U.S. DEPARTMENT OF ENERGY | Office of Science

High Energy Physics and Quantum Information Science

Basic Energy Sciences Advisory Committee

March 2018

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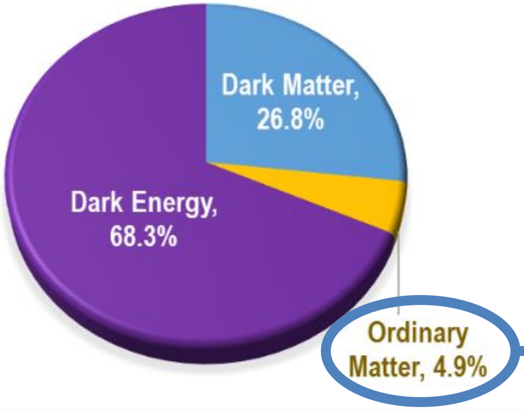
Office of Science
U.S. Department of Energy

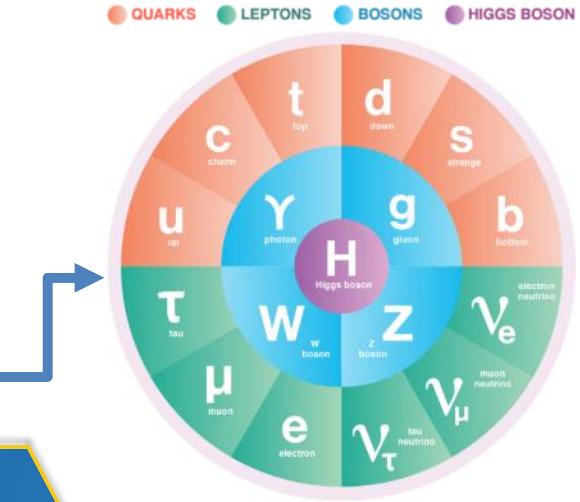
The High Energy Physics Program Mission

… is to understand how the universe works at its most fundamental level:

- Discover the elementary constituents of matter and energy
- Probe the interactions between them
- Explore the basic nature of space and time

- The DOE Office of High Energy Physics fulfills its mission by:
  - Building **projects** that enable discovery science
  - Operating **facilities** that provide the capability for discoveries
  - Supporting a **research** program that produces discovery science

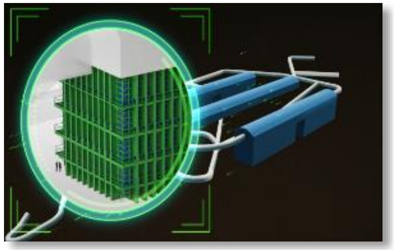




U.S. Long-Term Particle Physics Strategy

- The global vision presented in the 2014 Particle Physics Project Prioritization Panel (P5) report is the culmination of years of effort by the U.S. particle physics community
  - 2012 – 2013: Scientific community organized year-long planning exercise ("Snowmass")
  - 2013 – 2014: U.S. High Energy Physics Advisory Panel convened P5 to develop a plan to be executed over a ten-year timescale in the context of a 20-year global vision for the field

- P5 report enables discovery science with a balanced program that deeply intertwines U.S. efforts with international partners
  - **U.S. particle physics community** strongly supports strategy
  - **U.S. Administration** has supported implementing the P5 strategy through each President's Budget Request
  - **U.S. Congress** has supported implementing the P5 strategy through the language and funding levels in appropriations bills
  - **International community** recognizes strategy through global partnerships



The Science Drivers of Particle Physics

The U.S. long-term strategy report identified five **intertwined science drivers**, compelling lines of inquiry that show great promise for discovery:

- Use the **Higgs boson** as a new tool for discovery ***2013***
- Pursue the physics associated with **neutrino mass** ***2015***
- Identify the new physics of **dark matter**
- Understand **cosmic acceleration**: dark energy and inflation ***2011***
- **Explore the unknown**: new particles, interactions, and physical principles

**** Since 2011, three of the five science drivers have been lines of inquiry recognized with Nobel Prizes***

Enabling the Next Discovery

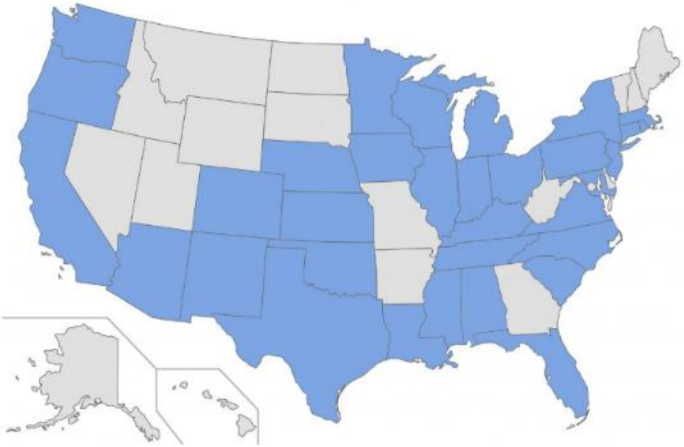
- P5 identified **5 Science Drivers** to address the scientific motivation in particle physics
- **Research Frontiers** are useful categorization of experimental techniques and serve as the basis of the budget process
- Research Frontiers are complementary
  - No one Frontier addresses all science drivers
  - Each Frontier provides a different approach to address science driver
  - Enables cross-checking scientific results

	Energy Frontier	Intensity Frontier	Cosmic Frontier
Higgs Boson	●		
Neutrino Mass		●	●
Dark Matter	●	●	●
Cosmic Acceleration			●
Explore the Unknown	●	●	●

Energy Frontier: LHC, ATLAS, and CMS

The Large Hadron Collider at CERN is the centerpiece of the U.S. Energy Frontier program

- U.S. ATLAS represents ~20% of the international ATLAS Collaboration
  - 41 universities, 4 national labs (Argonne, Brookhaven, Lawrence Berkeley, SLAC)
  - Brookhaven is host lab for U.S. ATLAS
- U.S. CMS represents ~27% of the international CMS Collaboration
  - 48 universities, 1 national lab
  - Fermilab is host lab for U.S. CMS

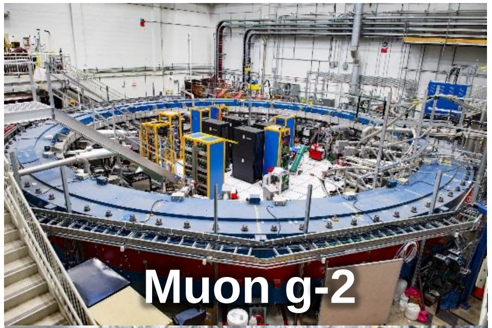


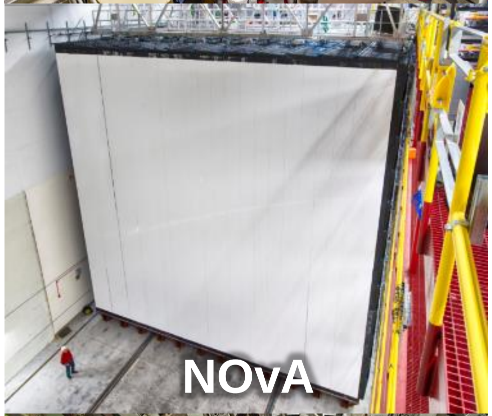
States hosting members of the U.S. LHC experimental program

Intensity Frontier Program

Intensity Frontier experiments address the P5 Science Drivers through intense beams and sensitive detectors

- Exploring the unknown through precision measurements:
  - Muon g-2, Muon-to-Electron Conversion Experiment (Mu2e), Belle II, K0TO
- Identify the new physics of dark matter:
  - Heavy Photon Search
- Pursuing the physics associated with neutrino mass:
  - NOvA, Daya Bay, MINERvA, Super-K, T2K ongoing
  - Ramping up Fermilab Short-Baseline Neutrino Program (MicroBooNE, SBND, ICARUS)
  - Preparing to host world-leading neutrino program with the Long-Baseline Neutrino Facility and Deep Underground Neutrino Experiment (LBNF/DUNE)

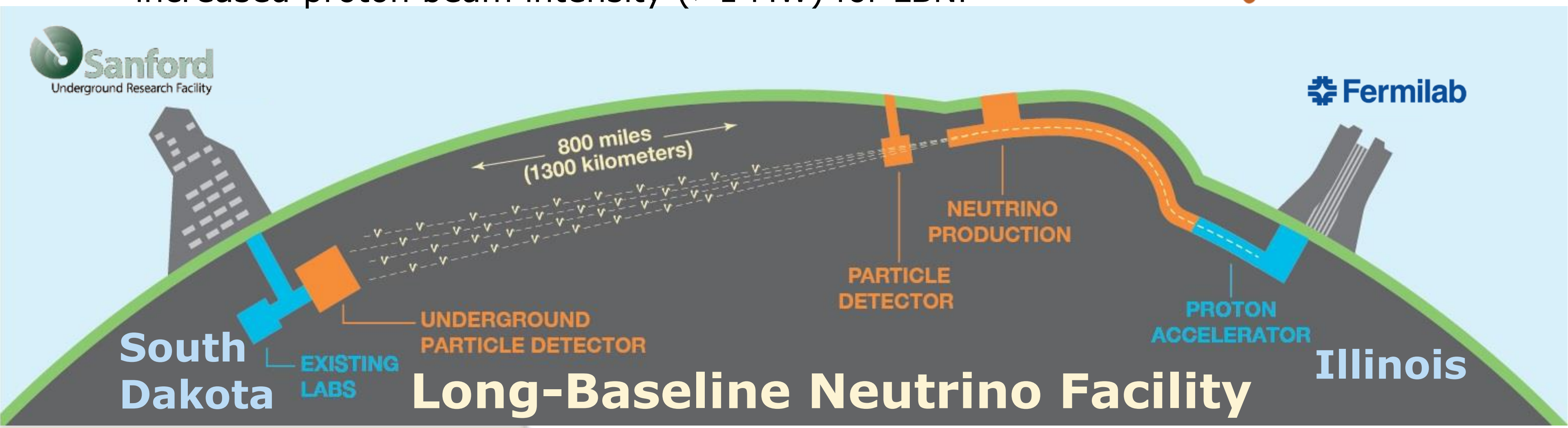




Long-Baseline Neutrino Facility and Deep Underground Neutrino Experiment

- P5 recommended Long-Baseline Neutrino Facility (LBNF) as the centerpiece of a U.S.-hosted world-leading neutrino program
  - LBNF will produce the world's most intense neutrino beam, send it 800 miles through the earth to DUNE
  - Strong support within the U.S. Government and many interested potential global partners
- International DUNE collaboration includes:
  - Over 1,100 collaborators from 176 institutions, 31 countries
- Proton Improvement Plan II (PIP-II) will provide increased proton beam intensity (>1 MW) for LBNF

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT



Cosmic Frontier Program

Dark energy program through suite of complementary surveys, in partnership with NSF

- Fast sky scanning surveys catch dynamic events, like supernovae: Dark Energy Survey (DES) operating, Large Synoptic Survey Telescope (LSST) camera in fabrication
- Deep, high accuracy surveys study dim, more distant objects: BOSS final results soon; eBOSS operating, Dark Energy Spectroscopic Instrument (DESI) in fabrication

Dark matter searches through direct detection experiments with multiple technologies, in partnership with NSF

- First-gen. experiments produced world’s most sensitive searches
- Progressing toward next generation experiments: ADMX-G2, LZ, SuperCDMS-SNOLAB

Study high-energy particles produced from cosmos, in partnership with NSF, NASA

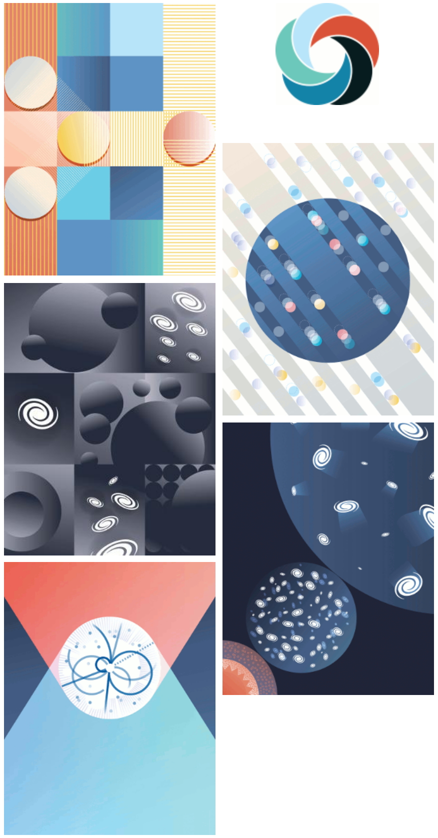
- Cosmic- and gamma-ray detectors on Earth and in space: Fermi/GLAST, AMS, and HAWC

Study cosmic acceleration imprint on cosmic microwave background (CMB), in partnership with NSF, NASA

- Currently observing with south pole telescopes: SPTpol, SPT-3G

Enabling Discovery

- **Advanced Technology R&D** supports and advances research at all three experimental Frontiers
  - Fosters cutting-edge research in the physics of particle beams, accelerator R&D, and particle detection
  - Three broad categories: **Near- to mid-term** directed R&D; **Mid-term** R&D to demonstrate feasibility; **Long-term** research to enable breakthroughs in technology
- **Theoretical and Computational HEP** provides the mathematical, phenomenological, and computational framework to understand and extend our knowledge of particles, forces, and the nature of space and time
  - **Theoretical research** essential for proper interpretation and understanding of the experimental research activities
  - **Advanced computing** tools necessary for designing, operating, and interpreting experiments and simulations

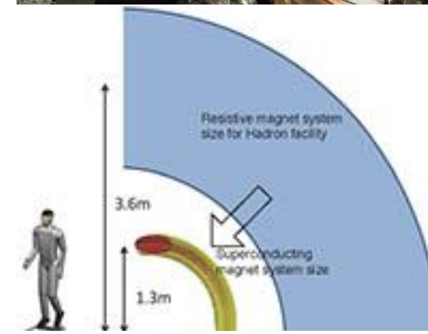


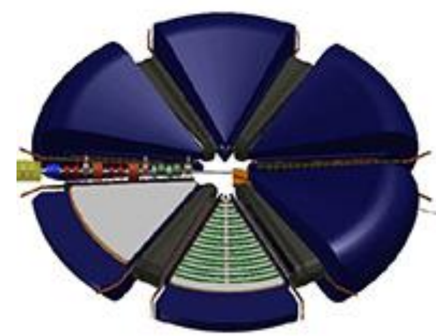
- Implementing the P5 strategy requires advancing computing infrastructure to handle the exponentially increasing needs
  - Partnerships with Advanced Scientific Computing Research (ASCR) are an important part of addressing HEP computing needs

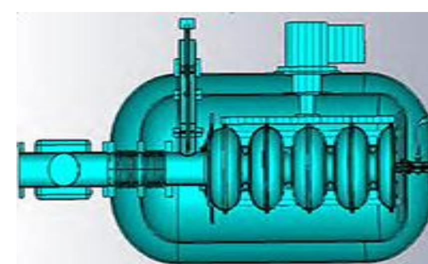
Accelerator Stewardship

Mission: Support fundamental accelerator science and technology development of relevance to many fields and to disseminate accelerator knowledge and training to the broad community of accelerator users and providers.

- Improve access to national lab accelerator facilities
  - Make resources and facilities, such as Brookhaven National Laboratory's Accelerator Test Facility II (ATF-II), available for industrial and for other U.S. government agency users and developers of accelerators and related technology
- Develop innovative solutions to critical problems outside of the DOE Office of Science
  - More performant, lower cost accelerators for medicine
  - 1000x speedup of laser-based science tools
  - Accelerator tech. for Energy & Environmental applications
- Broaden and strengthen the community
  - Bringing accelerator scientists, application scientists, and industrialists together to address high-impact challenges







Quantum Information Science in DOE-SC

ASCR	BES	HEP	NP
Quantum algorithms; uncertainty quantification and verification & validation methods; software stack; quantum networks	Synthesis, characterization, theory, modeling, and instrumentation to advance quantum materials & chemical phenomena	Black hole physics; quantum gravity and quantum error correction; fundamental aspects of entanglement	Isotopes and trapped ions for quantum devices; lattice quantum chromodynamics

Quantum Field Theory and Topology

Control of Quantum Phenomena

- SC Unique Strengths
  - Intellectual capital accumulated for more than a half-century
  - Successful track record of forming interdisciplinary yet focused science teams for large-scale and long-term investments
  - Demonstrated leadership in launching internationally-recognized SC-wide collaborative programs

QIS Scope and Relevance to HEP

- What's different now? Current and future QIS applications differ from earlier applications of quantum mechanics, such as the laser, by exploiting uniquely quantum properties:
  - **Superposition** – quantum particles or systems exist across all their possible states at the same time, with corresponding probabilities, until measured
  - **Entanglement** – a superposition of states of multiple particles in which the properties of each particle are correlated with the others, regardless of distance
  - **Squeezing** – a method of manipulating noise in systems that obey the Heisenberg uncertainty principle, by permitting large uncertainty in one variable to improve precision in the other related one
- Quantum information concepts and approaches are proving increasingly important across various high energy physics topics
  - Black hole information paradox
  - Testing of fundamental symmetries
  - Search for dark matter
  - Emergence of spacetime

HEP Engagement, Workshops, & Reports

- 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”
  - **Dec. 2017: APS/DPF** workshop on “Quantum Sensing for High Energy Physics” (report pending)

Overall HEP Goals for QIS Activities

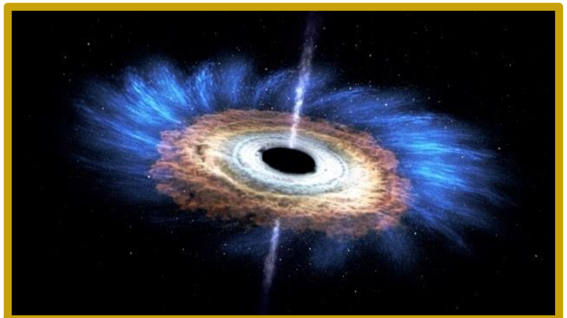
- Focused efforts in order to:
  - Advance the science drivers identified by P5 using QIS
  - Advance QIS itself through capabilities, expertise, and fundamental knowledge of the HEP community – in foundations, analogue simulation, controls, qubit technology, and more
  - Develop the appropriate and necessary interdisciplinary collaborations to advance high energy physics in particular and science more broadly
- As QIS is an SC cross-cutting initiative, partnerships with other SC programs, other agencies, and/or industry are expected where relevant

HEP Motivations and Thrust Areas in QIS

- **Fundamental High Energy Physics and QIS**
  - Foundational Concepts, including:
    - Convergent development of Black Hole physics, Quantum Error Correction, holographic duality
  - Field Theory/Analogue Simulations, including:
    - Perturbative QCD models exploiting QI, de Sitter space, & gauge duality
    - Tensor Networks/ Gauge symmetries
    - Field theories, including lattice gauge theories
  - Entanglement/QIS based Experiments
    - Exploiting superposition, entanglement, and squeezing
- **Quantum Computing for HEP**
  - Data analysis techniques, algorithms for HEP computations and modelling
- **Quantum Controls & Sensor Technology**
  - Controls, qubits, and other technology to advance dark universe & space time sensors

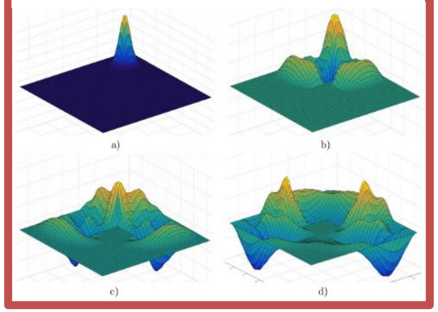
FY 2017 HEP Pilots in QIS

HEP has supported a number of modest pilot projects involving quantum information science in both National Laboratories and universities

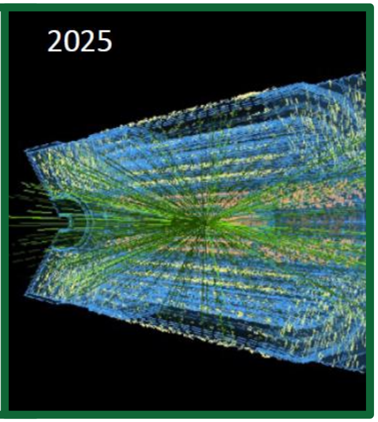


Black hole information paradox pilot experiment *(HEP/LBNL Norman Yao)*

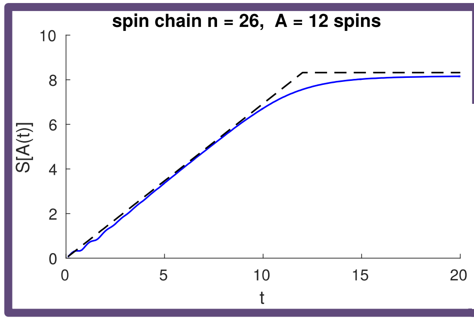
Simulated particle scattering off a complex boundary condition by quantum algorithms *(HEP-ASCR/U Maryland Stephen Jordan)*



Quantum pattern recognition for real time data tracking & quantum algorithms for exponentially increased storage *(HEP/LBNL Illya Shapoval)*



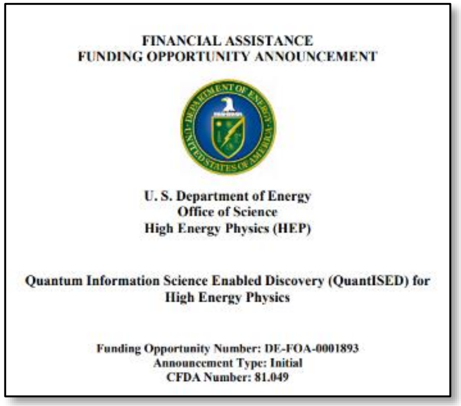
Quantum annealing for ML to separate signal/background in Higgs LHC data *(HEP/Caltech-FNAL Maria Spiropulo)* *published in Nature*



Entanglement & quantum chaos: toy models, holography, spin chains *(HEP-BES/Princeton Juan Maldacena & Shivaji Sondhi)*

FY 2018 QIS FOA & Lab Announcement

- **Quantum Information Science Enabled Discovery (QuantISED) for High Energy Physics**
- **Post Date:** February 28, 2018
  - **Letter of Intent Due:** 3/26/18, 5 PM Eastern **(required)**
  - **Close Date:** April 16, 2018, at 5 PM Eastern
  - **Awards:** Up to $13M total of awards in FY 2018 (FOA+LAB)



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

- **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
- **Topics:**
  - **A:** High Energy Physics and QIS Research
  - **B:** Quantum Computing for HEP on current or future quantum computing systems
- **Track 1:** Pioneering Pilots *(open to Topics A or B)*
  - **Work scope:** Novel concepts, test problems, design studies (TRL 1)
  - **Award:** $100k - $500k over 1-2 years
- **Track 2:** HEP-QIS Consortia *(Open to Topic A only)*
  - **Work scope:** Address P5, small experiments, early research on tools (TRL 1-2)
  - **Award:** FOA 500k – $2M (FOA) or $1M - $4M (LAB) over 2-3 years

Other Notable FY 2018 Activity

- **Dear Colleague Letter** on Accelerating Development of and Research Impacts from Quantum Information Science (QIS) issued by Office of Science (SC) Nov. 29, 2017
- **Request For Information** on Impacts From and to Quantum Information Science in High Energy Physics published Dec. 27, 2017
  - Responses were due Feb. 12, 2018; 17 substantive submissions received
  - Comments now posted on regulations.gov, Docket ID: DOE-HQ-2018-0003
- **Small Business Innovation Research (SBIR)** – new topic, included in HEP section, on Quantum Information Science (QIS) Supporting Technologies
  - Subtopics dealing with SRF cavities, low-temperature technologies, and optical-microwave transduction
  - Responses were due Feb. 26, 2018; proposals received and being assigned for review

Development of smaller cavities for higher frequencies pave the way towards dramatic improvement of qubit coherence time

HEP-related SC Laboratory Collaborations

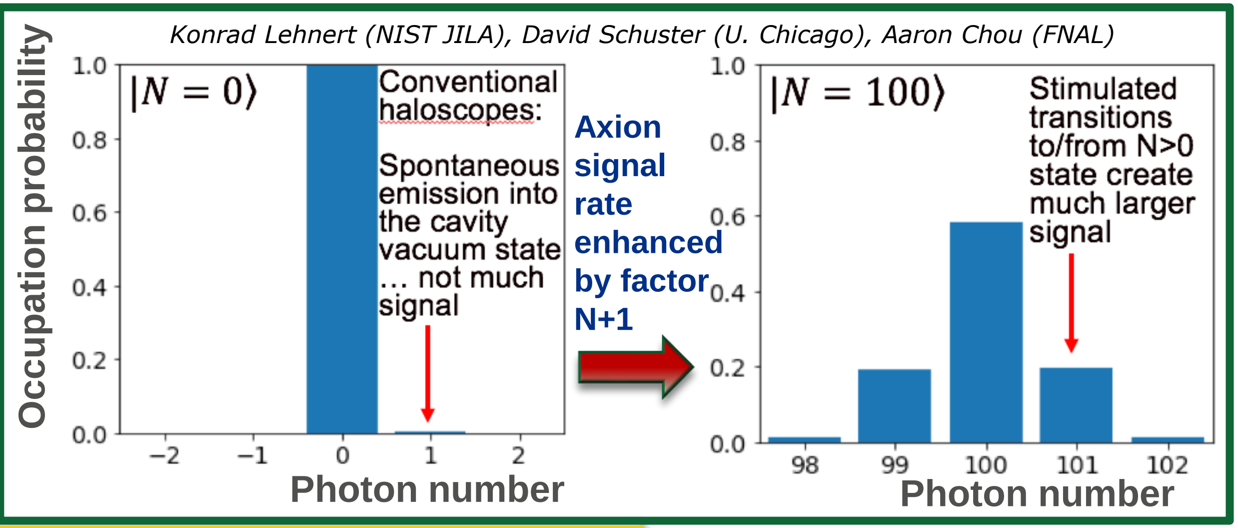
- Quantum networks
  - Intelligent Quantum Networks & Technologies (INQNET; AT&T and Caltech) is working with the Chicago Quantum Exchange (Fermilab, Argonne, and U. Chicago) to establish a quantum network testbed connecting its three sites
  - AT&T has already spent $1M for a pilot quantum teleportation experiment at Fermilab, and has committed a minimum of $5M to the consortium
  - Fermilab quantum teleportation experiment (FQNET) aims to establish time-binned photonic qubit teleportation on a 10 km scale using commercial fiber
- Quantum computing
  - Fermilab signed collaborative agreement with Google to become one of the five “alpha” users with privileged access to Google’s 22 qubit and 50 qubit quantum computers
  - Fermilab goal is to identify HEP applications with demonstrated quantum advantages

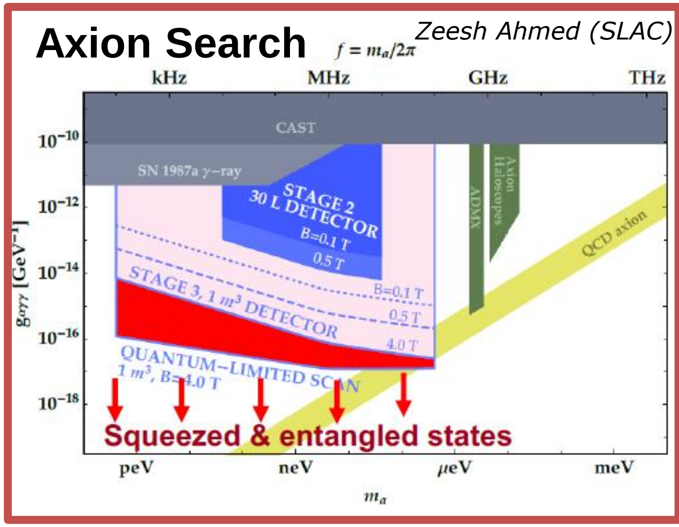
inqnet

Caltech Fermilab

HEP-related SC Laboratory Collaborations

- Collaboration between NIST JILA, U. Chicago, and Fermilab aims to use Fock states to stimulate emission from dark matter axions into cavity photons
  - Use qubits to load individual quanta into detection RF cavity
  - Resulting large N Fock state is a quantum superposition of all possible oscillation phases
  - Enhanced response to all possible signal phases
- Collaboration between SLAC, KIPAC, and Heising-Simons exploring using quantum sensors to dramatically enhance sensitivity to axions





Future Plans

- Quantum Information Science in FY 2019 HEP President's Budget Request: $27.5M
  - The FY 2019 Request will support new foundational QIS research and supporting technology. HEP will employ the latest developments in QIS from the private sector, contribute to the national effort, and promote American competiveness.
  - Focus of support will be on QIS research techniques and algorithms, quantum computing for HEP experiments and modeling, development and use of specialized quantum controls and precision sensors.

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