U.S. DEPARTMENT OF ENERGY | Office of Science

# HEP-QIS Program and QuantISED 2018 Awards

HEPAP Meeting Nov. 29$^{th}$ 2018


## Lali Chatterjee

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

# HEP-QIS Program – part of National Quantum Initiative

- **Science Committee Seeks to Launch a National Quantum Initiative:** 'to create a 10-year National Quantum Initiative aimed at increasing America's strategic focus on quantum information science and technology development.'
- Jacob Taylor, Assistant Director for quantum information science, OSTP recently stressed the nascent nature of the field: *"From my perspective, what we see is that there is a tremendous amount of fundamental science still to be done,"*
- NSTC SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE  co chaired by OSTP, DOE, NIST, and NSF
- A new "strategic overview" document published by the White House's National Science and Technology Council (NSTC) says the U.S. government's efforts to advance quantum information science (QIS) will **"focus on a science-first approach that aims to identify and solve Grand Challenges: problems whose solutions enable transformative scientific and industrial progress."**

# 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**

## DOE/SC Contributions to QIS

Fundamental Science ⟷ Tools, Equipment, Instrumentation

DOE Community Resources

⟷

## QIS Applications

**Quantum Computing:**
Simulation, Optimization, Machine Learning

**Analog Quantum Simulation**

**Sensing and Microscopy**

# 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

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

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

# HEP and QIS Entanglement

**Other Agencies – NSF, DOD, NIST, …**

**Significant Contributions over many years…**

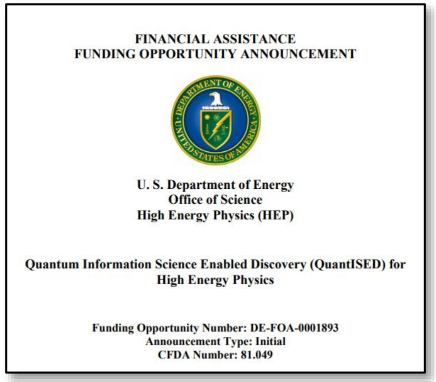
**DOE Labs have been working on HEP-QIS as well …**

- 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** *(Topics A or B):* Novel concepts, test problems, design studies (TRL 1)
- **Track 2: HEP-QIS Consortia** (*Topic A only*)**:** Address P5, small experiments, early research on tools (TRL 1-2) [ 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

# Research Topics responsive to the Announcement

**Topic A:** High Energy Physics and QIS Research

- (i) Theoretical, Computational, and/or experimental research exploiting recent convergence of developments in quantum gravity, computational complexity, AdS/CFT holographic correspondence, quantum information theory, emergence of space-time, quantum error correction, black hole physics, scrambling, and qubit system thermalization;
- (ii) Foundational field theory techniques, gauge symmetries, and tensor networks invoking quantum information and entanglement concepts that advance knowledge including description of scattering, bound state problems, and advanced gauge theories;
- (iii) Analog simulations/quantum emulators/teleportation experiments that advance HEP and QIS, including tests of fundamental string theory and other particle physics models in qubit systems;
- (iv) Novel experiments probing HEP science drivers using QIS technology and tools exploiting superposition, entanglement, and/or squeezing with goals for near term science goals and/or steps to scientific discovery

# Topic A continued and Topic B

- (v) HEP relevant instrumentation, data transfer and quantum communication tools using QIS concepts and QIS technology exploiting superposition, entanglement, and/or squeezing that produce new experimental methods for HEP;
- (vi) Foundational and/or technological advances in QIS by incorporation of techniques, tools, and physical principles from particle physics
- **Topic B**: Quantum Computing for HEP on current or future quantum computing systems
- (i) Quantum field theory algorithms and simulations including quantum chromodynamics and electrodynamics, accelerator modeling codes, and computational cosmology relevant to HEP science drivers and P5 projects and experiments;
- (ii) Quantum machine learning and data analysis techniques and tools that can enhance efficiency or analysis methods for HEP applications. Applications using available annealer platforms are within scope and so are use of quantum computers simulated classically;
- (iii) Developing quantum computing simulators and/or frameworks for HEP applications to be developed on existing computers or hybrid systems.

# HEP-QIS Programmatic Thrusts - Summary

**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**

**Small (QIS) Experiments**

# QuantISED Proposals and Review – Some Details

- DE-FOA-0001893/LAB 18-1893 **Closed on April 16th.**
- **Overwhelming Response from Community**
- **Number of proposals received: 69**
- **Total Request $ 78 M (FY18 QIS Budget: 18 M)**
- **Number of mail reviewers (prior to panel): 76**
- **Timelines Constraints for Actions had to be followed**
- **Panel review held on May 30- 31.**
- **DOE internal discussions(HEP and with SC1)**

# 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/
- Total HEP Awards: $ 31 M (over 3 years – most 2 years)
- **[note BES and ASCR total awards much more]**
- **HEP Awards: 15 University led projects + 17 lab led projects**
- **Most projects multi institutional and inter disciplinary**

# Awards Across Categories

**Somewhat Blurred Boundaries...**

**Cosmos and Qubits**

**(Quantum Simulation Experiments, Theory, QI)**

**(17 %)**

**HEP tools for QIS**

**Research technology**

**(SRF/controls...)**

**(10 %)**

**Quantum Field Theory, Entanglement**

**(Quantum Computation & Simulation Experiments)**

**(17 %)**

**HEP-QIS**

**Request**

**69 Proposals: $76.4M**

**Awards**

**32 Announced: $31M**

**QIS based Quantum Sensors for HEP**

**(40 %)**

**Small (QIS) Experiments**

**Quantum Computing for HEP**

**Data analysis/ML/ Algorithms**

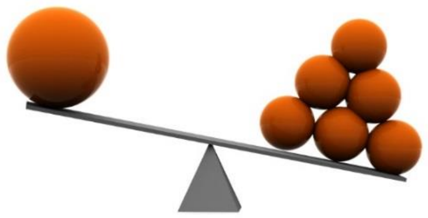
**(16 %)**

# Overall HEP Goals for QIS Activities

- **Advance the science drivers identified by P5 using QIS**
- **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**
- **Connections with HEP Frontiers and Technology Thrusts**
- **Connections with SC Programs and other agencies**
- **Connections with identified NSTC Thrusts**

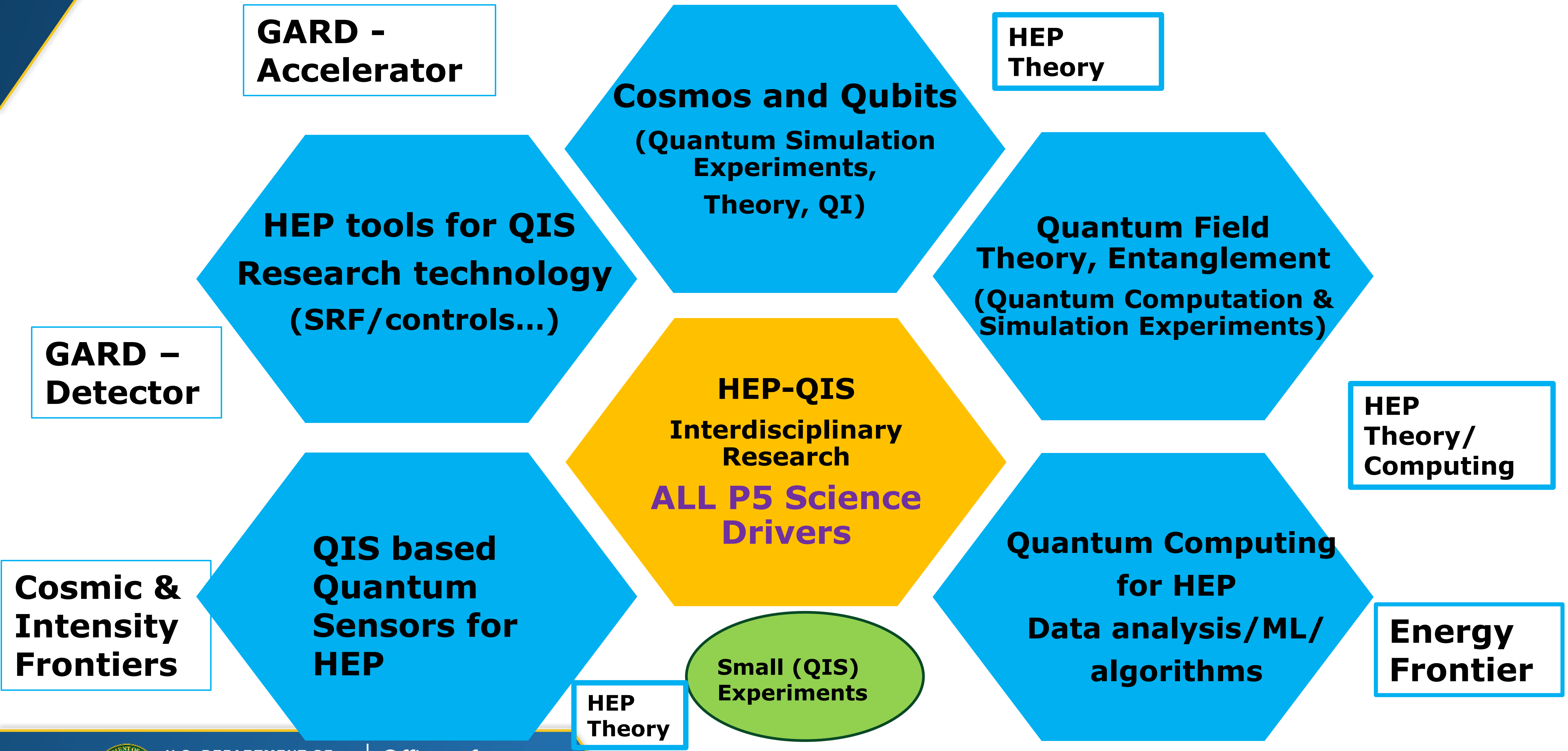
**HEP-QIS Entanglement See Saw**

**QIS for HEP** | **HEP for QIS**



**Credit – Microsoft Bing search**

# HEP-QIS Connections to HEP Frontiers and Thrusts



# HEP Interagency & SC QIS Partnerships

## NIST - HEP coordinated partnerships on QuanTISED:

Quantum Sensors and precision instrumentation for HEP Detectors and fundamental physics research (four of the QuantISED awards)

**HEP and NIST:** Mission synergy to understand fundamental constants and Beyond Standard Model Physics.

## DOD – HEP coordinated QIS partnerships

We have two Pilots on the Cosmos and Qubits Theme

## HEP-BES partnership:

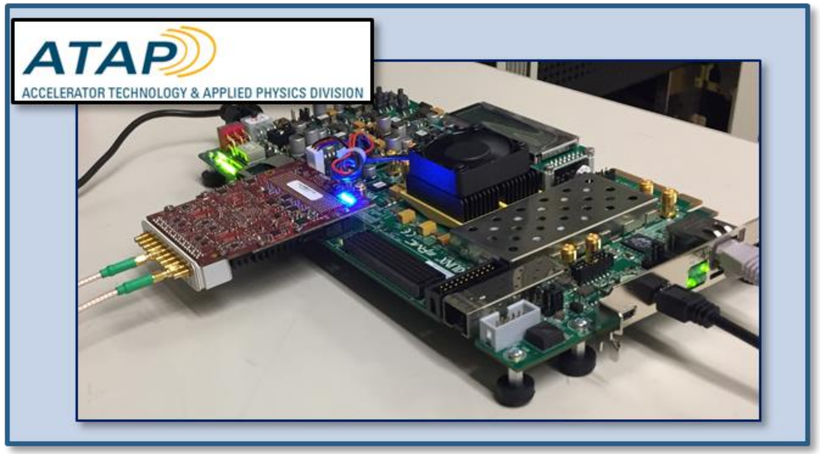
Gauge Theories and entanglement and spin systems.

**HEP-ASCR partnership**: One pilot completed, Collaborating PIs…

# 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**

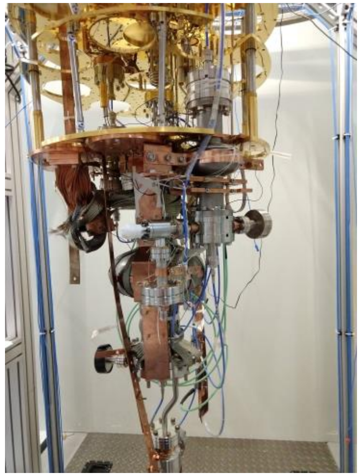
**Can be adapted and developed to make better qubits**



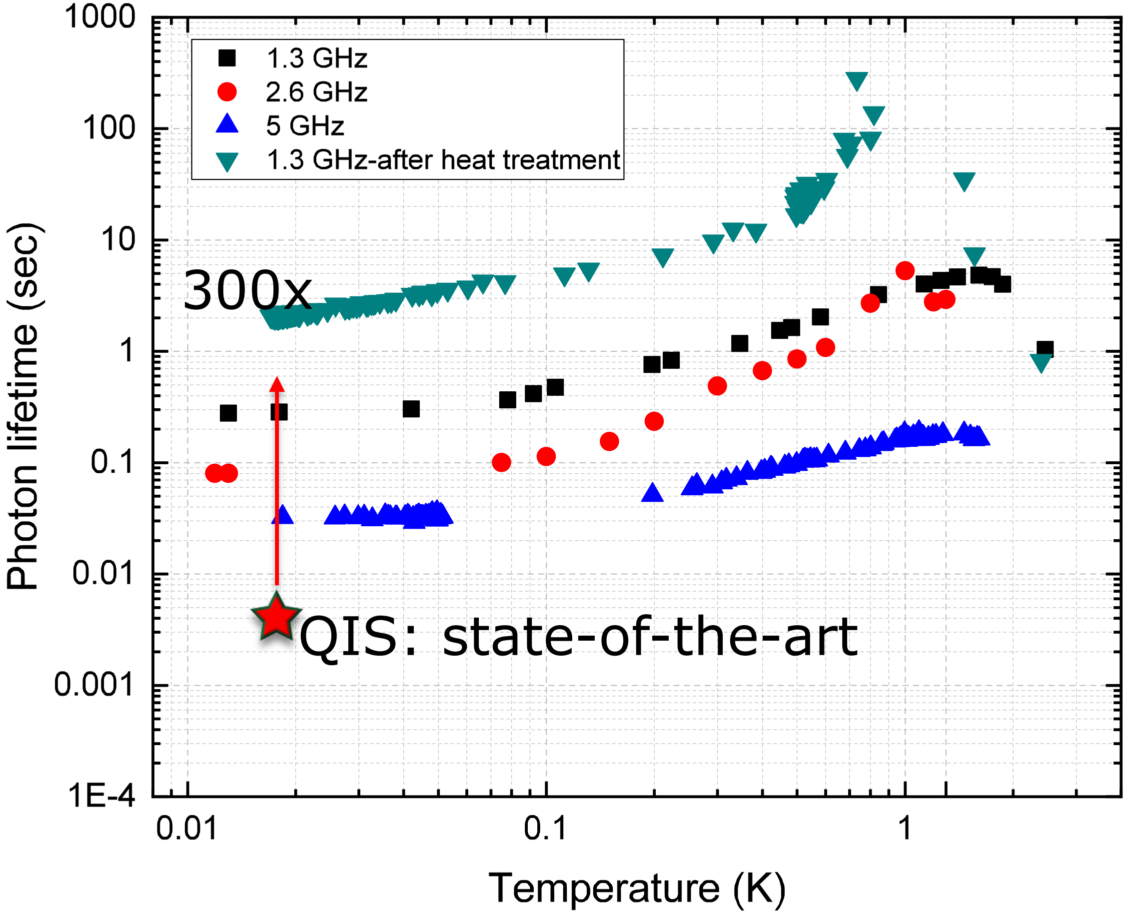

Development of advanced superconducting radio frequency (SRF) cavities (example from FNAL), cryogenics, and other technologies supporting development of qubits, their ensembles, quantum sensors, and quantum controls at LBNL are being developed for QIS

# QuantISED: Record high photon lifetimes achieved at Fermilab

*Accelerator cavities adopted for quantum regime* ***(NIST Partnership)***

Seconds of coherence after targeted treatment



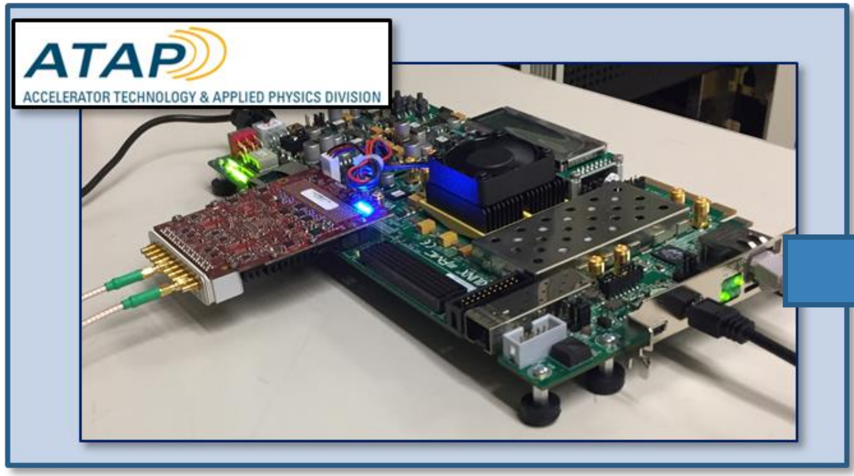

**A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703**
**A. Romanenko and D. I. Schuster, Phys. Rev. Lett. 119, 264801 (2017)**

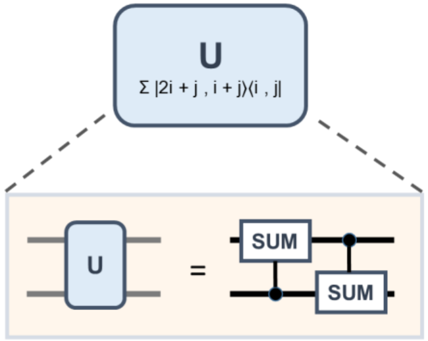
# FPGA-based quantum control for HEP simulations with qutrits

*I. Siddiqi, Lawrence Berkeley National Laboratory*

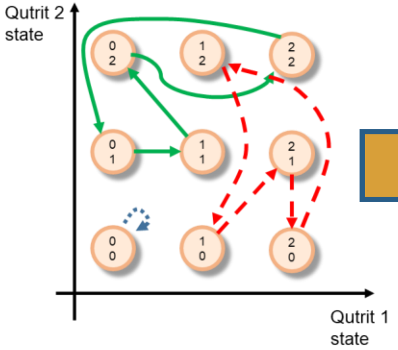
BERKELEY LAB

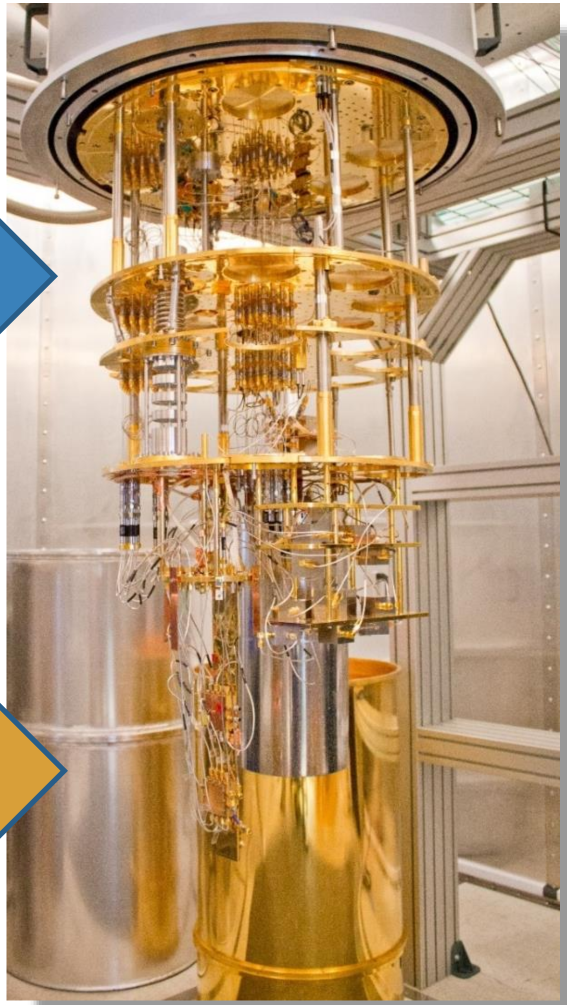
**HEP for QIS & Cosmos & Qubits**




CSUM |i , j⟩ = |i , i + j⟩



## 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:

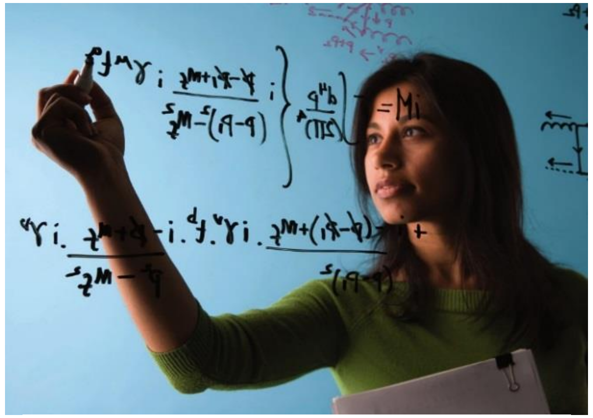
- Cost-effective, extensible electronics leveraging HEP engineering expertise for practical quantum computation
- Quantum processors optimized to test scrambling, Ads/CFT correspondence, and advanced error correction

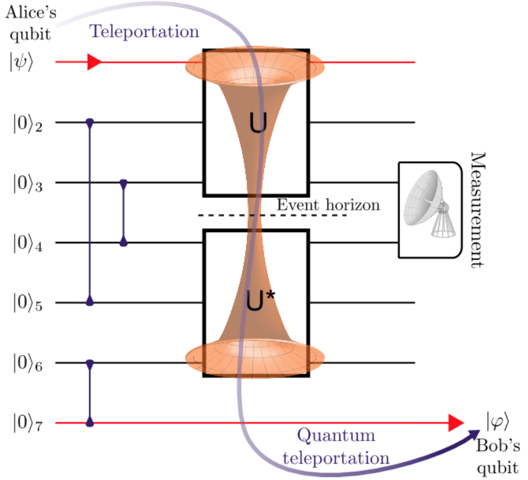
## MILESTONES:

- 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)

# Cosmos and Qubits

## Powerful new windows to accomplish HEP mission & advance QIST






**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**

**Cosmos**
**and**
**Qubits**

# 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.

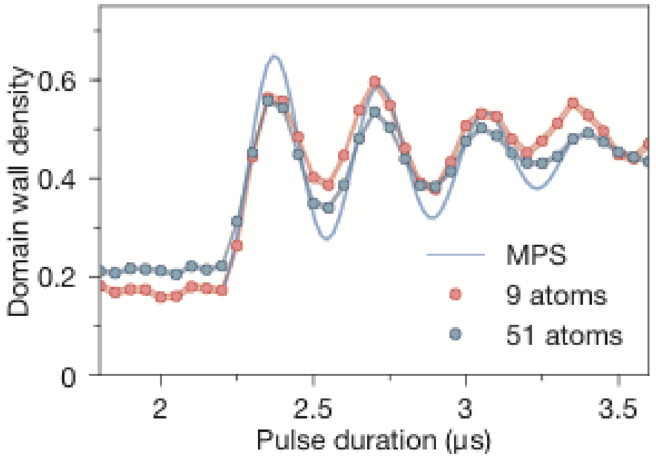
### "Learning the alpha-bits of black holes"

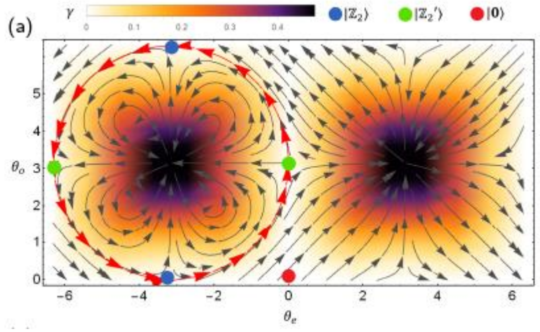
Applications of the recently developed theory of universal subspace QEC to the reconstruction of black hole microstates in AdS/CFT duality. Explains how the approximate error-correcting code underlying the bulk-to-boundary dictionary becomes exact in the semi-classical limit.

# Discovery of Quantum Many-body Scars

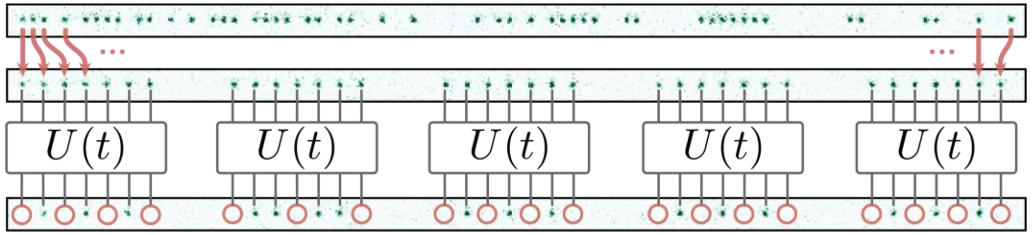
*Experiments on programmable Rydberg atom simulator: Vuletic-Lukin DoE/DoD pilot*

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



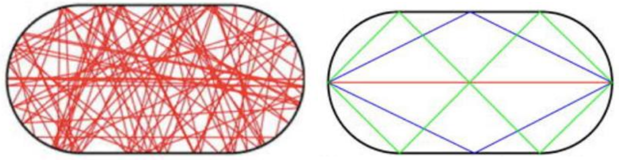

Description in terms of locally entangled Matrix Product States [3]



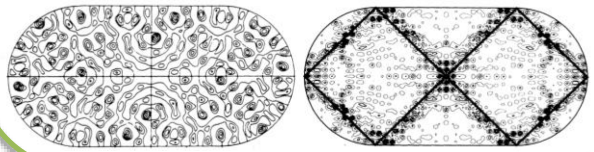

*Explanation in terms of quantum many-body scars: states embedded throughout the thermalizing many-body spectrum, but exhibit robust dynamics [2]*

*Quantum scars: eigenstates resembling classical periodic orbits in chaotic system*

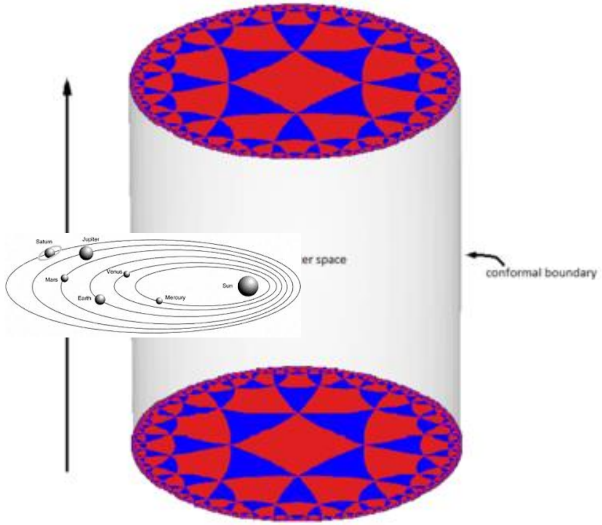
Classical trajectories in a stadium:



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**

# The Dark Matter Radio: First Pilot operation with Q=148,000

*PI: Kent Irwin, Co-PI: Peter Graham (Nov. 25, 2018)*

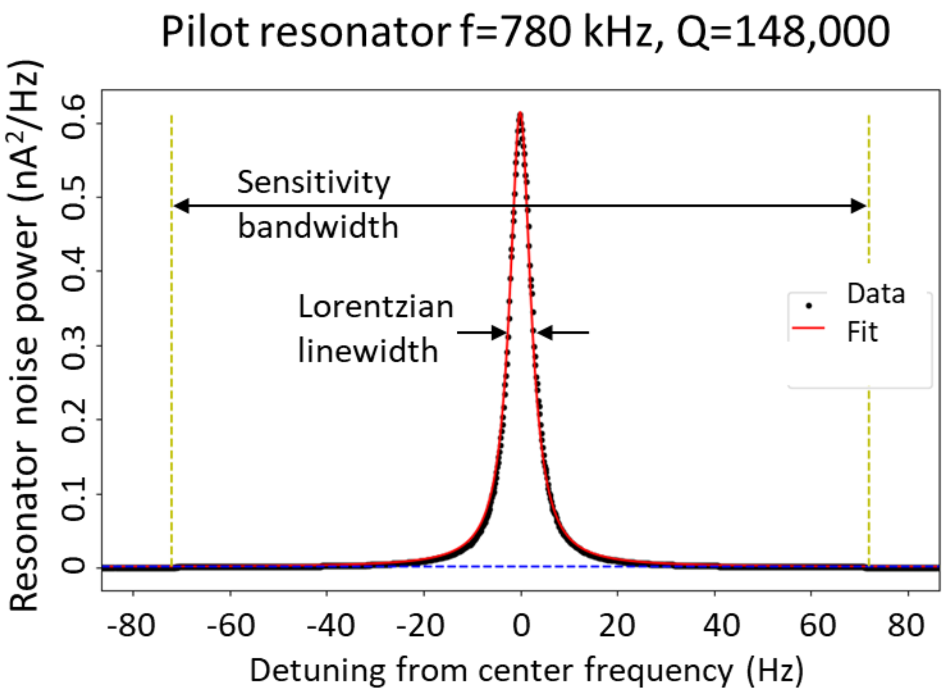
### *The Dark Matter Radio*

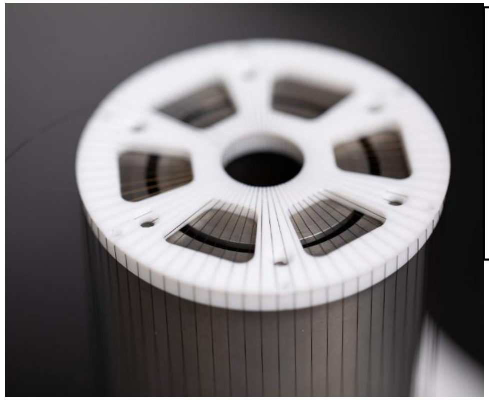
- A quantum-enhanced dark-matter search for axions and hidden photons
- A testbed for quantum sensors

### *Recent Progress with Pilot*

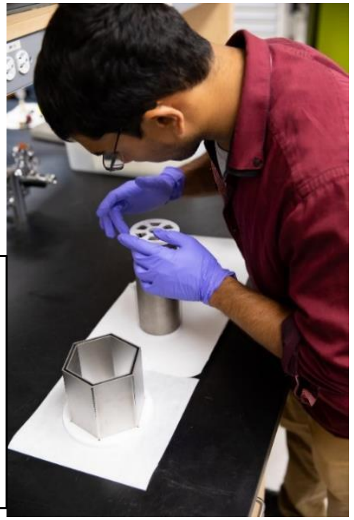
- First cooldown of the DM Radio Pilot
- Demonstrated Q=148,000, limited by calibration coil (which will be removed)
- Setting initial science limit on hidden photons (data under analysis)

- **QuantISED award**



DM Radio Pilot resonator sheath



Assembly of the DM Radio Pilot Resonator

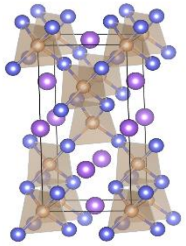
# Progress Highlight: Quantum Sensors HEP-QIS Consortium

*LBNL- UC Berkeley - U. of Massachusetts || M. Garcia-Sciveres PI*

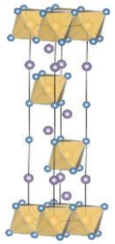
Consortium focuses on extending search for low mass Dark Matter particles by exploiting quantum sensors, QIS techniques, and new target materials

- Examples of existing, understood target materials are liquid He and cryogenic GaAs
- New target materials should have lower energy threshold for excitations and better coupling of excitations to quantum sensors. Try ultra low bandgap materials.
- Expertise and data from outside HEP are critical for this task
- => LBNL Molecular Foundry is a member of the consortium: Sinead Griffin (LBNL MSD), PI.
- Recent highlight: 3 new low mass DM target material candidates identified:

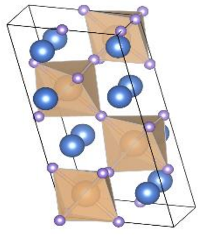
$InCuTe_2$
bandgap
= 27meV



$SrSn_2As_2$
bandgap
= 68meV



$Li_6Bi_2O_7$
Bandgap
= 146meV



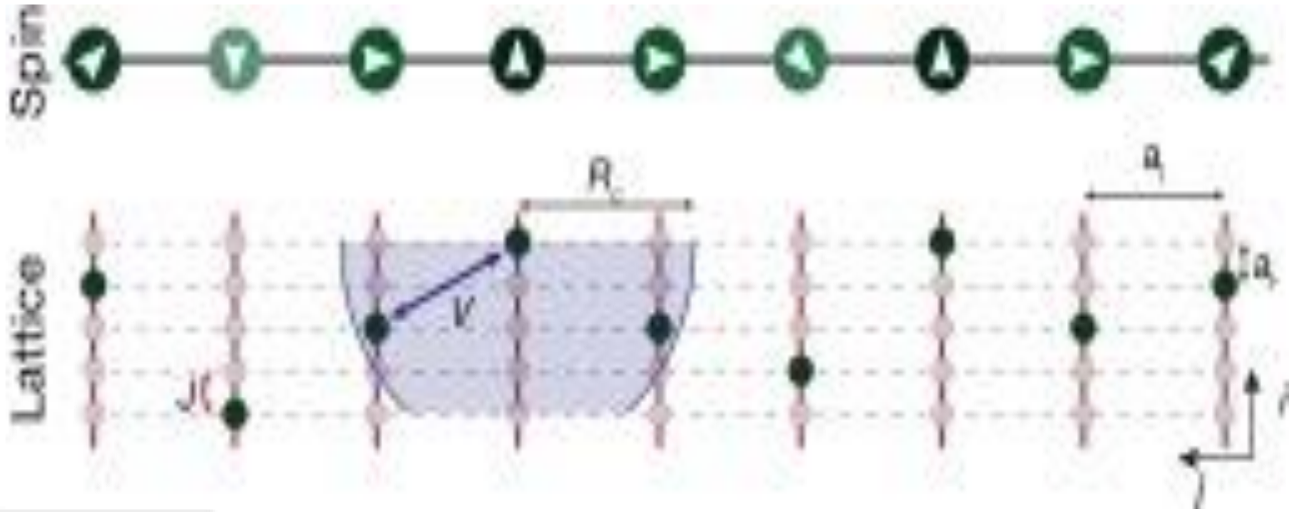
- Work made use of 86K compound MATERIALS PROJECT database together with novel use of spin-orbit splitting to generate small bandgaps
- **This collaboration would not have happened without QuantISED funding.**

# Quantum Simulation of the Universal Features of the Polyakov loop – QuantISED project

*Jin Zhang, J. Unmuth-Yockey, J. Zeiher, A. Bazavov, S.-W. Tsai, and Y. Meurice*

**Physical Review Letters, in press**

The ultimate goal of ``quantum simulations'' is to provide answers to open questions that cannot be answered using classical computers. Some quantum simulations use actual physical systems of cold atoms trapped in optical lattices, whose interactions are engineered using Rydberg atom techniques. The authors' work outlines an experimental strategy for quantum simulating the ``Abelian Higgs model.'' The main idea is to use a ladder structure sketched in the picture below. The short direction represents the spin degrees of freedom.

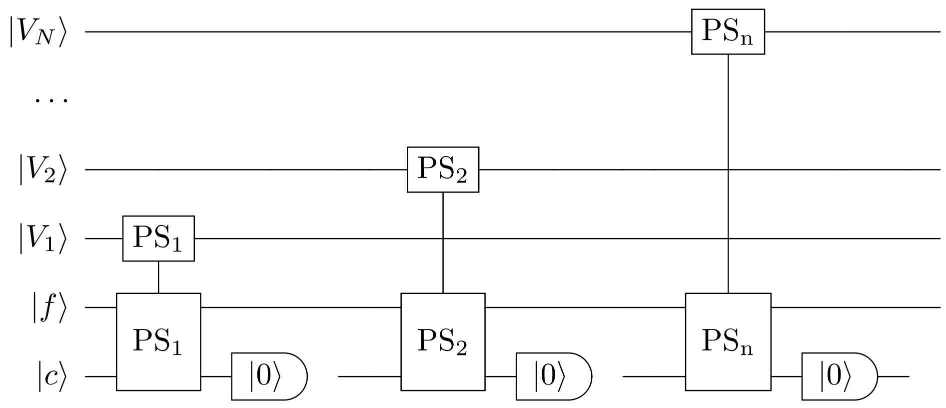


# Quantum Algorithm for parton shower

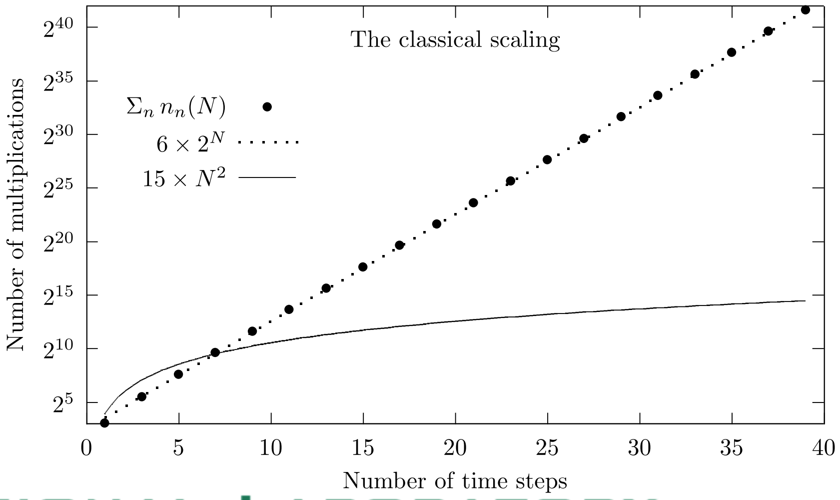
## PI C. Bauer

- Main goal: Develop quantum algorithms that allow for event simulation that can not be achieved efficiently using classical algorithms
- Developed simple HEP inspired model: single fermion that can either emit gauge boson or switch chirality.
- Choose NT time-steps and study scaling as NT→∞
- Best classical algorithm we found scales as $2^{NT}$, while quantum algorithm scales as $NT^2$ (exponential speedup)

Quantum circuit



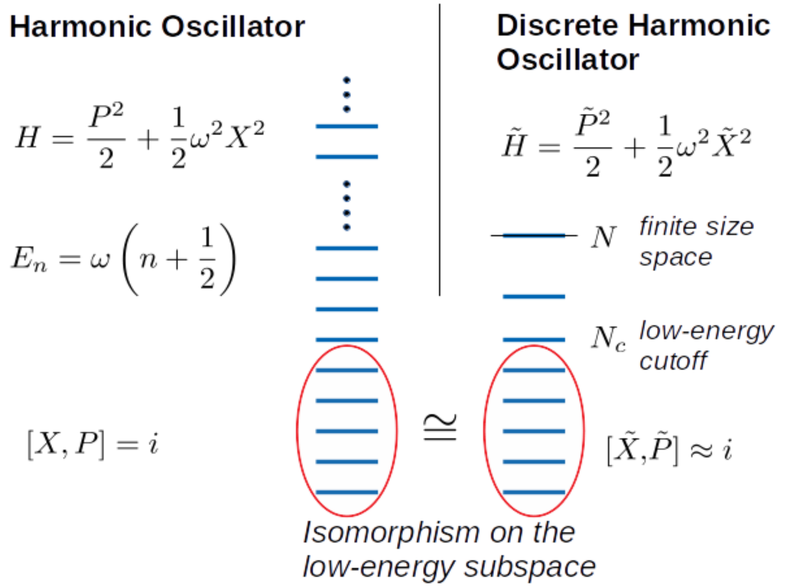

Scaling with NT



# Field Theory research: from fermions to bosons to gauge theories

## *FermiLab Pilot and QuantISED Award*

- Quantum simulations of many-fermion systems promising on near-term devices
- But bosons on qubits are challenging (accuracy and efficiency of resources)
  - Need bosons for quantum simulations of HEP problems
- Fermilab pilot: **new approach** for fermion-boson systems: boson representation in the coordinate basis (achieving exponential accuracy!)
  - efficient on quantum computers!
  - tested using **Quantum Phase Estimation** on the ATOS @ ANL and Google simulators
    - Holstein polaron model (simple enough to benchmark)
- Next step: investigate QCD applications (calculation of localized quantities)




*A. Macridin, P. Spentzouris, J. Amundson, R. Harnik,* **Phys. Rev. Lett. 121, 110504, 2018**

*A. Macridin, P. Spentzouris, J. Amundson, R. Harnik,* **Phys. Rev. A 98, 042312, 2018**

# Algebraic approach towards quantum information in quantum field theory and holography - *QuantISED award*

## Science goals

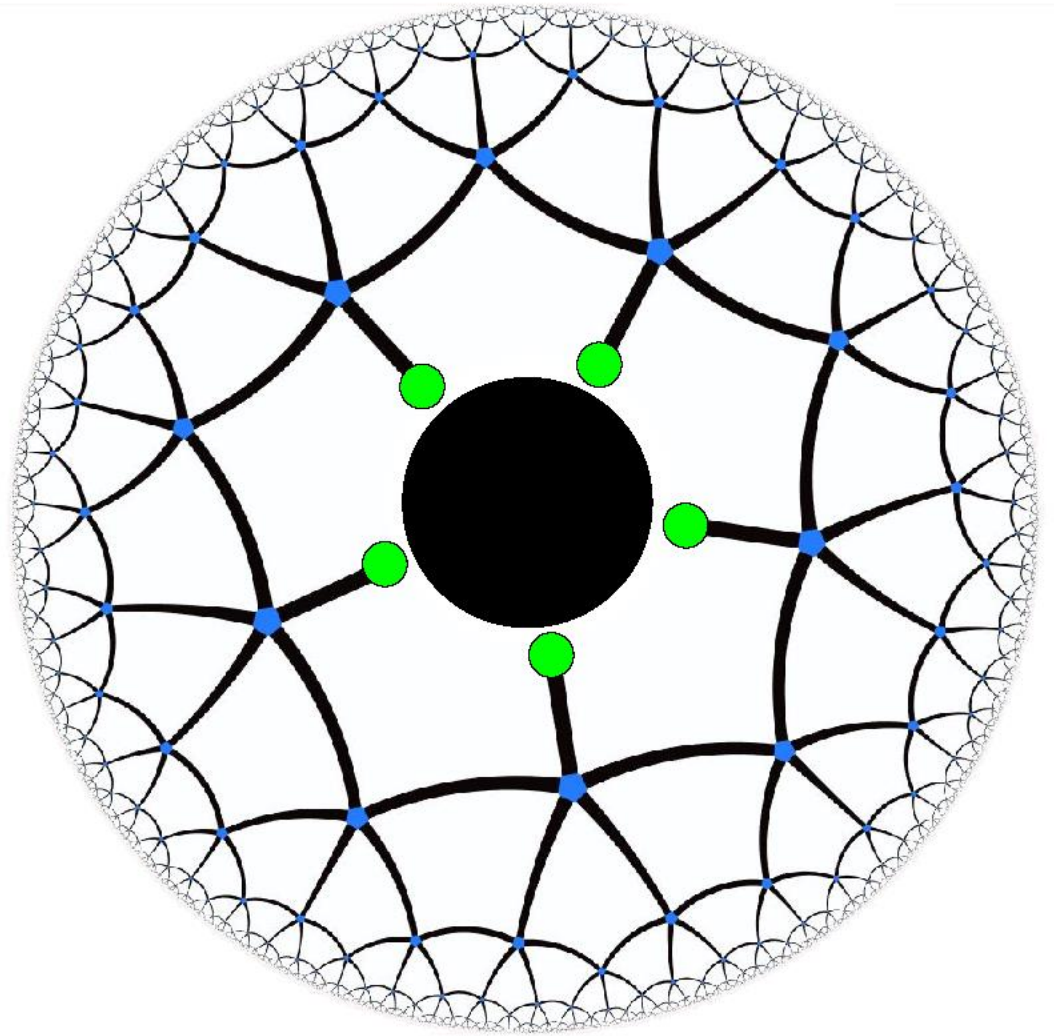
**Daniel Harlow**, Aram Harrow, Hong Liu (MIT)

- How is bulk information in holography encoded in the boundary description?
- What do new bounds relating local energy and entropy teach us about many-body dynamics and gravity?
- Does holography give us a new way of generating approximately-Markov states that are useful for quantum computation?
- What can be learned about all of these questions using operator-algebraic methods?

**Using entanglement to forbid global symmetries in quantum gravity – hep-th/1810.05337**

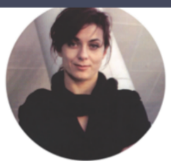
**A flat Renyi spectrum in quantum gravity at fixed area – hep-th/1811.05382**

**Algebraic relative entropy in simple quantum field theories – hep-th/1811.05052**



# QCCFP: Quantum Communication Channels for Fundamental Physics

- ❑ Theoretical study black hole entanglement link (wormhole) protocols
- ❑ Implementation of protocols on available quantum computation platforms (e.g. CIRQ)
- ❑ Quantum teleportation/ quantum network experiments and advanced protocol implementation in the lab.



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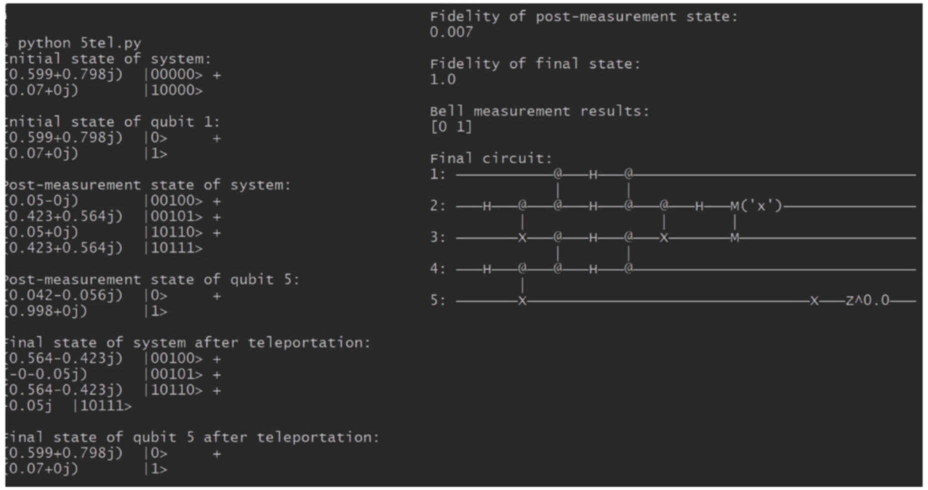
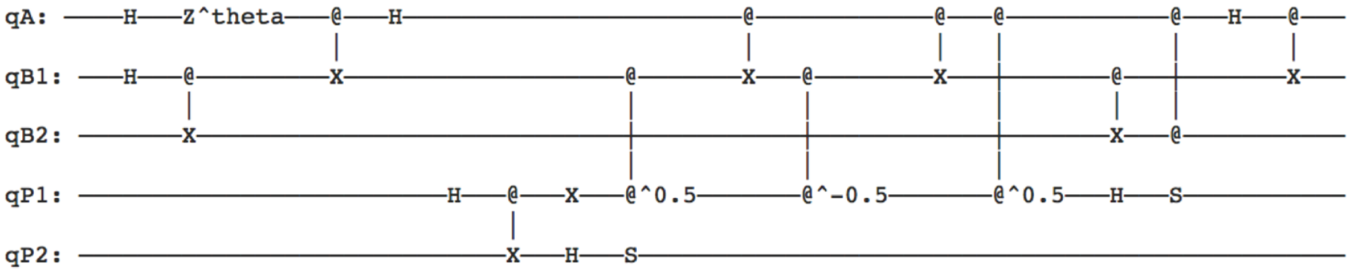
## Example of protocols run on CIRQ

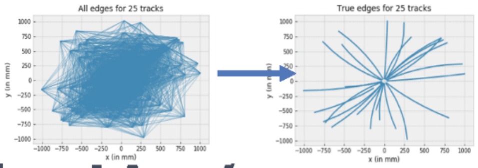


```
$ python 5tel.py
Initial state of system:
(0.599+0.798j)  |00000> +
(0.07+0j)       |10000>

Initial state of qubit 1:
(0.599+0.798j)  |0>     +
(0.07+0j)       |1>

Post-measurement state of system:
(0.05-0j)       |00100> +
(0.423+0.564j)  |00101> +
(0.05+0j)       |10110> +
(0.423+0.564j)  |10111>

Post-measurement state of qubit 5:
(0.042-0.056j)  |0>     +
(0.998+0j)      |1>

Final state of system after teleportation:
(0.564-0.423j)  |00100> +
(-0-0.05j)      |00101> +
(0.564-0.423j)  |10110> +
-0.05j  |10111>

Final state of qubit 5 after teleportation:
(0.599+0.798j)  |0>     +
(0.07+0j)       |1>

Fidelity of post-measurement state:
0.007

Fidelity of final state:
1.0

Bell measurement results:
[0 1]

Final circuit:
1: ───────────@───H───@──────────────────────────
              │       │
2: ───H───@───@───H───@───@───H───M('x')─────────
          │               │       │
3: ───────X───@───H───@───X───────M──────────────
              │       │
4: ───H───@───@───H───@──────────────────────────
          │
5: ───────X───────────────────────────X───Z^0.0──
```



# QMLQCF: Quantum Machine Learning and Quantum Computation Frameworks for HEP

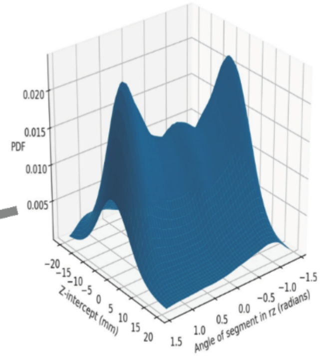
## Pioneering Pilot




## 'Quantum Tracking'

Represent each edge as a binary variable (s = 1 or 0, on or off)

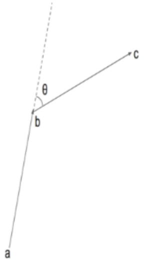
Create quadratic unconstrained binary problem that considers individual edges and doublets of adjacent edges




Geometric edge affinity score

$$E = -\frac{1}{2}\left(\sum_{ab}(\alpha P(s_{ab}) - \beta)s_{ab} - \sum_{ab,bc}\cos^{\lambda}(\theta)s_{ab}s_{bc}\right)$$

Beam term | Inhibition term | Connection term

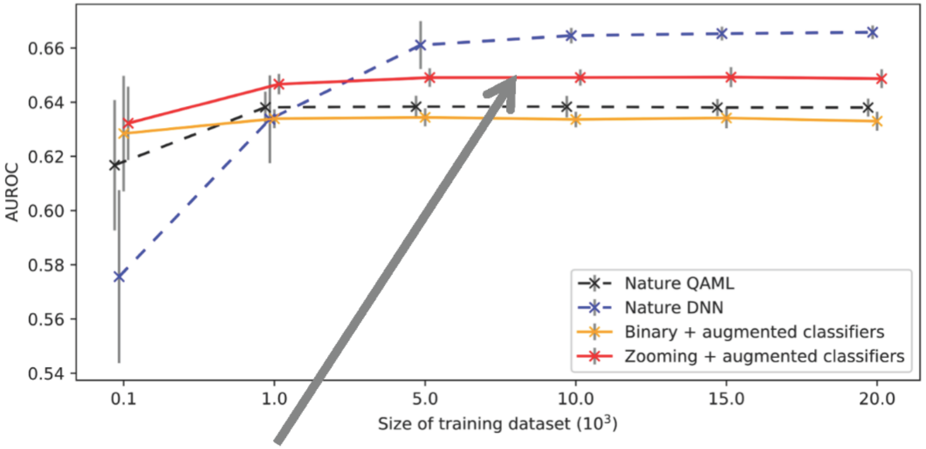



Cast the trajectory pattern recognition using an Hopefield approach as a QUBO problem. Solved with D-Wave and Simulated annealing.

→ACAT 2019 https://indico.cern.ch/event/708041/abstracts/95103/
→CtD 2019 https://indico.cern.ch/event/742793/abstracts/94976/

**Quantum annealing mitigates some of the scaling problems classical algorithms face**

## Continuous QAML




### Improvement: Zooming Algorithm

- Strong classifier: $R(\mathbf{x}_\tau) = \sum_i^N \mu_i c_i(\mathbf{x}_\tau)$
- Substitution: $s_i c_i(\mathbf{x}_\tau) \to \sigma_i s_i c_i(\mathbf{x}_\tau) + \mu_i c_i(\mathbf{x}_\tau)$
- Hamiltonian: $H = 2\sum_{i=1}^N s_i\sigma_i\left(-C_i + \sum_{j=1}^N \mu_j C_{ij}\right) + 2\sum_{i=1}^N\sum_{j>i}^N s_i s_j \sigma_i \sigma_j C_{ij}$

Boosting approach to the method applied on the Nature paper
https://doi.org/10.1038/nature24047

Caltech | MIT | USC | inqnet Alliance for Quantum Technologies | Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

# Future Opportunities – Stay Tuned

- **HEP –QIS strategy aligned to SC QIS Strategy & National Initiative**
- **Office of Science (SC) also had Calls from BES and ASCR**
- **HEP-QIS is competed separately from the traditional HEP sub programs**
- **Requires interdisciplinary partnerships**
- **Future opportunities are anticipated for 2019**
- **May have inter - office SC partnerships**
- **Awaiting updates on QIS Legislation and related DOE plans**
- **SC QIS PI Meeting Jan 31-Feb 1, 2019**

  (Limited Space as multi- program)
- HEP-QIS PIs and co -PIs also welcome to HEP PI Meeting in Summer 2019

**QIS for HEP & HEP for QIS**

# Back Up

# 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!**

**Industry has made available test systems and there are exploratory systems in academia and Labs. As we move forward the QIST confluence of QUANTUM**

***theory*information*entanglement*experiment*simulation*computing*technology …**

**will help explore the unknown and other science drivers and a lot more along the way.**

# International Competition in HPC Continues to Intensify – Slide from B. Helland

## China will open a $10 billion

## Russian Researchers Claim First Quantum-Safe Blockchain

## University of Melbourne joins IBM's quantum computing club

## Quantum Technologies: A £1 billion future industry for the UK

## Japan enters quantum computing race -- ar offers free test drive

### Quantum Canada Vision

*A vibrant Canadian quantum ecosystem with world-leading R&D, innovative technologies, and globally reaching Canadian companies – all driving social, economic, and environmental solutions for Canada*

## Europe's billion-euro quantum project takes shape

## Engineering of Swedish Quantum Computer Set to Start

| # | Site | Manufacturer | C… | | | | |
|---|---|---|---|---|---|---|---|
| | | | …nw… C… 260C 1.45GHz | | | | |
| | | | Tianhe-2 …DT TH-IVB-FEP, …C 2.2GHz, IntelXeon Phi | China | 3,120,000 | 33.9 | 17.8 |
| | | | Piz Daint Cray XC50, 2.6GHz, Aries, NVIDIA Tesla P100 | Switzerland | 361,760 | 19.6 | 2.27 |
| 4 | Japan Agency for Marine Earth-Science and Technology | ExaScaler | Gyoukou | | | | 1.35 |
| 5 | Oak Ridge National Laboratory | Cray | | | | | …21 |
| | Lawrence Livermore | | Se… Blue… …er BQC 1… | | | | |
| | | | T… Cra… …on Phi 7250 68C 1.4GHz, Aries | | | | |
| | | | Cori Cray XC40, …s Phi 7250 68C 1.4 GHz, Aries | USA | 622,336 | 14.0 | 3.94 |
| | | | Oakforest-PACS …RIMERGY CX1640 M1, …Phi 7250 68C 1.4 GHz, OmniPath | Japan | 556,104 | 13.6 | 2.72 |
| 10 | RIKEN Advanced I… Computational S… | | | | | | |