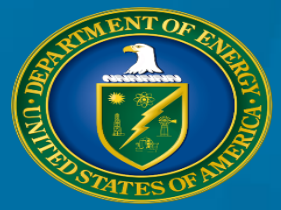


U.S. DEPARTMENT OF ENERGY | Office of Science

HEP-QIS Program
QuantISED
(Quantum Information Science Enabled Discovery)

APS DPF Meeting July 31st 2018

Lali Chatterjee

Program Manager
Office of High Energy Physics
Office of Science, U.S. Department of Energy

Outline of Talk

- Highlights of the HEP-QIS Program
- HEP-QIS as part of the national QIS effort
- QIS at DOE Office of Science
- HEP-QIS program status
- Other Updates and going forward

Highlights of the HEP –QIS Program

QuantISED

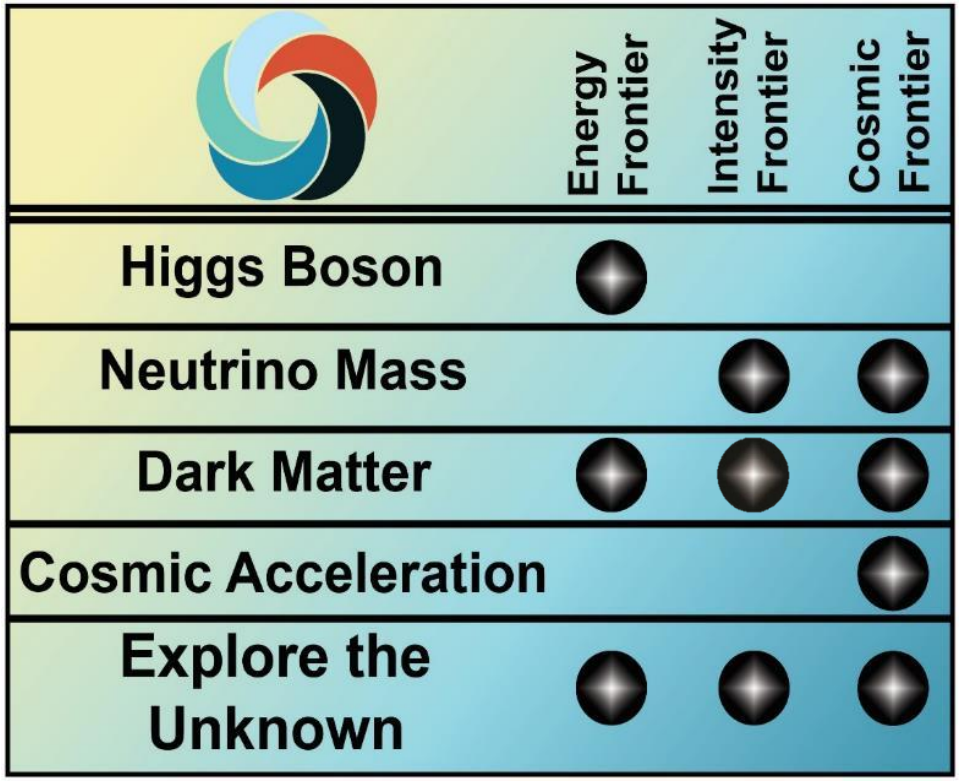
Quantum **I**nformation **S**cience **E**nabled **D**iscovery

HEP-QIS Based Discovery for Science Drivers

HEP-QIS Interdisciplinary Consortia

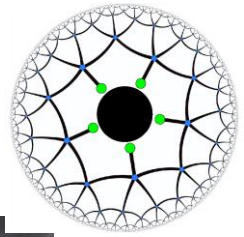
- Foundational HEP-QIS Research
- Quantum Simulation Experiments
- Quantum computing for HEP
- Quantum Sensors using QIS
- HEP tools for QIS
- QIS based small experiments

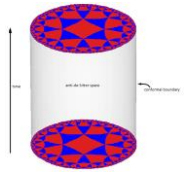
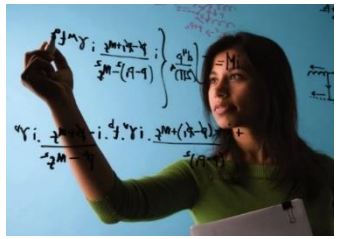
P5 Science Drivers



In parallel, the program fosters contribution to QIS Technology (QIST) using HEP tools and expertise in partnership with the QIS community

Major Thrust Areas for QuantISED





Cosmos and Qubits
(Theory, QI, & Quantum Simulation Experiments)

HEP tools for QIS Research technology
(SRF/controls…)

Quantum Field Theory, Entanglement
(Quantum Computation & Simulation Experiments)

HEP-QIS
Interdisciplinary Research, Research Technology, Discovery

QIS based Quantum Sensors for HEP

Quantum Computing for HEP
Data analysis/ML/ algorithms

QuantISED Exemplars or Experiments ?

Some Coordinated partnerships with NIST and DOD

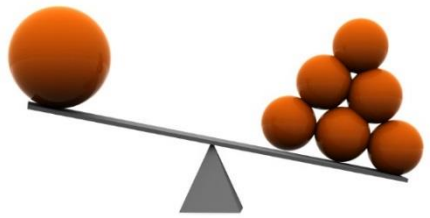
Overall HEP Goals for QIS Activities

- Advance the science drivers identified by P5 using QIS
- Connected with HEP Frontiers and Technology Thrusts
- Advance QIS itself including qubit controls & technology - through capabilities, expertise, and fundamental knowledge in the HEP community
- Develop the appropriate and necessary interdisciplinary collaborations to advance high energy physics and QIST

HEP-QIS Entanglement See Saw

QIS for HEP

HEP for QIS



- Connected with SC Programs and other agencies
- Connected with identified national thrusts

Credit – Microsoft Bing search

HEP-QIS as part of the National QIS Effort

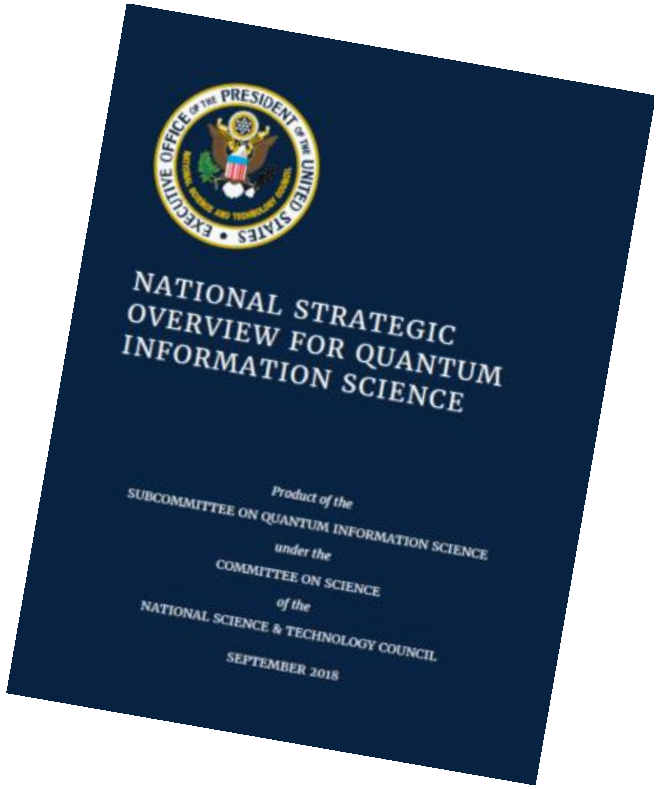
NSTC Committee/ NQI/DOE

National Science and Technology Council (NSTC) Subcommittee on Quantum Information Science

- Established June 2018, at elevated level from earlier interagency working groups
- Create and maintain a national strategy for quantum information science (QIS)
- Coordinate current and future efforts across the agencies
- Co-chairs: DOE, NSF, NIST

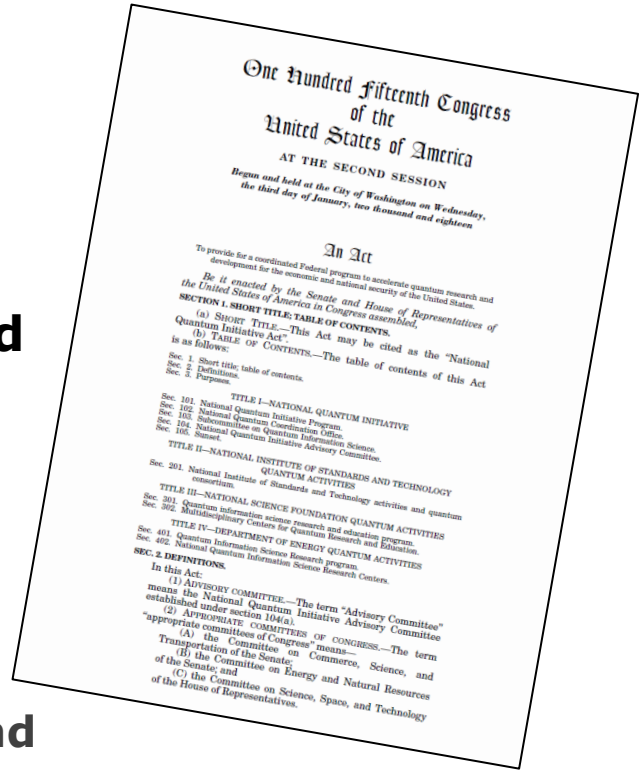
National Strategic Overview for QIS

- Issued September 2018
- Policy recommendations:
  - Focus on **a science-first** approach that aims to identify and solve Grand Challenges: problems whose solutions enable transformative scientific and industrial progress;
  - Build a quantum-smart and diverse workforce to meet the needs of a growing field;
  - Encourage industry engagement, providing appropriate mechanisms for public-private partnerships;
  - Provide the key infrastructure and support needed to realize the scientific and technological opportunities;
  - Drive economic growth;
  - Maintain national security; and
  - Continue to develop international collaboration and cooperation



National Quantum Initiative

- **National Quantum Initiative Act – Public Law 115-368, signed by President Trump 12/21/2018**
- **Established National Quantum Coordination Office, National Quantum Initiative Advisory Committee, and NSTC Subcommittee on QIS**
- **Authorized specific quantum activities for NIST, NSF, and DOE**
- **DOE roles**
  - **Provide support for the National Quantum Coordination Office**
  - **Serve as co-chair on the NSTC Subcommittee on QIS**
  - **Leverage the collective body of knowledge from existing quantum information science research**
  - **Provide research and training for additional undergraduate and graduate students**
  - **Establish 2 to 5 National Quantum Information Science Research Centers**



One Hundred Fifteenth Congress
of the
United States of America

AT THE SECOND SESSION

Begun and held at the City of Washington on Wednesday, the third day of January, two thousand and eighteen

An Act

To provide for a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE; TABLE OF CONTENTS.

(a) SHORT TITLE.—This Act may be cited as the "National Quantum Initiative Act".

(b) TABLE OF CONTENTS.—The table of contents of this Act is as follows:

SEC. 2. DEFINITIONS.

In this Act:

(1) ADVISORY COMMITTEE.—The term "Advisory Committee" means the National Quantum Initiative Advisory Committee established under section 104(a).

(2) APPROPRIATE COMMITTEES OF CONGRESS.—The term "appropriate committees of Congress" means—

(A) the Committee on Commerce, Science, and Transportation of the Senate;

(B) the Committee on Energy and Natural Resources of the Senate; and

(C) the Committee on Science, Space, and Technology of the House of Representatives.

Quantum Information Science: Agency Approaches

QIS at DOE Office of Science

QIS started sequentially across the Six Programs at Office of Science with a formal

Office of Science QIS Initiative in 2018

The DOE Office of Science Research Priorities

Basic Energy Sciences (BES)	• **Understanding, predicting, and ultimately controlling matter and energy flow at the electronic, atomic, and molecular levels**
Advanced Scientific Computing Research (ASCR)	• **Delivering world leading computational and networking capabilities to extend the frontiers of science and technology**
Biological and Environmental Research (BER)	• **Understanding complex biological, climatic, and environmental systems**
Fusion Energy Sciences (FES)	• **Building the scientific foundations for a fusion energy source**
High Energy Physics (HEP)	• **Understanding how the universe works at its most fundamental level through research, projects, and facilities**
Nuclear Physics (NP)	• **Discovering, exploring, and understanding all forms of nuclear matter**

https://www.energy.gov/science/office-science

Quantum Information Science (QIS) in the DOE Office of Science (SC)

QIS is a thriving area of multidisciplinary science.

- It exploits particular quantum phenomena to measure, process, and transmit information in novel ways that greatly exceed existing capabilities.

QIS provides a basic foundation for numerous application areas.

- Potential transformative impact on SC grand challenges.

QIS is at a tipping point.

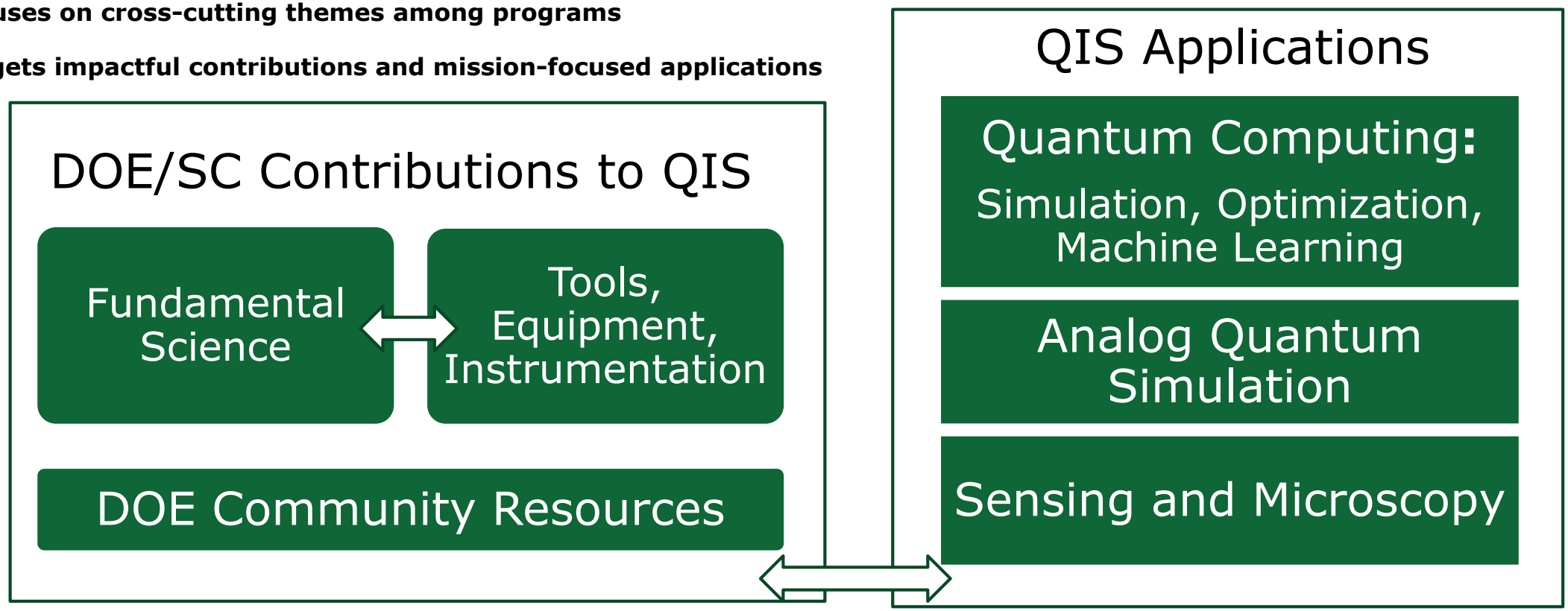
- Major companies are embracing QIS, foreign competition is expanding rapidly.

Progress in QIS is driven by basic research in physical sciences.

- DOE SC is the Nation's leading supporter of basic research in physical sciences.

SC's QIS Strategy

- ✓ **Builds on community input**
- ✓ **Highlights DOE/SC's unique strengths**
- ✓ **Leverages groundwork already established**
- ✓ **Focuses on cross-cutting themes among programs**
- ✓ **Targets impactful contributions and mission-focused applications**



The DOE SC QIS Initiative and Budget

DOE SC resources devoted to QIS have ramped up rapidly in the past few years, and the President's Budget Request for next year (FY 2020) invests further:

Dollars in thousands	FY 2018	FY 2019	FY 2020		
Quantum Information Science	Enacted Approp.	Enacted Approp.	President's Request	Request vs. FY 2019 Enacted	
Total across Office of Science	62,379	123,483	168,492	45,009	36.4%

- QIS Identified as a priority by both Congress and the Executive Office of the President
- Cuts across all six SC research programs (and several other DOE programs)
- **The HEP QIS budget is allocated to HEP from the overall SC QIS Budget**
- FY 2020 request highlights establishment of DOE quantum centers:
  - "(ASCR, BES, and HEP will partner to) establish at least one multi-disciplinary QIS center to promote basic research and early stage development to accelerate the advancement of QIS through vertical integration between systems and theory and hardware and software."

HEP-QIS Program Status

HEP and QIS – How we Started

Other Agencies – NSF, DOD, NIST, …

Significant Contributions over many years…

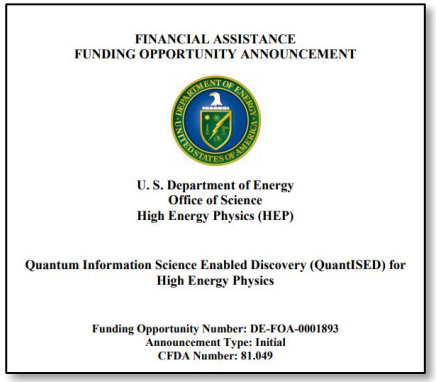
DOE Labs have been working on HEP-QIS as well …

- HEP has been working with the community, SC, and other agencies to identify its QIS connections since 2014, including participation in the NSTC Interagency Working Group
- Workshops and community reports inform program growth:
  - **Jan. 2015: ASCR-HEP** Study Group on "Grand Challenges at the Interface of Quantum Information Science, Particle Physics, and Computing"
  - **Feb. 2015: BES-HEP** Round Table Discussion on "Common Problems in Condensed Matter and High Energy Physics"
  - **Feb. 2016: HEP-ASCR** Roundtable on "Quantum Sensors at the Intersections of Fundamental Science, Quantum Information Science and Computing"
  - **July 2016: NSTC** report on "Advancing Quantum Information Science: National Challenges and Opportunities" (HEP Participation)

And then….2018 QIS Budget

HEP FY 2018 QIS FOA QuantISED (Closed)

- **Quantum Information Science Enabled Discovery (QuantISED) for High Energy Physics [DE-FOA-0001893/LAB 18-1893]** (Funding Opportunity Announcement)
- **Objective:** **Forge new routes to scientific discovery along HEP mission and P5 science drivers, invoking interdisciplinary advances in the convergent field of QIS, and intersection with expertise, techniques, technology developed in HEP community**
- **Track 1: Pioneering Pilots** Novel concepts, test problems, design studies **Track 2: HEP-QIS Consortia** [required a DOE Lab partner]
- **Out of Scope:**
  - General quantum computing algorithms or computing hardware
  - Requests for basic research within the mission space of other SC programs
  - Purchase of equipment or instruments exceeding 10% of the total project
  - or $20,000 whichever is less


FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U. S. Department of Energy
Office of Science
High Energy Physics (HEP)

Quantum Information Science Enabled Discovery (QuantISED) for High Energy Physics

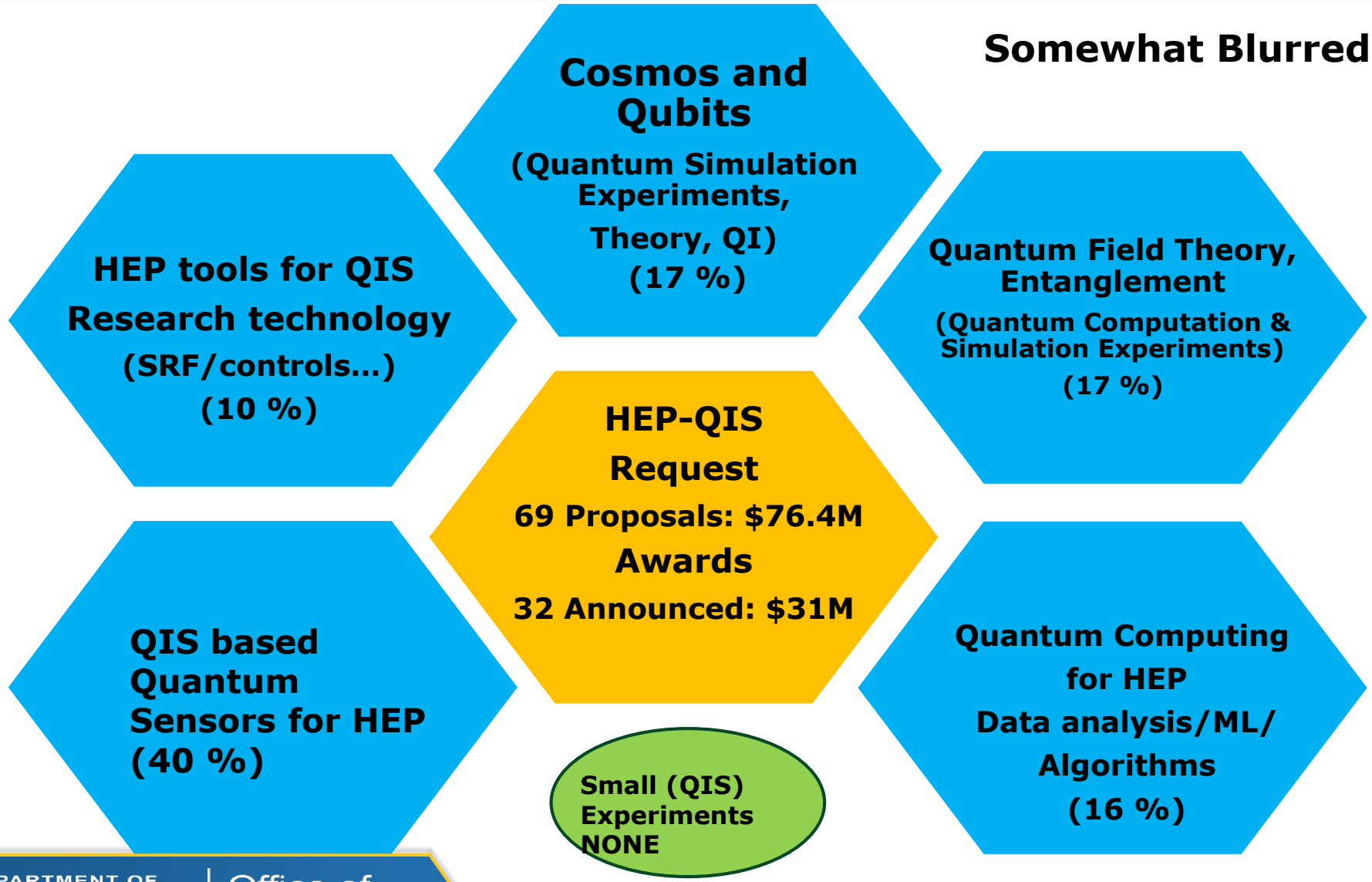
Funding Opportunity Number: DE-FOA-0001893
Announcement Type: Initial
CFDA Number: 81.049

Award Announcements by DOE On Sept 24,2018

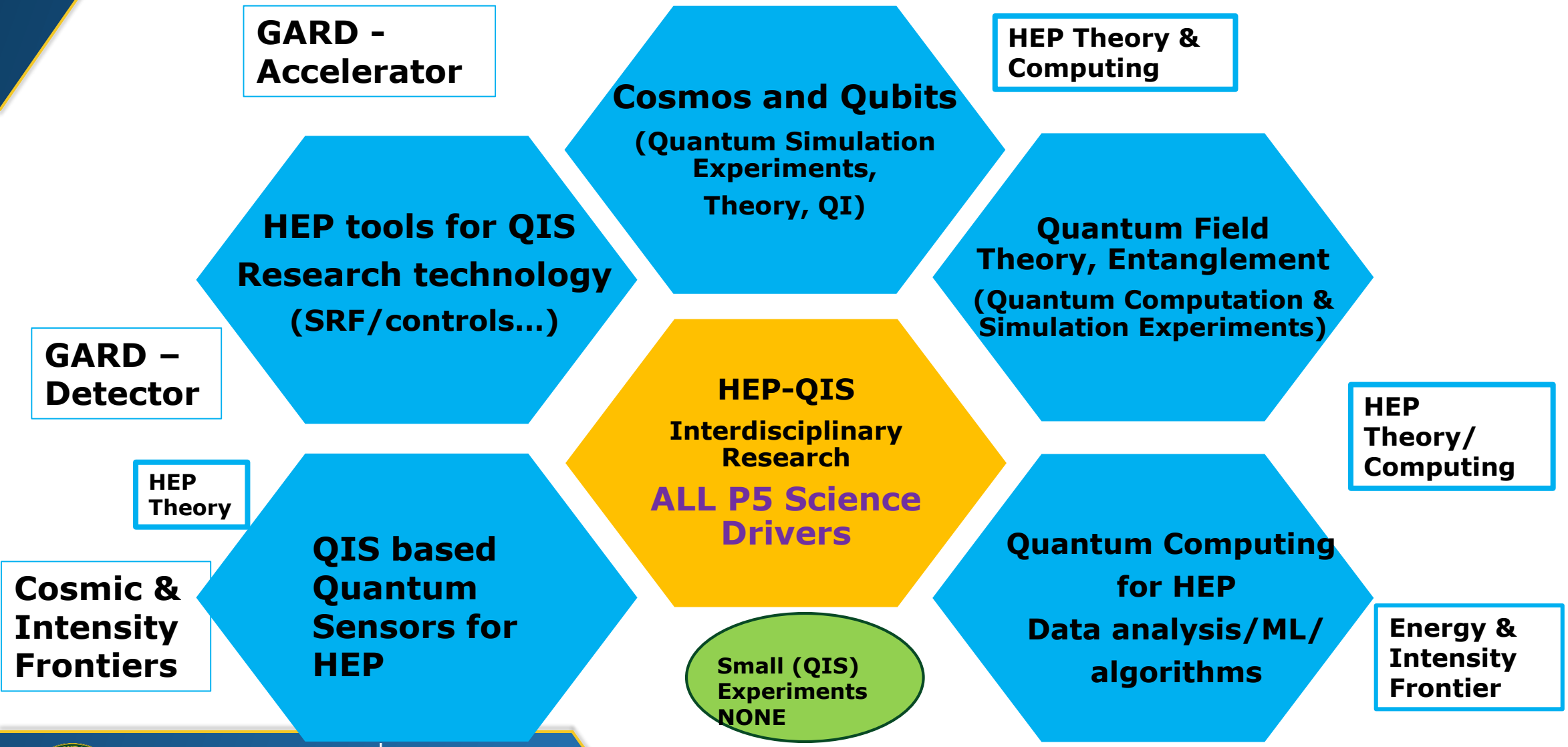
- Awards for FY 2018 HEP Funding Opportunity Announcement (FOA) and Lab Announcement Quantum Information Science Enabled Discovery (QuantISED) have been announced:
- https://www.energy.gov/articles/department-energy-announces-218-million-quantum-information-science
- The specific HEP awards are listed at: https://science.energy.gov/hep/ (website being updated)
- Total HEP Awards: $ 31 M (over 3 years)
- **HEP Awards: 15 University led projects + 17 lab led projects**
- **Most projects multi institutional and inter disciplinary**

Awards Across Categories

Somewhat Blurred Boundaries…

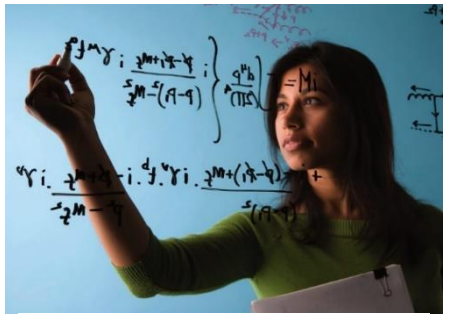


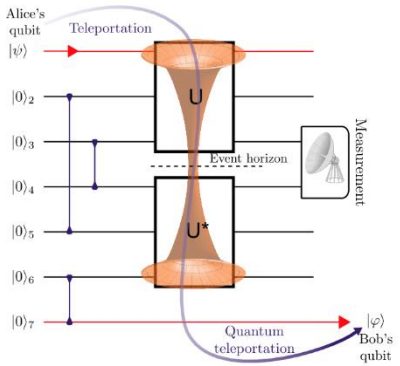
HEP-QIS Connections to HEP Frontiers and Thrusts



Example - Cosmos and Qubits

Powerful new windows to accomplish HEP mission & advance QIST
Foundational theory, computing, sensors, technology, experiments





Example: Cosmos and Qubits

Foundational concepts and mathematical formulations that explore black hole physics and how black holes scramble information lead to new ways to study how qubits stabilize in the laboratory & fault tolerance. Simulating worm holes/study of teleportation protocols…

Quantum Simulation Experiments

https://www.nature.com/articles/s41586-019-0952-6

Cosmos and

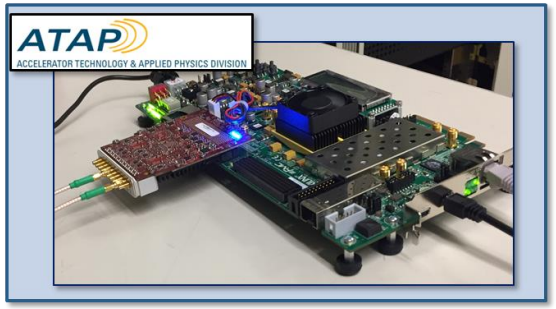
Qubits

Partnerships with DOD on above

QIS based Quantum Sensors and QIST

- **Most qubits are also precision quantum sensors**
- **New ways to explore dark universe and elusive neutrinos**
- **HEP expertise and technology can advance QIS- example**
- **Technology underpinning giant particle accelerators**

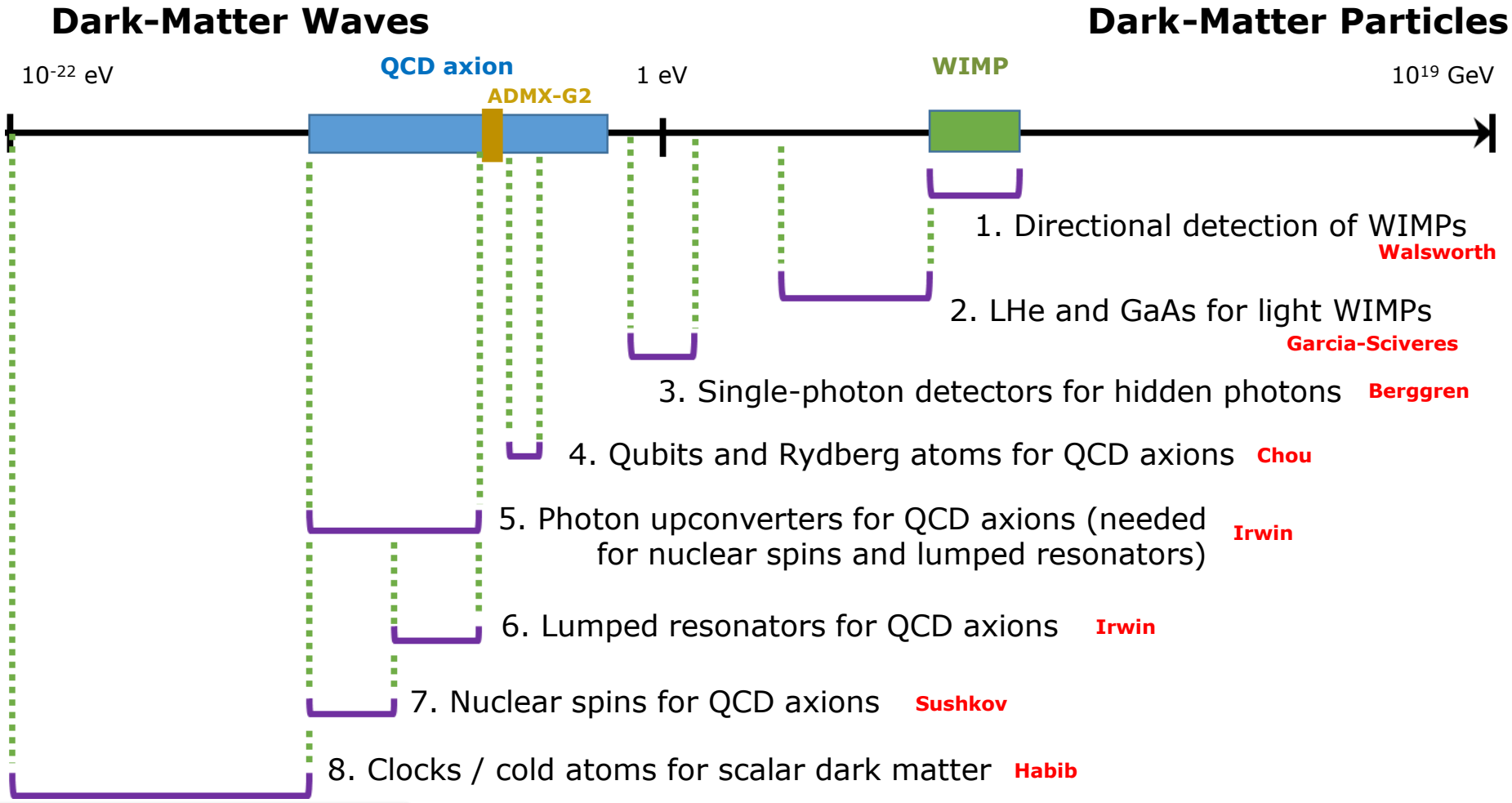
  Can be adapted and developed to make better qubits



Development of advanced superconducting radio frequency (SRF) cavities (example from FNAL), cryogenics, and other technologies supporting development of qubits, their ensembles, quantum sensors, and quantum controls at LBNL are being developed for QIS

HEP-QIS QuantISED Sensor Portfolio

For Dark Sector, New Interactions, and QIST



NIST/HEP partnership: Summary and Update

NIST

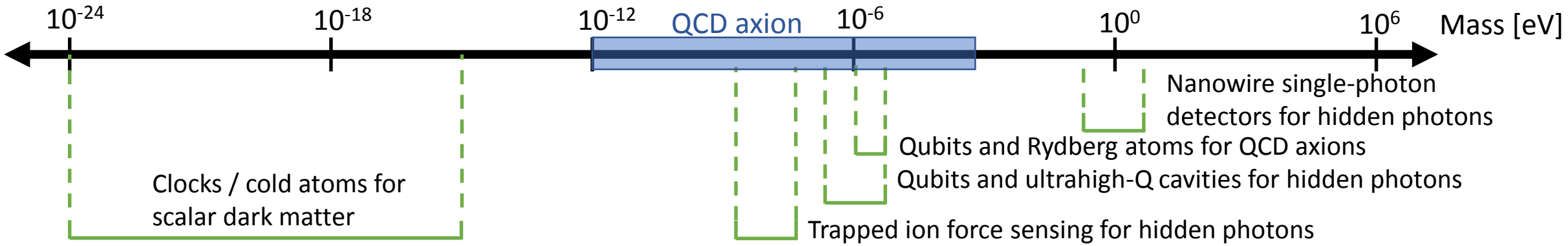
- Precision metrology
- Quantum technologies
  - Single photon detectors
  - Atomic sensors
  - Superconducting circuits

Quantum technologies for fundamental physics

- Particle physics
- Cosmology
- Accelerator and Detector Technologies

HEP

New capabilities for probing the dark sector



- **Dark matter** search over a previously inaccessible range of masses and sensitivity
- Quantum technologies with broad impact on quantum sensing

Quantum Error Correction and Spacetime Geometry

John Preskill (Caltech) and Patrick Hayden (Stanford)

HEP-DOD Pilot

Goal: To develop further the deep connections between quantum error correction (QEC) and the holographic principle by advancing the theory of QEC and by clarifying how this theory can be used to build more general and powerful approaches for probing spacetime physics.

"Continuous symmetries and approximate quantum error correction"

Bounds on the accuracy of any approximate error-correcting code that is covariant with respect to a continuous symmetry. These bounds relate to properties of the AdS/CFT dictionary such as approximate bulk global symmetries and bulk time evolution.

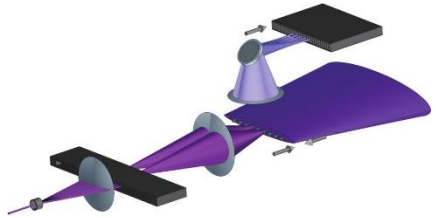
"Learning the alpha-bits of black holes"

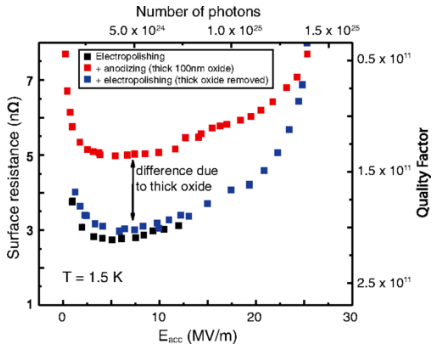
Applications of the recently developed theory of universal subspace QEC to the reconstruction of black hole microstates in AdS/CFT duality. Explains how the approximate error-correcting code underlying the bulk-to-boundary dictionary becomes exact in the semi-classical limit.

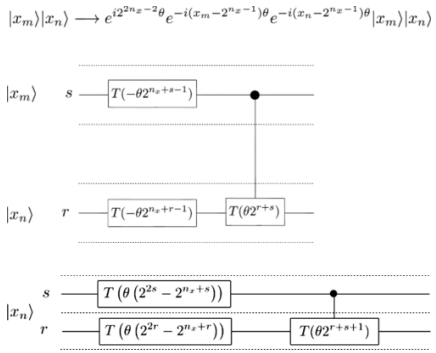
HEP-QIS Research Program Updates

Quantum Information Science Enabled Discovery (QuantISED) for High Energy Physics Highlights

- Cosmos and Qubits
  - "Verified quantum information scrambling"
    - https://www.nature.com/articles/s41586-019-0952-6
- Research Technology for QIST
  - "Understanding Quality Factor Degradation in Superconducting Niobium Cavities at Low Microwave Field Amplitudes"
    - Phys. Rev. Lett. 119, 264801
- Quantum Computing for HEP:
  - "Electron-Phonon Systems on a Universal Quantum Computer"
    - Phys. Rev. Lett. 121, 110504, 2018
  - "Digital quantum computation of fermion-boson interacting systems"
    - Phys. Rev. A 98, 042312, 2018



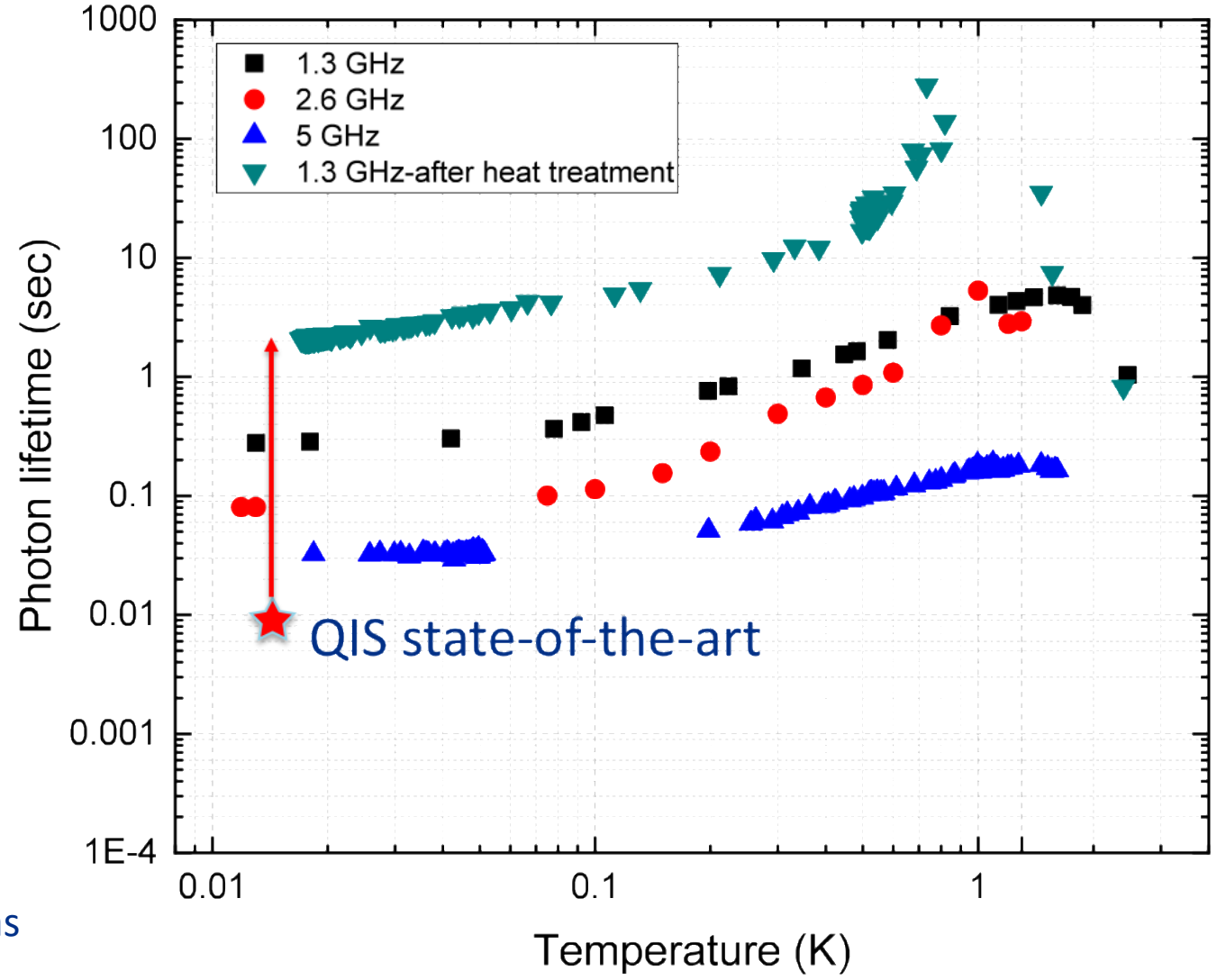




Ultra-High Q Superconducting Accelerator Cavities for Orders of Magnitude Improvement in Qubit Coherence Times and Dark Sector Searches

Record long photon lifetimes in SRF cavities for QIS t = 2 sec, outperforming QIS state-of-the-art by > 200x https://arxiv.org/abs/1810.03703

SRF cavities taken to quantum regime: More than 200x improvement as compared to QIS records



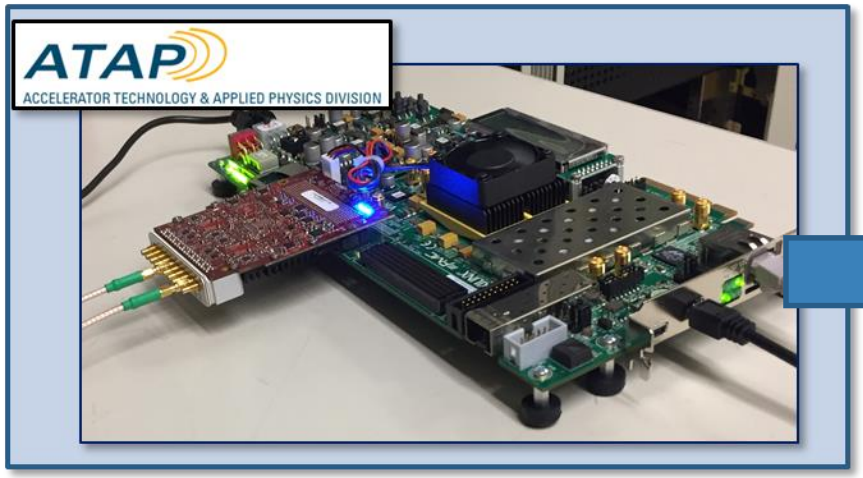
US patent pending, serial no 62/742,328

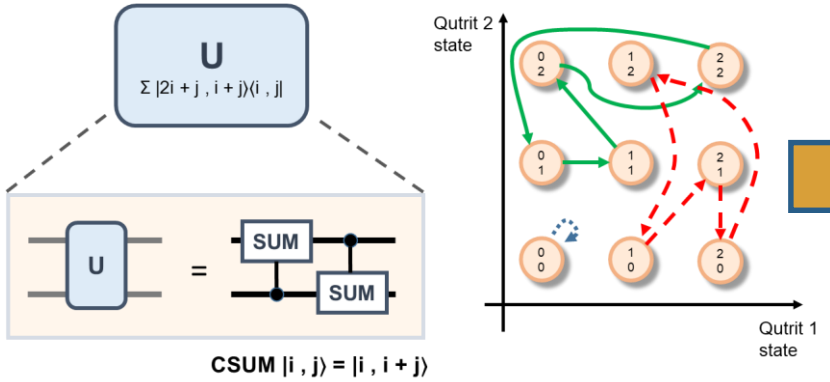
Fermilab

FPGA-based quantum control for HEP simulations with qutrits

I. Siddiqi, Lawrence Berkeley National Laboratory

HEP for QIS & Cosmos & Qubits





OBJECTIVES:

- Demonstrate optically interconnected, FPGA-based modular digital circuitry for quantum control and readout
- Develop superconducting quantum devices and logic gate sets suitable for executing HEP specific algorithms

IMPACT:

- Cost-effective, extensible electronics leveraging HEP engineering expertise for practical quantum computation
- Quantum processors optimized to test scrambling, Ads/CFT correspondence, and advanced error correction

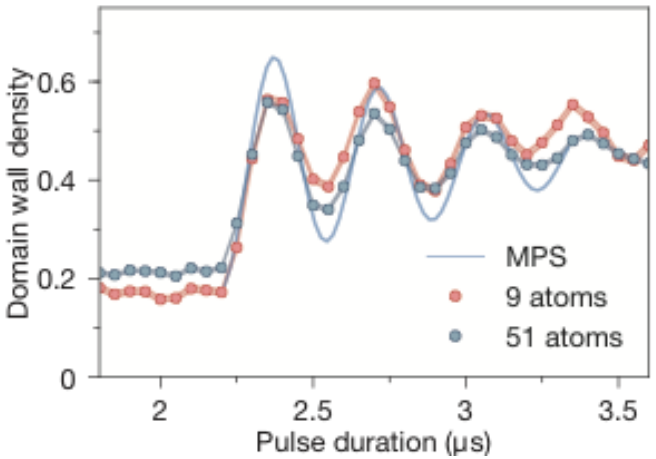
MILESTONES:

- Developed first stand-alone control module and performed initial quantum state readout/control
- Accessed larger Hilbert space with transmon qutrits and demonstrated initial logic gates
- Developed 5 qutrit quantum teleportation protocol to test informational scrambling (N. Yao)

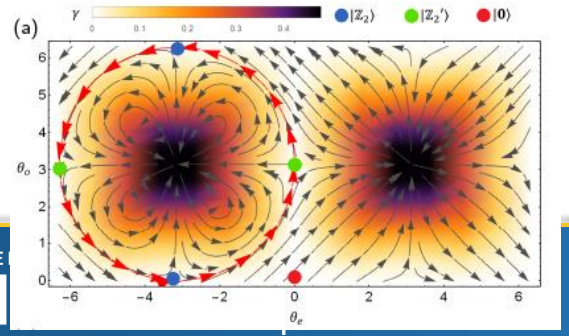
Discovery of quantum many-body scars

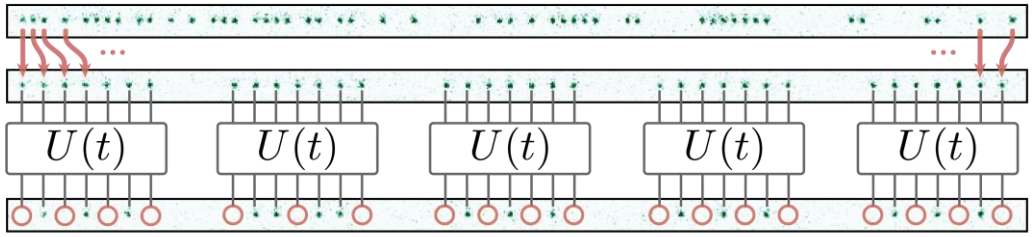
Experiments on programmable Rydberg atom simulator: Vuletic-Lukin DoE/DoD pilot

Surprising observation of long-lived order parameter oscillation after sudden quench across quantum phase transition [1]



Description in terms of locally entangled Matrix Product States [3]

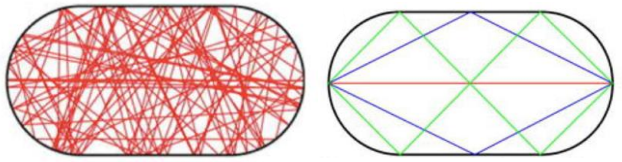




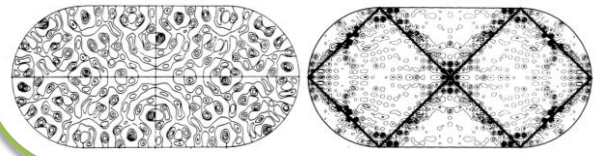
Explanation in terms of quantum many-body scars: states embedded throughout the thermalizing many-body spectrum, but exhibit robust dynamics [2]

Quantum scars: eigenstates resembling classical periodic orbits in chaotic system

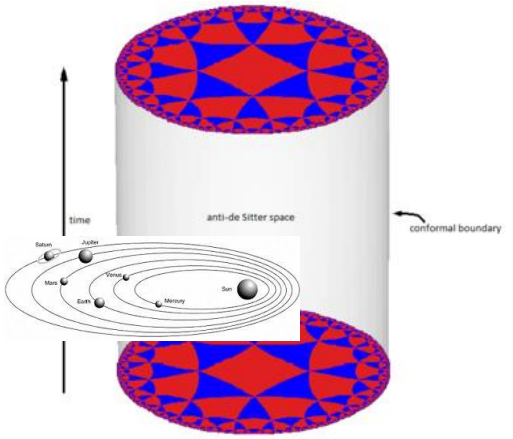
Classical trajectories in a stadium:



Quantum description: Heller, *PRL* 53, 1515 (1984)



Intriguing connection: Keppler orbits in dual dynamics/quantum gravity (Daniel Jafferis)



[1] Bernien et al., Nature (2017), [2] Turner et al, Nature Physics (2017), [3] Ho, et al, arXiv:1807.01815

Quantum Metrology Techniques for Axion Dark Matter Detection

Lead PI: Aaron Chou (Fermilab)

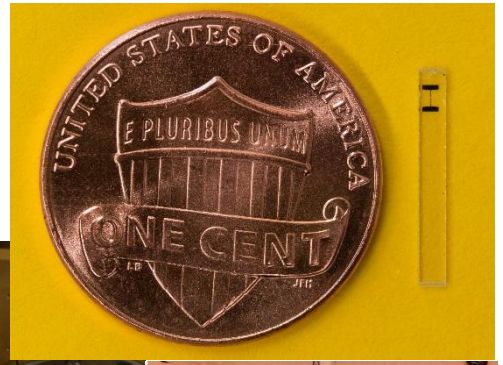
Co-PIs: Konrad Lehnert (Colorado/NIST), Reina Maruyama (Yale), David Schuster (U.Chicago)

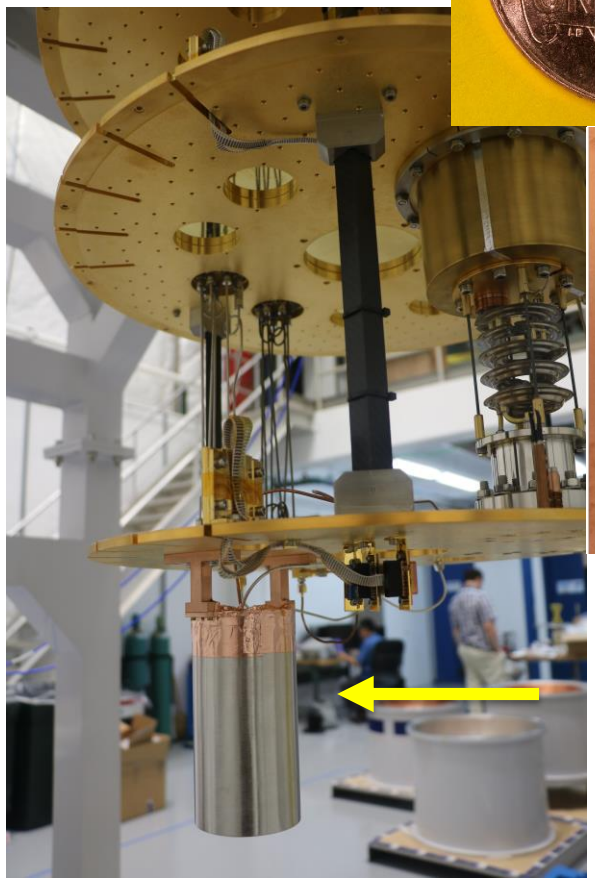
- **Goal: Implement QIS technologies to improve signal/noise ratio in future high mass axion searches**

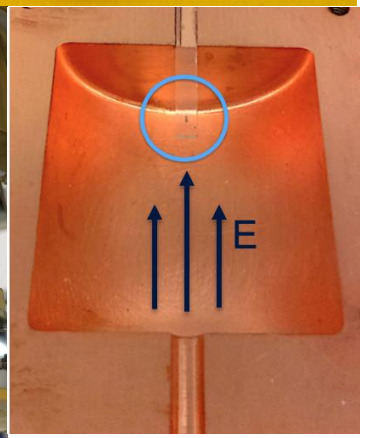
  → Enable next generation of axion DM experiments

- Recent progress:
  - Demonstrated repeated quantum non-demolition single microwave photon measurements with noise well below that of quantum-limited amplifiers used in current experiments
  - Designed single microwave photon extraction mechanism, tested with room temperature prototype at Colorado
  - Commissioned new dilution refrigerator test stands at Fermilab, Yale
  - Started construction of 2-D cooled Rydberg atom source at Yale

An “artificial atom” qubit with large antennae to sense cm-wave photons







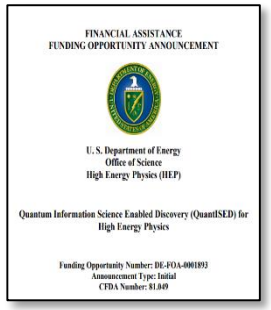
Qubit sensor + 10 GHz cavity mounted in new Fermilab mK test stand

Other Updates & Going Forward

Expect to see more success stories…

Quantum Information Science Enabled Discovery (QuantISED) for High Energy Physics – FOA & Lab Call Issued 2/11/2019

- **Closed April 16, 2019 -**
- **Awards will be announced by DOE Press Release**
- **HEP received an even more enthusiastic response**
- **Objective:** Forge new routes to scientific discovery along HEP mission and P5 science drivers, invoking interdisciplinary advances in the convergent field of QIS, and its intersection with expertise, techniques, technology developed in HEP community on topics:
  - **A:** Cosmos and Qubits
  - **B:** Foundational QIS-HEP Theory and Simulation
  - **C:** Quantum Computing for HEP
  - **D:** QIS-based Quantum Sensors
  - **E:** Research Technology for QIST
  - **F: Innovative HEP-QIS Small Experiments** exploring P5 science drivers using QIS based tools and techniques that satisfy all the criteria in the call


FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U. S. Department of Energy
Office of Science
High Energy Physics (HEP)

Quantum Information Science Enabled Discovery (QuantISED) for High Energy Physics

Funding Opportunity Number: DE-FOA-0001893
Announcement Type: Initial
CFDA Number: 81.049

DOE/SC QIS PI Meeting
Held - January 31 to February 1, 2019

Attendees: 267 with PIs, observers from all SC programs, and observers from other Federal Agencies

- **Plenary speakers included:**
  - Jake Taylor, OSTP; John Preskill, Caltech; Irfan Siddiqi, LBNL; and David Awschalom, ANL/U Chicago
- **Topical Breakout Discussion Sessions:**
  - Quantum computing for application-specific research: machine learning, data analysis, and related topics
  - Foundational quantum physics and information theory
  - Quantum qubits and computing platforms
  - Advanced synthesis and characterization tools (including validation)
  - Computer science and applied math challenges for quantum computing
  - Quantum sensors and detectors
  - Quantum computing for application-specific research: chemistry, materials, variational techniques, field theories
  - Analog simulations and quantum simulation experiments
- **SC Program Office Breakout Discussions**
- **Lightning round of Quantum Center Pitches**

Future Opportunities – Stay Tuned

- **HEP –QIS strategy aligned to SC QIS Strategy & National Initiative – with 'Science First' focus**
- **HEP-QIS is competed separately from the traditional HEP sub programs**
- **Requires interdisciplinary partnerships**
- **Awaiting updates on FY20 Appropriations**
- **DOE RFI for Centers has closed**
- **Future opportunities for 2020 will be determined after appropriations…**

QIS for HEP & HEP for QIS

HEP-QIS Entanglement Continues

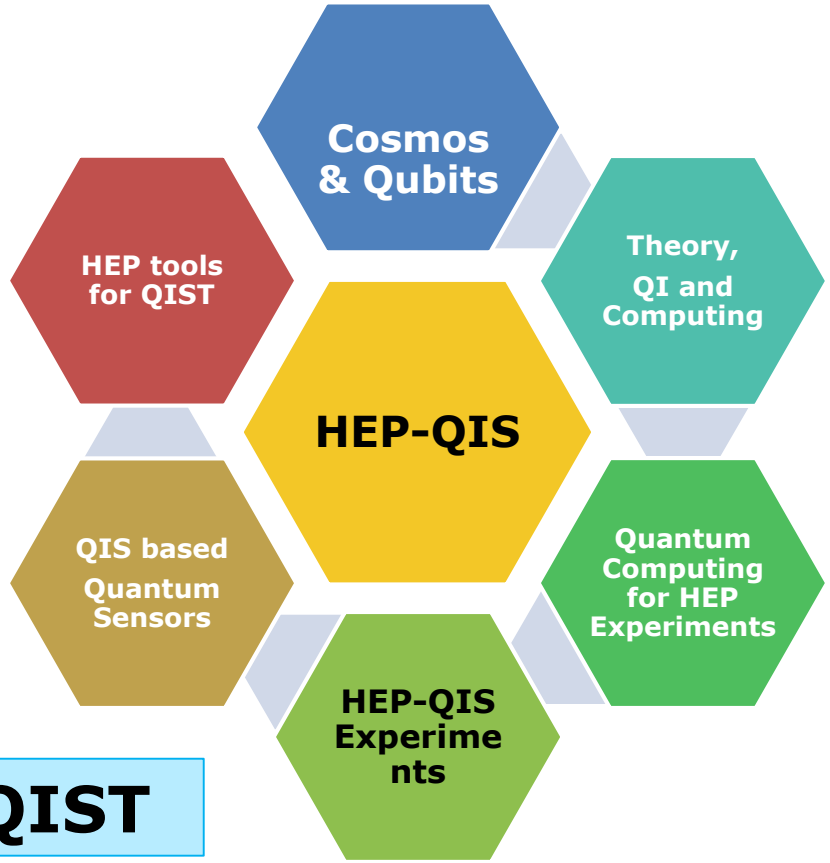
Simulating Physics with Computers by Richard P. Feynman
International Journal of Theoretical Physics, VoL 21, Nos. 6/7, 1982

Some of the questions Feynman asked starting in the seventies:

Can a classical, universal computer simulate any physical system?

And in particular, what about quantum systems?

While we still don't know the answers – we have a lot of qubit systems to try working with!



HEP Mission -P5 Science Drivers - QIST