DOE National Quantum Information Science (QIS) Research Centers and HEP Science Impacts

High Energy Physics Advisory Panel (HEPAP)

December 4, 2020

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DOE HEP / Office of Science

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QIS Spans the Technical Breadth of DOE SC

ASCR
Algorithms; Computer Science; Networking; Testbeds

NP
Many Body Systems; QIS Ready Workforce

BES
Quantum Systems and Computing: Model, Make, and Measure

HEP
Field Theory; Dark Matter; Gravity; Event Tracking; Fundamentals

FES
Qubit Synthesis; Ion Traps; Fusion Plasma Modeling

BER
Bioimaging Applications, Sensing and Measurement Capabilities

Fundamental Science

Quantum Computing

Quantum Communication

Quantum Sensing

Intellectual Capital Based on 100+ Years

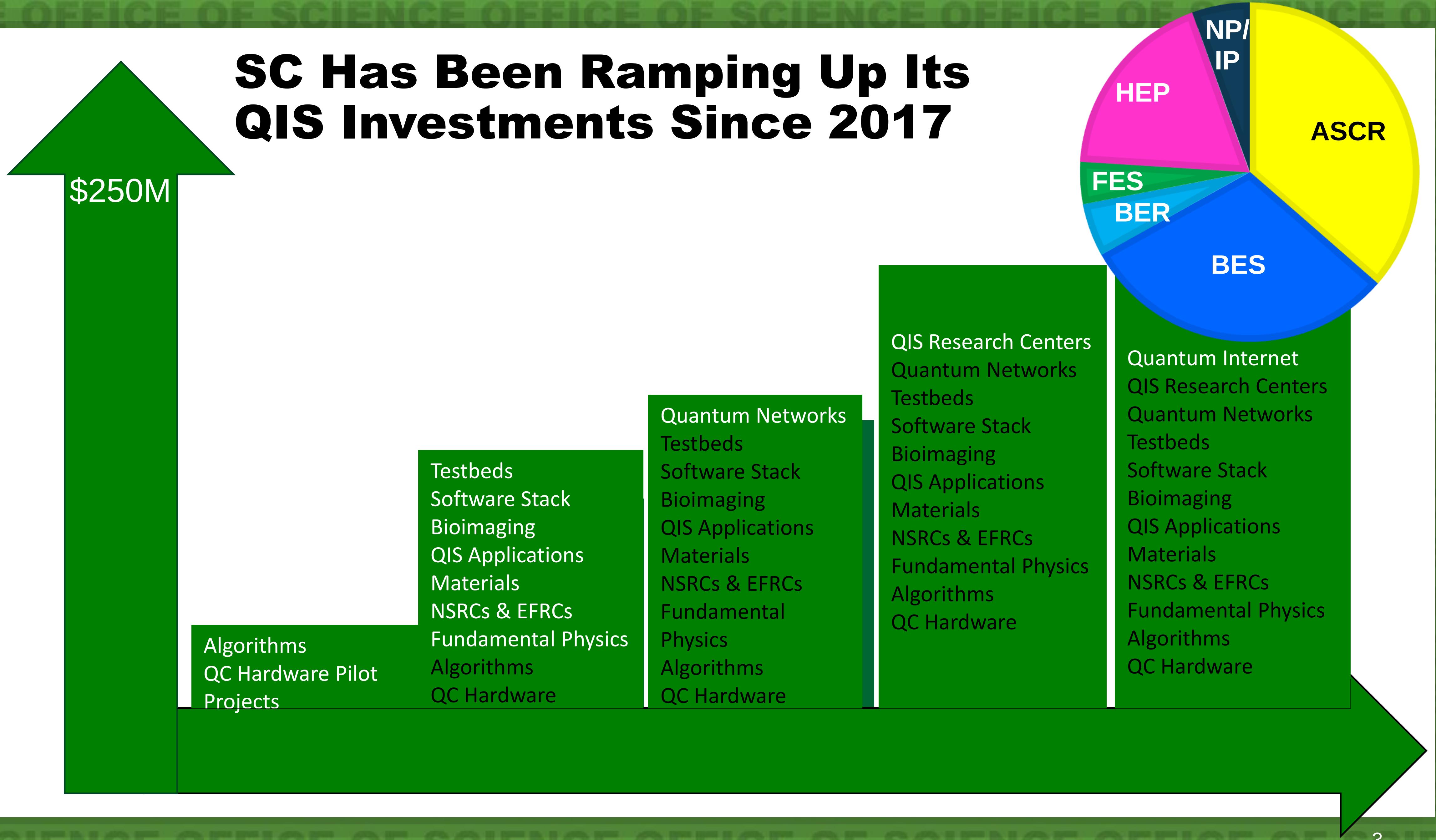
Large-Scale & Long-Term Investments for Interdisciplinary Teams with Specific Focus

Key Supporting Technologies (e.g. Isotope research, production & enrichment by IP)

Leadership in Launching Internationally-Recognized Collaborative Programs

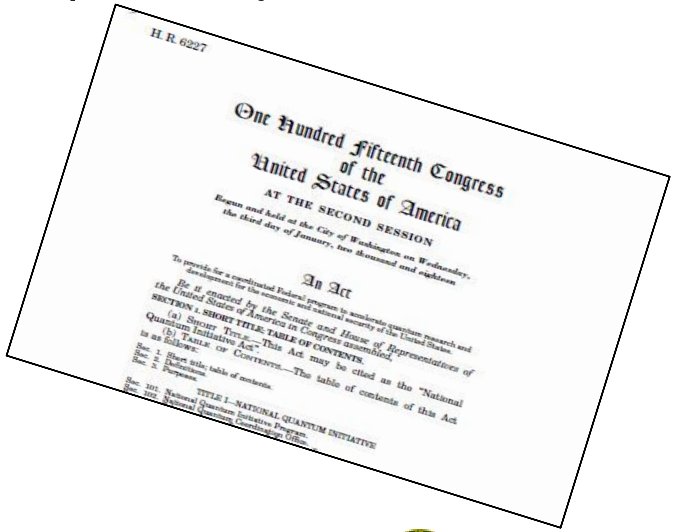
SC Unique Strengths to Advance Basic Science and Quantum Based Technology

SC Has Been Ramping Up Its QIS Investments Since 2017



National QIS Research Centers

- First large-scale QIS effort that crosses the technical breadth of SC
- Scope built on extensive community-wide RFI inputs– from technical scope to partnership model to management construct
- Seamlessly integrates the S&T innovation chain to accelerate progress in QIS R&D
- Maximizes teaming flexibility and options (TIAs, cooperative agreements, field work authorizations, interagency agreements) to foster direct participation by academics, national/federal labs, and for-profits
- Leverages other federal agency investments such as NSF’s Quantum Leap Challenge Institutes and the NIST Quantum Economic Development Consortium (QED-C)
- Authorized by and consistent with the National Quantum Initiative Act, signed into law in December 2018



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National QIS Research Centers: Essential Components

S&T Innovation Chain with Targets

Applications
Computing, communications and sensing for science and industry

Prototypes
Computing, sensing, network testbeds

Systems
SRF cavities, QPUs, detectors

Devices
Superconducting, ion trap, neutral atom, topological qubits, national quantum devices database, sensors, repeaters

Fundamental Science
Materials, theory, foundries, algorithms, software

Complementary Technical Areas of Interest

- Quantum Communication
- Quantum Computing and Emulation
- Quantum Devices and Sensors
- Materials and Chemistry for QIS Systems and Applications
- Quantum Foundries

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National QIS Research Centers: Essential Components

Management Structures

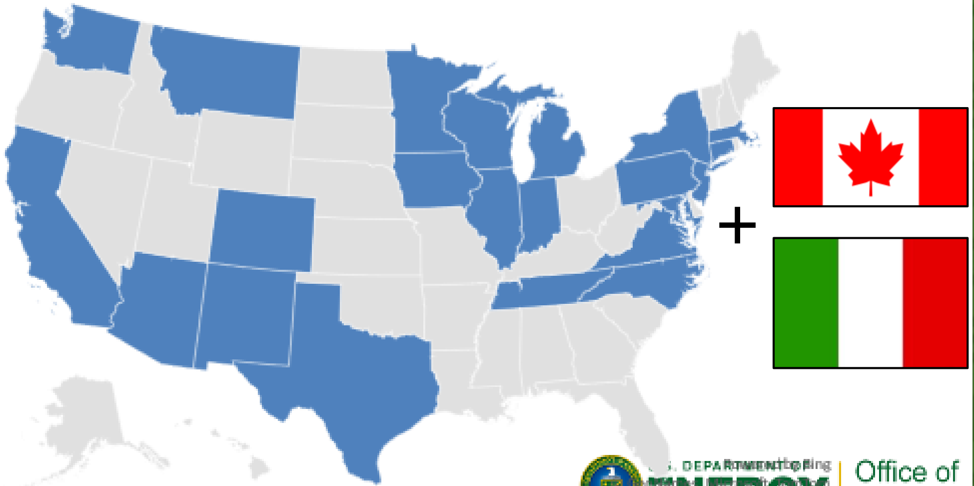
- Diverse personnel and approaches
- Recognition of a range of management good practices: ECP-like (ORNL) to Lean (FNAL)
- Extensive communication and coordination processes to promote integrated, synergistic collaboration
- BEST experts in the world, clear commitment to significant national impact

Instrumentation & Facilities

- Full leverage of DOE facilities across the lab complex
- Building new capabilities: e. g. ANL and SLAC quantum foundries
- Incorporating industry: e. g. ANL (Intel testbed)
- Using international facilities: e.g. FNAL (Gran Sasso, largest underground laboratory in the world)

QIS Ecosystem Stewardship

- 39 Academic institutions + 11 DOE Labs + 14 Companies + 3 Other agency entities + 2 Foreign institutions =
  - **69 Institutions from 22 states + DC + Canada + Italy**
- Members of QED-C, connections to NSF Quantum Leap Challenge Institutes (e.g. Jun Ye in LBNL-led Center)
- Unique approaches for workforce development and industry outreach (e.g. Simons Institute, pilot programs)
- Leveraging other DOE investments (e.g. Testbeds, JCESR)



Five National QIS Research Centers

Q-NEXT • Next Generation Quantum Science and Engineering
(David Awschalom, ANL)

Q-NEXT
NEXT GENERATION QUANTUM SCIENCE AND ENGINEERING

C²QA • Co-design Center for Quantum Advantage
(Steve Girvin, BNL)

C²QA
Co-design Center for Quantum Advantage

SQMS • Superconducting Quantum Materials and Systems Center
(Anna Grassellino, FNAL)

SQMS

- ✓ Significant National Impact
- ✓ Major Cross-Cutting Challenge
- ✓ Science and Technology Innovation Chain
- ✓ QIS Ecosystem Stewardship
- ✓ Multi-Disciplinary Leadership
- ✓ Collaborative Management Structure
- ✓ Well-Structured Plan and Metrics

QSA • Quantum System Accelerator
(Irfan Siddiqi, LBNL)

QUANTUM SCIENCE CENTER

QSC • The Quantum Science Center
(David Dean, ORNL)

https://science.osti.gov/Initiatives/QIS

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Q-NEXT
Next Generation Quantum Science and Engineering

Lead Institution

Argonne National Laboratory

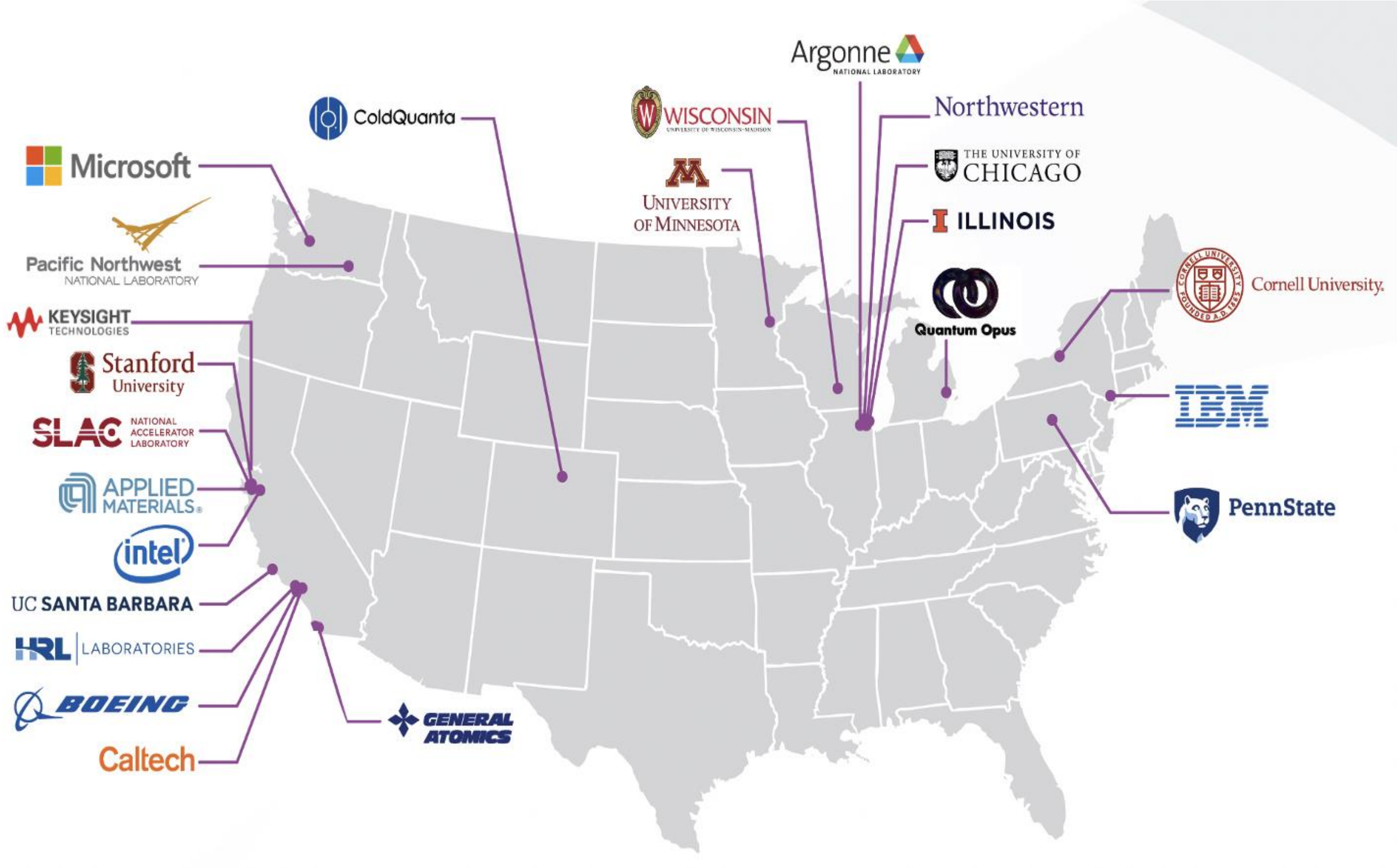
Director

David Awschalom

Scope

A focused, connected ecosystem to deliver quantum interconnects, to establish national foundries, and to demonstrate communication links, networks of sensors, and simulation testbeds.

Participating Institutions



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Q-NEXT innovations create a technology and training pipeline

https://www.q-next.org/

Promoting U.S. competitiveness with impactful science

5-year goals include repeater-enabled quantum interconnects, networked ultra-precise sensors, and a national resource for quantum materials.

Creating industrial engagement at all levels

10 U.S. member companies, leaders in their respective fields, provide pathways to the practical commercialization of quantum technology. *Q-NEXT will host the Intel Solid State Quantum Test Bed at Argonne*.

Training a quantum smart workforce

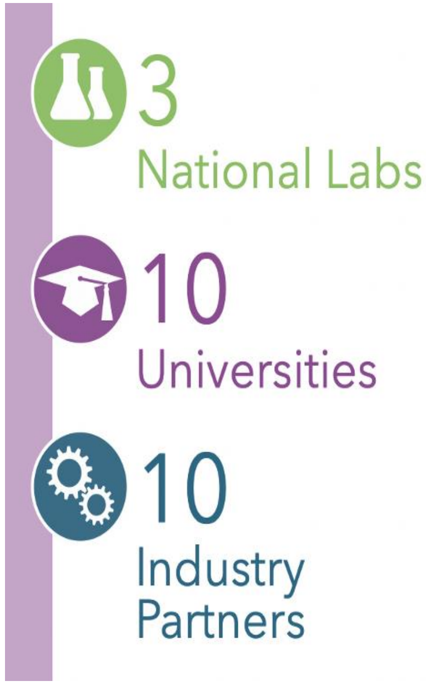
The Q-NEXT NEXT-GEN program builds on the successful NSF QISE-NET program to pair students with co-advisors at industry and National Laboratories. Q-NEXT will broaden access to quantum academic degrees and certifications.

Developing quantum standards

Incorporating processes, metrology, and tests into a National Quantum Devices Database.

Forging connectivity across the quantum ecosystem

Creating new synergies between investments in quantum research centers and leveraging world-class facilities including 3 light sources at ANL and SLAC, Argonne's leadership computing facility, and its nanoscience center. *Quantum foundries at ANL and SLAC.*



Q-NEXT investments will expand HEP science

Two Quantum Foundries will take fabrication of quantum devices for HEP science to a new level of process control and performance

- SLAC superconducting quantum devices foundry
  - Vertically integrated superconducting quantum sensors and devices
  - Hybrid devices
  - Fabrication of superconducting qubits and sensors with a new level of process control, uniformity, reproducibility
  - Qubits, photon counters, quantum upconverters
  - *Superconducting quantum sensors for HEP applications, including dark matter, new forces / fields, physics beyond the standard model*

SLAC NATIONAL ACCELERATOR LABORATORY

- Argonne semiconductor material / device foundry
  - Vertically integrated synthesis of spin qubits with atom-scale placement
  - On-chip integrated photonics and quantum emitters
  - Deterministic placement and optimal coherence
  - *Possible future application to QIS for HEP*

Argonne NATIONAL LABORATORY

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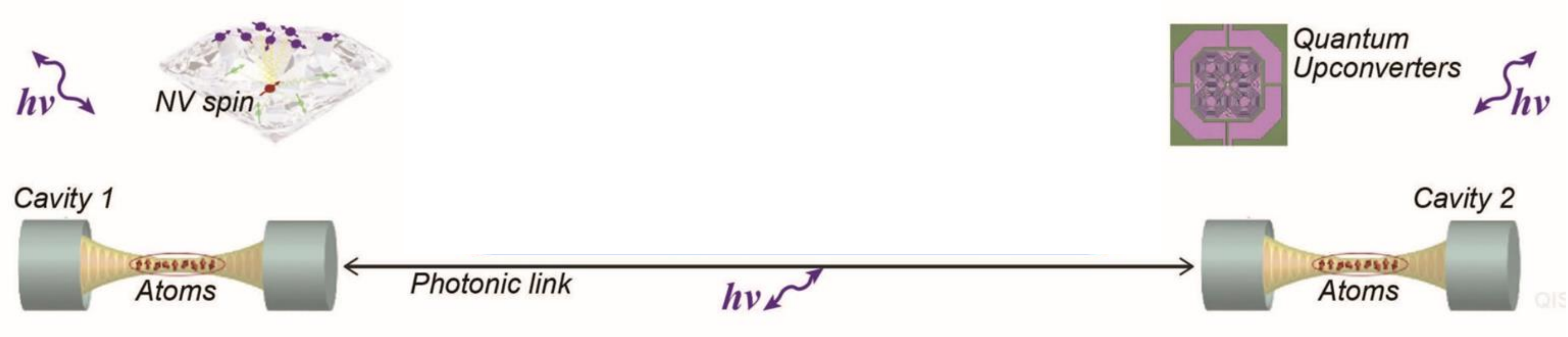
Q-NEXT: networking quantum sensors

Q-NEXT will enhance HEP science by integrating quantum sensors (including those developed under QuantISED) into entangled networks. Network-enhanced sensors will take advantage of quantum correlations to improve sensitivity and enable imaging and interferometry (e.g. of dark-matter wave signals).

Atomic sensors (e.g. MAGIS), spin-based sensors (e.g. CASPEr), superconducting sensors (e.g. ADMX, DM Radio) play important roles in HEP science



Q-NEXT photonic links (center) will be used to entangle atomic, spin-based, and superconducting sensors (e.g. quantum upconverters and photon detectors).

C²QA
Co-design Center for Quantum Advantage

Lead Institution

Brookhaven National Laboratory

Director

Steve Girvin

Scope

Beyond NISQ - quantum advantage for computations in high-energy, nuclear, chemical and condensed matter physics. 5-year goal - 10x improvement in software optimization, underlying materials and device properties, quantum error correction; combined 1,000x improvement in appropriate computation metrics

Participating Institutions

Brookhaven National Laboratory
IBM
Massachusetts Institute of Technology
Pacific Northwest National Laboratory
Princeton University
Yale
Stony Brook University

- Ames Laboratory
- Caltech
- City College of New York
- Columbia University
- Harvard University
- Howard University
- Jefferson Laboratory
- Johns Hopkins University
- Montana State University
- NASA Ames Research Center
- Northwestern University
- SUNY Polytechnic Institute
- University of California-Santa Barbara
- University of Massachusetts-Amherst
- University of Pittsburgh
- University of Washington
- Virginia Tech

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bnl.gov/quantumcenter/

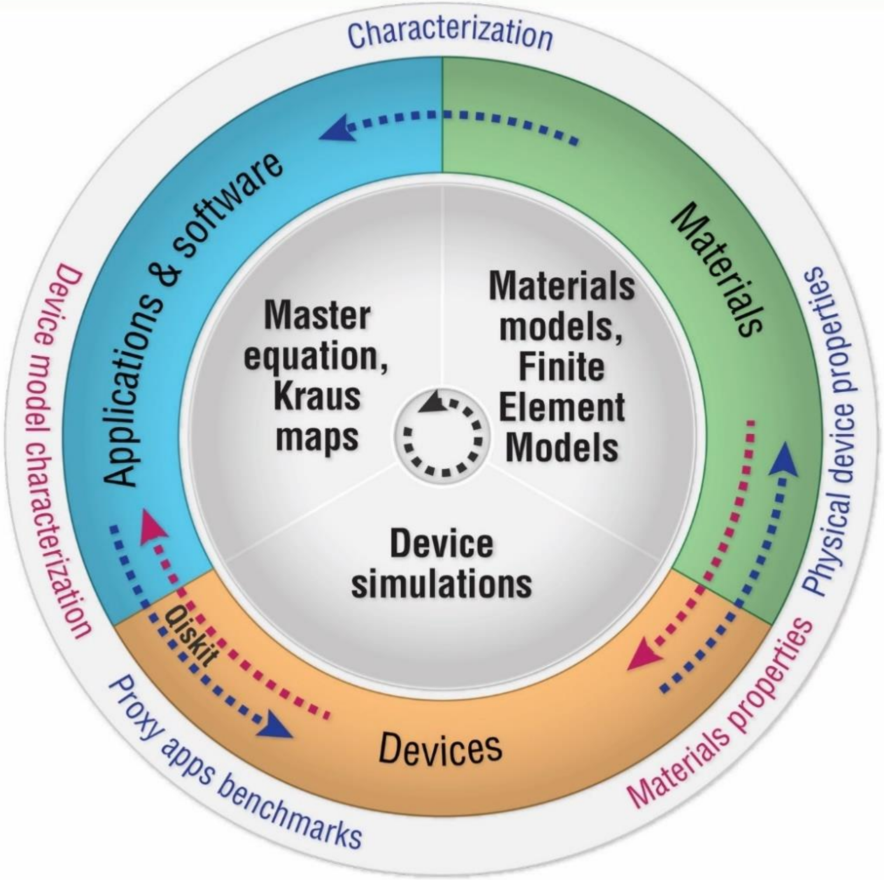
C²QA: Co-design Center for Quantum Advantage

THE PROBLEM

Quantum computers have the potential to solve scientific and other kinds of problems that would be practically impossible for traditional supercomputers. Current Noisy Intermediate-scale quantum computers suffer from a high error rate due to noise, faults and loss of quantum coherence.

WHAT IS CO-DESIGN

Traditional co-design is the joint design of hardware and software. We will develop and apply quantum co-design principles to target three research thrusts: Algorithms and Software, Devices and Materials.



OUR GOAL

Through materials, devices, and software co-design efforts, our team will understand and control material properties to extend coherence time, design devices to generate more robust qubits, optimize algorithms to target specific scientific applications, and develop error-correction solutions.

OUR APPROACH

Our interdisciplinary team of world-leading scientists will integrate expertise across the Center's 24 partner institutions to develop co-design tools and benchmarks, develop and discover new materials and qubit devices and architectures.

BUILDING THE U.S. WORK FORCE OF THE FUTURE

Enhancing the quantum educational programs already underway at our team institutions, we will expand upon the quantum processing, quantum mechanics and quantum computing knowledge to develop programs for the general public, K-12 students, internships and training, career events, and online resources and videos.

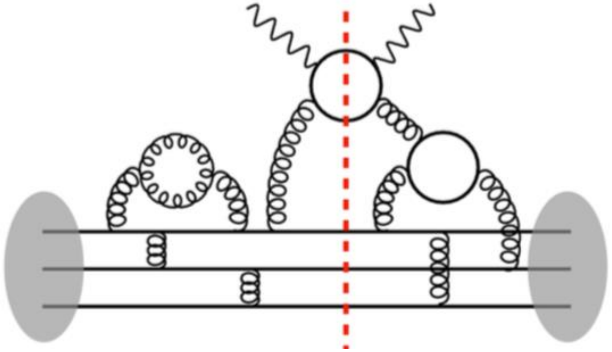
MORE INFO

For more information:
www.bnl.gov/quantumcenter

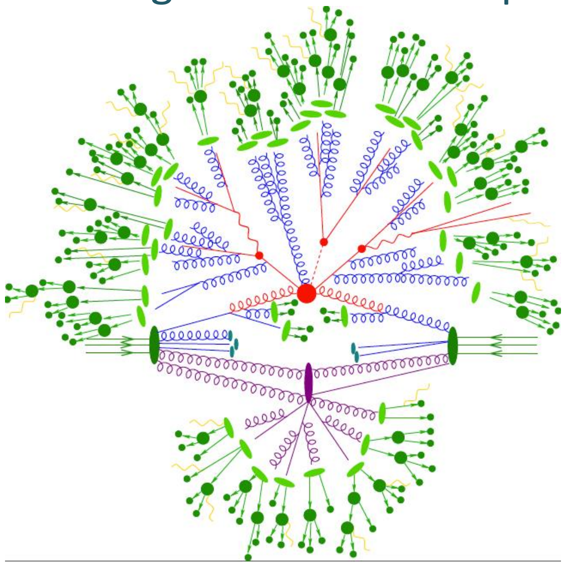
C^{2}QA & HEP

C^{2}QA will address outstanding problems in High Energy Physics:

- First-principles field theory simulations of high-energy scattering
- Computation of real-time correlations corresponding to jet fragmentation functions and parton distribution functions
- Phase diagrams of strongly interacting matter that suffers from the sign problem at finite chemical potential
- Quantum simulations of gauge theories
- Multipartite entanglement



Pdfs as spacelike real-time correlators of electromagnetic currents in proton



Jet fragmentation functions – time-like real-time energy-energy correlators

C^{2}QA: On-going work towards these goals in the NISQ era includes:

Digital simulation of the massive Schwinger model

- quantum simulation of topological transitions in the vicinity of a critical point.
- exploring how entanglement mimics thermalization in this model

Single-particle digital simulation of high-energy cross-sections for a φ^4 field theory, including quantum circuits for state preparation, time evolution and measurement

QFT world-line inspired techniques to model quantum-classical hybrid computations of jet fragmentation functions and parton distribution functions

Exploration of the phase diagram of a Z(3) model with quarks in 1+1 dimensions, simplest model with a sign problem

Theoretical work on digital real-time simulation of gauge theories vis-à-vis tensor network and hybrid digital/analog quantum simulation methods

C2QA Journal Club: Mondays @ 2pm, https://indico.bnl.gov/category/325/

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SQMS
Superconducting Quantum Materials and Systems Center

Lead Institution

Fermi National Accelerator Laboratory

Director

Anna Grassellino

Scope

Transformational advances in understanding and eliminating decoherence mechanisms in superconducting 2D and 3D devices, to enable construction and deployment of superior quantum systems for computing and sensing; foundry capabilities and quantum testbeds for materials, physics, algorithms, and simulations

Participating Institutions

Fermilab

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Northwestern University
NASA Ames Research Center
Ames Laboratory
University of Colorado Boulder
University of Illinois Urbana-Champaign
Stanford University
Colorado School of Mines
Johns Hopkins University
Temple University
The University of Arizona
Illinois Institute of Technology
Università degli Studi di Padova
NIST National Institute of Standards and Technology U.S. Department of Commerce
INFN Istituto Nazionale di Fisica Nucleare
Goldman Sachs
Janis
Lockheed Martin
Unitary Fund

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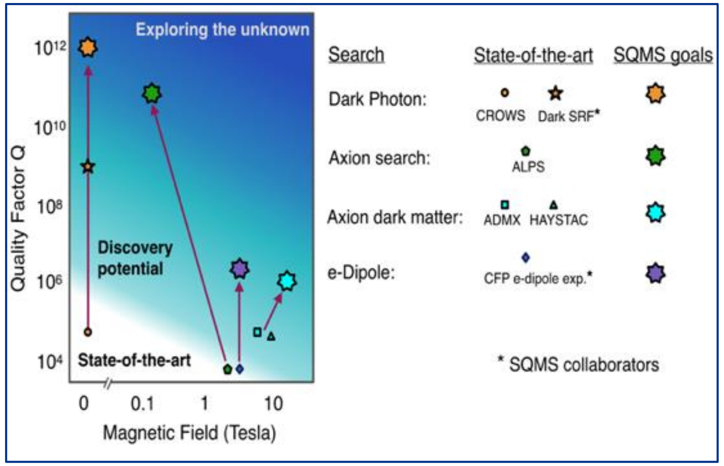
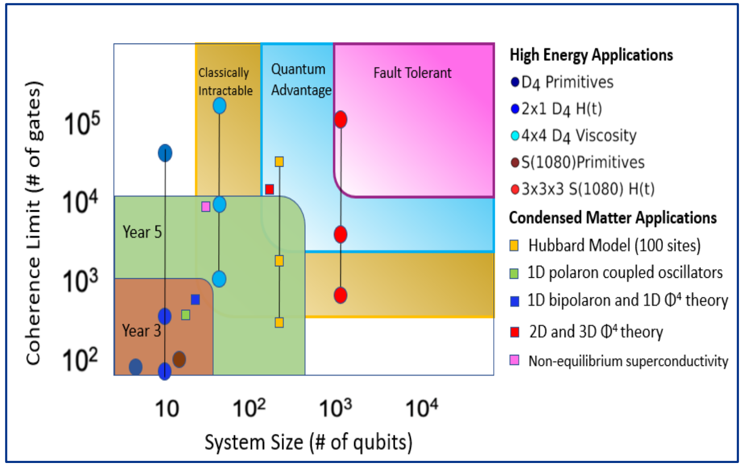
HEP as a driver and a beneficiary of SQMS

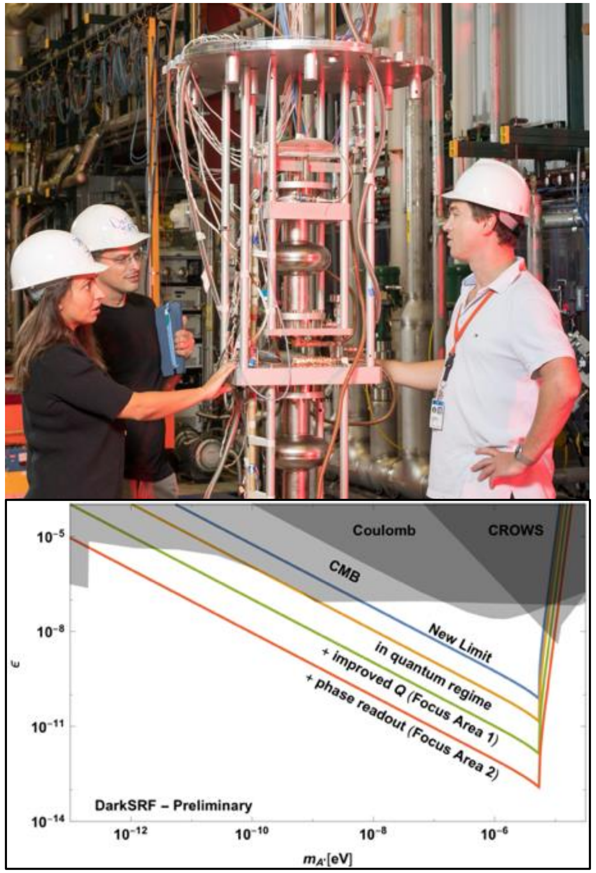
- Center uniqueness: it encompasses from the HEP and QIS technology experts to the science end users, working in ‘co-design’
- HEP science drivers provide unique motivation and push for advancement of quantum technologies
- And SQMS technological advancements will open new opportunities for physics discovery
- As some examples, HEP theorists and QIS technology experts will work together towards the development and deployment of: new quantum sensing schemes for dark sector particle searches, new quantum computing prototypes for simulations of quantum field theories



SQMS quantum sensing goals



SQMS Quantum computing roadmap



Dark SRF experiment at FNAL

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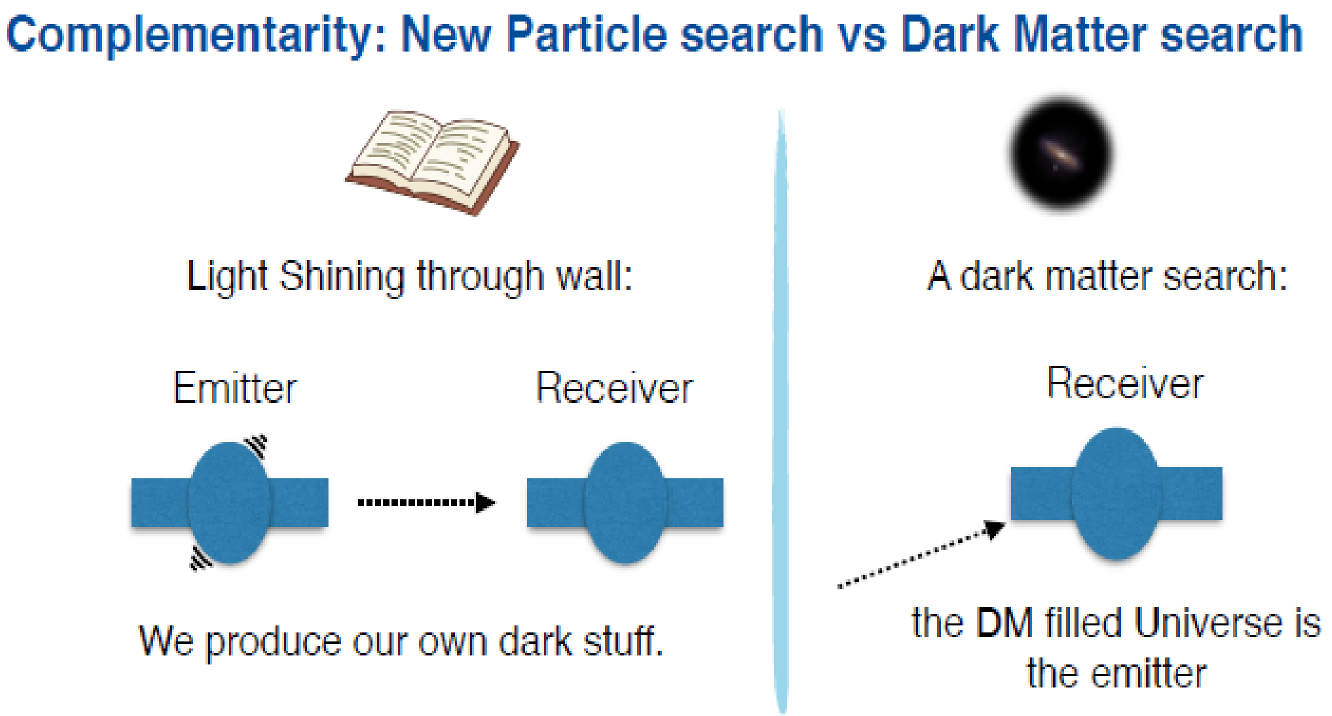
SQMS: Quantum Sensing for Dark Matter



- Dark Matter searches are contending with the limits imposed by standard measurement techniques. The so-called "standard quantum limit".
- New quantum sensing techniques are needed to make progress in the axion DM parameter space.
- Coherence time will play an important role - SQMS systems can have an impact!
  We will explore a range of possibilities.

QSA
Quantum Systems Accelerator

Lead Institution

Lawrence Berkeley National Laboratory

Director

Irfan Siddiqi

Scope

Co-design algorithms, devices, and engineering solutions for quantum advantage in scientific applications. Pair advanced quantum prototypes—neutral atoms, trapped ions, and superconducting circuits—with algorithms for imperfect hardware to demonstrate optimal applications in scientific computing, materials science, and fundamental physics. Deliver prototypes to broadly explore the quantum technology trade-space, laying basic science foundation to accelerate the maturation of commercial technologies.

Participating Institutions

Berkeley Lab
Sandia National Laboratories
University of Colorado Boulder
MIT Lincoln Laboratory
Caltech
Duke Pratt School of Engineering
USC
Texas — The University of Texas at Austin
Tufts University
Berkeley — University of California
MIT
Harvard University
University of Maryland
UNM
Université de Sherbrooke

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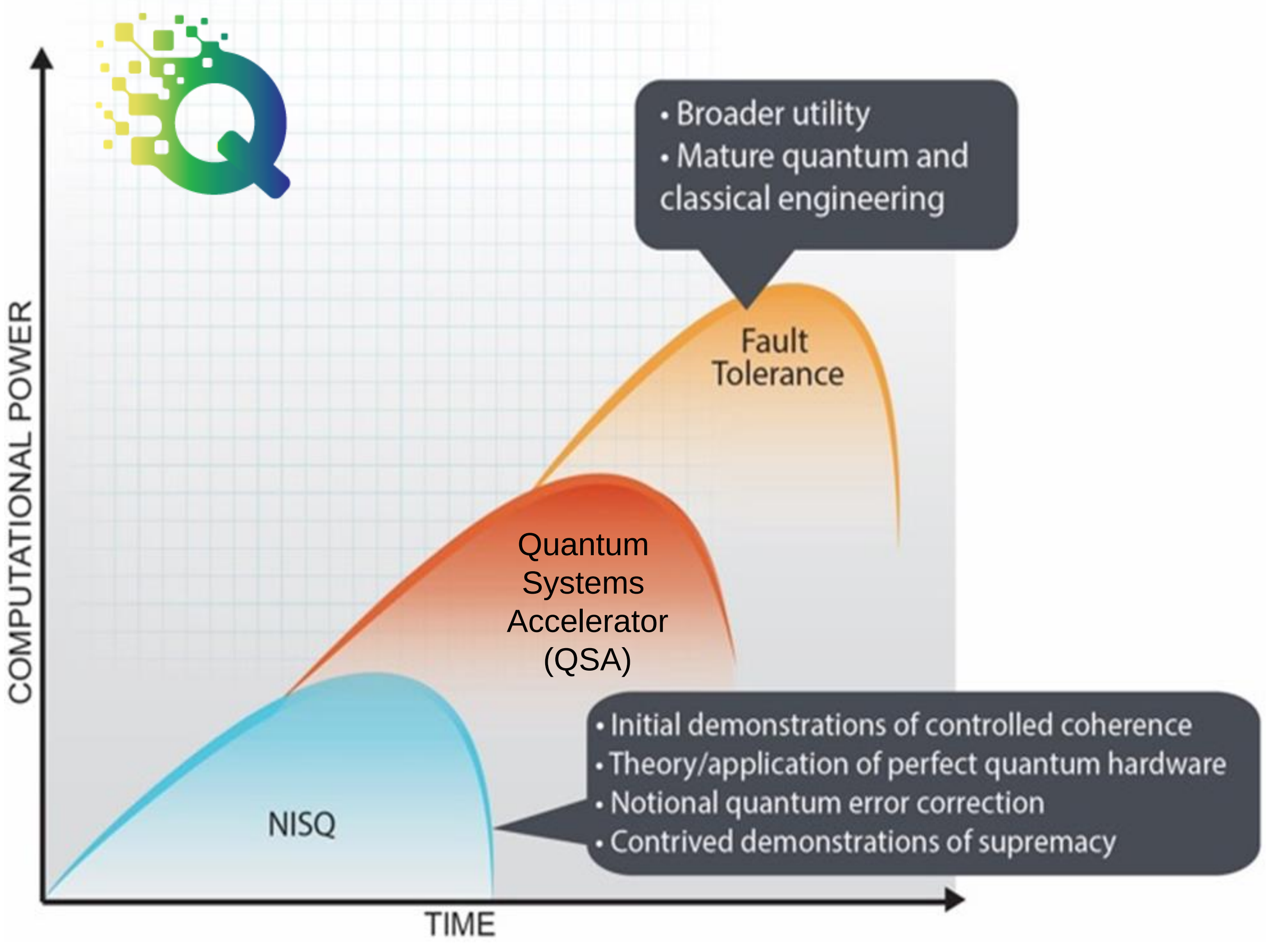
quantumsystemsaccelerator.org

Quantum Systems Accelerator: Innovation Roadmap



Harnessing Quantum

QSA will address how quantum complexity can be transformed into an engineering resource.

Programming Quantum

QSA will establish the precision tools to control naturally occurring atomic qubits and better engineered superconducting qubits for existing classical controls.

Engineering Quantum

QSA will establish metrics, benchmarks, and technology roadmaps to guide industry and bring quantum from the laboratory to the factory.

Engaging Quantum

QSA will establish a stable platform for cooperative research and a launchpad for young and mid-career scientists and engineers.

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Quantum Systems Accelerator: HEP Alignment

QUANTUM SYSTEMS ACCELERATOR

Catalyzing the Quantum Ecosystem

QSA Initial Research Areas Relevant to High Energy Physics

Quantum Simulations / Quantum Field Theories

- Conformal field theories and confined dynamics in lattice gauge theories with atom tweezers
- Magnetism under SU(N) on optical lattices
- Hardware tailoring of VQE approach to QFTs
- Comparison of algorithms for exactly solvable Hamiltonians

Early QSA research will enable expanded exploration of HEP science in future project phases. Proposed QSA applications for quantum simulation algorithms include:

- Probes of entanglement in HEP models
- Dynamics of quantum information scrambling near black holes
- Superconductivity of gluon color in neutron stars
- Relationship of AdS/CFT and error correction
- Quantum interference in simulation of events with high final state multiplicity

QSC
The Quantum Science Center

Lead Institution

Oak Ridge National Laboratory

Director

David Dean

Scope

Overcome key roadblocks in quantum state resilience, controllability, and scalability of quantum technologies, through integration of discovery, design, and demonstration of revolutionary topological quantum materials, algorithms, and sensors, catalyzing development of disruptive technologies.

Participating Institutions

Berkeley UNIVERSITY OF CALIFORNIA
Caltech
ColdQuanta The Quantum Atomics Company
Fermilab
HARVARD UNIVERSITY
IBM
Los Alamos NATIONAL LABORATORY EST. 1943
Microsoft
OAK RIDGE National Laboratory
Pacific Northwest NATIONAL LABORATORY
PRINCETON UNIVERSITY
PURDUE UNIVERSITY
UCSB UNIVERSITY OF CALIFORNIA SANTA BARBARA
UNIVERSITY OF MARYLAND
THE UNIVERSITY OF TENNESSEE KNOXVILLE
W UNIVERSITY of WASHINGTON

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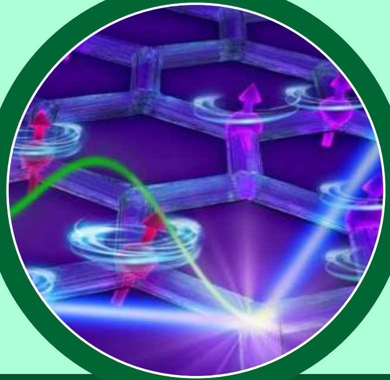
QUANTUM SCIENCE CENTER℠

Overcoming roadblocks in quantum state resilience and controllability to enable scalable quantum technologies

https://qscience.org/

Thrust 1

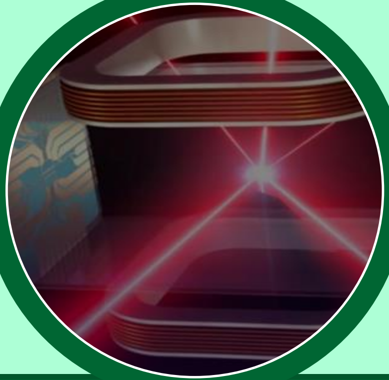
Address the fragility of quantum states through the **design of new topological materials** for QIS



Accelerated quantum information processing

Thrust 2

Develop **algorithms and software** for computation and sensing with current and future QIS hardware



Prediction of new physical and chemical behaviors

Thrust 3

Design new **quantum devices and sensors** to detect dark matter and topological quasiparticles

New quantum sensing capabilities to explore the previously unmeasurable

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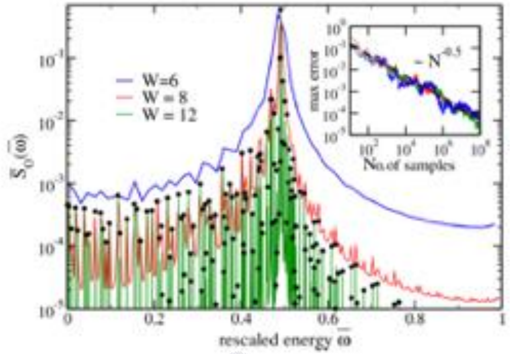
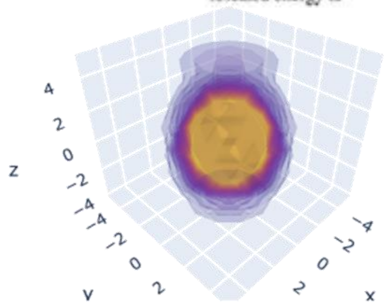
Quantum Science Center: Connections to HEP





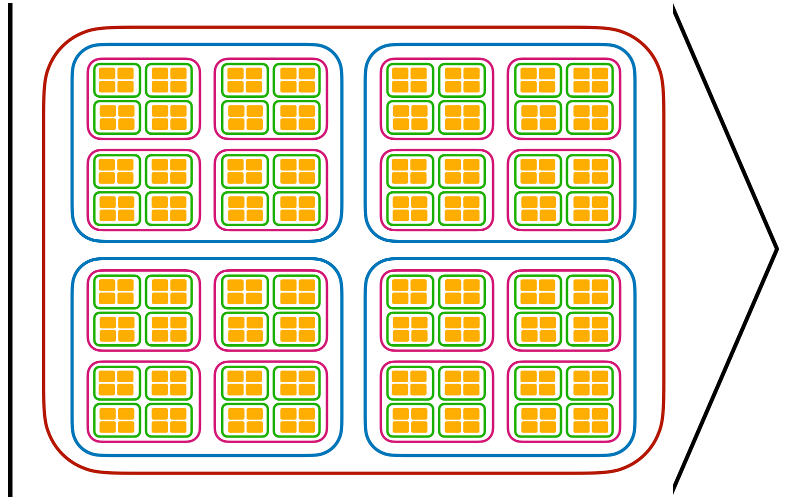
Nuclear Response

(Electron & Neutrino-Nuclear Dynamics)

Real Time Evolution,
Explicit Final States,
and Quantum-Classical Transition

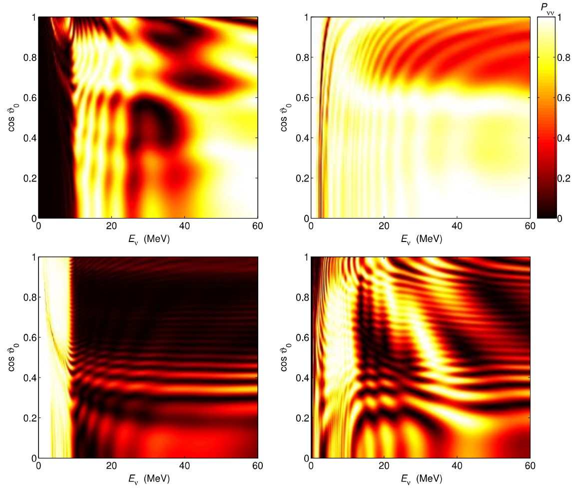
Renormalization group framework within QI theory

- efficient extraction of information while "coarse-graining away" irrelevant information.
- Needed to process high complexity output states of quantum simulations of physical systems of relevance to HEP.



Astrophysical Neutrinos

Flavor Evolution,
Full Quantum Evolution
vs Mean Field
Dynamics of Entanglement
~ Quantum Spin Model



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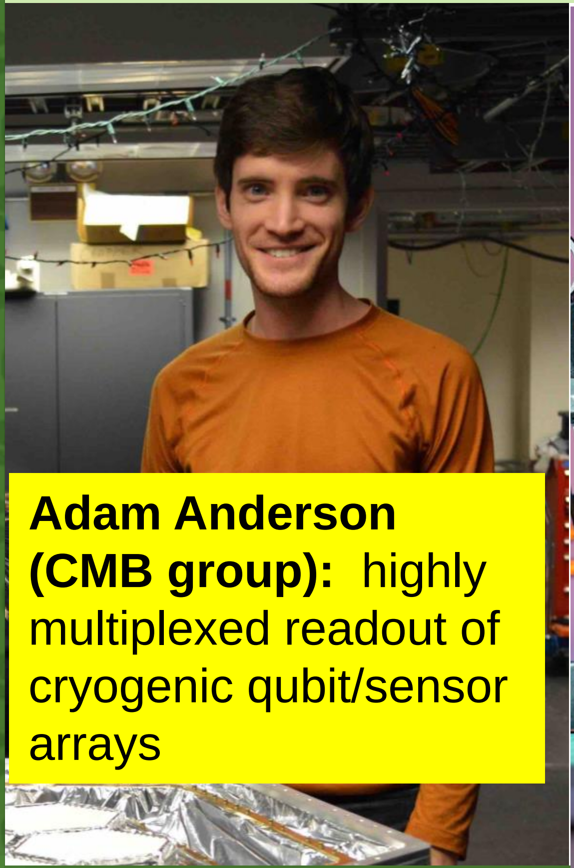
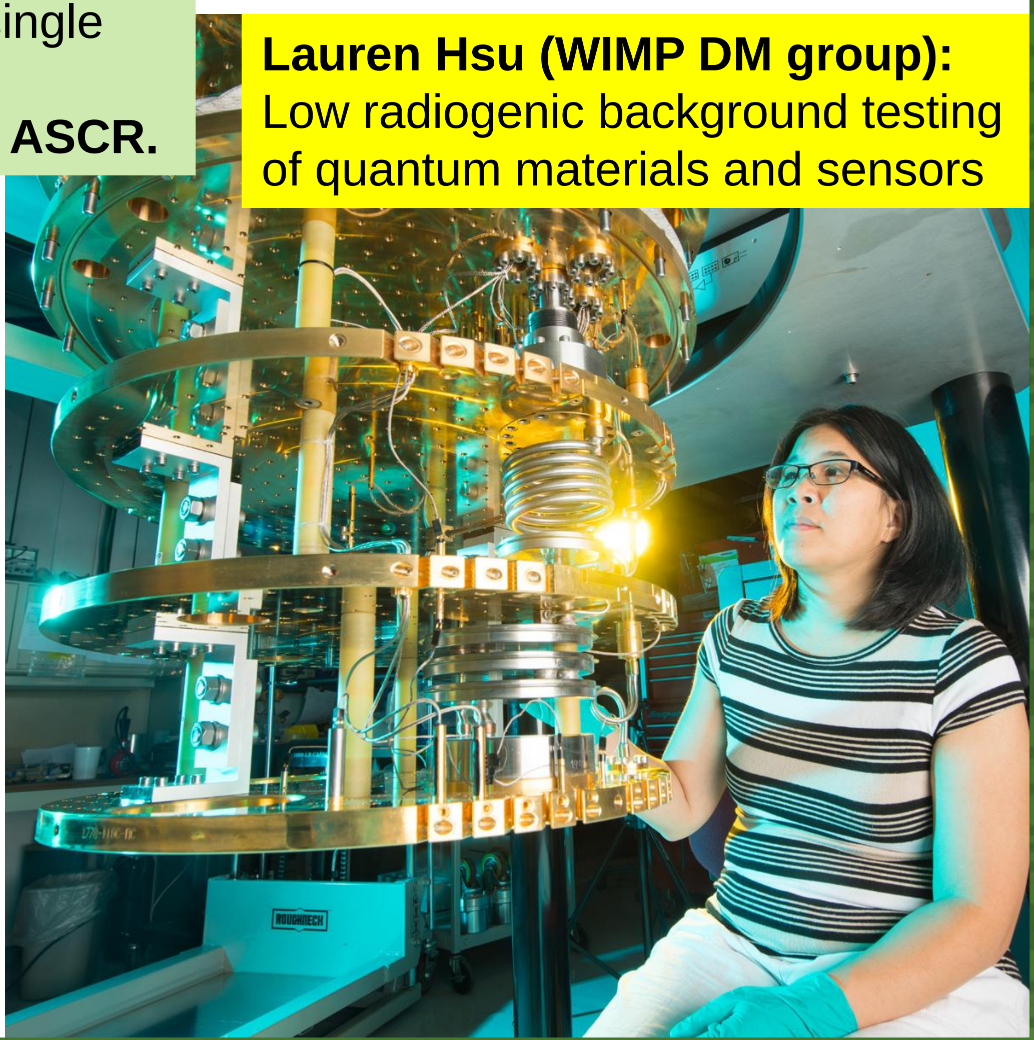
QSC: Fermilab/HEP's unique instrumentation expertise facilitates development of new quantum materials, devices, and sensors

Science targets: Topological quantum materials/computing, single photon detectors, microcalorimetry for dark matter searches.
Engages materials design/synthesis capabilities of BES, ASCR.



Adam Anderson (CMB group): highly multiplexed readout of cryogenic qubit/sensor arrays

Farah Fahim (ASICs group): Cryogenic qubit control systems



Lauren Hsu (WIMP DM group): Low radiogenic background testing of quantum materials and sensors

National QIS Research Centers are a critical part of our QIS Portfolio

<u>All of SC, All of QIS</u>

- DOE team approach in preparation of the solicitation (FOA)
- Cross-program coordination of QIS within SC
- SC-wide and QIS-wide scope, management, and expected impacts

<u>Community Engagement</u>

- Formal Request For Information as a prelude to the FOA
- New SC web-site: https://science.osti.gov/Initiatives/QIS
- Stewardship role

<u>Coordination & Partnerships</u>

- Facilitate participation by different types of institutions by flexible arrangements
- Focus on all levels of the S&T innovation chain

- QIS S&T Innovation Chain
- Technical Areas of Interest
- QIS Ecosystem Stewardship
- Management Structure
- Instrumentation and Facilities

QIS Center synopses and links at science.osti.gov/Initiatives/QIS