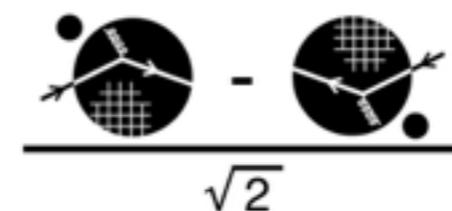


Interim Report to NSAC - April 2019

NSAC Subcommittee on Quantum Computing and
Quantum Information Science for Nuclear Physics

Washington DC, April 8, 2019 (20+10 minutes)

Martin J. Savage



INSTITUTE for
NUCLEAR THEORY

Quantum Information Science and Quantum Computing

Defining feature(s) of Quantum Mechanics:

- Quantization: eigenvalues and eigenstates, Uncertainty Principle
- Entanglement and Non-Locality

Advances in:

- Information
- Control of entanglement over macroscopic distances and times - atoms, photons, electrons, superconductors, ... - devices
- Measurement and Detection

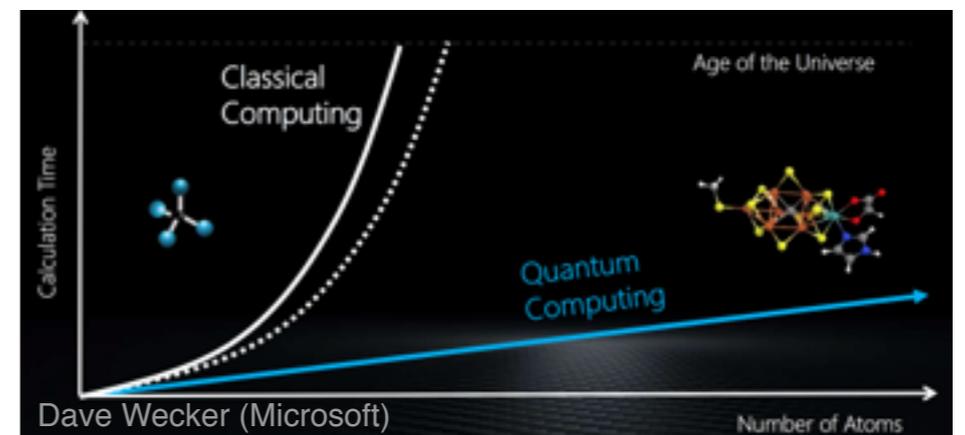
Paradigm shifts:

- Sensing
- Computation
- Communication
- Security

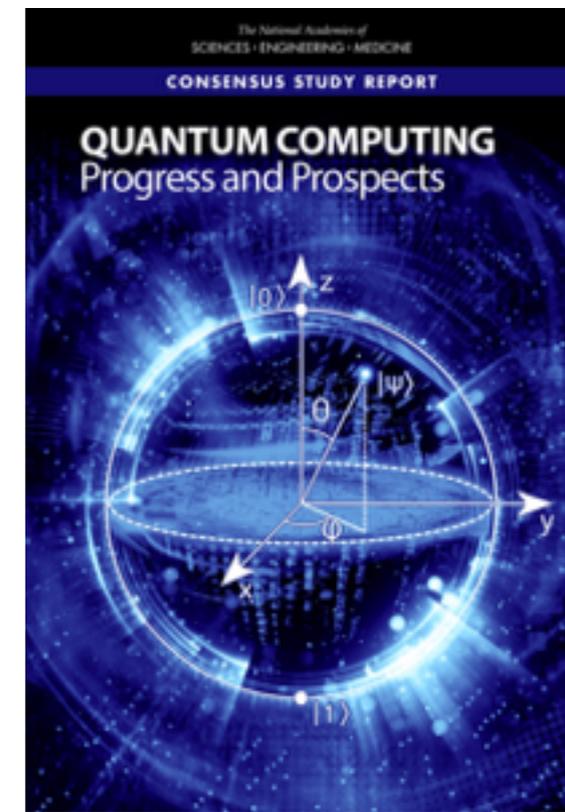
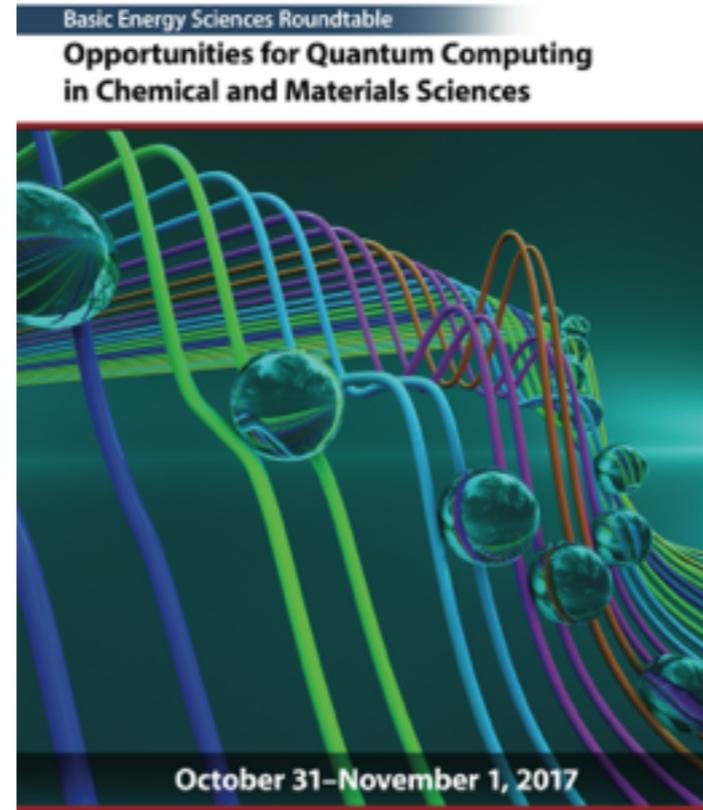
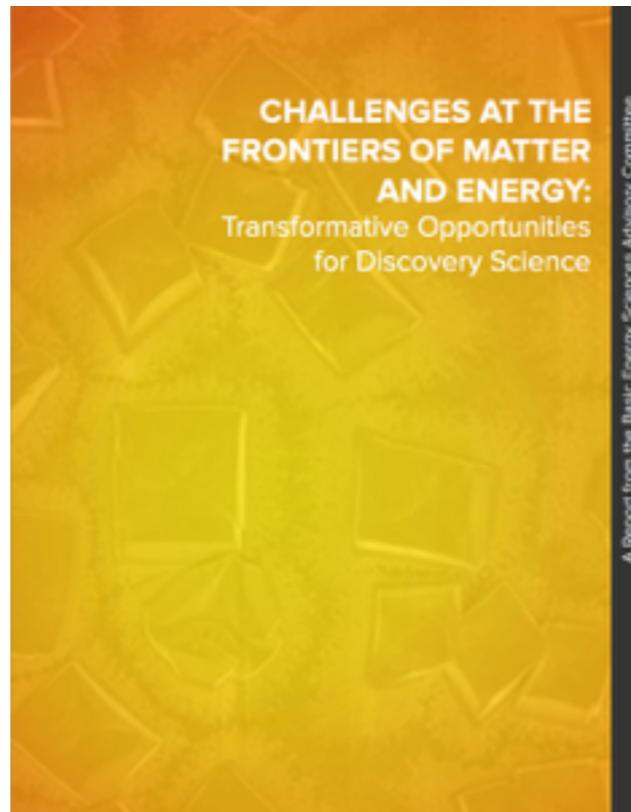
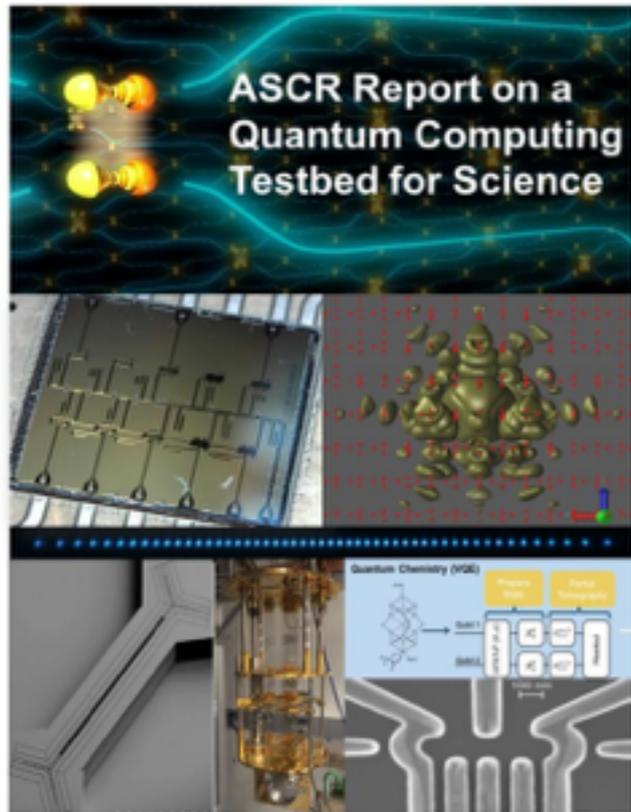
Cross-disciplinary

Experiment - Theory - Simulation

Quantum workforce



QC and QIS in Broader Community



DOE Study Group Report

Grand Challenges

at the Interface of

Quantum Information Science,
Particle Physics, and Computing

Edward Farhi, Stephen Jordan, Patrick Hayden (co-chair),

Mikhail Lukin, Juan Maldacena, John Preskill (co-chair),

Peter Shor, Jacob Taylor, Carl Williams

17 January 2015

Quantum Sensing for High Energy Physics

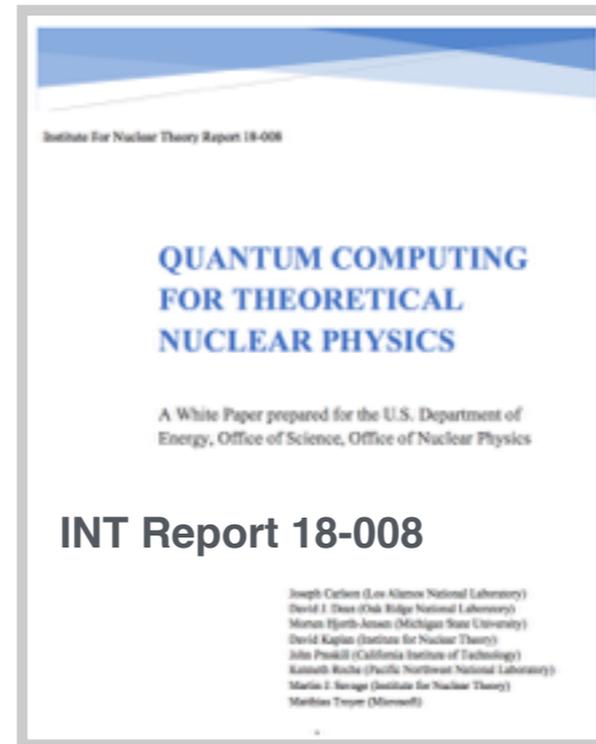
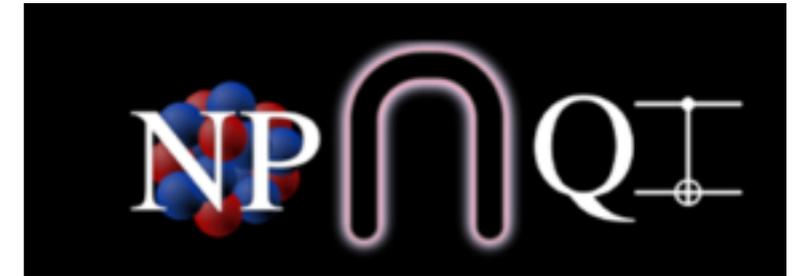
Report of the first workshop to identify approaches and techniques in the domain of quantum sensing that can be utilized by future High Energy Physics applications to further the scientific goals of High Energy Physics.

Organized by the Coordinating Panel for Advanced Detectors of the Division of Particles and Fields of the American Physical Society

March 27, 2018

+ ...

Community Activities in Nuclear Physics



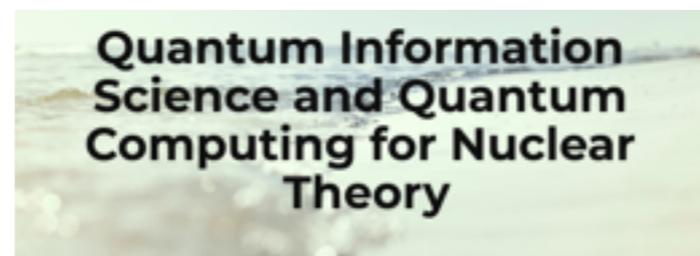
Computational Complexity and HEP
July-31 — August 2, 2017

Quantum Computing for Nuclear Physics
November 14-15, 2017

Intersections Between NP and QIS
Argonne National Laboratory
March 28-30, 2018



Near-term Applications of Quantum Computing, December 6-7, 2017



Quantum Entanglement at Collider Energies

10-12 September 2018
CFNS Stony Brook
Stony Brook
September 10-12, 2018



Group photo from the workshop Intersections Between Nuclear Physics and Quantum Information held at Argonne National Laboratory on 28-30 March 2018. Names of participants can be found in Appendix A.

Charges to NSAC and QIS+QC Subcommittee



U.S. Department of Energy
and the
National Science Foundation

October 29, 2018



DEPARTMENT OF PHYSICS

UNIVERSITY of WASHINGTON

College of Arts & Sciences

Box 351560
Seattle, WA 98195

Tel: 206-543-1493

Professor David Hertzog
Chair
DOE/NSF Nuclear Science Advisory Committee
Department of Physics
University of Washington
Seattle, Washington 98195

Dear Professor Hertzog:

This letter requests that the Department of Energy (DOE)/National Science Foundation (NSF) Nuclear Science Advisory Committee (NSAC) conduct a study to identify unique opportunities for U.S. nuclear physics research to contribute to advances in Quantum Computing and Quantum Information Science (QIS). In carrying out this study, NSAC should provide information assessing the relative importance and potential benefits of QIS to nuclear physics and the potential contributions that nuclear physics can make to QIS.

QIS research is playing an increasingly central role in the vision for the future of U.S. science and technology. Emerging QIS priority areas provide promising new avenues for addressing challenges of enormous complexity, including, for example dramatic extensions of the application of Quantum Field Theory to the analysis of physical systems at scale with heretofore intractably large numbers of degrees of freedom that cannot be addressed by conventional computing. In another area of rapid development, quantum entanglement in multi-particle states is opening new horizons in quantum sensing, quantum communication, quantum computing, and quantum simulations.

Decades of accumulated intellectual capital, extensive experience in interdisciplinary research, considerable technical infrastructure at labs and universities, and a long history of international leadership in collaborative research have positioned the DOE Office of Nuclear Physics and the NSF nuclear physics research programs to engage in QIS relevant research. However, QIS is newly emergent as a priority area for Research & Development (R&D) investment in nuclear science. Furthermore, private sector R&D investment in QIS, as well as investment by other Federal agencies, has been ongoing for some time. NSAC is therefore requested, in the context of Federal and private sector research efforts already underway, to articulate the unique role nuclear science research, aligned with the DOE and NSF nuclear physics programs, can and should play in Quantum Information Science. While unique, this role should nevertheless align broadly with the goals outlined in the national strategy for QIS¹.

¹ <https://www.whitehouse.gov/wp-content/uploads/2018/09/National-Strategic-Overview-for-Quantum-Information-Science.pdf>

Please submit your report to DOE and NSF by summer of 2019. The agencies very much appreciate NSAC's willingness to undertake this task and anticipate that the information provided in this report will be important in guiding DOE and NSF nuclear physics investments in this newly emergent area for Federal R&D.

Sincerely,

J. Stephen Binkley
Deputy Director for Science Programs

Anne L. Kinney
Assistant Director, Directorate for

January 9, 2019

Professor Martin Savage
Institute of Nuclear Theory
University of Washington

Dear Martin,

J. Stephen Binkley, Deputy Director for Science Programs at the Department of Energy, and Anne L. Kinney, Assistant Director of Mathematical and Physical Sciences at the National Science Foundation, have requested that NSAC form a Subcommittee to identify unique opportunities for the U.S. nuclear physics research community to contribute to advances in Quantum Computing (QC) and Quantum Information Science (QIS) and to identify potential benefits of QIS and QC to Nuclear Physics. Their charge letter is attached.

I am writing to formally ask you to serve as the Chair of this new NSAC Subcommittee, and to help me establish a broad and diverse membership having a collective expertise across a wide range of QIS and QC subjects. As you are well aware, Quantum Information Science – broadly defined – is now a high-priority, multi-disciplinary initiative within the U.S. science and technology community at large. Significant funding opportunities have been enabled by recent legislation with the aim to widely distribute support to different specialty areas. In that context, your committee should develop guidance as to how the Nuclear Science community can most effectively contribute to the advancement of QIS; for example, one anticipates topics ranging from quantum computing for science applications to development of sensitive quantum sensors. These are areas for which U.S. nuclear scientists are already beginning to make valuable contributions. Your committee will likely need to host one or more information meetings with the aim of acquiring expert input and advice that will be folded into your report. To be most useful, NSAC would appreciate receiving your report by early Summer 2019.

I realize this is a heavy responsibility and a burden on your time and that of the Subcommittee. I, and our whole community, will owe you an enormous debt of gratitude.

Sincerely yours,

David W. Hertzog,
Chair NSAC

Attachments: Charge Letter

NSAC Subcommittee Membership



Photo by Michelle Shinn

Douglas Beck	(UIUC)	David Hertzog	(UW) (NSAC Chair)
Amber Boehnlein	(JLab)	Christine Muschik	(Waterloo)
Joseph Carlson	(LANL)	Jeffrey Nico	(NIST)
David Dean	(ORNL)	Alan Poon	(LBNL)
Matthew Dietrich	(ANL) (Co-Chair)	John Preskill	(Caltech)
William Fairbanks Jr	(CSU)	Sofia Quaglioni	(LLNL)
Joseph Formaggio	(MIT)	Krishna Rajagopal	(MIT)
Markus Greiner	(Harvard)	Martin Savage	(INT) (Chair)

Subcommittee Meetings



MEETING #1

Bethesda, Maryland

Nuclear Physics Exploration of the
Quantum Information Science and
Quantum Computing Landscape

March 28-29, 2019

Doubletree by Hilton, 8120 Wisconsin Ave, Bethesda, Maryland 20814

***Brenda May
Christine Izzo***

***Ida Boeckstiegel
Brenda May
Christine Izzo***



MEETING #2

Seattle, Washington

Quantum Computing and
Quantum Information Science: A
Deep Dive

April 30 - May 1, 2019

University of Washington, HUB

Scope of Subcommittee Activities

Identify Opportunities for NP

- Experiment
- Data
- Theory
- Computation and Simulation
- Applications

Identify NP specific

Scope of Subcommittee Activities

NP for QIS and QC

- Identify components of NP program, e.g. Isotopes
- Dual impact components

Identify NP specific

Scope of Subcommittee Activities

Considerations to include:

- Quantum Information Science
- Quantum Computation
- Quantum Sensing
- Quantum Communication and Encryption
- National - NQI, Office of Science, DOE and NSF
- International Programs
- Laboratory/Regional programs
- Technology companies

Agenda of Meeting 1

NSAC QIS+QC Subcommittee: Meeting #1 NP Exploration of the Quantum Landscape March 28-29, 2019 Doubletree Hotel, Bethesda, Maryland

Day 1 (Thursday, March 28)

08:00 – 08:30	Executive Session	
08:30 – 09:00	Welcome and Subcommittee Orientation Timothy Hallman (DOE), David Hertzog (UW), Martin Savage (INT/UW)	
09:00 – 09:35	OSTP/NSTC National Strategic Overview for QIS and QC Jake Taylor (OSTP)	<i>Context</i>
09:35 – 10:10	The National Quantum Initiative Act David Dean (Oak Ridge National Laboratory)	
10:10 – 10:35	Coffee Break	
10:35 – 11:05	QIS and QC Perspective from NSF Anne Kinney (NSF)	
11:05 – 11:40	QIS and QC Perspective from NIST Carl Williams (NIST)	<i>Agencies</i>
11:40 – 12:15	QIS and QC Perspective from DOE Steve Binkley (DOE)	<i>Photo !!!</i>
12:15 – 13:30	Working Lunch	
13:30 – 14:05	Overview of the HEP QIS and QC Report Maria Spiropulu (California Institute of Technology)	
14:05 – 14:40	Overview of the BES QIS and QC Report/Zoom Giulia Galli (University of Chicago)	<i>Related domains and NAS</i>
14:40 – 15:15	Overview of the NAS QC Report Mark Horowitz (Stanford University)	
15:15 – 15:35	Coffee Break	
15:35 – 16:10	Overview of the Nuclear Physics QIS and QC Workshops at INT and ANL Mathew Dietrich (Argonne National Laboratory)	<i>Nuclear Community</i>
16:10 – 17:30	Executive Session	
17:30	Adjourn Day 1	

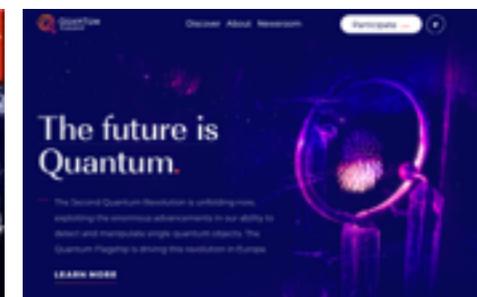
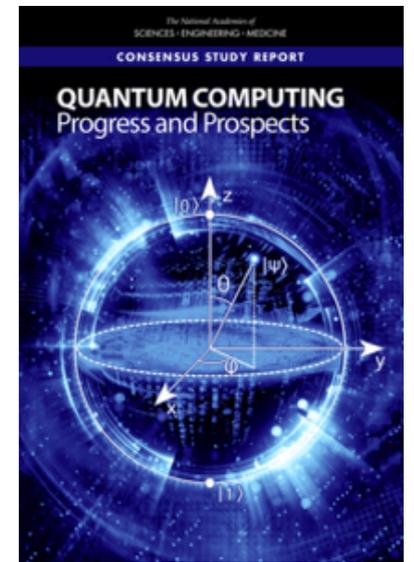
NSAC QIS+QC Subcommittee: Meeting #1 NP Exploration of the Quantum Landscape

Day 2 (Friday, March 29)

8:15 – 8:45	An Overview of QIS and QC programs in Europe/Zoom Tommaso Colarco (Forschungszentrum Juelich)	<i>International</i>
8:45 – 9:15	An Overview of QIS and QC programs in China/Zoom Jian-Wei Pan (University of Science and Technology of China)	
9:15 – 9:45	An Overview of QIS and QC programs in Canada David Cory (University of Waterloo)	
9:45 – 10:05	Coffee Break	
10:05 – 10:35	QIS and QC Interest of laboratories in the Northeast Eden Figueroa (Stony Brook University)	
10:35 – 11:05	QIS and QC Interest of laboratories in the Midwest/Zoom Salman Habib (Argonne National Laboratory)	<i>Labs and Regional</i>
11:05 – 11:35	QIS and QC Interest of laboratories in the West Coast Irfan Siddiqi (University of California, Berkeley)	
11:35 – 12:05	QIS and QC Interest of laboratories in the Southeast David Dean (Oak Ridge National Laboratory)	
12:05 – 13:30	Working Lunch	
13:30 – 14:00	Overview of ASCR QIS and QC Programs Barbara Helland (DOE-ASCR)	<i>ASCR</i>
14:00 – 14:30	Overview of NP QIS and QC Programs Timothy Hallman (DOE-NP)	<i>Nuclear Programs</i>
14:30 – 15:00	Isotopes for QIS and QC Joel Grimm (DOE-NP)	
15:00 – 15:20	Coffee Break	
15:20 – 16:20	Executive Session	
16:20	Adjourn Meeting	

Meeting 1 High-level

- US anticipates long-term, sustained support for developing a quantum ecosystem and economy, and for broad application of QIS and QC [OSTP, NSF, DOE, NIST,...]
 - National Quantum Initiative in process
 - Nationwide interest and engagement
 - Inherently multidisciplinary
 - Science phase
 - Report by National Academy
- Significant and impressive International efforts in QIS and QC
 - Canada, China, Europe [Australia]
 - collaboration viewed as beneficial
 - planning, growth and long-term vision
 - no mention of NP objectives, but HEP and CM



Meeting 1 High-level

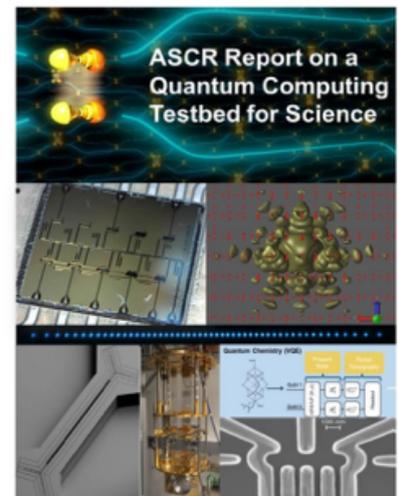
- NSF, DOE and NIST are fully engaged
 - ASCR and other Domain Science areas [HEP, BES, ...] within DOE
 - QIS Kickoff meeting in Jan 2019
 - some overlap in “types of problems/challenges” with BES and HEP
 - identification of opportunities
 - plans and funding
 - workforce development ideas and programs

- US National Laboratories have diverse, exciting programs in QIS and QC
 - qubits
 - algorithms
 - infrastructure
 - science
 - collaborations with Universities and Technology companies

Meeting 1 High-level

- ASCR supporting TestBed (Hardware) and Algorithm development (Software) significantly
 - does not expect QC within the next 5 years

- Nuclear Isotopes program @ ORNL
 - identified a selection of isotopes that may be of interest for QIS and QC
 - e.g. ^3He for dilution refrigerators



Meeting 1 NP-related Presentations Included:

- Cryogenics experiences, especially with lowest temperatures and large volumes, e.g. including CUORE, nEDM, ADMX, ...
- Low background experiments (ultra-pure materials, negligible natural radioactivity)
- Experience with low S/N measurements
- Readout of very cold electronics and electronics multiplexing
- Particle detection with high single particle sensitivity (0vbb, Dark Matter, ...)
- Experience with large system controls and operations
- Superconducting RF cavities and microwave measurement techniques. High Q resonators; Squid amplifiers.
- Big data analysis techniques
- Collaborative work toward single goals
- Quantum Many-Body and Lattice Field Theory expertise
- Nuclear Isotopes Program
- Workforce development

Scope of Subcommittee Activities

Identify connections with other areas

- ASCR : e.g. Testbeds, co-design,
- HEP : e.g. Sensors, QI, lattice QFT,
- BES : e.g. materials, sensors,
- CS : e.g. complexity, (Q)I,
- QIS : e.g. quantum many-body systems
- QC : e.g. quantum many-body theory

Scope of Subcommittee Activities

What is the Path Forward for NP ?

- Framed in context of NP Reports: LRP, NAS, Exascale, EIC, ...
- QIS and QC knowledge and technology exchange
- Collaboration between
 - National Labs
 - Tech Companies
 - Universities
- Intellectual Property - codes, data, technology,
- International Collaborations
- Integration with existing NP activities and infrastructure
 - Role of existing components

Scope of Subcommittee Activities

What is the Path Forward for NP ?

- Addressing NP challenges
 - Co-design ?
 - Partners ?
 - Existing successful models, e.g. SciDAC ?
- Workforce
 - Career paths ?
 - Publishing ?
- Classical Resources for Quantum, e.g. HPC ?

Examples of Identified Quantum Information Science for NP - minimally deliberated and unrefined

- Sensor and Detector Technology
- Quantum Devices/computers for simulation, development

Preliminary Agenda of Meeting 2

NSAC QIS+QC Subcommittee: Meeting #2 A Deep Dive

Day 1 (Tuesday, April 30)

08:00 – 08:30: Executive Session

08:30 – 09:00: Overview of Quantum Sensors **Joel Ullom (University of Colorado/NIST)**

09:00 – 09:30: Superconducting qubits for QIS and QC **Brent VanDevender (PNNL)**

09:30 – 10:00: Quantum electron microscopy **Mark Kasevich (Stanford)**

10:00 – 10:30 Coffee Break

10:30 – 11:00: Superconducting cavities and QIS **Alexander Romanenko (FermiLab)**

11:00 – 11:30: Superconducting Nanowire Single-Photon Detectors and Transition Edge Sensors
tbd

11:30 – 12:00: Quantum Defects for Sensing and Computing, and Isotopic Purity
Xing Rong (University of Science and Technology in China)

12:00 – 12:30: Technology for EDM Detection **Matthew Dietrich (ANL)**

12:30 – 13:30 Lunch

13:30 – 14:00: Quantum Encryption and Quantum Communication
Christine Muschik (University of Waterloo)

14:00 – 14:30: QIS and QC Interests of LANL, LANL and Sandia **tbd**

14:30 – 15:00: Quantum Sensors in High-Sensitivity Experiments
Gray Rybka (University of Washington)

15:00 – 15:30 Coffee Break

15:30 – 17:00: **Technology Panel** on Engagement and Collaboration with Universities and Labs
50 minutes presentation by panel member (10 minutes each)

40 minutes of Q+A

Microsoft **tbd**

IBM **tbd**

Google **Dave Bacon**

D-Wave **Eric Ladizinsky**

17:00 – 18:30: Executive Session

18:00: Adjourn Day 1

Sensors

Tech Companies

Day 2 (Wednesday, May 01)

08:00 – 08:30: Executive Session

08:30 – 09:00: Quantum Simulation **Matthias Troyer (Microsoft)**

09:00 – 09:30: Atoms, and Engineering challenges **Markus Greiner (Harvard)**

09:30 – 10:00: Ions, RF and Optical Engineering – IonQ **Jungsang Kim (Duke/IonQ)**

10:00 – 10:30 Coffee Break

10:30 – 11:00: QIS and QC with Photons **Pavel Lougovski (ORNL)**

11:00 – 11:30: Qudits @ LLNL **Jonathan Dubois (LLNL)**

11:30 – 12:00: Theoretical Advances for QIS and QC **John Preskill (Caltech)**

12:00 – 12:30: Quantum Simulations for NP **David Kaplan (INT)**

12:30 – 13:30 Lunch

13:30 – 15:00: Subcommittee Deliberations

Compile subcommittee Comments

Establish Findings for the Report

15:00 – 15:30 Coffee Break

14:30 -16:30: Subcommittee Deliberations

16.30 – 17:30: Formulate Draft Recommendations

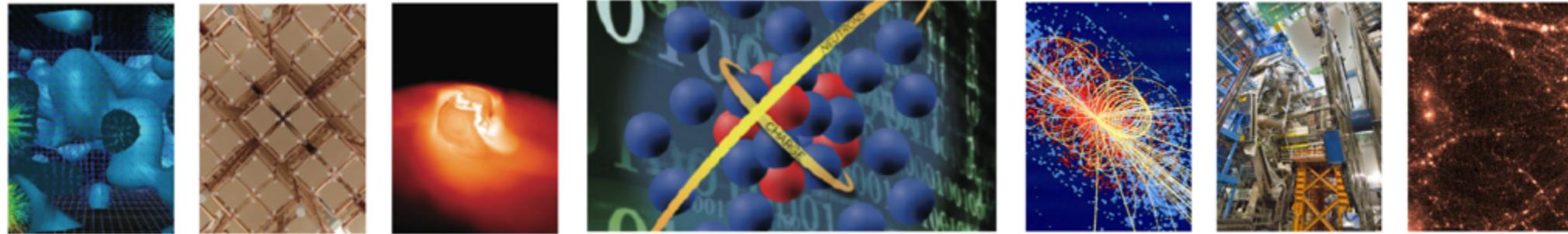
Finalize Report writing assignments

17.30: Adjourn Day 2

*Quantum
Computing*

*Committee
Deliberations*

Summary



- Subcommittee gathered “high level” information from Meeting #1
 - good discussions and deliberations
 - more d+d are required
- Meeting #2 is a deeper dive
 - agenda was refined after Meeting #1
 - includes Technology company panel
 - significant time for d+d
- Report is due early summer
 - on track



MEETING #1

Bethesda, Maryland

Nuclear Physics Exploration of the
Quantum Information Science and
Quantum Computing Landscape

March 28-29, 2019

Doubletree by Hilton, 8120 Wisconsin Ave, Bethesda, Maryland 20814



MEETING #2

Seattle, Washington

Quantum Computing and
Quantum Information Science: A
Deep Dive

April 30 - May 1, 2019

University of Washington, HUB