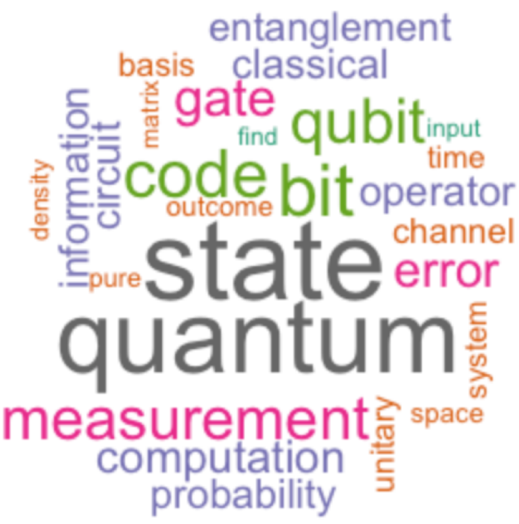
Quantum Science and Technology at Fermilab

Joe Lykken

Fermilab PAC Meeting

July 20, 2019



Outline

- Strategy and goals of the program
- Funded activity and partnerships
- Status:
  - HEP applications of quantum computing
  - HEP technology applied to quantum systems
  - Quantum sensors for HEP experiments
  - Quantum communications
- Quantum organization and National Quantum Centers

How long before quantum computers destroy the world economy?

How to factor 2048 bit RSA integers in 8 hours using 20 million noisy qubits

Craig Gidney[1,*] and Martin Ekerå[2]

[1] *Google Inc., Santa Barbara, California 93117, USA*
[2] *KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden*
Swedish NCSA, Swedish Armed Forces, SE-107 85 Stockholm, Sweden

(Dated: May 24, 2019)

We significantly reduce the cost of factoring integers and computing discrete logarithms over finite fields on a quantum computer by combining techniques from Griffiths-Niu 1996, Zalka 2006, Fowler 2012, Ekerå-Håstad 2017, Ekerå 2017, Ekerå 2018, Gidney-Fowler 2019, Gidney 2019. We
estimate the approximate cos
scale superconducting qubit p
a characteristic physical gate
reaction time of 10 microseco
the need to make repeated att
2048 bit RSA integers, our co
estimates from earlier works
model (which ignores overhea
uses $3n + 0.002n \lg n$ logical q
depth to factor n-bit RSA int
for RSA and for schemes base

Craig Gidney giving the first ever public tutorial by Google on quantum computing software: Fermilab 9/13/18

How long before quantum computers have a positive impact on the world economy?

According to the latest estimate from the Boston Consulting Group, we are almost there

EXHIBIT 2 | The Expected Phases of Quantum Computing Maturity

	NISQ era 3–5 years	Broad quantum advantage 10+ years	Full-scale fault tolerance 20+ years
Technical achievement	Error mitigation	Error correction	Modular architecture
Example of business impact	Material simulations that reduce expensive and time-consuming trial-and-error lab testing	Near-real-time risk assessment for financial services firms (e.g., quant hedge funds)	De novo drug design with large biologics that have minimal off-target effects
Estimated impact (operating income)	**$2 billion–$5 billion**	**$25 billion–$50 billion**	**$450 billion–$850 billion**

Source: BCG analysis.

Quantum Science and Technology

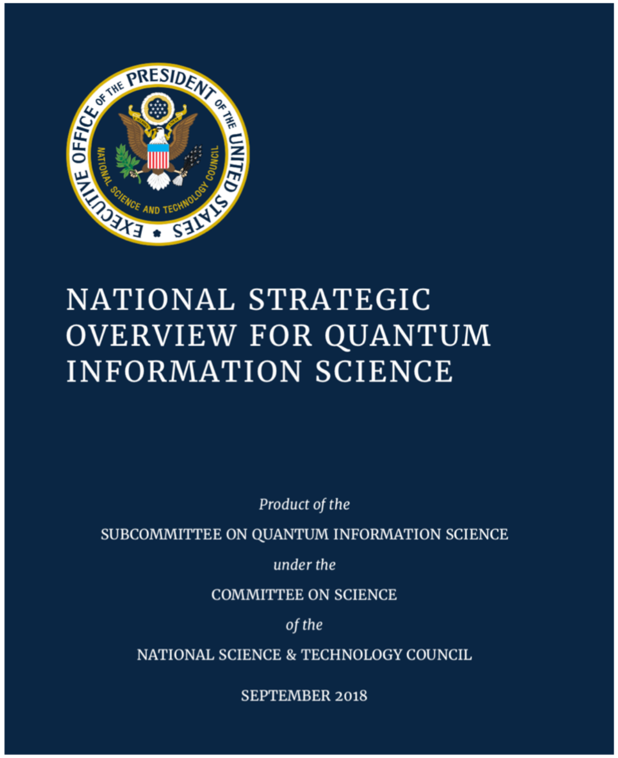
“Quantum Information Science” too narrow to capture all current activity

- **Quantum computing:** computers that manipulate qubits instead of bits
  - universal “digital” gate-based quantum computers
  - “analog” quantum computers

- **Quantum sensors:** using quantum devices as sensors, exploiting quantum properties such as superposition, entanglement, squeezing, and quantum nondemolition measurements

- **Quantum communications:** moving quantum information over macroscopic distances coherently, with applications such as secure communications, and networking of quantum computers or sensors

National Quantum Initiative

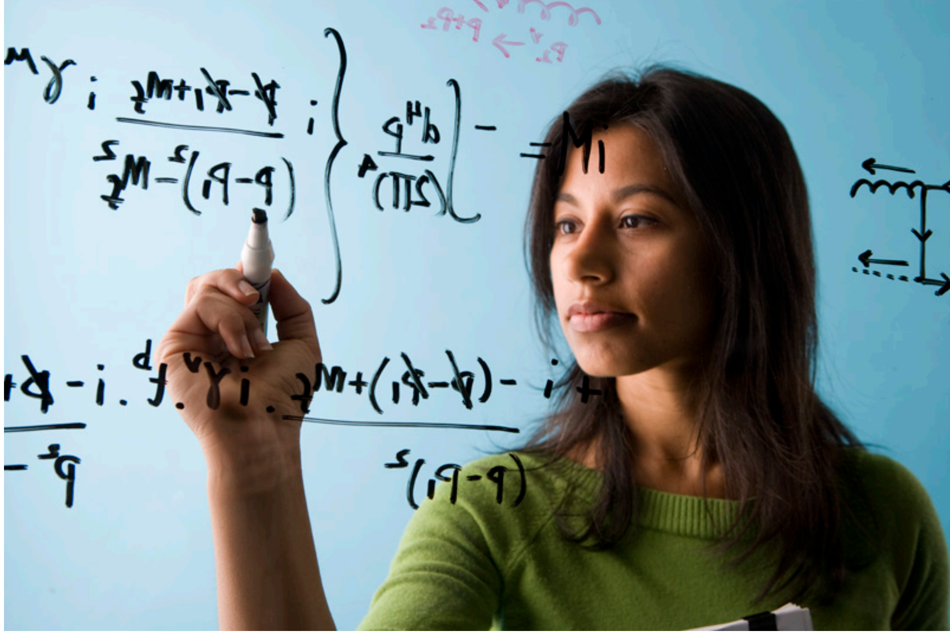


"This is a country that can do anything we need to do that physics allows. We just need to get on with it." – Michael Griffin 4/17/2019

SEC. 402. NATIONAL QUANTUM INFORMATION SCIENCE RESEARCH CENTERS.

(a) IN GENERAL.—The Secretary of Energy shall ensure that the Office of Science carries out a program, in consultation with other Federal agencies, as appropriate, to establish and operate up to 5 National Quantum Information Science Research Centers to conduct basic research to accelerate scientific breakthroughs in quantum

QIS for HEP



- Higgs boson
- Neutrinos
- Dark matter, dark energy
- Exploring the unknown

➔ HEP science goals drive technology innovation

- All of the easy experiments have already been done
- Pushing the boundaries of technology enables new experiments

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

Fermilab quantum research funded by DOE QuantISED:

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, **[pending technical review]** additional support from the Moore Foundation
11. RF readout and controls for quantum systems, Gustavo Cancelo PI **new**
12. Large scale simulation of quantum systems, Adam Lyon PI **new**
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

Fermilab quantum collaborators (for DOE funded research)

HEP/NP co-PIs

1. Berkeley (MAGIS)
2. Caltech (quantum communications, quantum theory, HEP applications)
3. Harvard (quantum communications)
4. LBNL (quantum imaging)
5. Univ. of Liverpool (MAGIS)
6. Los Alamos (HEP applications)
7. Northern Illinois Univ. (MAGIS)
8. Univ. of Washington (quantum theory, HEP applications)

Industry

1. AT&T (through Caltech)
2. Google
3. IBM (through Oak Ridge)
4. Lockheed Martin
5. Raytheon (through NIST)

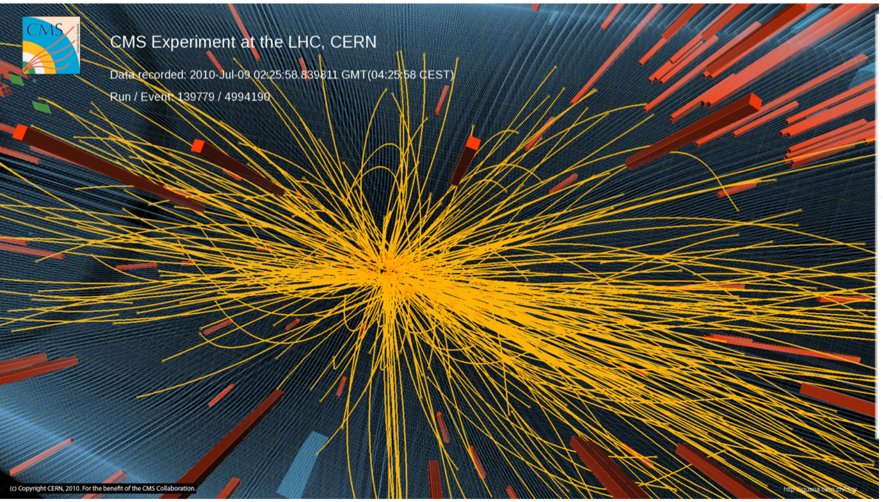
QIS/BES/ASCR co-PIs

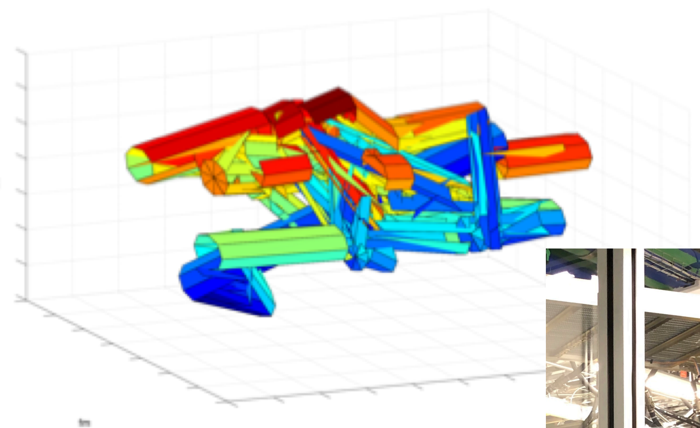
1. Univ. of Chicago (quantum sensors, sc systems, controls)
2. Georgia Tech (quantum imaging)
3. JPL (quantum communications, imaging)
4. LLNL (sc systems)
5. Univ. of Maryland (quantum theory)
6. MIT (HEP applications)
7. NIST (sc systems, quantum sensors)
8. Northwestern (sc systems, quantum communications, MAGIS)
9. Oak Ridge (HEP applications)
10. Stanford (MAGIS)
11. USC (HEP applications)
12. Univ. of Wisconsin (sc systems)
13. Yale (quantum sensors)
14. Univ. of Waterloo (HEP applications)

HEP applications of quantum computing

QIS for Applied Quantum Field Theory

Caltech: John Preskill, Junyu Liu, Barak Sahinoglu
Institute For Nuclear Theory: David Kaplan, Martin Savage, Natalie Klco, Jesse Stryker
Fermilab: Marcela Carena (PI), James Amundson, Joshua Isaacson, Roni Harnik, Ciaran Hughes, Andreas Kronfeld, Alexander Macridin, Panagiotis Spentzouris, James Simone





- We do this 40 million times per second at the LHC
- But even Summit cannot simulate the real-time QCD dynamics of these collisions
- We are beginning to map these kinds of problems to quantum computing
- A long-term program with many challenges

Challenges for HEP applications on quantum processors

- Breaking down big problems into small enough problems that they can run on near-term quantum machines and you still learn something.
- Understand the roles of gate-based quantum computers vs analog simulators
- Rethinking HEP formalisms from scratch instead of just trying to map standard approaches to quantum processors

We need to start with something simple!

Slide from Yannick Meurice

Figure: Mike Creutz's calculator used for a Z_2 gauge theory on a 3^4 lattice (circa 1979).

Mapping gauge field theories to qubits

Hamiltonian Formulation of Wilson's Lattice Gauge Theories
John B. Kogut (Cornell U., LNS), Leonard Susskind (Yeshiva U. & Tel Aviv U. & Cornell U., LNS). Jul 1974.
Published in **Phys.Rev. D11 (1975) 395-408**
Print-74-1186 (CORNELL)
DOI: 10.1103/PhysRevD.11.395
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI.gov Server
Detailed record - Cited by 1711 records 1000+

- Discretize space to a spatial lattice with finite volume
- Discretize fermion fields to map to a finite number of qubit states per lattice site: the quantum chemists already figured this out
- Truncate and discretize the boson fields to efficiently map to a finite number of qubit states per lattice site:

Electron-Phonon Systems on a Universal Quantum Computer
Alexandru Macridin, Panagiotis Spentzouris, James Amundson, and Roni Harnik
Phys. Rev. Lett. **121**, 110504 – Published 12 September 2018

- Discretize the gauge degrees of freedom efficiently

Digitizing Gauge Fields: Lattice Monte Carlo Results for Future Quantum Computers
Daniel C. Hackett,[1,*] Kiel Howe,[2,†] Ciaran Hughes,[2,‡] William Jay,[1,2,§] Ethan T. Neil,[1,3,¶] and James N. Simone[2,**]
arXiv:1811.03629

- Discretize the time evolution using Trotterization:

$$e^{-iH\Delta t} = \prod_m e^{-iH_m\Delta t} + \mathcal{O}(\Delta t^2)$$

Mapping gauge field theories to qubits

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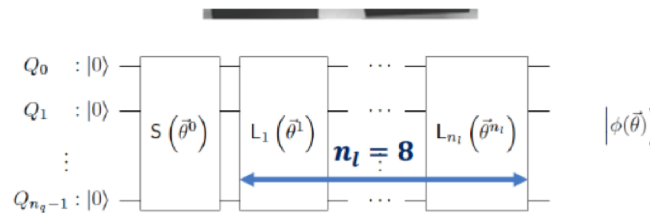
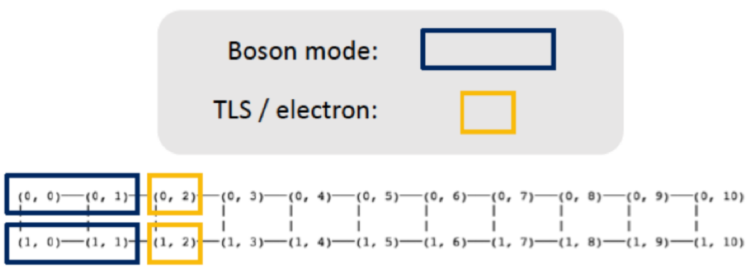
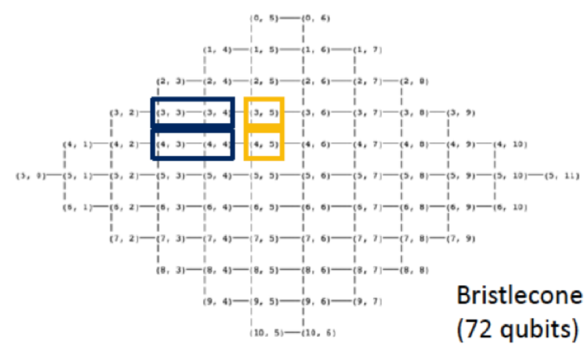
- Implementation:
  - Maximum of 3 bosons per mode
    → 2 qubits to encode 1 boson mode
  - Preparation circuit: 8 layers





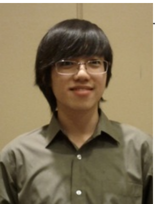
Foxtail (20 qubits)

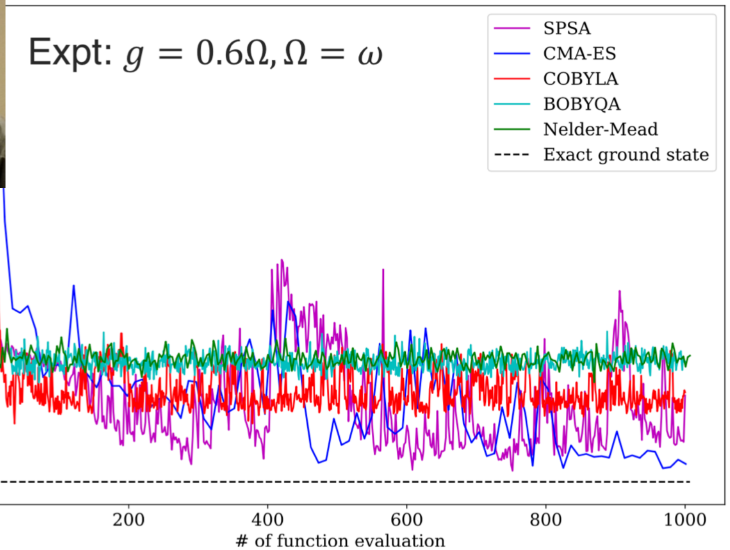


- Running on the Google, IBM, and Rigetti quantum computers
- Use simple models, address basic issues
- Results relevant not just to HEP, but also BES, NP, …

Fermilab-led theory consortium producing lots of results

Optimizers with noisy device





FERMILAB-PUB-18-615-T

Digitizing Gauge Fields: Lattice Monte Carlo Results for Future Quantum Computers

Daniel C. Hackett,[1,*] Kiel Howe,[2,†] Ciaran Hughes,[2,‡]
William Jay,[1,2,§] Ethan T. Neil,[1,3,¶] and James N. Simone[2,**]

epartment of Physics, University of Colorado, Boulder, Colorado 80309, USA
[2]*Fermi National Accelerator Laboratory, Batavia, Illinois, 60510, USA*

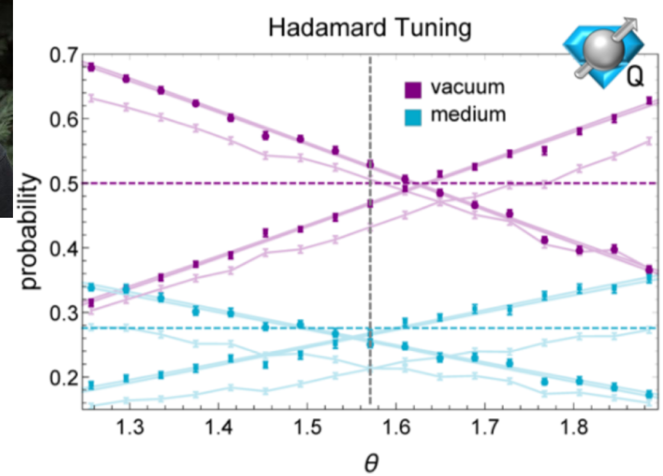
Approximating gauge theories like QCD on a quantum computer

Minimally-Entangled State Preparation of Localized Wavefunctions on Quantum Computers

Natalie Klco[*] and Martin J. Savage[†]

Institute for Nuclear Theory, University of Washington, Seattle, WA 98195-1550, USA

(Dated: April 30, 2019 - 0:31)

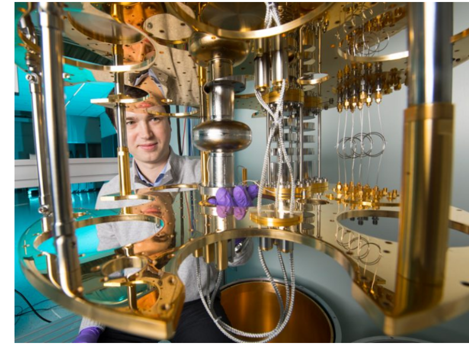


IG. 3. (Color online) For vacuum tuning of the Hadamard, probabilities in states $|0\rangle$ and $|8\rangle$ are ıeasured after implementation of IBM's $U_3(\theta, \phi, \lambda) = U_3(\theta, 0, \pi)$ gate. The active qubits were: 11, 15, and 10 of IBM chip **Poughkeepsie**. For in-medium tuning, probabilities in states $|7\rangle$

Correcting measurement errors of an IBM quantum computer

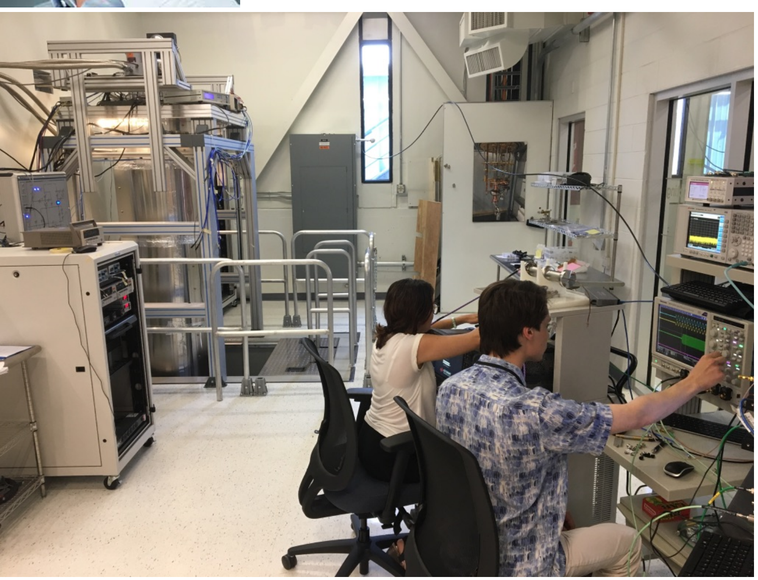
HEP technology applied to quantum systems

Fermilab quantum labs for superconducting quantum systems

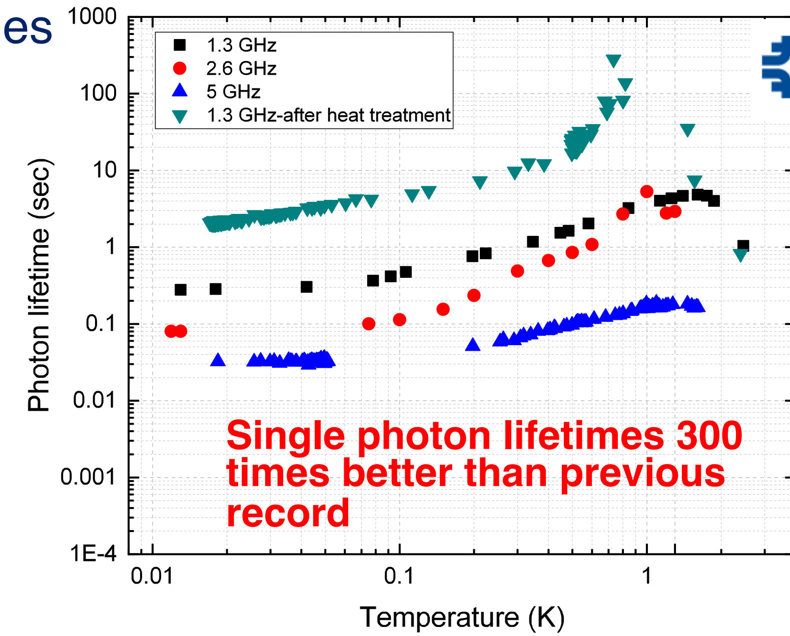


Now expanding to a second test stand, and a microwave channel connecting the test stands

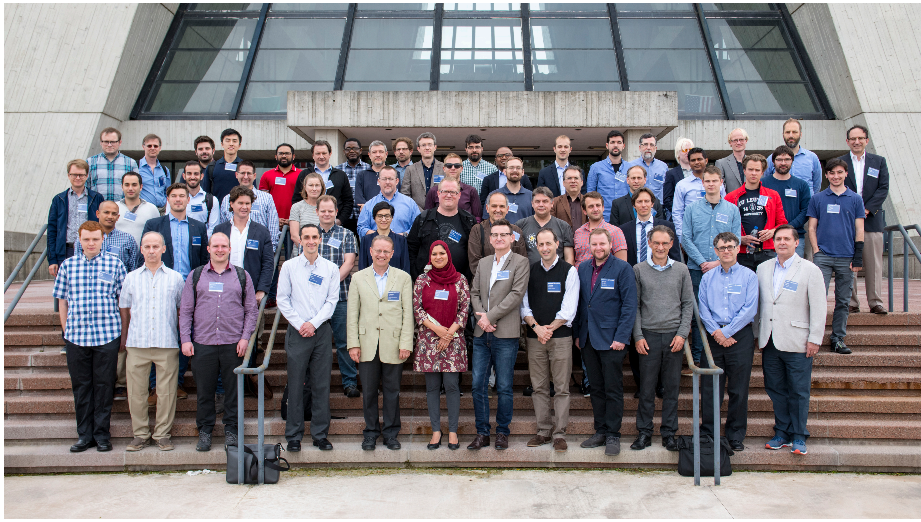
our first strategic quantum hire: Eric Holland from Livermore



Fermilab breakthrough with niobium SRF cavities applicable to a variety of superconducting quantum systems, including quantum computers and quantum memories



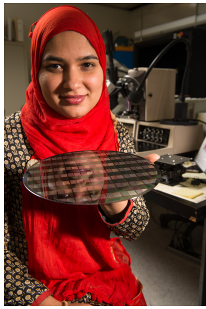
A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703



New annual workshop series focused on the fast-growing field of cryogenic electronics and cryo-CMOS for use in quantum systems including

- Quantum computing
- Quantum sensing/imaging
- Quantum communications
- Quantum security

IwCEQS



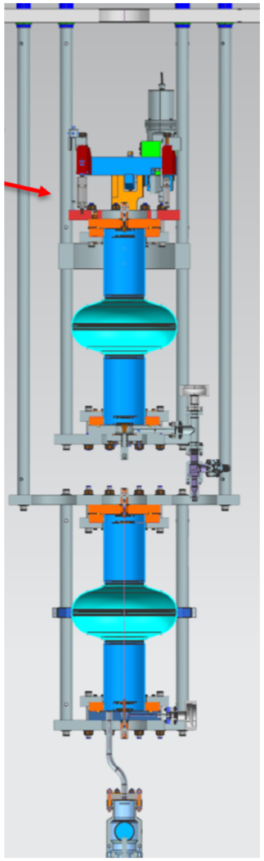
Farah Fahim

Fermilab

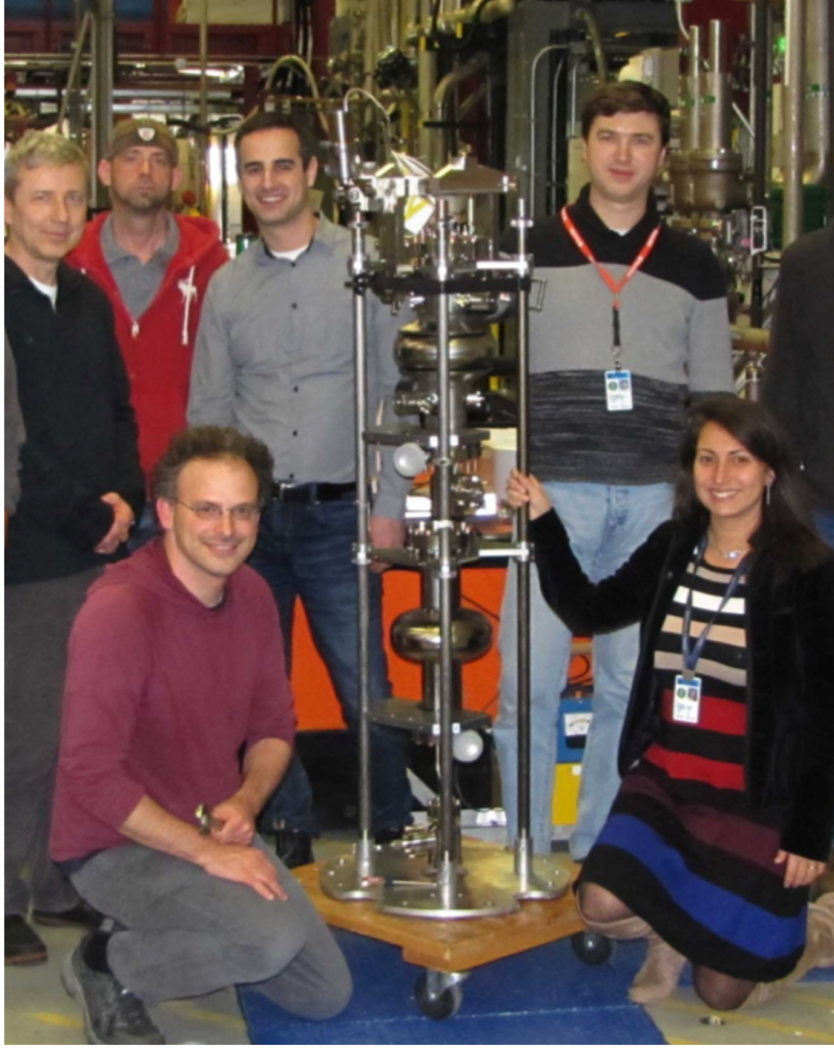
Quantum sensors for HEP experiments

Fermilab Dark SRF Experiment

Fermilab Vertical Test Stand used for cryogenic tests of accelerator SRF cavities



Tunable powered "Emitter" cavity and quiet "Receiver" cavity



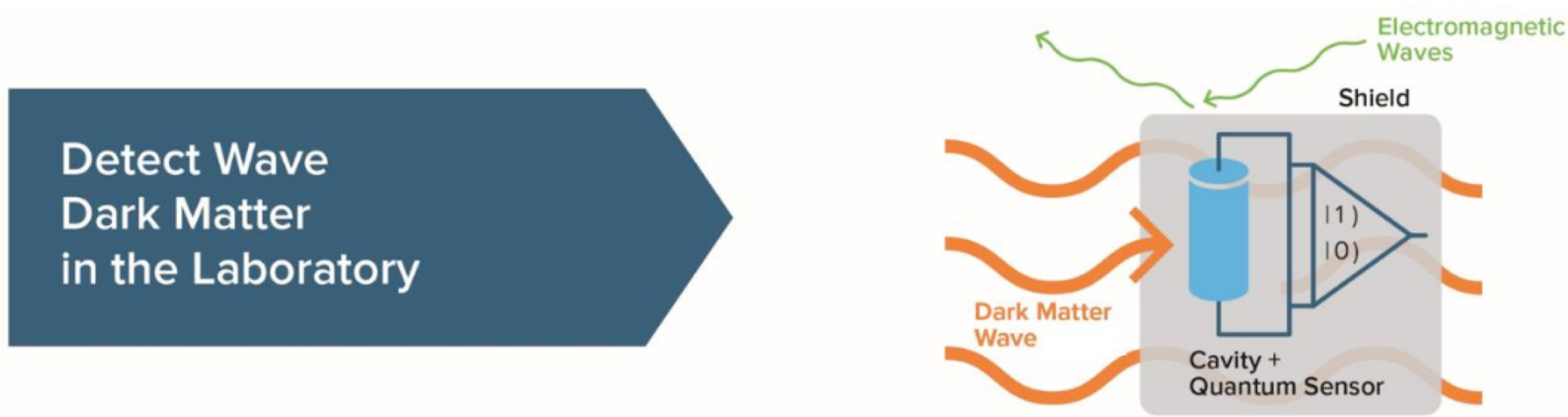
Prototype "R2D2" ready for testing: supported by the DOE QuantISED program

Quantum-enhanced sensing for axion dark matter searches

Aaron S. Chou (Fermilab)
Fermilab Seminar
April 5, 2019

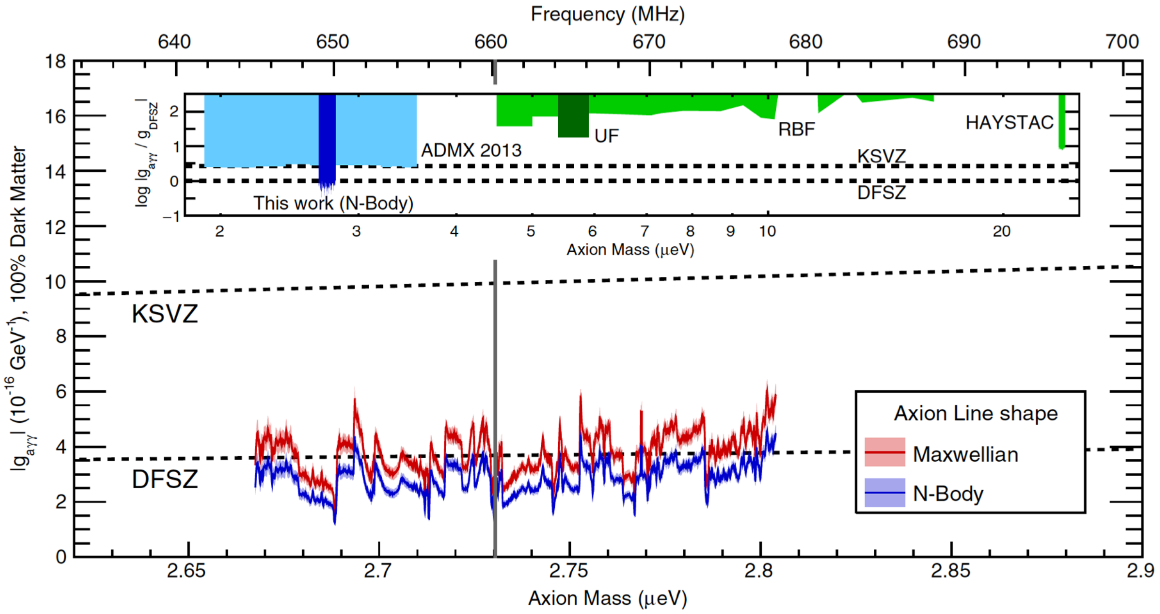
Featured in 2018 DOE Basic Research Needs workshop whitepaper:

PRD 3: Detect galactic dark matter waves using advanced, ultra-sensitive detectors with emphasis on the strongly motivated QCD axion. [1]



ADMX axion dark matter experiment

ADMX at U.Washington,
FNAL = DOE lead lab



PRL 120, 151301 (2018)

Operate an ultrasensitive radio in a cold, RF-shielded box to tune in to the axion broadcast.

Look for "spontaneous" emission from local axion dark matter into the empty cavity mode.

Signal power level = 10^{-23} W
Need 15 minutes integration per frequency bin to beat thermal noise power at 500 mK.

Fermilab-led Consortium: Quantum Metrology for Dark Matter Axion Detection

- Aaron Chou/Daniel Bowring (**FNAL**), David Schuster(**U Chicago**): Qubit sensors
- Konrad Lehnert(**Colorado/JILA**): Stimulated emission of photons from axions
- Reina Maruyama (**Yale**): Rydberg atom-based single photon detection

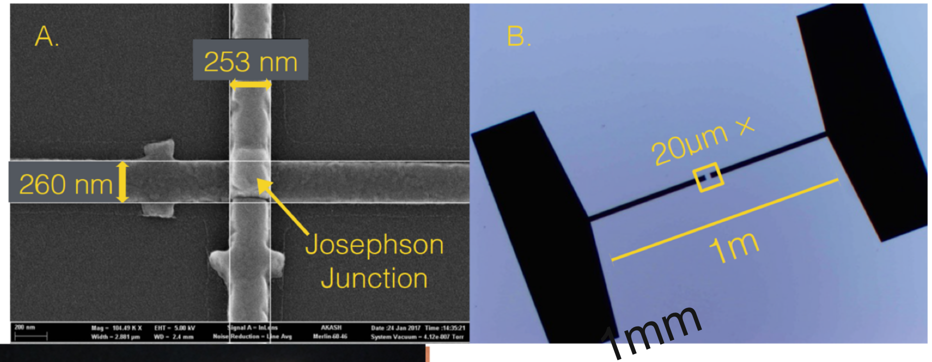
R. Khatiwada A. Dixit A. Agrawal D. Speller S. Cahn

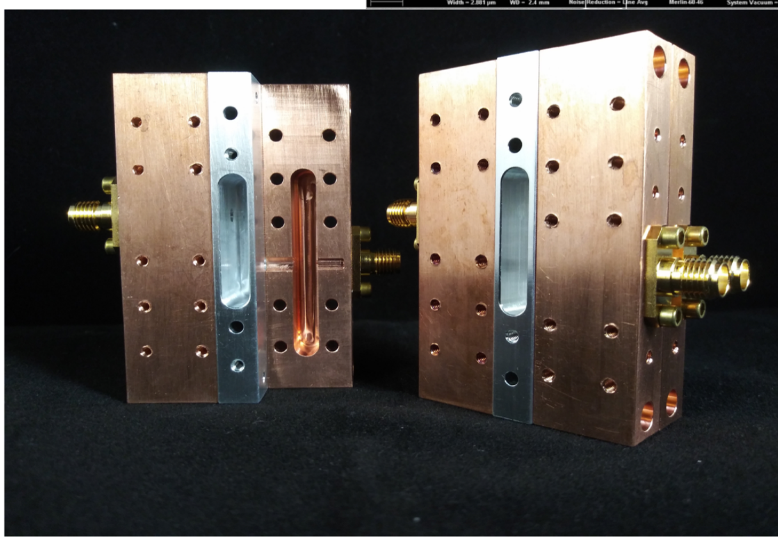
Using superconducting qubits to nondestructively sense photons

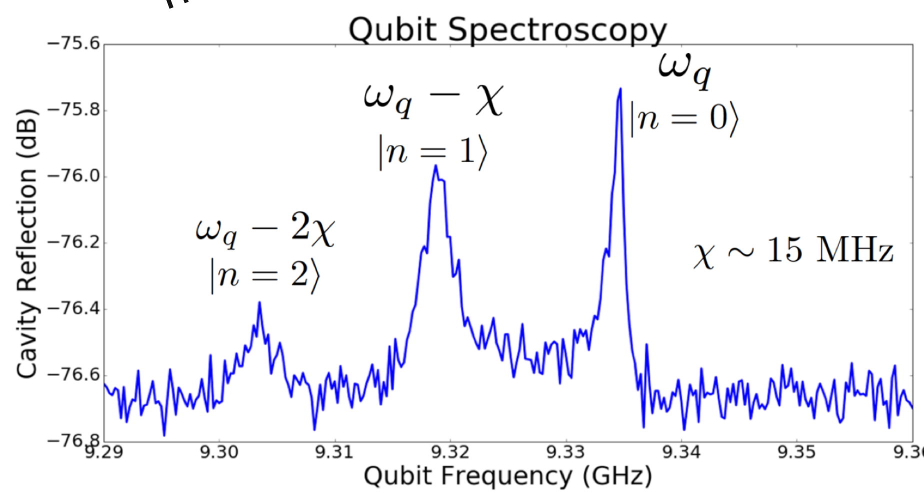
Aaron Chou (FNAL), David Schuster, Akash Dixit (U.Chicago)

Funded by DOE HEP and

HEISING-SIMONS FOUNDATION

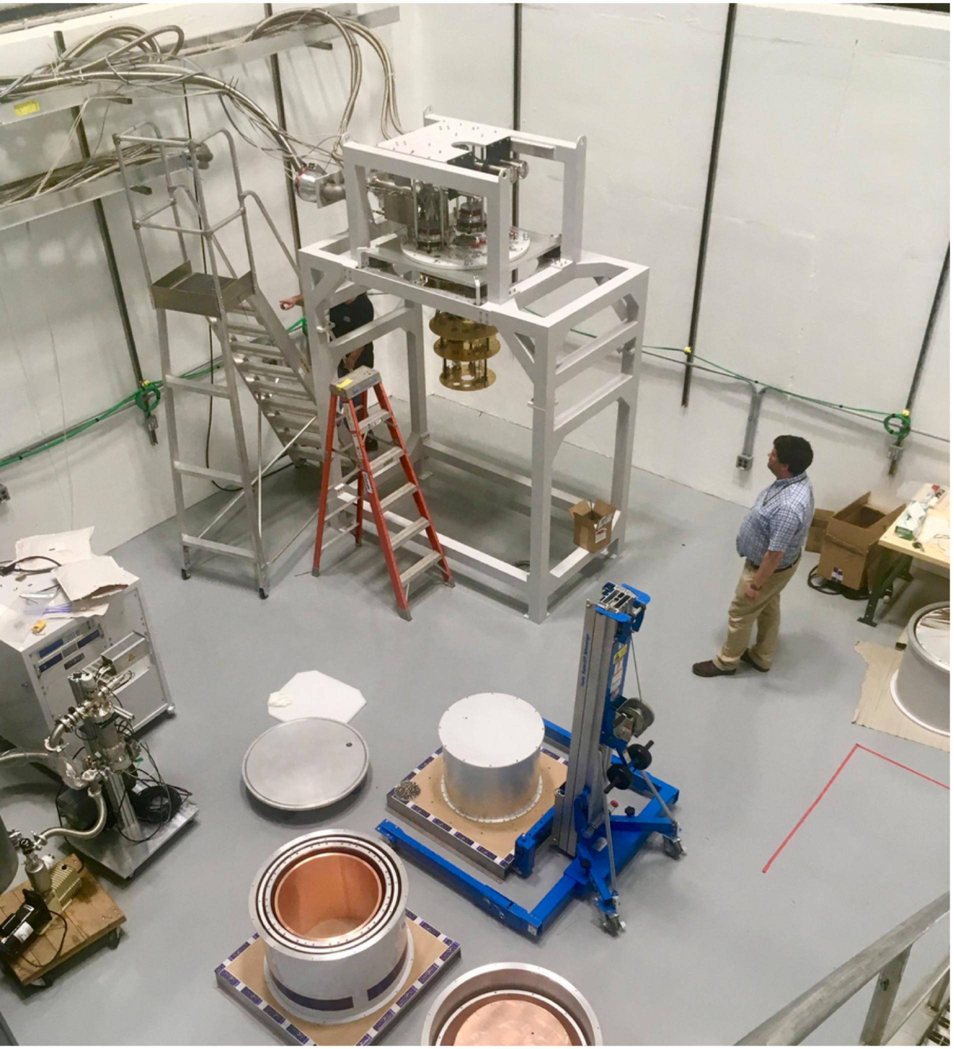


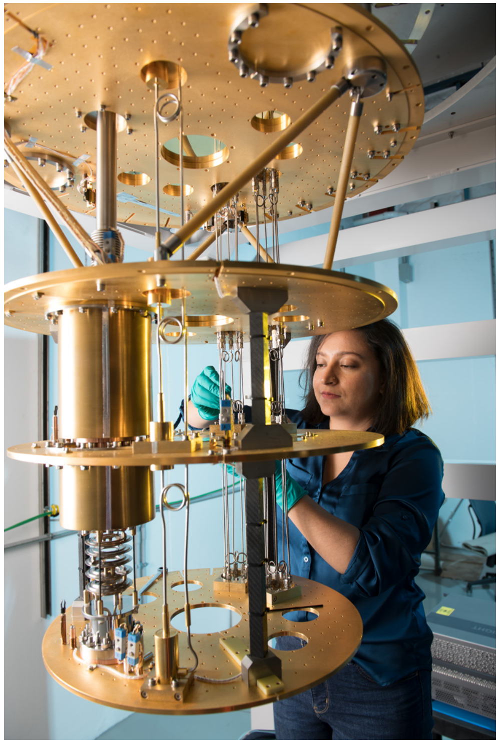


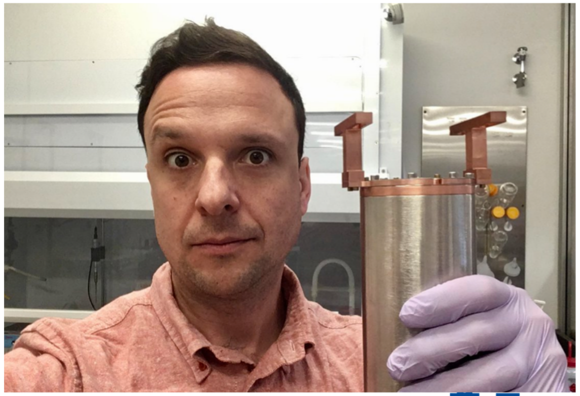


Has already achieved photon counting dark rate 100 times better than the Standard Quantum Limit

Fermilab Quantum Sensor lab at SiDet

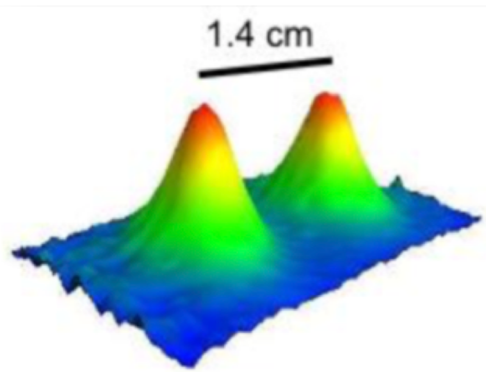






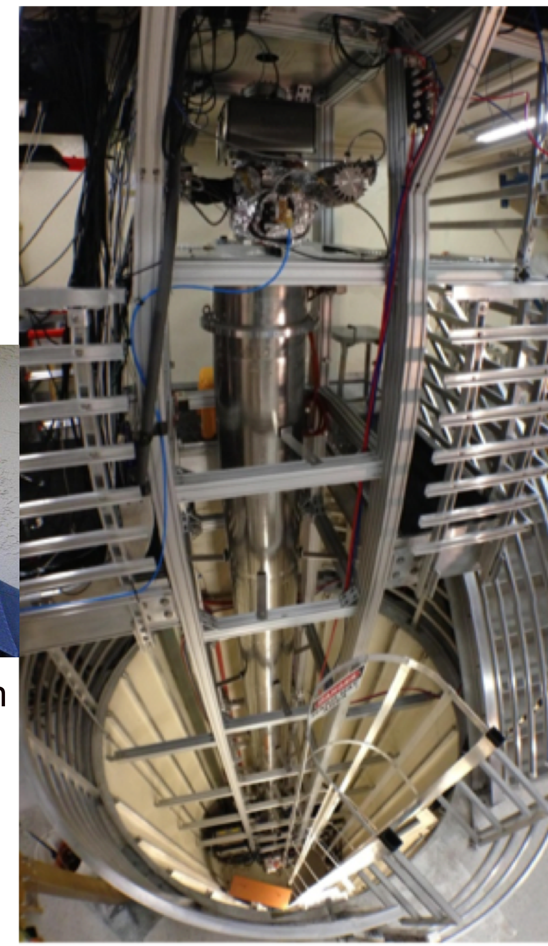
MAGIS-100 cold atom gradiometer:
an incredibly sensitive quantum measuring device, first of its kind

- Use the same ultra-cold strontium atoms that are the basis of the best atomic clocks
- Proof-of-concept using the Stanford 10m scale prototype
- Advancing quantum science with long-range superpositions and entanglement of atoms
- Sensitivity to ultralight dark matter
- Technology pathfinder for future gravitational wave detectors

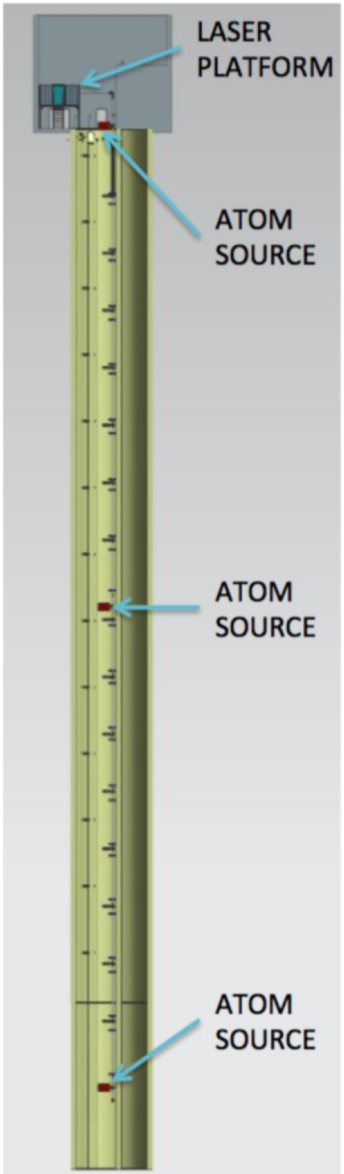


Data from Stanford 10m setup shows single atoms in quantum superposition of two locations 1.4 cm apart

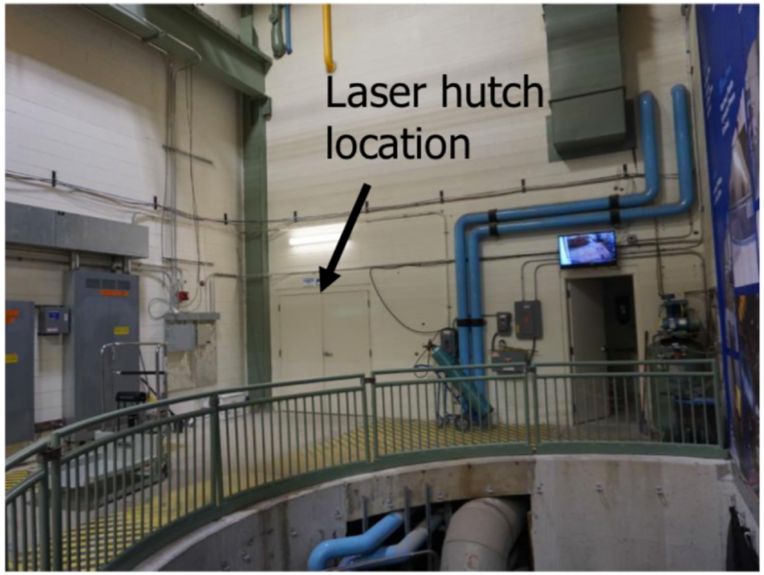
Jason Hogan (Stanford)



Proposed MAGIS-100 at Fermilab



Cross section

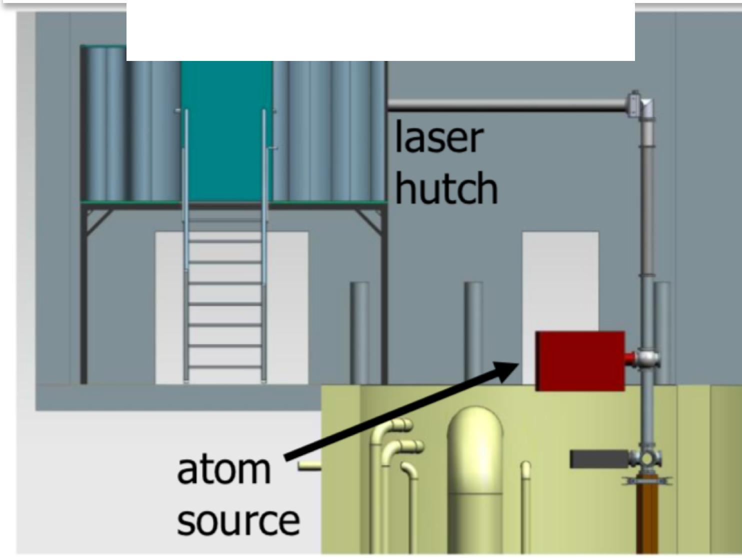


- $10M from the the Moore Foundation includes R&D for world's first entangled cold atom sources
- DOE HEP funding is pending technical review in August

GORDON AND BETTY
MOORE
FOUNDATION

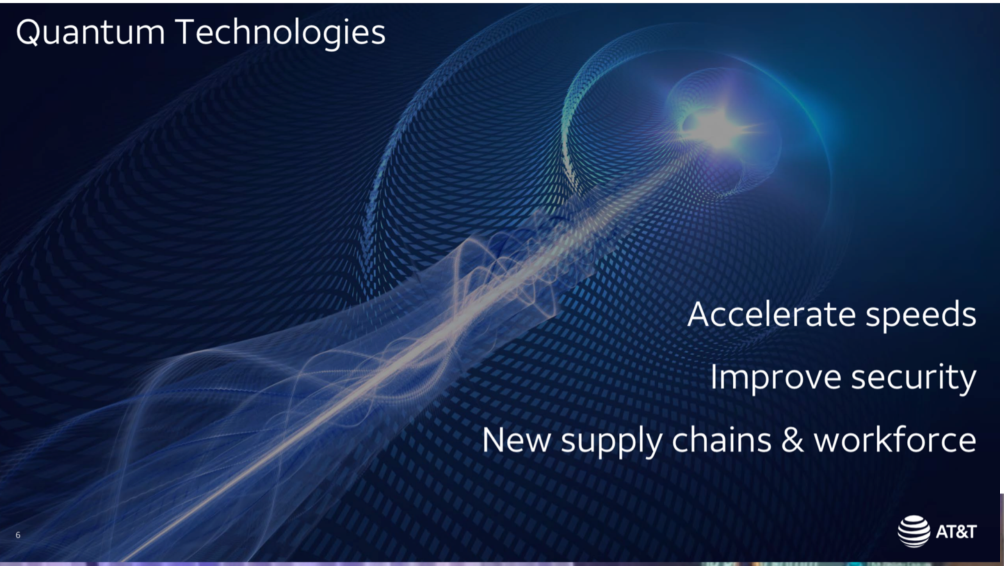
System Components:

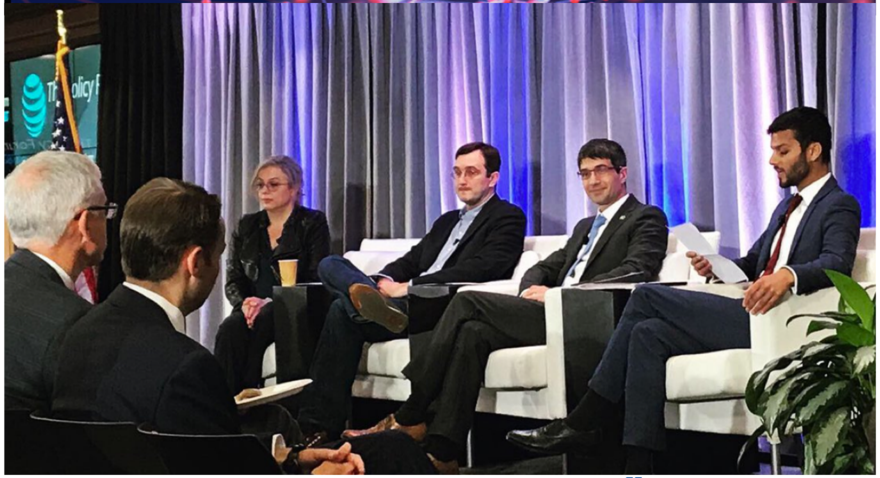
- 10 times larger than Stanford setup
- Located in MINOS shaft
- 90 meter vacuum tube (vertical)
- Three atoms sources
- Laser system for implementing atom interferometry (hutch at top)



Side view of top of detector

Quantum communications





FQNET quantum communications

- Develop a modular, long range, high fidelity, high rate system
- First node commissioning – **teleportation already achieved**
- Second Fermilab node under construction
- Third node at Northwestern (Prem Kumar collaboration)
- More nodes under development

Caltech

JPL
Jet Propulsion Laboratory
California Institute of Technology

AT&T

HARVARD

NORTHWESTERN UNIVERSITY 1851

Maria Spiropulu
FQNET Co-Spokesperson
FQNET PI
CALTECH

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

inqnet
Alliance for Quantum Technologies

Fermilab

Tektronix

Photon Spot

TeraXion

UNIVERSITY OF CALGARY

OZ Optics

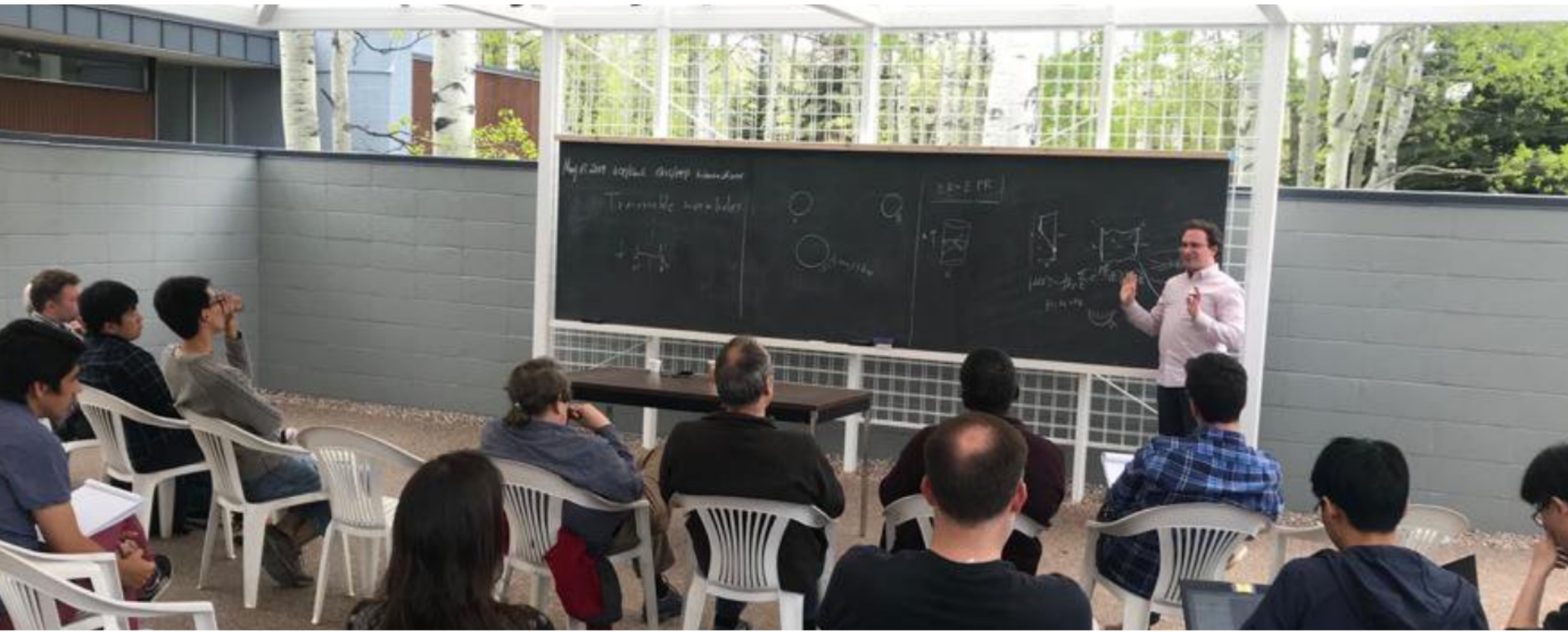
HighFinesse
Laser and Electronic Systems

Quantum Opus

AdvR

Quantum Communications Channels for Fundamental Physics (supported by DOE QuantISED)

Dan Jafferis (Harvard) explaining wormhole teleportation at the Kavli Aspen quantum workshop, May 2019



Quantum organization at Fermilab

- We expect Quantum Science and Technology to become a significant long-term DOE HEP base-funded research concentration of Fermilab, at a level at least comparable to the current Cosmic program.
- Trying to get by with a “virtual” organization leads to confusion and missteps that have large potential for damaging effects given the high-profile nature of quantum and our many nascent partnerships in this area.
- We will be rolling out a new internal quantum organization by Oct 1

Organizing principles

- We require a single transparent organizational entity, with clearly-defined scope and responsibilities, and clear reporting lines up to the Lab Director.
- We are not creating a new Division. Current quantum activities are spread across FNAL divisions, and have moved more quickly and strongly by virtue of support and leveraging within those divisions.
- The new quantum organization will not own buildings and will own only a small fraction of the staff involved in quantum research. Most staff involved in quantum will be matrixed from divisions in a similar fashion to what is done for projects.
- The internal Fermilab quantum organization will be synergistic with the National Quantum Center structure that we will be proposing with quantum partners.

DOE SC National Quantum Centers

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(a) IN GENERAL.—The Secretary of Energy shall ensure that the Office of Science carries out a program, in consultation with other Federal agencies, as appropriate, to establish and operate up to 5 National Quantum Information Science Research Centers to conduct basic research to accelerate scientific breakthroughs in quantum

DEPARTMENT OF ENERGY

Notice of Intent and Request for Information: Quantum Information Science Centers

AGENCY: Offices of Advanced Scientific Computing Research (ASCR), Basic Energy Sciences (BES), and High Energy Physics (HEP), Office of Science, Department of Energy (DOE).

ACTION: Notice of intent (NOI) and request for information (RFI).

- $25M/yr for 5+5 years to consortia of labs, universities, and industry
- Sponsored by DOE BES, ASCR, and HEP
- Expect the first two or three Centers to be funded in FY20

National Quantum Center organization

- Fermilab will co-lead a National Quantum Center proposal.
- The DOE Office of Science FOA for these Centers is expected sometime between Sept 2019 and March 2020.
- The National Center could be governed by (e.g.) an Executive Board consisting of representatives from the major partners. They would have bylaws and choose their own leadership.