Quantum systems and Fermilab

Joe Lykken
PAC Meeting, July 2017

Quantum Information Science (QIS)

- **QIS identified as a national (interagency) and Office of Science priority**
- **HEP QIS emphasis (both near-term and long-term) is on:**
  - P5 science drivers – exploiting entanglement and QIS technology
  - New computational and foundational techniques via QIS
  - Advancing the national QIS enterprise
- **Approach: Interdisciplinary partnerships via connections with other SC programs and/or other federal agencies**
- **Areas of focus for HEP research via coordinated partnerships:**
  - Quantum Computing and Foundational QIS
    - Simulations, entanglement, algorithms, machine learning, data analysis on qubit systems
  - Quantum Sensor Technology
    - Sensors developed in alignment with qubit technology that expand the measurement ranges for experiments
  - Experiments Exploiting Quantum Entanglement
    - New windows on research utilizing QIS foundations, tools, and techniques
- **Reports available at:**
  - http://science.energy.gov/hep/community-resources/reports/
- **Program Manager: Lali Chatterjee**

U.S. DEPARTMENT OF ENERGY | Office of Science

Fermilab

What are the overlaps between HEP and Quantum Science?

Foundational entanglement theory: e.g. holography, black holes, emergent gravity or spacetime, long-range entanglement

Beyond Moore's Law computing: even if general purpose quantum computers or quantum-accelerated computers are 15-20 years away, they are relevant for HEP experiments underway now (ATLAS/CMS/DUNE etc) that will be running in 2035+

Quantum sensors: almost any device developed for quantum computing is also a quantum sensor with potential applications to HEP, e.g. detection of dark sector particles, and a variety of small experiments

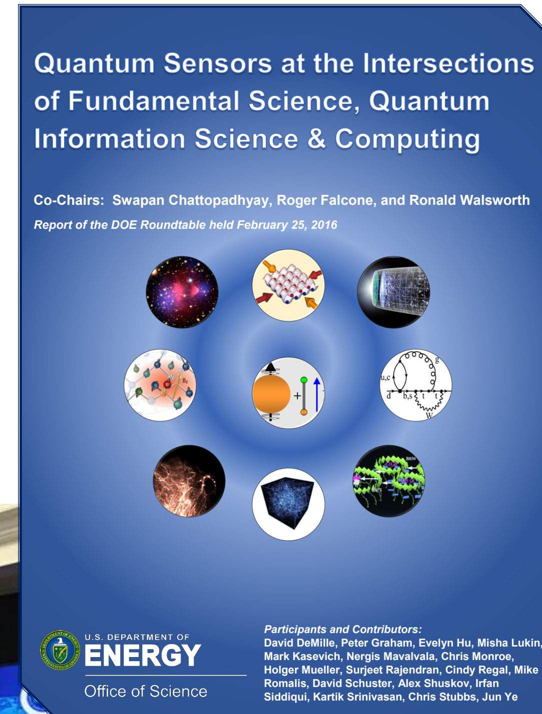
HEP applications of near-term quantum computers: e.g. multiparticle beam dynamics, quantum machine learning for LHC and neutrino data, etc.

HEP has investment and expertise in deploying and scaling the relevant technology: superconducting cavities, sub-Kelvin sensors, controls and readout, etc.

Fermilab and quantum connections

Lab has already done a lot of homework on overlaps between HEP and the fast-moving QIS field

- DOE HEP/ASCR roundtable Feb 2016
- OSTP quantum computing meeting Oct 2016
- POTUS meeting SpaceX Jan 2017
- ASCR quantum testbeds workshop Feb 2017
- U. Chicago – Argonne – Fermilab meeting May 2017
- Visits to Google, IBM, AT&T



Fermilab

Fermilab and quantum connections: partners

Fermilab has identified partners who want to work with us:
Caltech, U. Chicago, industry, other labs, private foundations

In particular we are part of the recently-announced Chicago Quantum Exchange; David Awschalom is the director.

In addition, many of our international partners for neutrinos have expressed interest in collaborating on quantum: Canada, Australia, UK

Chicago Quantum Exchange to create technologically transformative ecosystem

UChicago, Argonne, Fermilab prepare for quantum information revolution

Quantum initiatives

Based on discussions with partners, we have identified four thrusts as entry points for Fermilab to participate in the DOE SC quantum initiative

Supporting initially with LDRD, private foundation and industry funding

Coordinating closely with DOE HEP

Together with partners, we submitted successful pre-proposals to both of the recent ASCR quantum program announcements

We are also trying to develop a fifth thrust on quantum field theory applications

Fermilab thrusts

1. Quantum sensors

2. Superconducting technologies (cavities, materials, systems)

3. HEP applications of near-term quantum computers, algorithms

4. Quantum networks

1. Quantum sensors

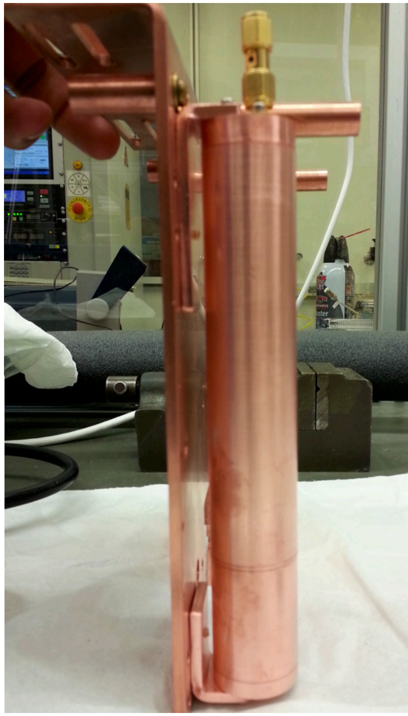
Adapting quantum devices for use as quantum sensors for particle physics experiments such as direct dark matter detection

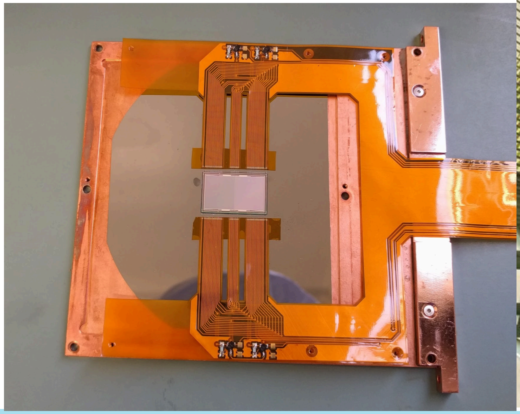
1-1: Quantum computers as axion detectors

1-2: SENSEI dark matter detection with “skipper” CCDs

1-3: Cold atom interferometers for dark sector expts

See next talk by William Wester



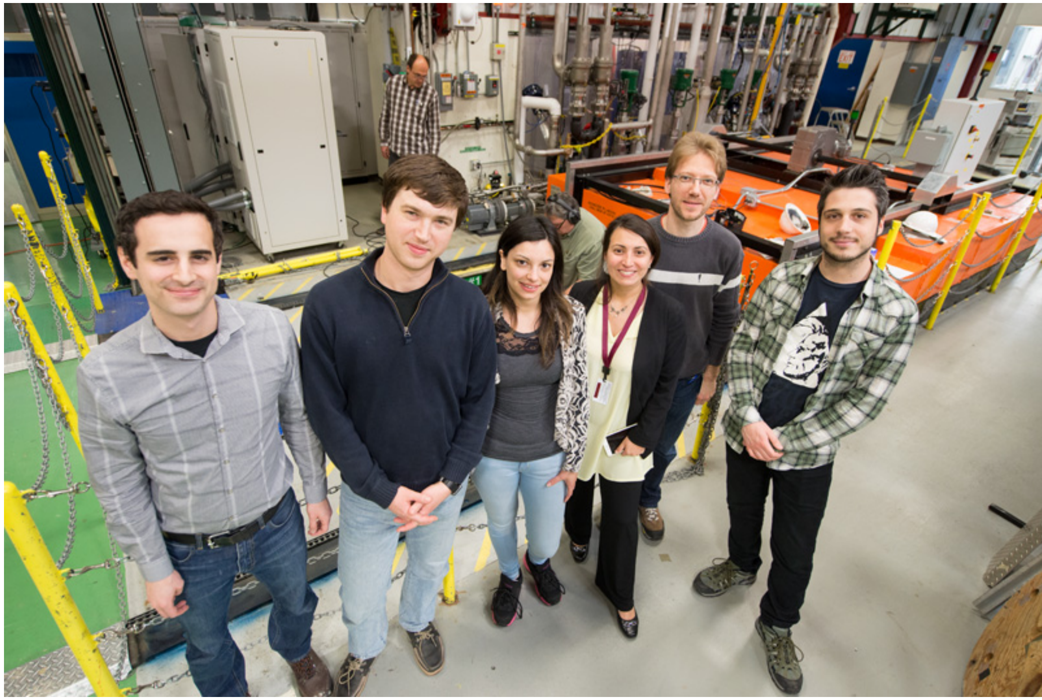


2. Superconducting technologies for quantum systems

Hosting and improving scalable superconducting quantum computers that use microwave photons in cavities

- Working with U. Chicago David Schuster group (and talking to other PIs)
- Fermilab has the world's leading SRF/superconducting materials effort
- We have the relevant expertise in subkelvin cryogenics, controls, readout and systems engineering for scaling up superconducting quantum computers

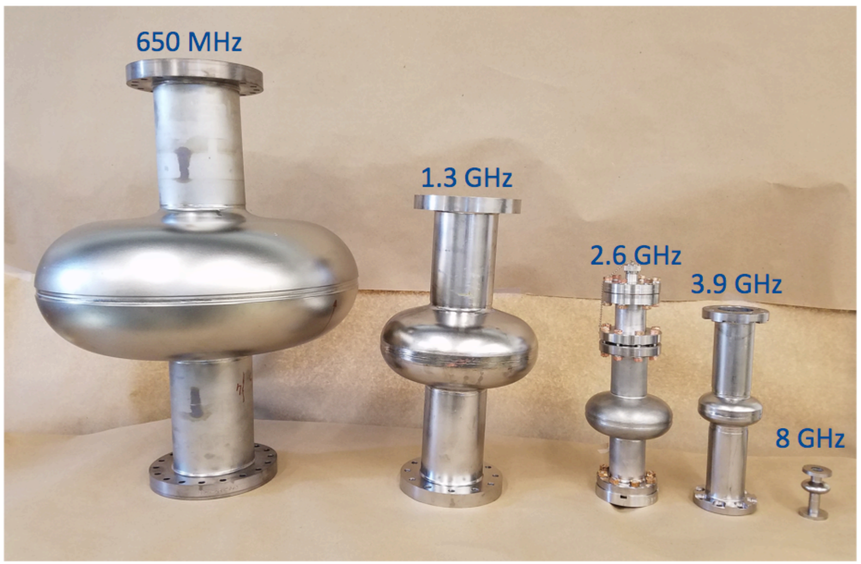
Fermilab SRF team includes 3 DOE Early Career Awardees and a 2017 Presidential Early Career Awardee



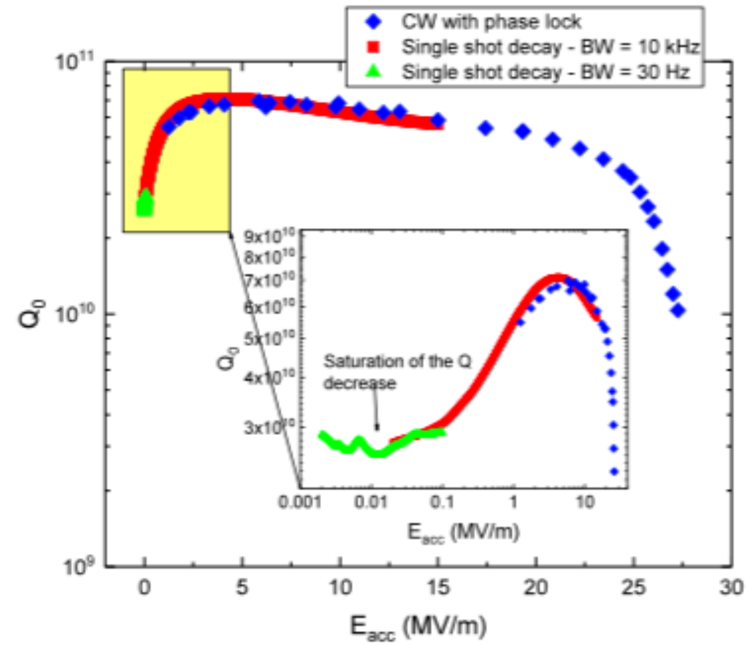
2. Superconducting technologies for quantum systems

- We have begun R&D toward higher Q cavities for quantum computers, which translates e.g. to longer coherence times
- Supported by LDRD

From PIP-2, LCLS-2 to Quantum Computing



This is superconducting materials science of the kind we already do, but in a new regime



Nature of the Low Field Q Degradation in Superconducting Niobium Cavities*

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(Dated: May 31, 2017)

In niobium superconducting radio frequency (SRF) accelerating cavities a decrease of the quality factor at lower fields - a so called *low field Q slope or LFQS* - has been a long-standing unexplained effect. By extending the high Q measurement techniques to ultralow fields we discover two previously unknown features of the effect: i) saturation at rf fields lower than $E_{acc} \sim 0.1$ MV/m; ii) strong degradation enhancement by growing thicker niobium pentoxide. Our findings suggest that the LFQS may be caused by the two level systems in the natural niobium oxide on the inner cavity surface, thereby identifying a new source of residual resistance and providing guidance for potential non-accelerator low field applications of SRF cavities.

3. HEP applications of near-term quantum computers

HEP has shovel-ready use cases, e.g. quantum machine learning for LHC, supported by DOE HEP, partnership of Caltech/USC/Fermilab

Solving a Higgs optimization problem with quantum annealing for machine learning

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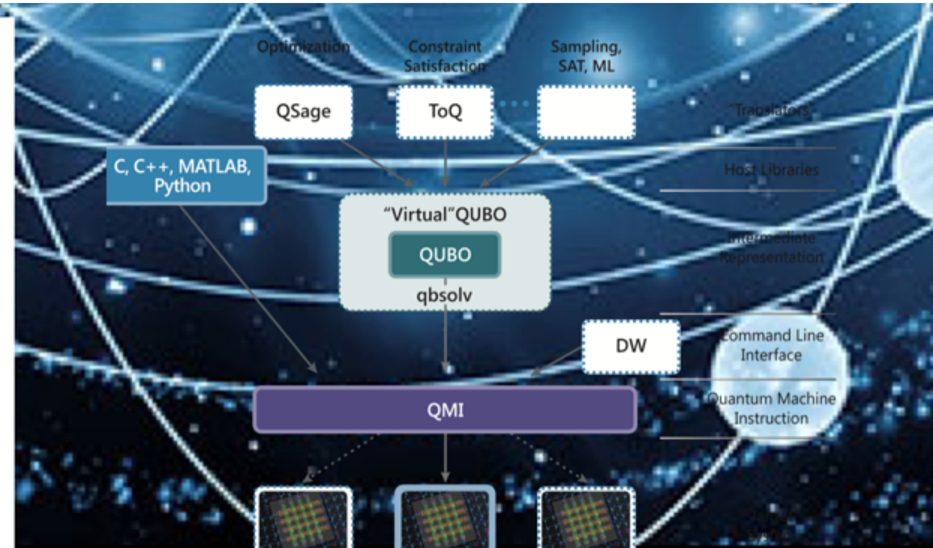
SUMMARY PARAGRAPH

The discovery of the Higgs boson decays in a background of Standard Model processes was assisted by machine learning methods.[1,2] The classifiers used to separate signal from background are trained using highly unerring but not completely perfect simulations of the physical processes involved, often resulting in label noise and systematic errors. We investigate the application of quantum[3–6] and classical annealing[7,8] in solving a Higgs signal versus background machine learning optimization problem. We bag a set of weak classifiers built based on the kinematic observables of the Higgs decay photons into a strong classifier that is highly resilient against overtraining and errors in the Monte Carlo simulation correlations of the physics observables. The resulting quantum and classical annealing classifier systems perform comparably to current state of the art machine learning methods used in particle physics[9,10] and are simple functions of directly interpretable experimental parameters with a clear physical meaning. The annealer-trained classifiers exploit the excited states in the vicinity of the ground state and demonstrate some advantage for small training sizes. This technique may find application in other areas of experimental particle physics given the algorithm's relative simplicity and robustness to error.

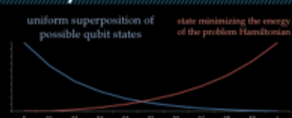


A. User maps the optimization problem into search for "lowest point in a vast landscape"
B. System processes an enormous search space (e.g. 2^{N_q}) with one instruction
C. Processor considers all possibilities simultaneously, finds lowest energy solutions
D. Multiple solutions returned to the user, sorted by optimal probability

ADIABATIC QUANTUM ANNEALING/OPTIMIZATION

Start from setup Hamiltonian H(0), easy to construct ground state (large transverse magnetic field)

Turn on our problem Hamiltonian H_P while turning off slowly and smoothly the setup Hamiltonian



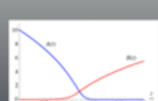
$$H(t) = A(t)H(0) + B(t)H_P$$

ARRIVE IN GROUND STATE OF H_P, I.E. SOLUTION OF QUBO PROBLEM

$$E(\vec{s}) = \sum_i h_i s_i + \sum_{ij} J_{ij} s_i s_j \quad , \quad s_i \in \{-1, +1\}$$

$$H_{\text{Ising}} = \sum_i h_i \sigma_i^z + \sum_{ij} J_{ij} \sigma_i^z \sigma_j^z$$

$$H(t) = A(t) \sum_j \sigma_j^x + B(t) H_{\text{Ising}} \quad , \quad t \in [0, t_f]$$



Solved a Higgs signal/background optimization problem using quantum annealing for machine learning

February 17 2015, ASCR Workshop on QC Maria Spiropulu

3. HEP applications of near-term quantum computers

Fermilab has deep experience in co-design, middleware, interface, and algorithm development for distributed classical computing, will apply this to near-term quantum computers

Partnered on two pre-proposals to the ASCR solicitation on Quantum Algorithm Teams; both made it to proposal stage

Partnered on two pre-proposals to the ASCR solicitation on Quantum Testbeds; both made it to proposal stage

4. Quantum networks

- Secure **communication** networks using entangled photons to link quantum devices & computers over large distances with optical fiber and quantum repeaters

- Caltech and AT&T have formed a strategic 5-year partnership for co-design, systems engineering and integration of **IN**telligent **Q**uantum **NE**tworks & **T**echnologies, i.e. the **INQNET**

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Alliance for Quantum Technologies (AQT) to Harness the Power of Networked Quantum Computing Technologies

The AT&T Foundry innovation center in Palo Alto, California is joining the California Institute of Technology to form the Alliance for Quantum Technologies (AQT). The Alliance aims to bring industry, government, and academia together to speed quantum technology development and emerging practical applications.

4. Quantum networks

- Maria Spiropulu is the Caltech PI
- AT&T support is through the AT&T Foundry in Palo Alto

- Fermilab will host the **INQNET** backbone for technology demonstrators (photonics, fiber and repeaters)

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Summary

HEP science and technology overlaps with quantum science make it appropriate for DOE HEP to have a major role in the Office of Science quantum initiative

Fermilab has done a lot of homework to identify appropriate entry points, and have found strong partners with relevant expertise

We are exploiting leverage and flexibility from LDRD, industry, and private foundation support

We are focusing on areas where high impact results can be achieved on relatively short timescales, but also looking to the longer term