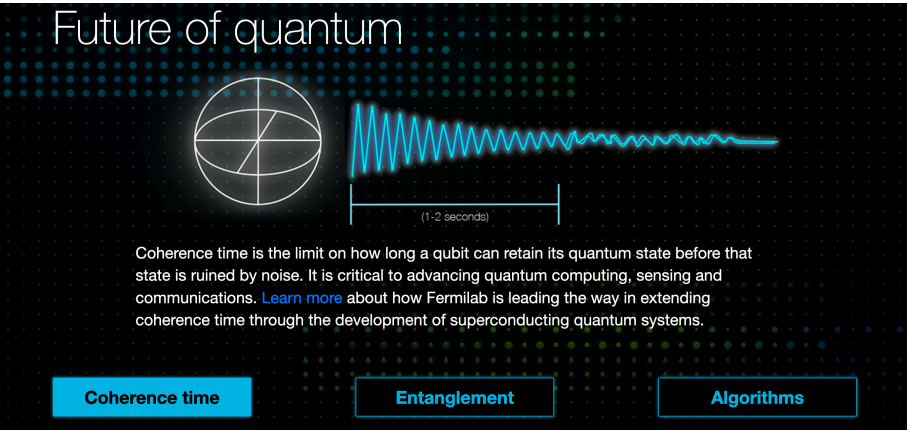
- Task 1: QIS and HEP Theory
- Collaborating institutions: Caltech, MIT, U. Wash, UIUC, Purdue
- Task 2: Quantum Networks and Analysis
- Collaborating institutions: Caltech, Los Alamos
- Task 3: SRF-based Quantum Technology and Sensing
- Collaborating institutions: Northwestern, U. Colorado/NIST, U. Wisc.
- Task 4: Quantum Sensors for Dark Matter
- Collaborating institutions: Caltech/JPL, MIT, LBNL, U. Chicago, U. Colorado/NIST, Yale, U. Wisc.

Quantum organization at Fermilab

- We expect Quantum Science and Technology to become a long-term part of the DOE HEP base program, with a research concentration at Fermilab roughly comparable to the current Cosmic program.

- This is in addition to our possible role co-leading an NQI center

- Recognizing this, the lab has established a new organizational entity, with clearly-defined responsibilities, and clear reporting lines to the Directorate.



- FQI went live as a line management organization on Oct 1, 2019
- Website: quantum.fnal.gov

FQI organization

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

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

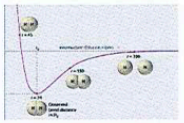
Farah Fahim
FQI Deputy Head of Quantum Science
Eric Holland
FQI Deputy Head of Quantum Technology

Most FQI members are matrixed from the Fermilab divisions

Recent news about industry partners

White House briefing on Google quantum supremacy result 10/22/19

Google / Department of Energy Collaboration Timeline



First Scalable Quantum Simulation (LBNL)

Google's 1st DOE Contract (Fermilab)

SC Benchmarking for QS Kickoff (ORNL)

Quantum Supremacy Publication (ORNL)

CRADA on Theory (LBNL)

DOE QC user program (ORNL)

2017 2018 2019 2020 2023

DOE Testbed Kickoff Participation

Cirq

Cirq & Cloud Alpha Testing (Fermilab)

Establishing QS Frontier @ 291 pFlop/s (ORNL)

First DOE experimental results on Sycamore (Fermilab)

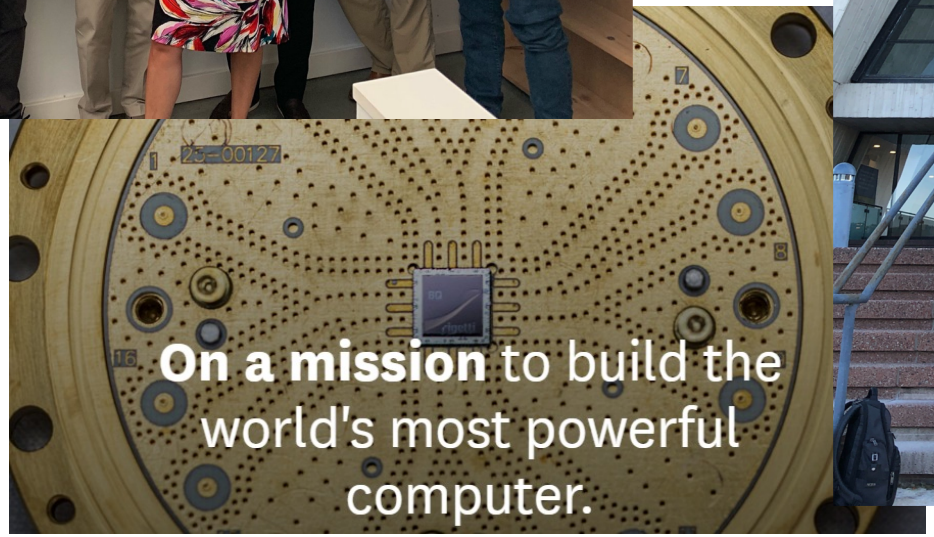
CRADA on Electronics (Fermilab)

Google AI Quantum

13

Fermilab @ rigetti

Aug 22-23 2019



rigetti @ Fermilab

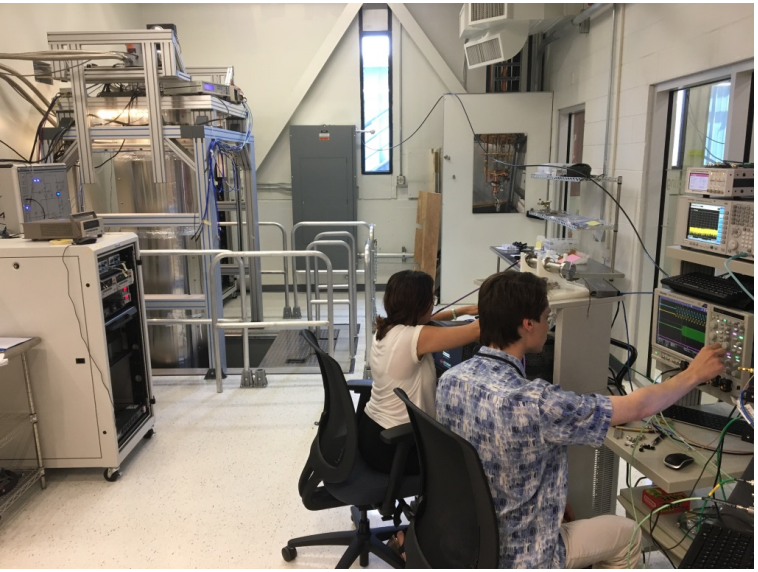
Sept 16-17 2019

Fermilab

New labs, new hardware

Fermilab lab for SRF-based quantum systems

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

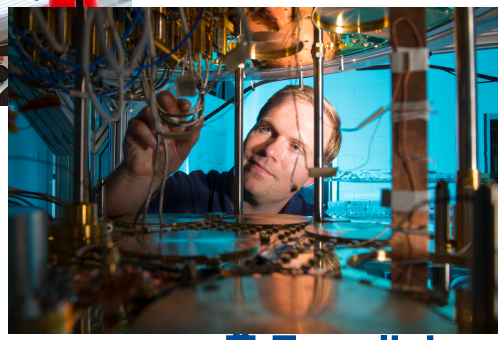


Fermilab

THE UNIVERSITY of WISCONSIN MADISON

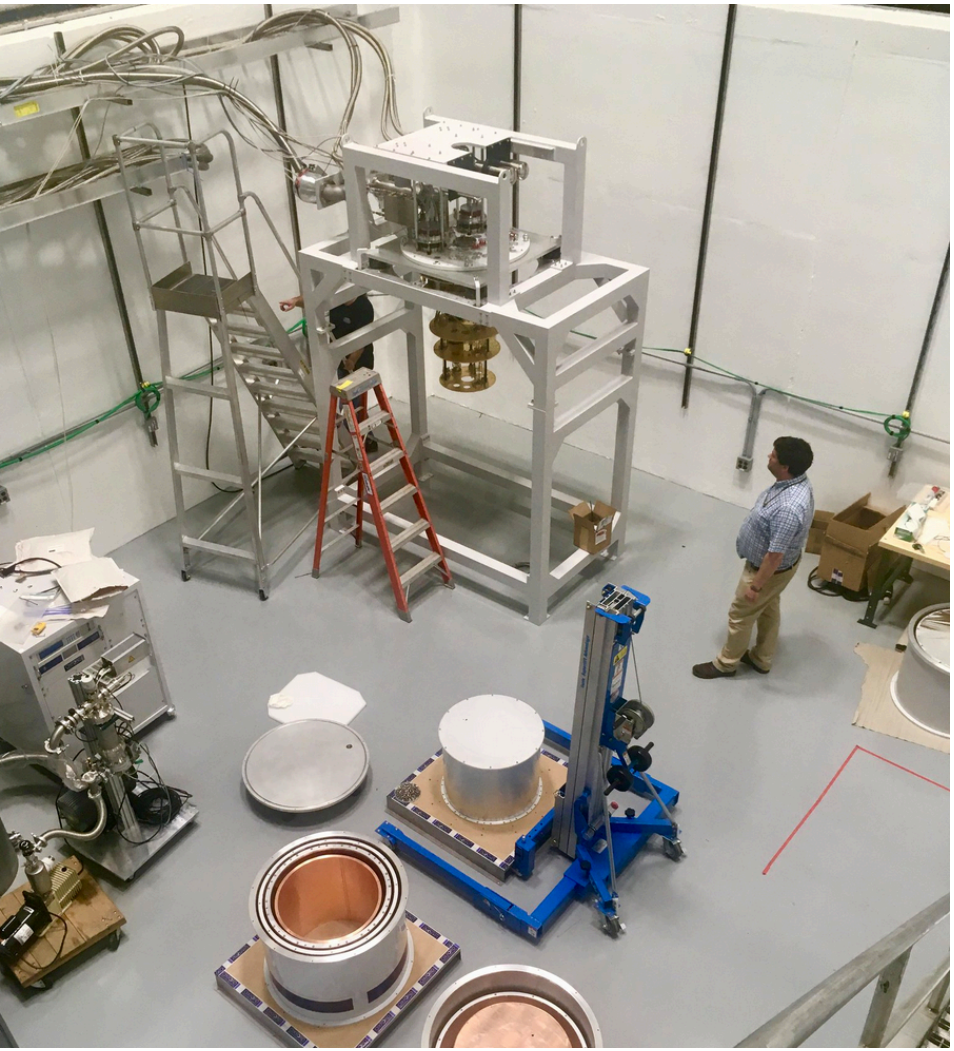
NIST

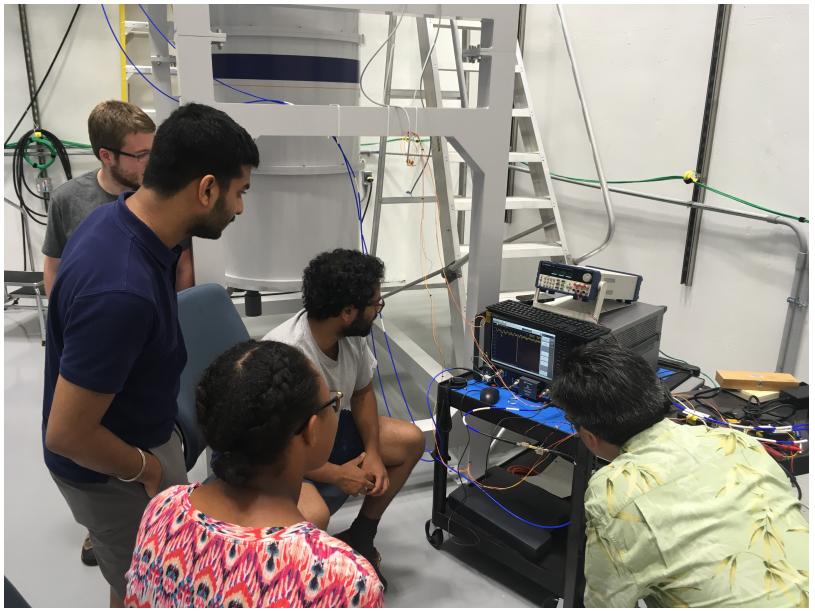
NORTHWESTERN UNIVERSITY
QUAECUMQUE SUNT VERA
1851

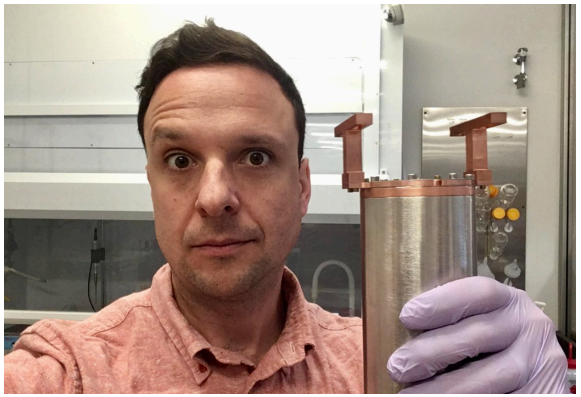


our first strategic quantum hire:
Eric Holland from Livermore

Fermilab quantum sensor lab at SiDet



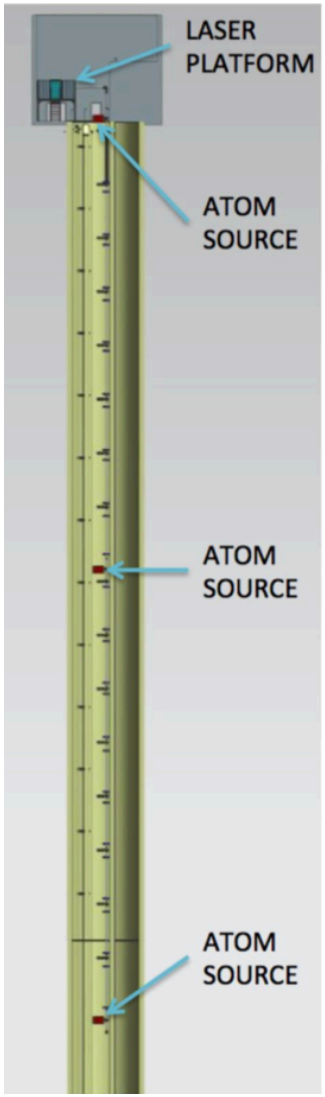




MAGIS-100 experiment moves forward

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

- Nigel has given the experiment Stage 2 approval
- 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)

Rob Plunkett

Fermilab

GORDON AND BETTY MOORE FOUNDATION

JOHNS HOPKINS UNIVERSITY

NIU

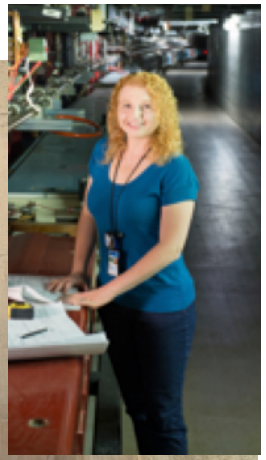
NORTHWESTERN UNIVERSITY 1851

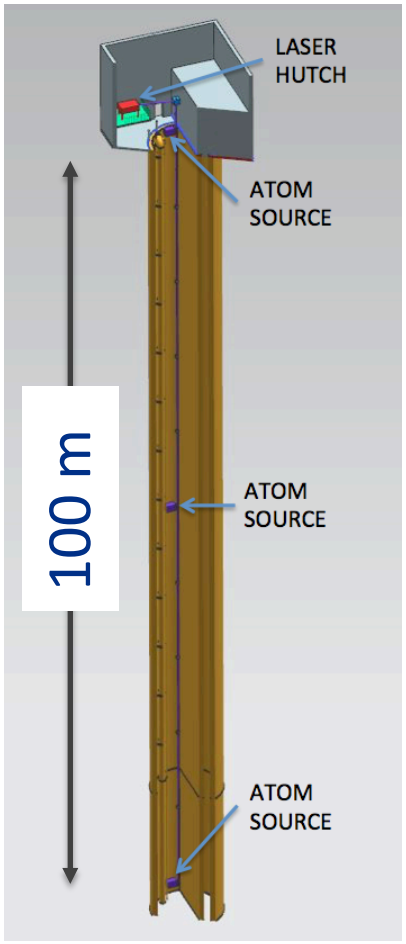
UNIVERSITY OF LIVERPOOL

MAGIS-100 cold atom gradiometer:
an incredibly sensitive quantum measuring device, first of its kind

- Will be built in the access shaft to the Fermilab underground neutrino area
- Requires a 100 meter shielded large aperture high vacuum system
- We do this for accelerators…

Linda Valerio

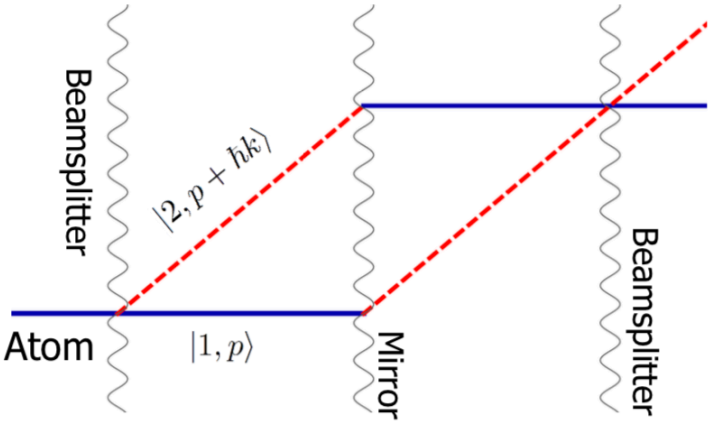




Rob Plunkett

supported by the DOE HEP QuantISED program

MAGIS-100 cold atom gradiometer:
using atom interferometry to compare free falling accelerometers

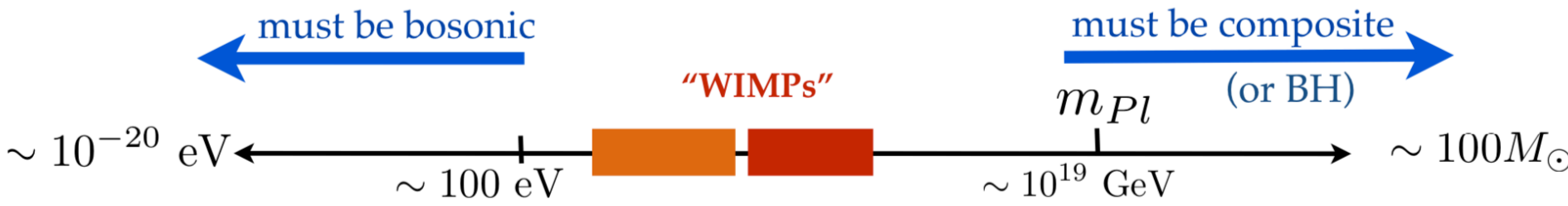


Atom interferometer

- Cold atoms in free fall
- Use lasers to split and recombine the wavefunction of single atoms
- Compare differential acceleration
- Sensitivity scales like the space-time area
- Goal is 10^{-13} g/Hz$^{1/2}$
- R&D to develop entangled atom sources

MAGIS will be a quantum measuring device enabled by quantum coherence over distances of several meters and times of several seconds

MAGIS-100 science target: dark matter

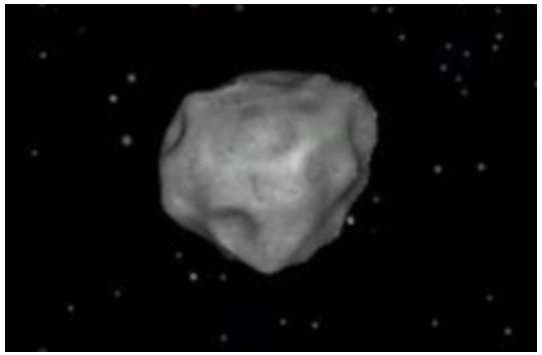


MAGIS could detect tiny effects from waves of ultralight dark matter sloshing in from space

MAGIS could detect the gravitational effects of heavy composite dark objects

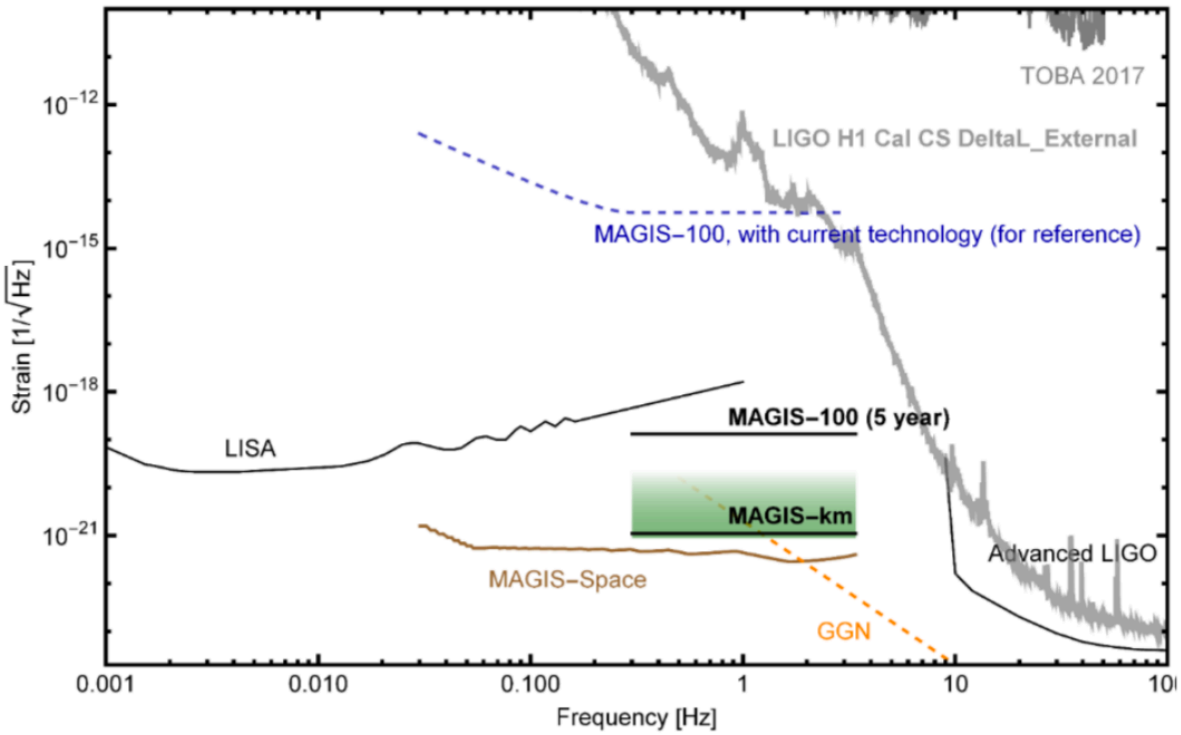
$$\frac{\phi}{M} F_{\mu\nu} F^{\mu\nu} \qquad \frac{m_e}{M} \phi \bar{\Psi} \Psi \qquad A_\mu J^\mu_{B-L}$$

Dilaton Relaxion B-L gauge boson



MAGIS-100: science targets: gravitational waves

- Pathfinder to a mid-band gravitational wave detector
- LIGO sources will spend days to months in the MAGIS band first
- Locate LIGO sources with degree-scale accuracy



MAGIS-100 could be succeeded by MAGIS-1000, located e.g. at the Sanford Underground Research Facility in South Dakota

News on quantum communications at Fermilab

FQNET quantum communications

inqnet
Alliance for Quantum Technologies

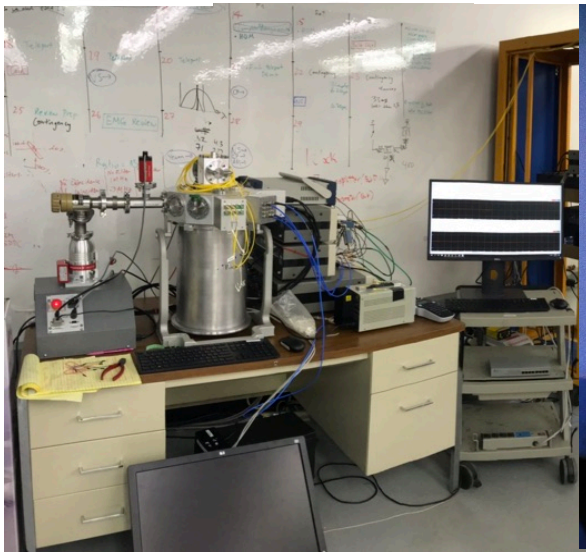
- Develop the world's first long range, high fidelity, high rate quantum communications system
- Teleportation already achieved, second node coming this year
- Funded to investigate wormhole teleportation

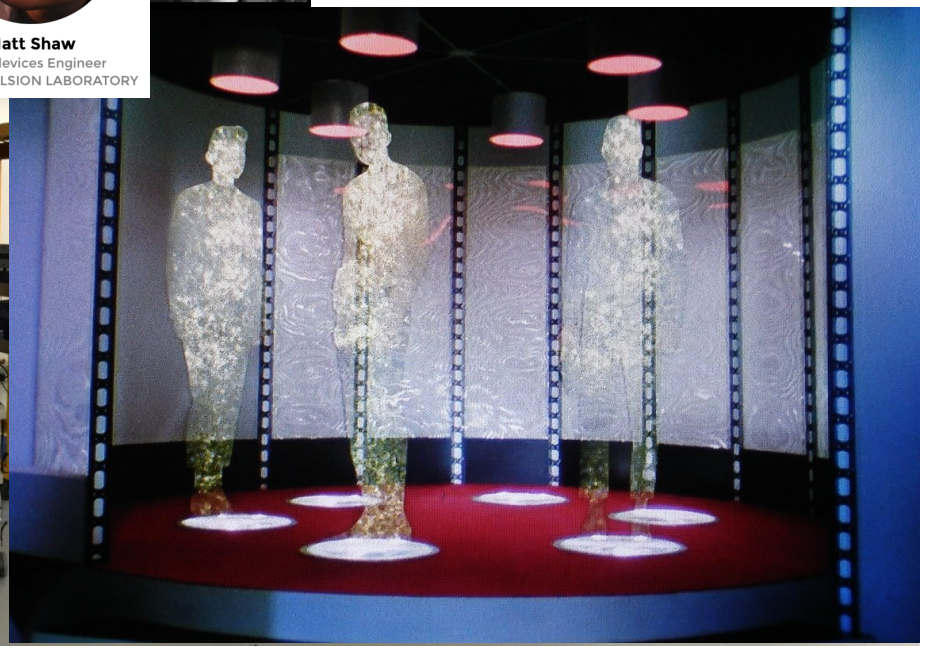
Maria Spiropulu
FQNET Co-Spokesperson
FQNET PI
CALTECH

Cristián Peña
FQNET Co-Spokesperson
FERMILAB LEDERMAN FELLOW
CALTECH INQNET FELLOW

Matt Shaw
Microdevices Engineer
JET PROPULSION LABORATORY

Panagiotis Spentzouris





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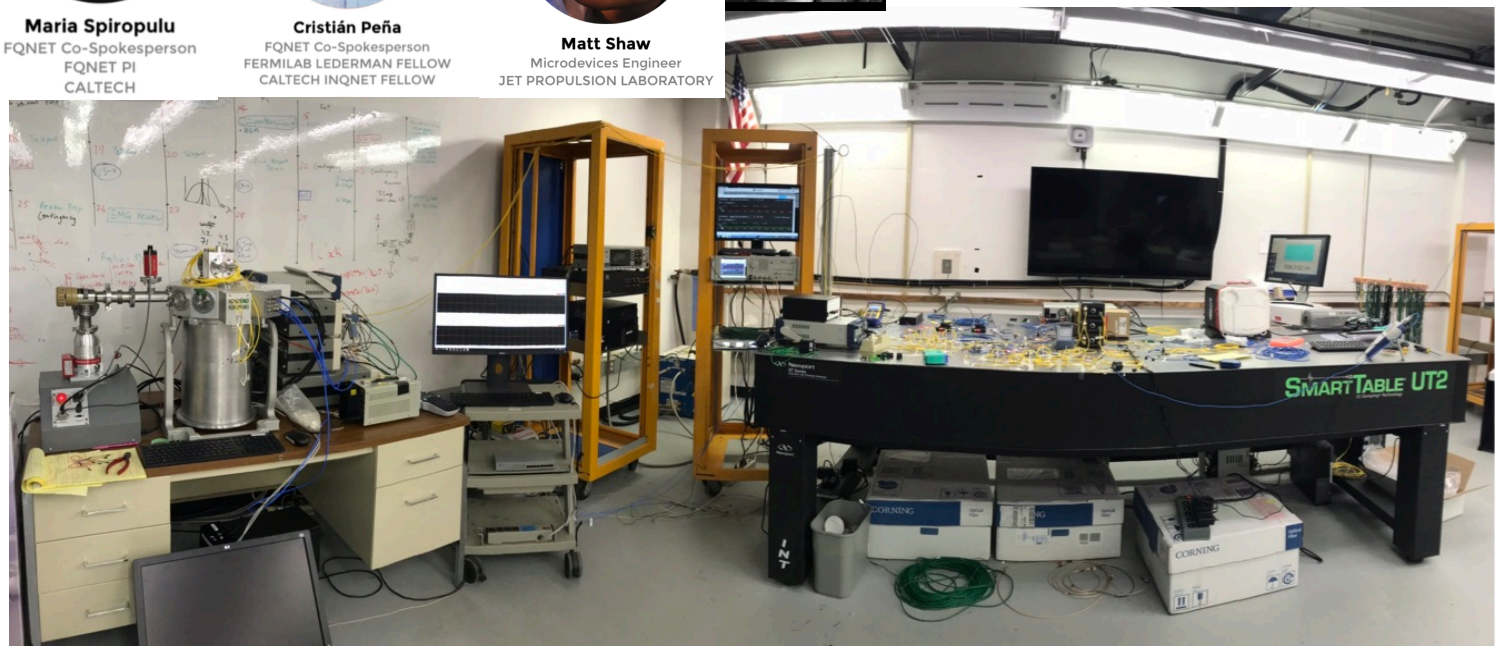
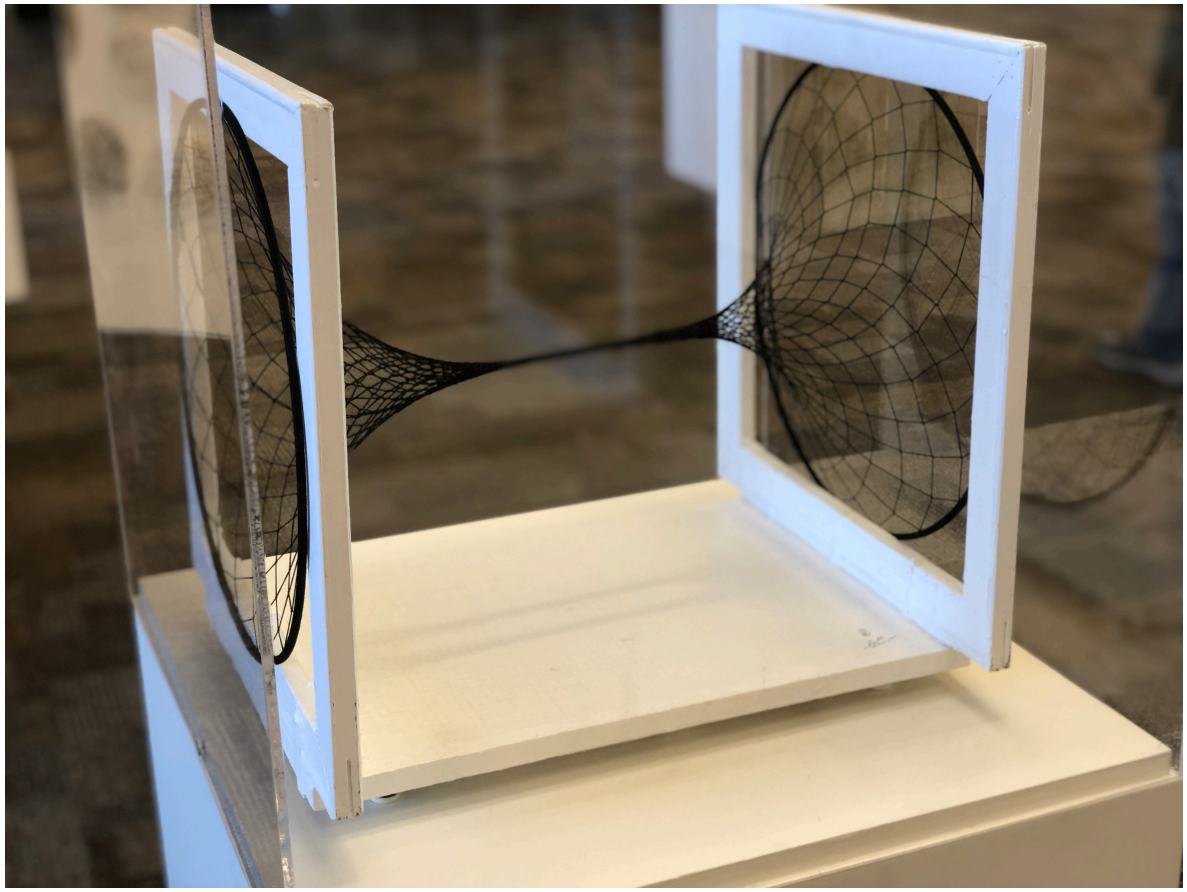
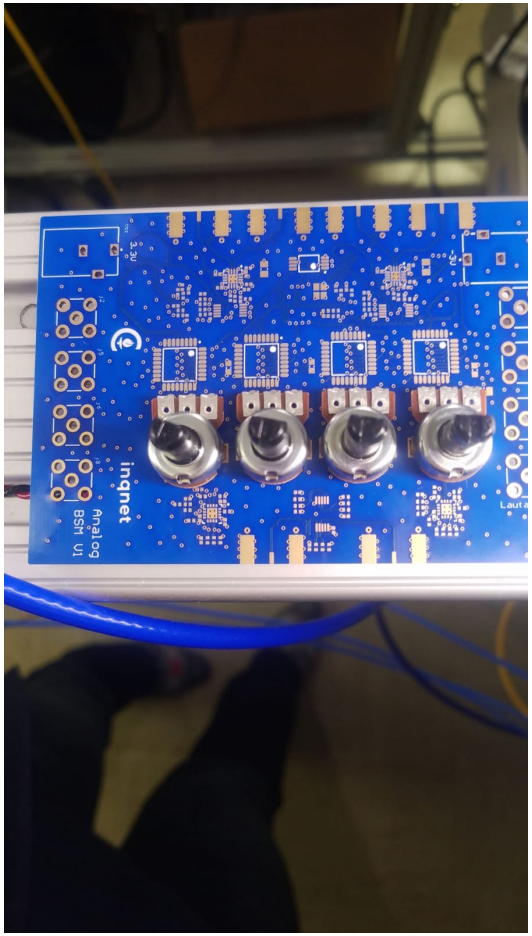
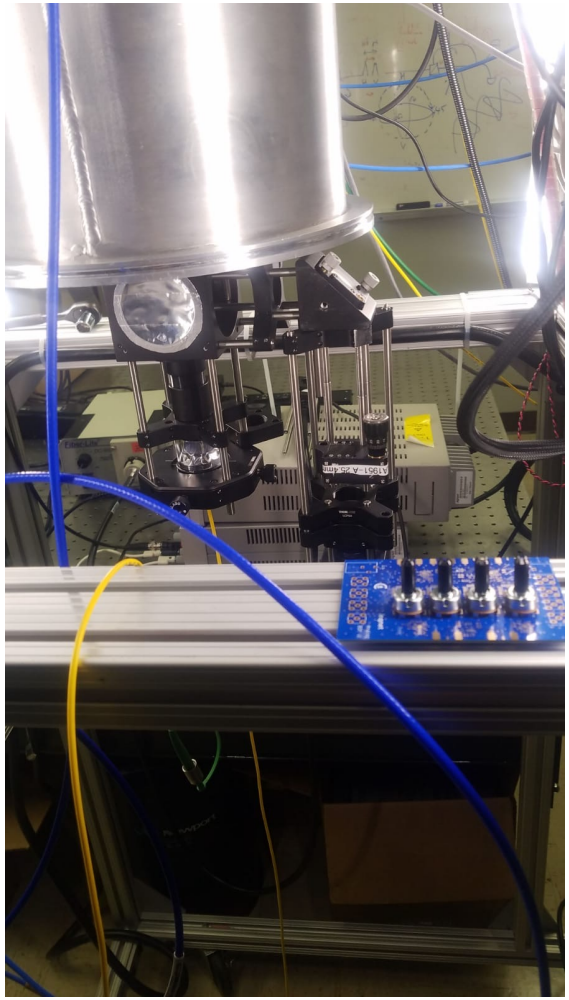


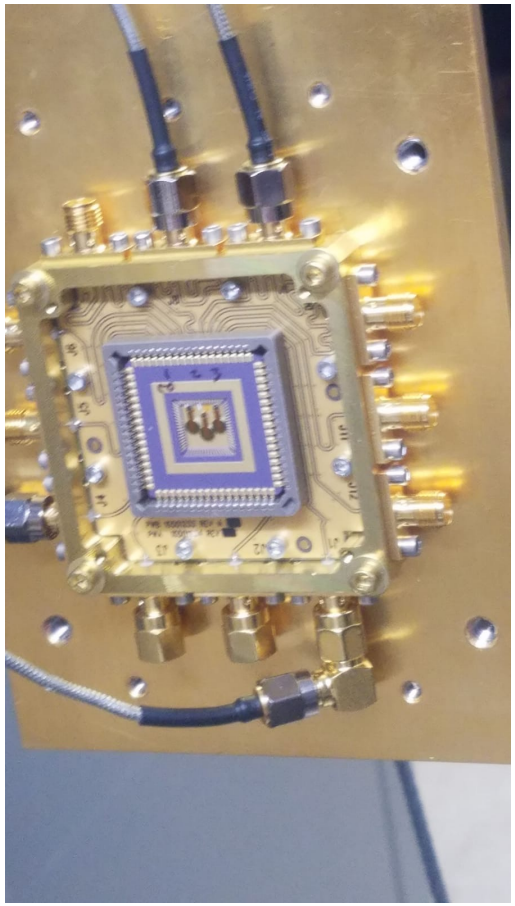
First wormhole at Fermilab



INQNET technology advances







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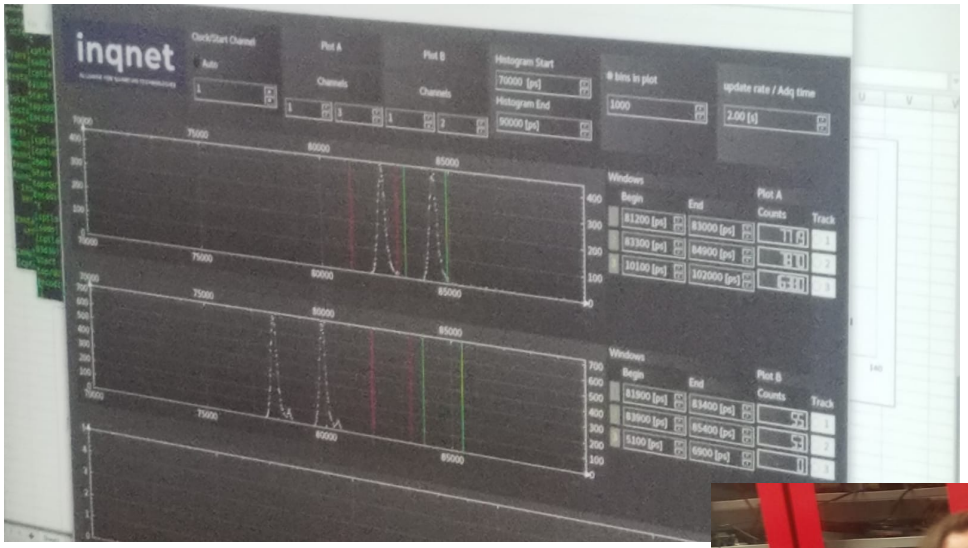

Fermilab

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 challenges of building a quantum internet

Perspectives on quantum transduction

Nikolai Lauk,[1,2] Neil Sinclair,[1,2,3] Shabir Barzanjeh,[4,5] Jacob P. Covey,[1]
Mark Saffman,[6] Maria Spiropulu,[1,2] and Christoph Simon[4]

[1] *Division of Physics, Mathematics and Astronomy, California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125, USA*
[2] *Alliance for Quantum Technologies (AQT), California Institute of Technology, 1200 E. California Blvd., Pasadena, CA 91125, USA*
[3] *John A. Paulson School of Engineering and Applied Sciences, Harvard University, 29 Oxford St., Cambridge, MA 02138, USA*
[4] *Institute for Quantum Science and Technology and Department of Physics and Astronomy, University of Calgary, 2500 University Dr. NW, Calgary, AB T2N 1N4, Canada*
[5] *Institute of Science and Technology Austria, 3400 Klosterneuburg, Austria*
[6] *Department of Physics, University of Wisconsin-Madison, 1150 University Avenue, Madison, WI 53706, USA*

(Dated: October 14, 2019)

DOE SC National Quantum Information Science Research Centers

DEPARTMENT OF ENERGY
OFFICE OF SCIENCE

- $25M/yr for 5+5 years to multi-disciplinary consortia of labs, universities, and industry
- Sponsored by DOE BES, ASCR, and HEP
- Expect 2-5 Centers to be funded in FY20 (proposals due April 10)

NATIONAL QUANTUM INFORMATION SCIENCE RESEARCH CENTERS

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

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

DOE SC National Quantum Information Science Research Centers

DEPARTMENT OF ENERGY
OFFICE OF SCIENCE

Fermilab is co-leading on a proposal with two other labs plus university and industry partners

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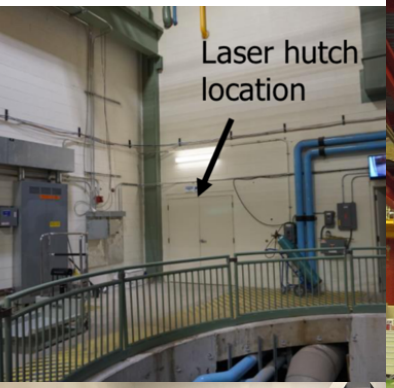
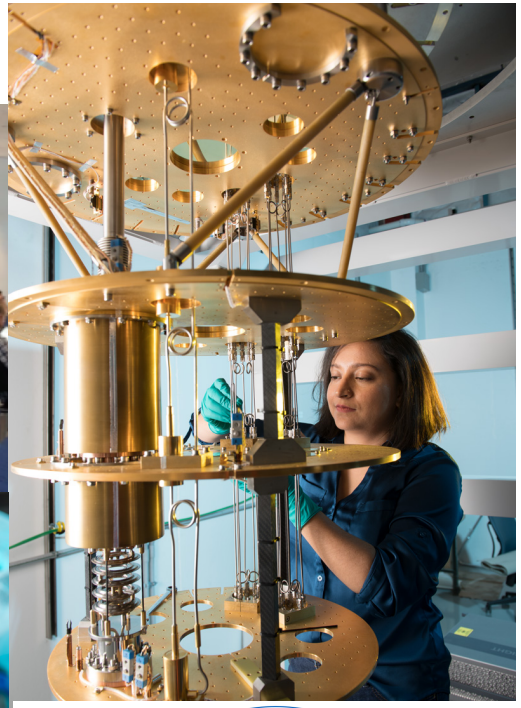
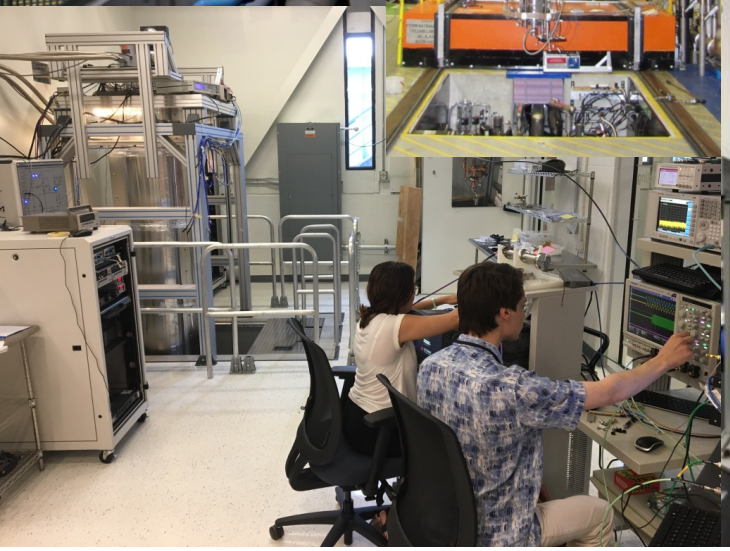
"Critical to America's leadership in this field, the new quantum research centers provide training and
collaboration opportunities for the next generation of QIS scientists and engineers," said **Ivanka Trump,**
Advisor to the President. "We thank Secretary Brouillette and the Department of Energy for its work to
maintain and strengthen our nation's competitiveness in this industry of the future."

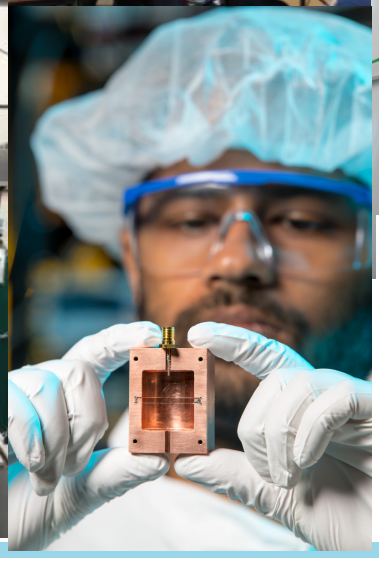
Fermilab

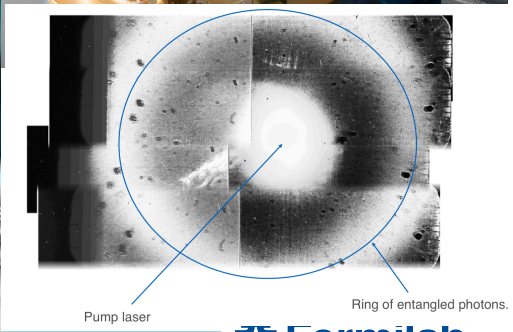
Questions?











Fermilab