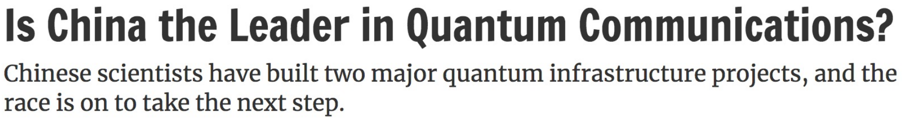
The Fermilab Quantum Science and Technology Program

Panagiotis Spentzouris
ICEPP Quantum Seminar
18 November 2021

Quantum Information Science and Technology (QIS&T)

QIS&T exploits quantum properties and elements of information science to acquire, communicate, and process information **beyond classical capabilities**. Very impressive progress in the last few years (even after allowing for amplification via media hype …)

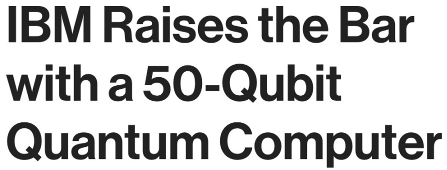


Is China the Leader in Quantum Communications?

Chinese scientists have built two major quantum infrastructure projects, and the race is on to take the next step.

Intel's New Chip Aims For Quantum Supremacy

The troubled chipmaking giant is one of the first to build a quantum computing chip that can outrun a modern classical supercomputer.



IBM Raises the Bar with a 50-Qubit Quantum Computer

COMMENT 9 February 2018

Is the quantum computer revolution really just five years away?

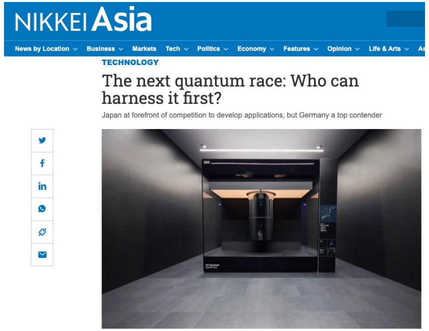
Article | Published: 23 October 2019

Quantum supremacy using a programmable superconducting processor

Frank Arute, Kunal Arya, […] John M. Martinis

Nature **574**, 505–510(2019) | Cite this article

Researchers Have Achieved Sustained Long-Distance Quantum Teleportation

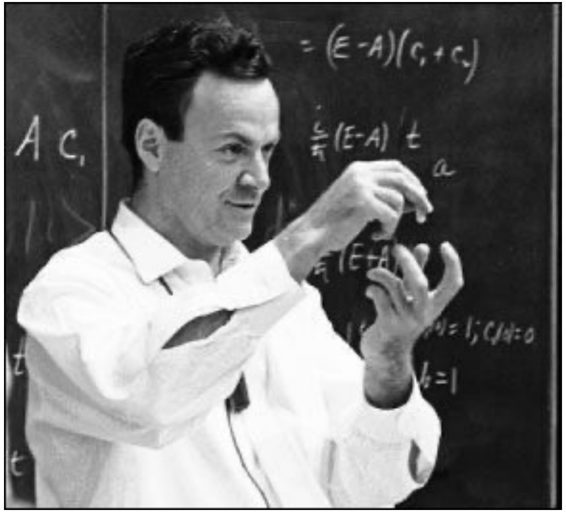


TECHNOLOGY

The next quantum race: Who can harness it first?

Japan at forefront of competition to develop applications, but Germany a top contender

Richard Feynman: the need for quantum computing (1981)



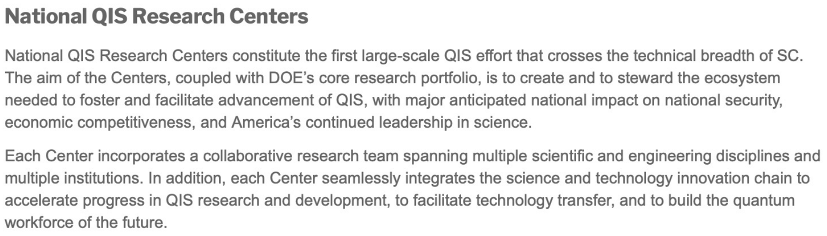
“Nature isn’t classical, dammit, and if you want a simulation of nature, you’d better make it quantum mechanical”

- First person to propose the idea of **quantum computers**

- Emphasized the idea of using quantum systems to simulate/solve quantum problems

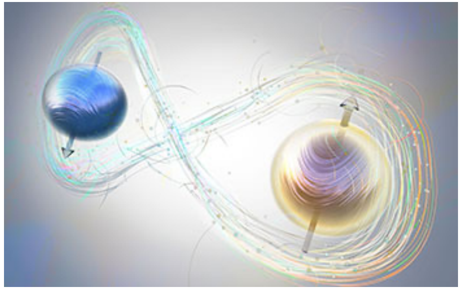
US National Quantum Initiative

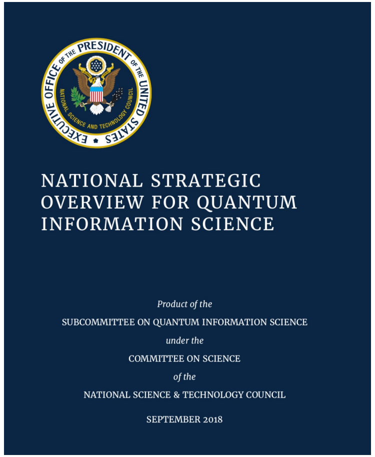
- **2018 White House summit announced major new quantum science initiatives**
  - DOE/SC first round ~$220M, also NSF and NIST
  - In addition, Congress authorized up to five DOE National Research Centers
- **End of summer 2020, DOE awards five National Quantum Research Centers (~$600M) and NSF three Quantum Institutes (~$75M) with five-year programs**


National QIS Research Centers

National QIS Research Centers constitute the first large-scale QIS effort that crosses the technical breadth of SC. The aim of the Centers, coupled with DOE's core research portfolio, is to create and to steward the ecosystem needed to foster and facilitate advancement of QIS, with major anticipated national impact on national security, economic competitiveness, and America's continued leadership in science.

Each Center incorporates a collaborative research team spanning multiple scientific and engineering disciplines and multiple institutions. In addition, each Center seamlessly integrates the science and technology innovation chain to accelerate progress in QIS research and development, to facilitate technology transfer, and to build the quantum workforce of the future.




EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES

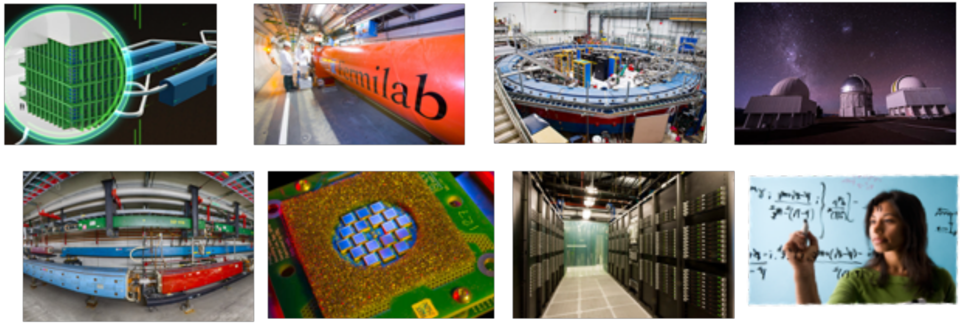
NATIONAL STRATEGIC OVERVIEW FOR QUANTUM INFORMATION SCIENCE

Product of the
SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE
under the
COMMITTEE ON SCIENCE
of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

SEPTEMBER 2018

Fermilab and Quantum Science & Technology

HEP science with neutrinos, the LHC, muons, and the cosmos



Underpinned by strong competencies in accelerator and detector science and technology, computing, and theory

Our **science goals** demand ever increasing precision instruments, driving the need for **innovative techniques and technologies**

Many fundamental **HEP** research areas can **benefit** from successful Quantum Science and Technology **(S&T) applications** and many **HEP competencies** and **technologies** can **advance quantum S&T**

Establishing a new and rapidly advancing program. First awards received Sep 2018 (DOE/HEP **QuantISED**), the **NQI center** awards (summer 2020) demonstrate the program maturation and success.

Approach for early program

Goal: Produce high impact quantum science results in the near term, while building capacity for HEP needs in the long term

Engage with the DOE/SC QIS Initiative in ways appropriate to our role (main US HEP lab)

- Focus on the science
- Keep activities aligned to HEP program needs
- Leverage existing Fermilab expertise and infrastructure
- Engage partners who already have leading QIS expertise
- Act as a gateway and hub for the larger HEP community to engage with QIS

Success: Strategy and early program investment and activities resulted to a Fermilab led NQI Center (**SQMS**) and major role in the ORNL led NQI Center (**QSC**)

Fermilab Quantum Science Program Thrusts, early program

Superconducting Quantum Systems: Leverage Fermilab's world-leading expertise in SRF cavities to advance qubit coherence times and scalability of superconducting quantum systems.

HEP Applications of Quantum Computing: Identify most promising HEP applications on near-term quantum computers; develop algorithms and experience with state-of-the-art machines.

Quantum Sensors: Adapt quantum technologies to enable new fundamental physics experiments.

- Qubit-cavity systems for dark matter detection
- Cold atom interferometry

Quantum Communications: quantum teleportation systems and entanglement distribution architecture for connecting quantum sensors and computers

Enabling technologies: cold electronics, readout & control systems; access to quantum resources for community building and workforce development

Foundational Quantum Science/HEP connections: quantum field theory, wormholes, emergent space-time.

Quantum communications and networks bring new capabilities and enable new applications

Crypto functions

Quantum Key Distribution
Leader election
Byzantine agreement
…

Low bandwidth

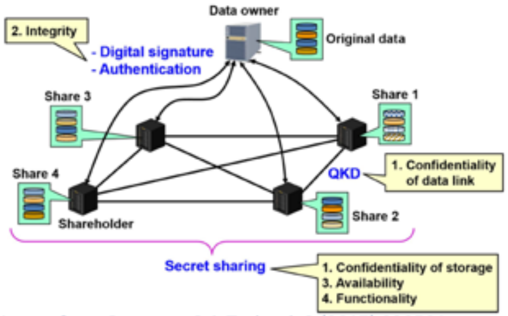


Image from Quantum Sci. Technol. 2 (2017) 020501

Sensing

Distributed clocks
Interferometry
- optical and IR telescope arrays
- Cosmology

…

High bandwidth

Quantum Computing (QC)

Blind QC
Client-server QC
Distributed QC
…

High to very high bandwidth

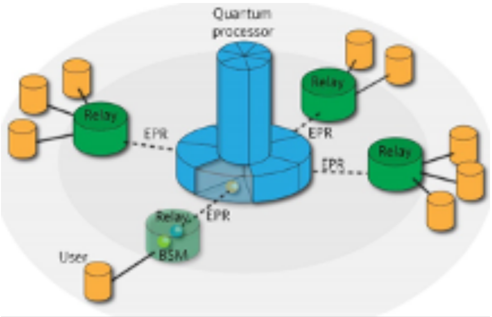


Image from *Nature Photon* **10**, 671–675 (2016).
https://doi.org/10.1038/nphoton.2016.179

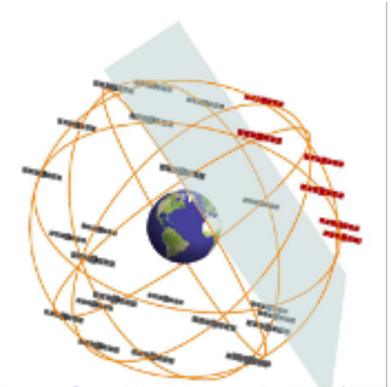


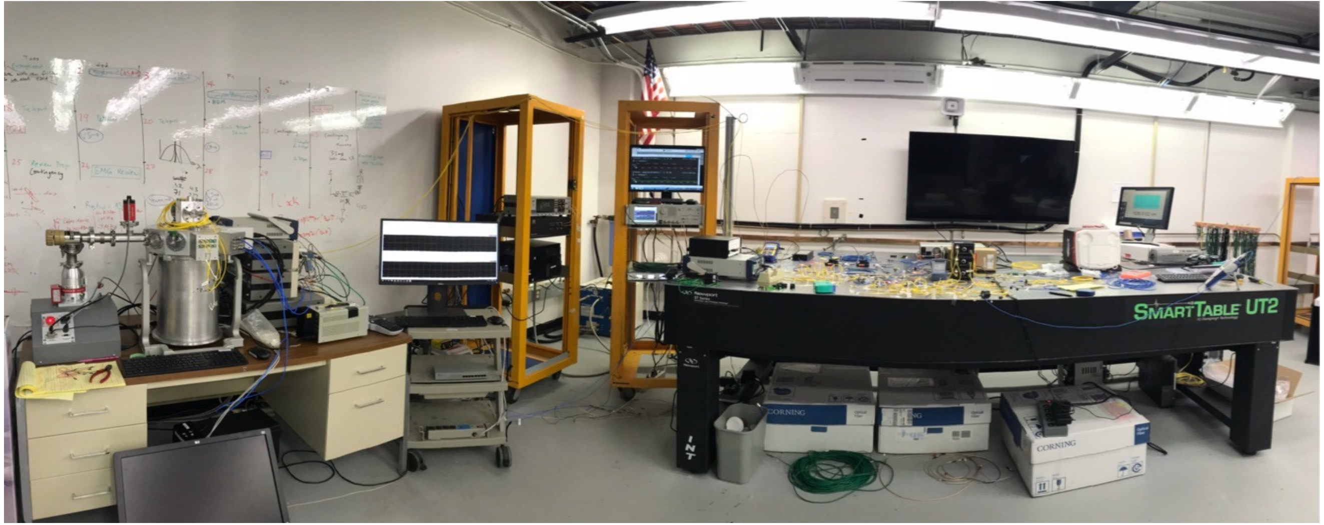
Image from Nat Commun **8**, 1195 (2017).

FQNET/CQNET experiments

Deploy a teleportation link using optical photonic qubits over telecom fiber, off the shelf components, cutting edge single photon detectors, and electronics and control systems developed for HEP experiments

- Aim to achieve best long range, high fidelity, high-rate quantum teleportation system
  - Project inception **2017**

FQNET



inqnet
ALLIANCE FOR QUANTUM TECHNOLOGIES

Caltech

JPL

AT&T

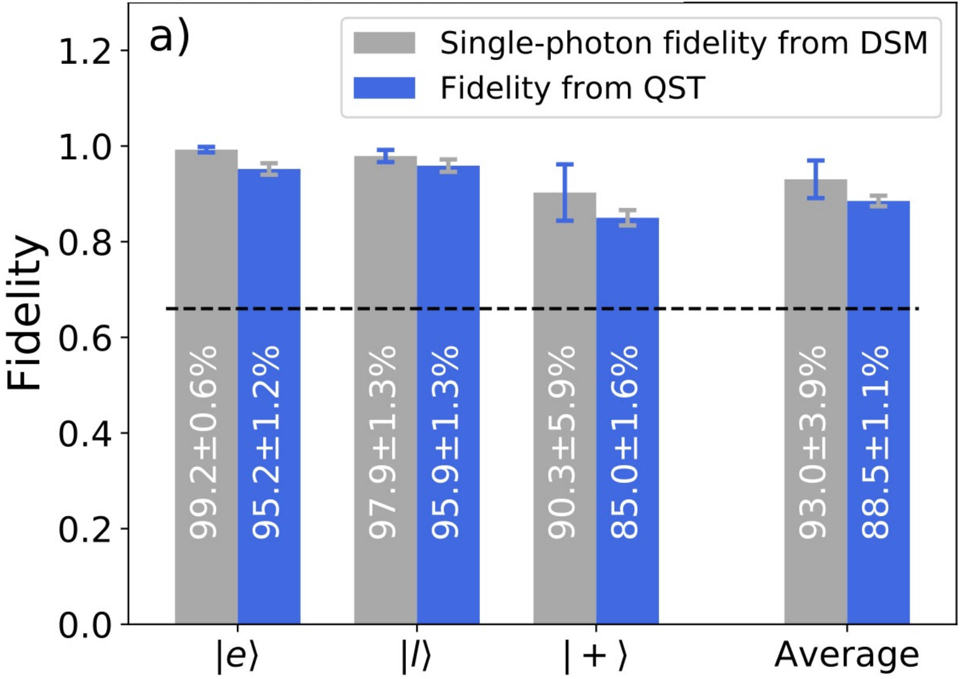
Fermilab

Record fidelity sustained teleportation

Results

- **Record** time-bin qubit teleportation fidelities over metropolitan scale distance of 44 km.
- **Sustained** 24/7 operation for ~week duration, achieving ~1HZ teleportation rate at 44 km

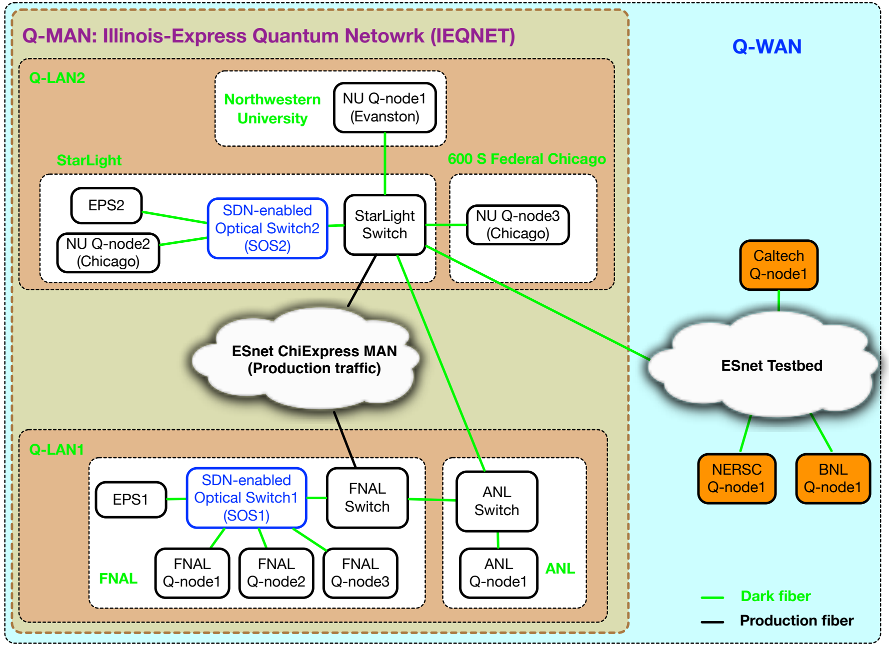
CQNET/FQNET 2020

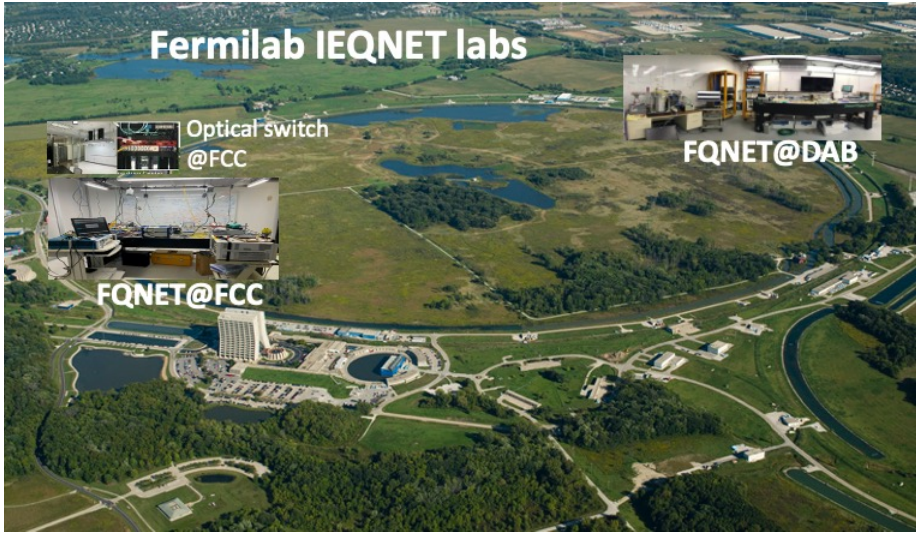


R. Valivarthi et al., PRX Quantum 1, 020317 (2020).

Network technology development: IEQNET

web site: https://ieqnet.fnal.gov



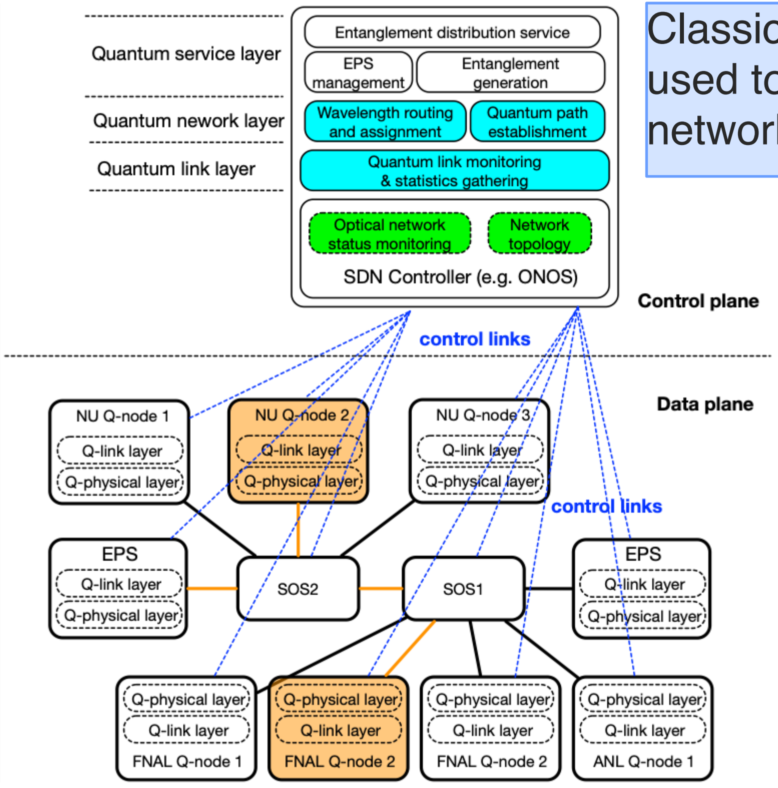


The IEQNET collaboration

Fermilab
Argonne National Laboratory
Caltech
Northwestern University
HYPERLIGHT
NuCrypt

- Design a **repeaterless transparent optical quantum network** and demonstrate multi-user use-cases in the Chicago metropolitan area
  - Leverage FQNET/CQNET systems
- **Incorporate new components** as they become available and test/co-design

IEQNET architecture and demonstrators



Quantum service layer

Quantum nework layer

Quantum link layer

Entanglement distribution service

EPS management

Entanglement generation

Wavelength routing and assignment

Quantum path establishment

Quantum link monitoring & statistics gathering

Optical network status monitoring

Network topology

SDN Controller (e.g. ONOS)

Control plane

control links

Data plane

NU Q-node 1 | Q-link layer | Q-physical layer

NU Q-node 2 | Q-link layer | Q-physical layer

NU Q-node 3 | Q-link layer | Q-physical layer

control links

EPS | Q-link layer | Q-physical layer

SOS2

SOS1

EPS | Q-link layer | Q-physical layer

Q-physical layer | Q-link layer | FNAL Q-node 1

Q-physical layer | Q-link layer | FNAL Q-node 2

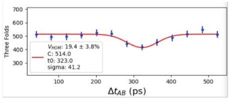
Q-physical layer | Q-link layer | FNAL Q-node 2

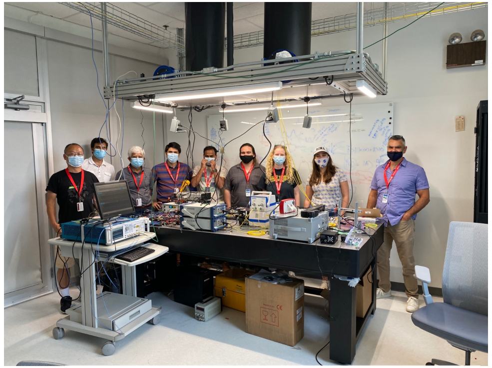
Q-physical layer | Q-link layer | ANL Q-node 1

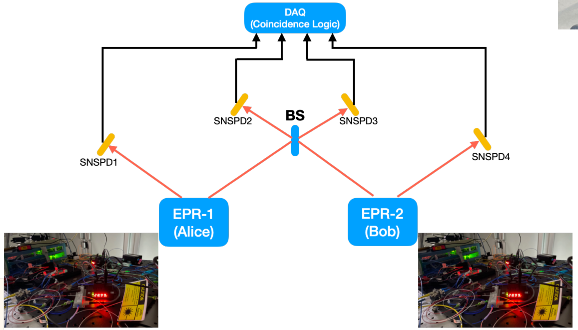
J. Chung, et al., in Quantum Information Science, Sensing, and Computation XIII vol. 11726, pp. 1 { 9, International Society for Optics and Photonics, SPIE, 2021.}

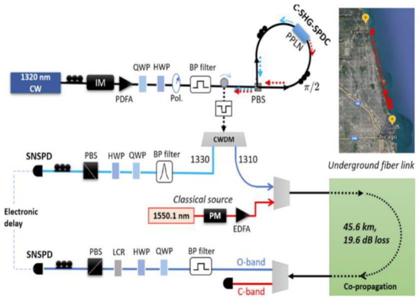
Classical Software-Defined Networking (SDN) technology is used to decouple the control and data planes and perform network functions through transparent optical switches.

Demonstrate entanglement distribution @ local and metropolitan scale



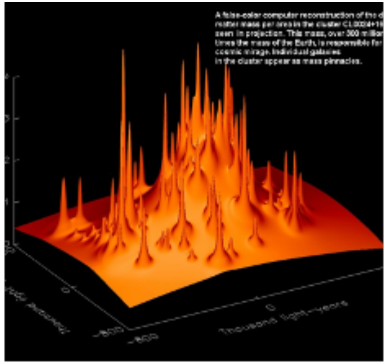




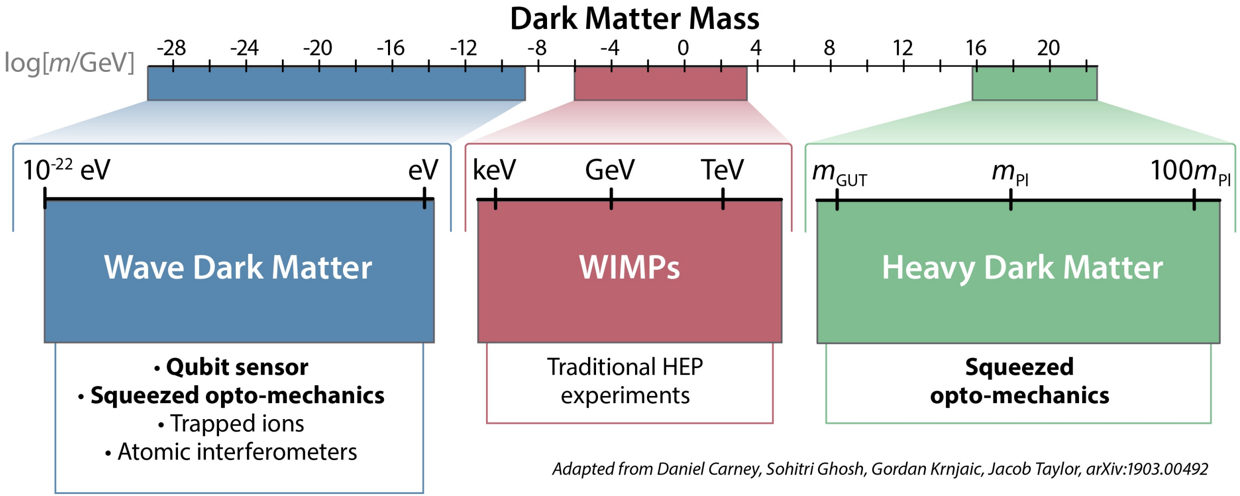


Qubits as sensors for dark matter detection

- So far everything we know about dark matter is from its gravitational effects out in the cosmos
- No one has detected dark matter particles in the laboratory
- Dark matter mass is almost completely unknown



Distribution of dark matter needed to explain the lensing



Wave Dark Matter

- **Qubit sensor**
- **Squeezed opto-mechanics**
- Trapped ions
- Atomic interferometers

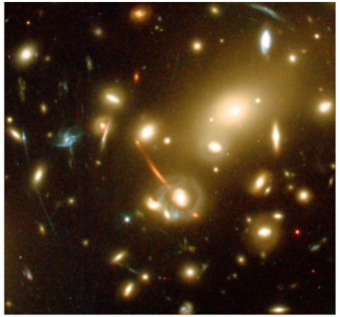
WIMPs

Traditional HEP experiments

Heavy Dark Matter

Squeezed opto-mechanics

Adapted from Daniel Carney, Sohitri Ghosh, Gordan Krnjaic, Jacob Taylor, arXiv:1903.00492

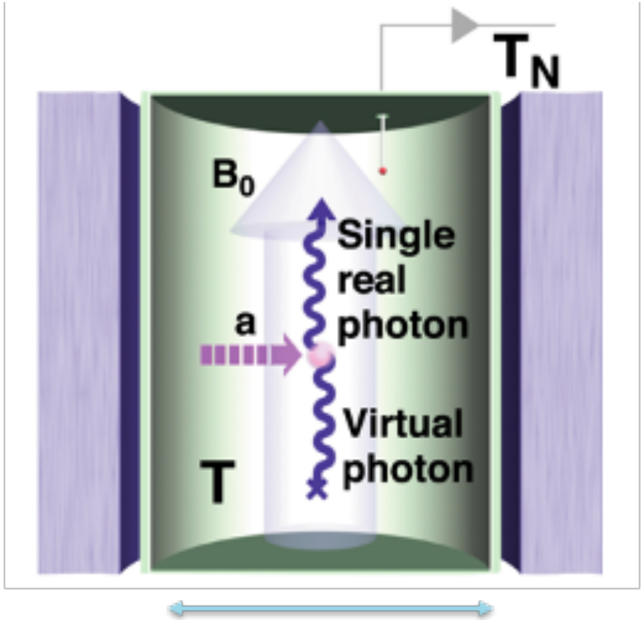


Gravitational lensing by dark matter distorts galaxy images

Axion dark matter interactions

Axion waves can **rotate B-fields into E-fields** (by an angle 10^{-18} degrees)

Use a strong laboratory magnetic field $B_0 \approx 10$ Tesla as the **target** for the dark matter

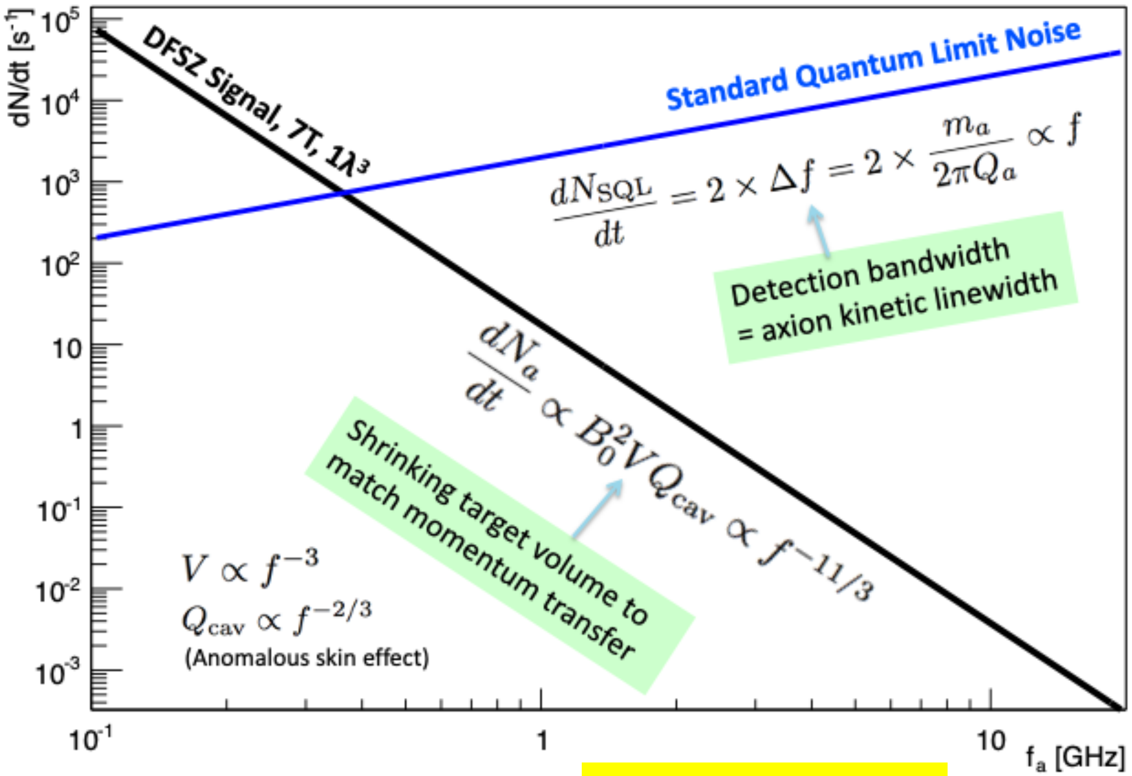


Combined with the B_0 field, the axion wave drives the electric field of a microwave photon wave stored in a shiny mirrored box (**a microwave cavity resonator)**

Expect puny signal power 10^{-23} W or only a few signal photons per second.

Cavity size must be matched to frequency (i.e the mass) of the axion wave.

Sensitivity as a function of axion mass



10 GHz = 40 μeV

Unfortunately, the axion signal/noise ratio plummets as the axion mass increases → **technique does not scale**.

Move from conventional phase preserving amplifiers to photon **number counting** to evade the quantum back-action noise

QuantISED R&D Consortium: Quantum Sensing for Dark Matter

Aaron Chou, lead PI (**FNAL**), David Schuster(**Chicago**): QND readout, non-classical states

Konrad Lehnert (**Colorado**): Squeezed microwave readout, photon transport

Reina Maruyama (**Yale**): Rydberg atom-based single photon detection

Robert McDermott (**Wisconsin**): Cooper pair-breaking sensors

Pierre Echternach (**JPL**): Quantum capacitance single THz photon detector

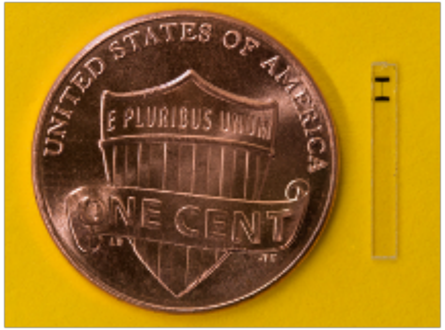
Karl Berggren (**MIT**), Sae Woo Nam (NIST): Superconducting nanowire SPD

Juan Estrada (**FNAL**): SENSEI parametric down conversion for hidden photon search

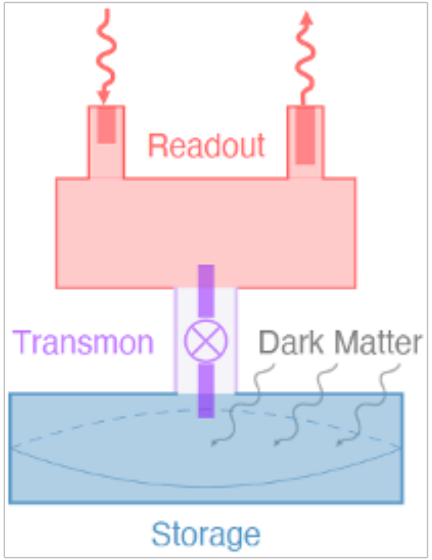
Rakshya Khatiwada (**IIT/FNAL**): single photon detector calibration

Detecting Dark Matter with a Superconducting Qubit

Transmon qubit = artificial atom with large antennae to efficiently couple to signal photons captured in microwave cavities

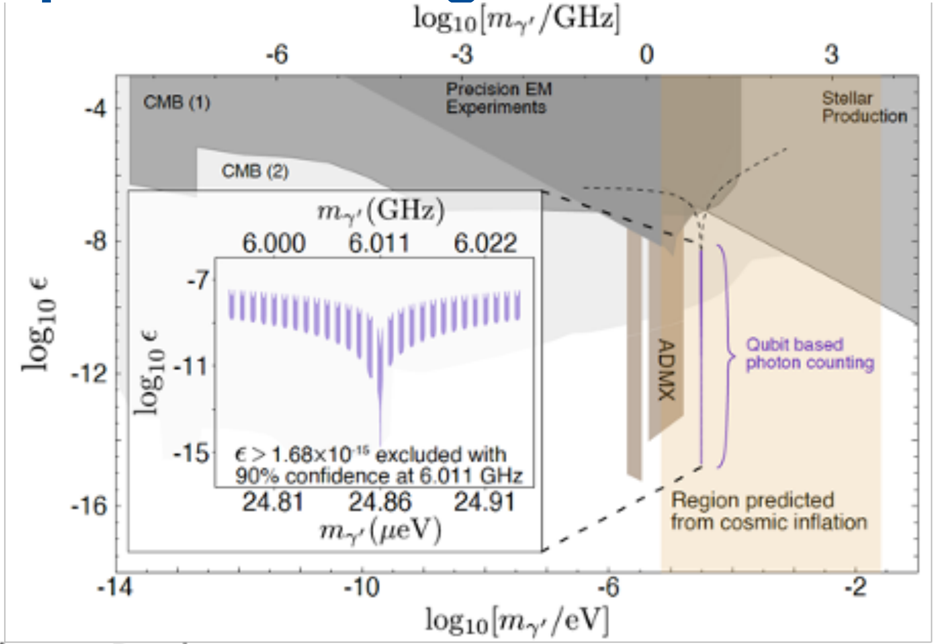


The photon's electric field stretches the qubit and causes its resonant frequency to change.



Single photon signals from dark matter create qubit frequency errors which can be read out with high fidelity QIS techniques.

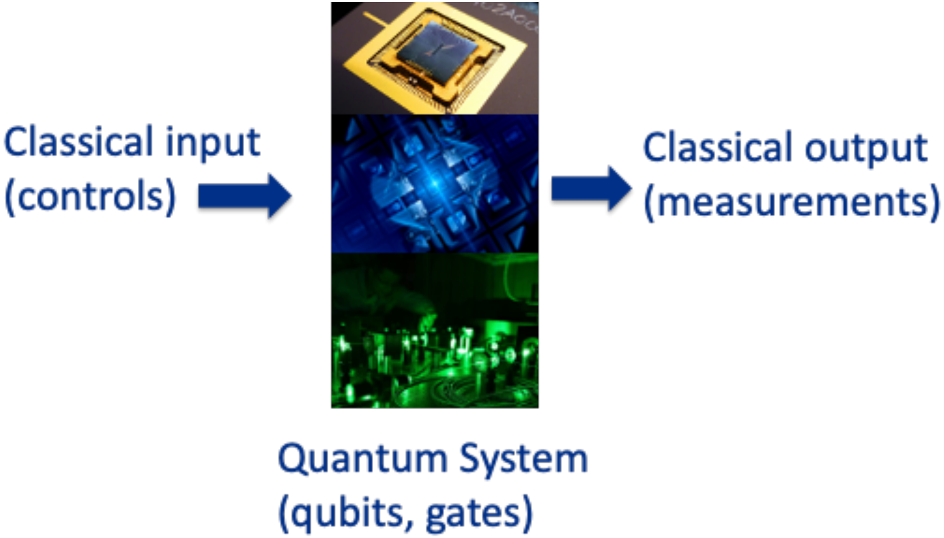
A. V. Dixit, et al., **Phys.Rev.Lett**. 126 (2021) 14, 141302, top 5% of all research papers scored by Altmetric



Results:

- World record quantum sensor noise suppression - **15.7 dB below standard quantum limit**
- World-leading dark photon sensitivity
- 1300x speed-up of future dark matter experiments

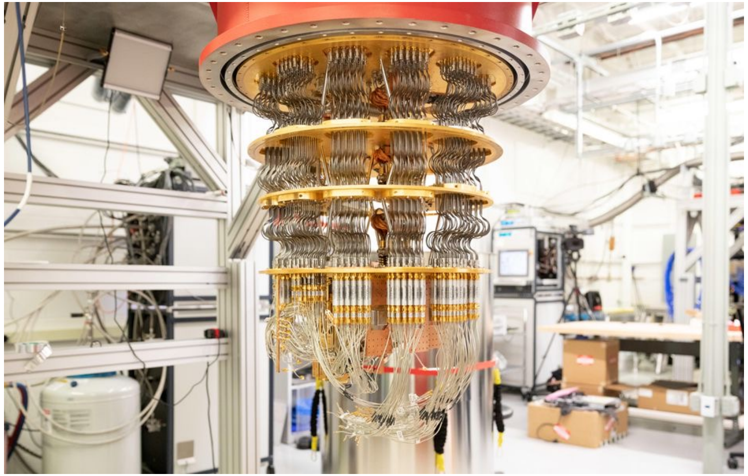
Quantum Systems

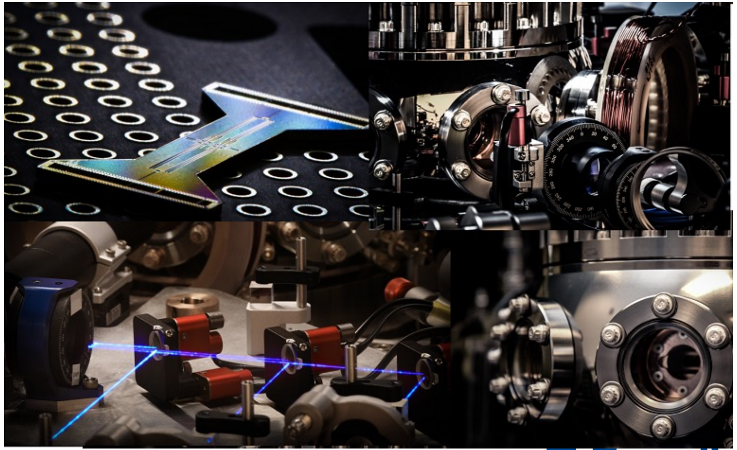


Classical input (controls)

Classical output (measurements)

Quantum System (qubits, gates)





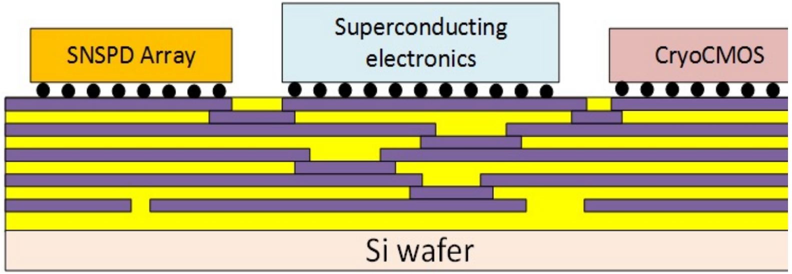
Challenges:

Controllability, coherence, scalability

Cryogenic electronics: major FNAL competency

Objectives:

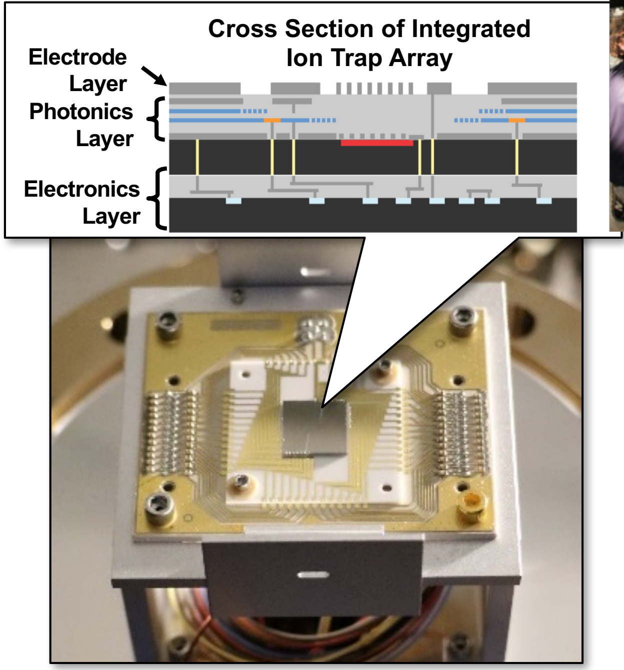
- Scalability of control electronics
  - On-chip, integration
- Scalability of the system
  - From ~100 to 1M qubits
- Performance (gate timing, …)

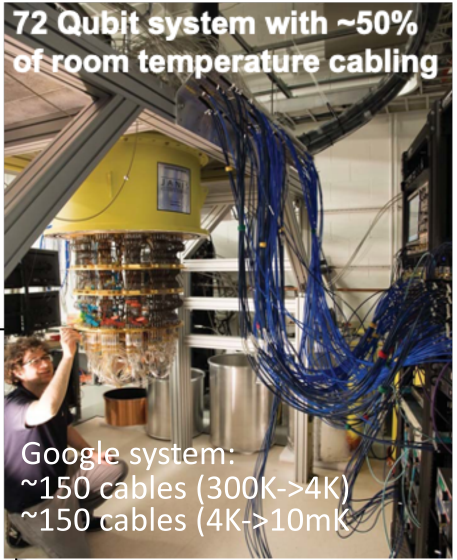


Super Conducting Multi Chip Module carrier

Collaborators: JPL, MIT/LL, SLAC, Georgia Tech, Microsoft, …

Applications: sensors (CCDs, SNSPDs, atomic clocks,…) computers (ion trap, superconducting systems, …)





72 Qubit system with ~50% of room temperature cabling

Google system:
~150 cables (300K->4K)
~150 cables (4K->10mK

Quantum ASICs - creating strategic partnerships

QUANTUM COMMUNICATION

SNSPD: Low Noise amplifier at 4K for 3 ps timing

1st cryoASIC at 4K submitted in Dec 2019 (QuantiSED)

SNSPD: 4M pixel cryogenic readout at 4K photon counting and picosecond timing (detector R&D): [space science applications, dark matter detection, sterile neutrino search]

QUANTUM SENSING

Portable optical atomic clocks

(Joint DOE-DOD development) (QuantiZED)

Skipper CCD readout: 16 channel analog multi-sampling and averaging cryo ASIC for compact, high-speed readout. (OSCURA – 10kg Dark Matter Experiment)

cryoCMOS for Quantum

cryoCMOS tool-kit (100mK – 4K) GF 22 FDX (LDRD)

cryoCMOS workshop @ IEEE Quantum week - Oct 2020

QUANTUM IMAGING

SiSeRo CCD: Novel Devices

Sub-electron noise, MHz – Non-destructive read

Skipper CCD in CMOS

Large area (4M pixel), High speed (1kfps), high resolution (~10um) ultra-low noise camera (< 0.3e-) [BES applications]

QUANTUM COMPUTING

Beyond NISC era scalable QC

Cryoelectronics testbed for 100 – 1000 quantum dots (LDRD)

NQI – Quantum Science Center

Control Cryoelectronics for Ion-Trap based QC

Co-design system for Spin-Liquid simulations

IceQubes 2019: Cryogenic Electronics for QIS

Workshop on Cryogenic Electronics for Quantum Systems

June 17- 20, 2019 • Fermilab

Chair: Prof. Edoardo Charbon, *AQUA Lab, EPFL* • *Co-Chair:* Farah Fahim, *Fermilab*

International Advisory Committee

Eric Dauler, MIT Lincoln Lab, USA
Malcom Carroll, Sandia National Lab, USA
Antonio Liscidini, U. Toronto, Canada
Robert Bogdan Staszewski, UCD, Ireland
John Cressler, Georgia Tech, USA
Joseph Bardin, UMass, USA
Stefano Pellarano, Intel Labs, USA

Fermilab

U.S. DEPARTMENT OF ENERGY | Office of Science

1st international workshop with a focus on cryogenic electronics for QIS

- 73 attendees
- 26 invited talks
- Discussing potential collaborations with
  - Global Foundries
  - EPFL
  - Google
  - Microsoft
  - MIT
  - NIST

FPGA based readout & control electronics: major FNAL competency

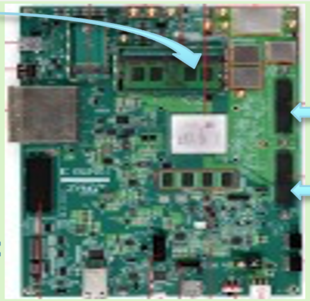
Currently at IBM and most QIS big labs


~$1M

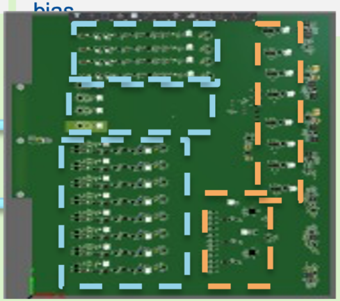
Gen3 (RFSoC) : FNAL Readout and Control: Up to ~80 qubits/module (if FMUXed) >1000 qubits/system


~$20K

FPGA+ADC+DAC+memory+interfaces



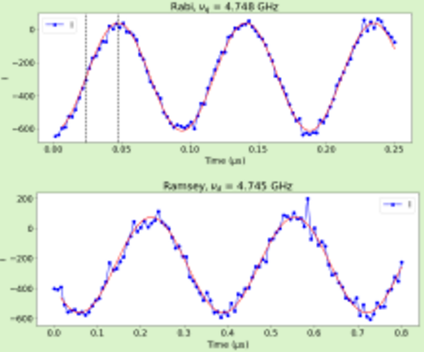
RF inputs, outputs, LO, fast flux control, high precision bias



FNAL Gen3 electronics stakeholders:

- U. Chicago: Davis Schuster lab.
- U Princeton: Andrew Houck lab.
- Fermilab: QSC Thrust 3 (A. Chou)
- UCSB: Ben Mazin Lab.
- U. Perdue: AlexRuichao Ma.
- IIT-FNAL: Rakshya Khatiwada.
- Fermilab CMB MKIDs (B. Benson).
- Fermilab DM MKIDs: NoahKurimsky.
- Fermilab DE MKIDs: Juan Estrada.

- **Fermilab: SQMS (A. Grassellino)**



Qubit measurements at U. Chicago.
D. Schuster lab

Goal: replace expensive equipment, messy cabling, and discrete components.

- ➢ Improve scalability, cost, performance

arXiv:2110.00557 [quant-ph]

Fermilab @ Quantum Science Center (QSC) –ORNL lead

QSC overarching goal:
Overcoming key roadblocks in quantum state resilience, controllability, and ultimately scalability of quantum technologies.

- Address the fragility of quantum states through the **design of new topological materials**
- Develop **algorithms and software** for computation and sensing (current/future hardware)
- **Design new quantum devices and sensors** to detect dark matter and topological quasiparticles

Fermilab leads the thrusts on **quantum devices and sensors** and the **co-design for sensing applications** activities

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

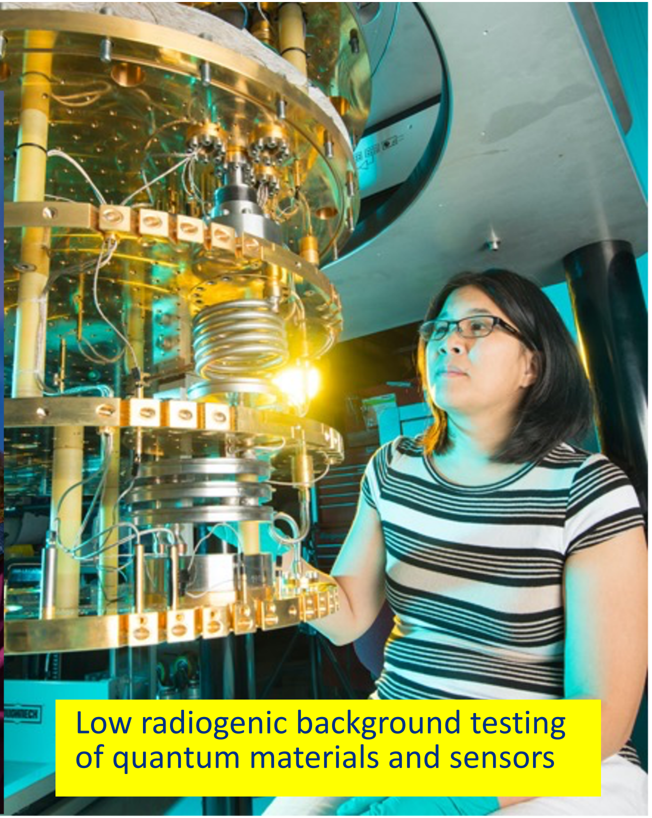
Strategy for QSC: Leverage Fermilab/HEP capabilities

Science targets: Topological quantum materials/computing, single photon detectors, microcalorimetry for dark matter searches.

Engages condensed matter/materials capabilities of BES and ASCR.

highly multiplexed readout of cryogenic qubit/sensor arrays

Cryogenic qubit control systems



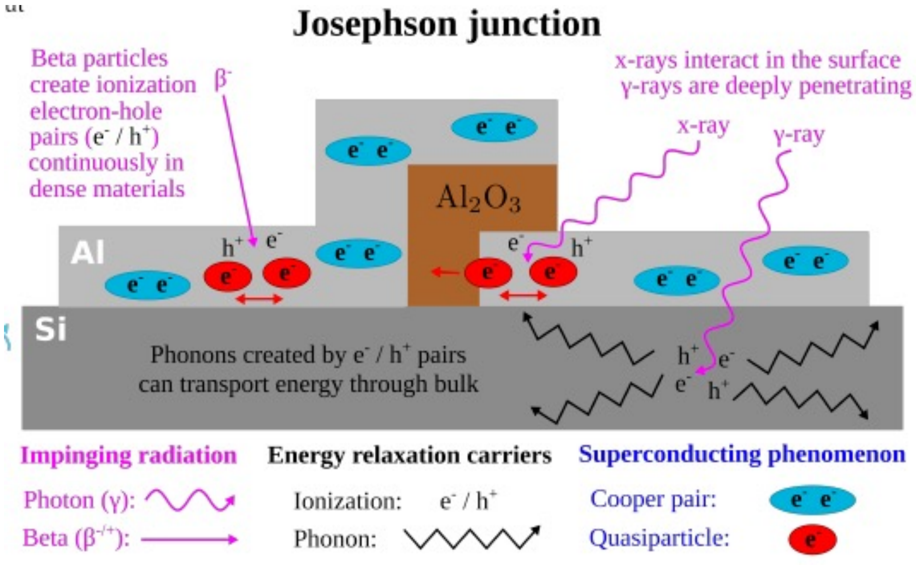
Low radiogenic background testing of quantum materials and sensors

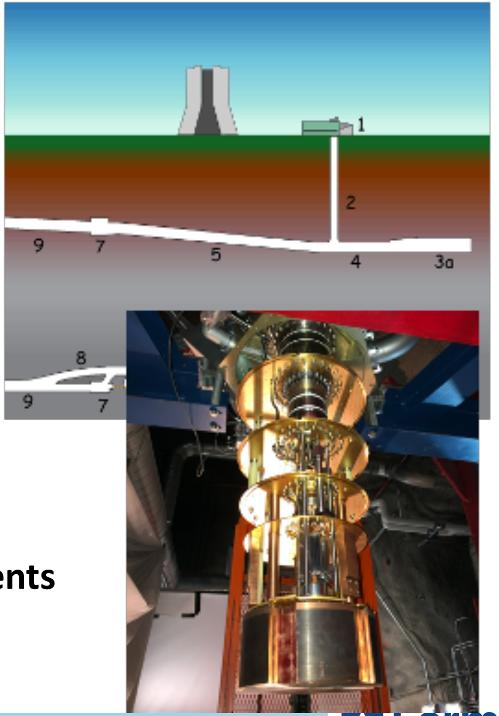
QSC cryogenic test stand leveraging Fermilab infrastructure

Study impact of **ionizing radiation** on qubits, quantum sensors, and quantum materials. Useful for reducing dark matter thresholds?

Qubits look just like dark matter detectors….

Vepsalainen, et.al, arXiv:2001.09190 (2020)

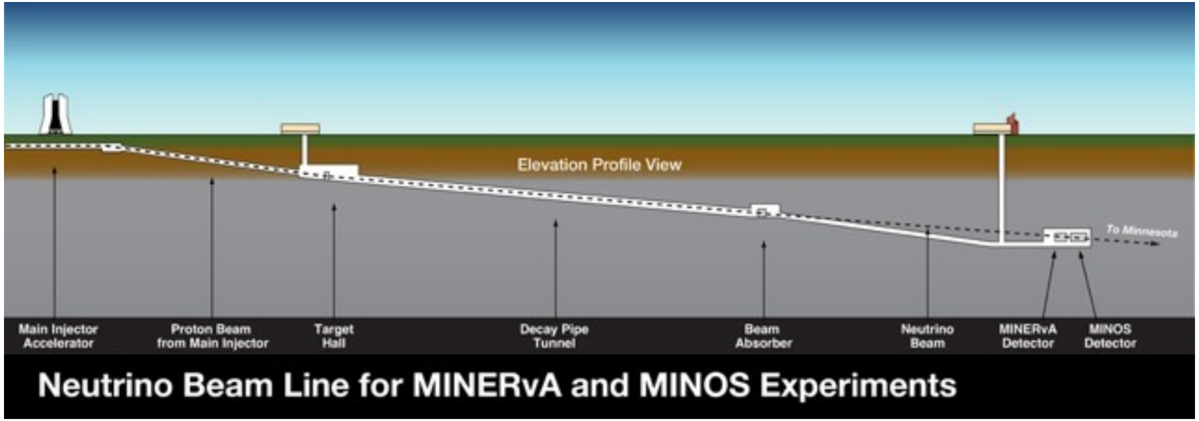




Ionizing radiation causes "catastrophic," "total chip-wide failure" and presents an "existential challenge" to superconducting quantum computing…

M.McEwen et.al, arXiv:2104.05219

MAGIS-100 experiment at Fermilab



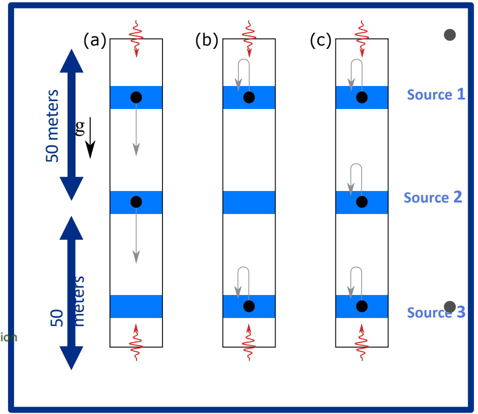
Neutrino Beam Line for MINERvA and MINOS Experiments

GBMF7945

QuantiSED 2019

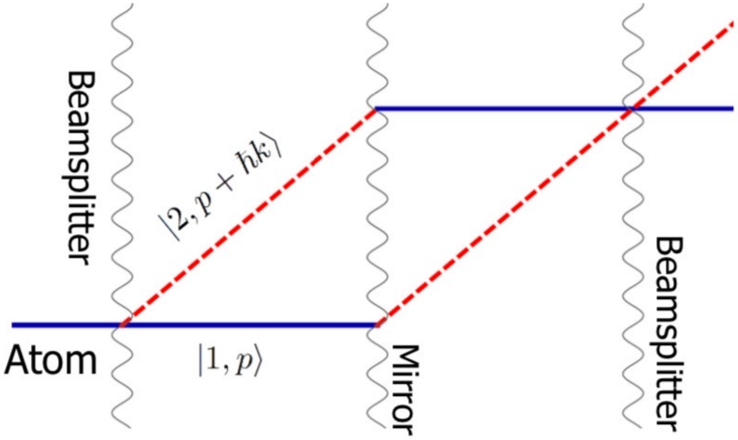
UK STFC

Kavli Foundation



- Major **technological advance** for studying very **low mass dark matter.**
  - 100 m baseline – order of magnitude better than current state-of-the-art
  - Uses ultra-precise Strontium clock transition.
- **Pathfinder** for longer baselines, sensitive to **~1 Hz gravitational waves.**

MAGIS-100 cold atom gradiometer: using atom interferometry to compare free falling accelerometers

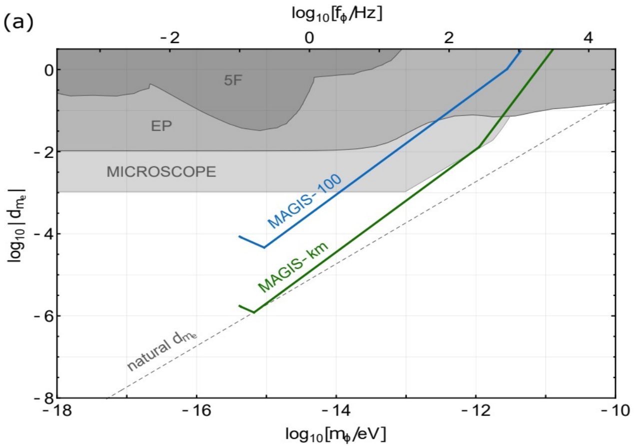


Atom interferometer

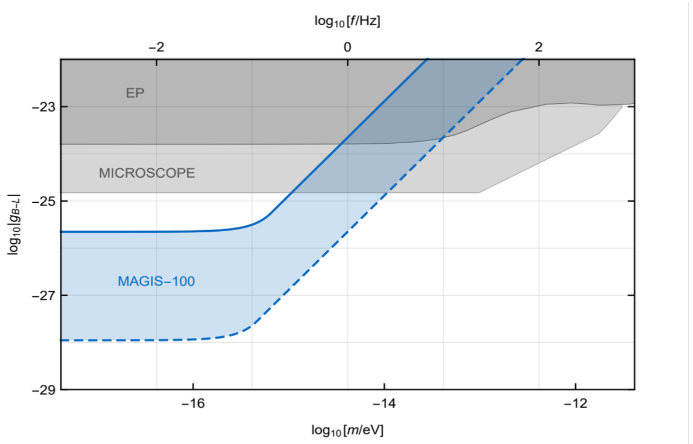
- Cold atoms in free fall
- Use lasers to split and recombine the wavefunction of single atoms
- Compare differential acceleration
- Sensitivity scales like the space-time area
  - ➢ Goal is 10^{-13} g/Hz$^{1/2}$
  - ➢ purshuing R&D to increase
- Advancing R&D for entangled atom sources

MAGIS is a quantum measuring device enabled by **quantum coherence over distances of several meters and times of several seconds**

Diverse MAGIS-100 Science Program



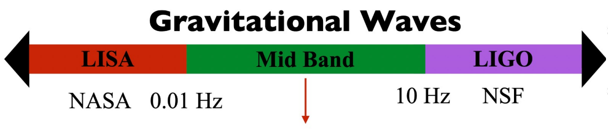
Ultralight Dark Matter Sensitivity – Electron Coupling



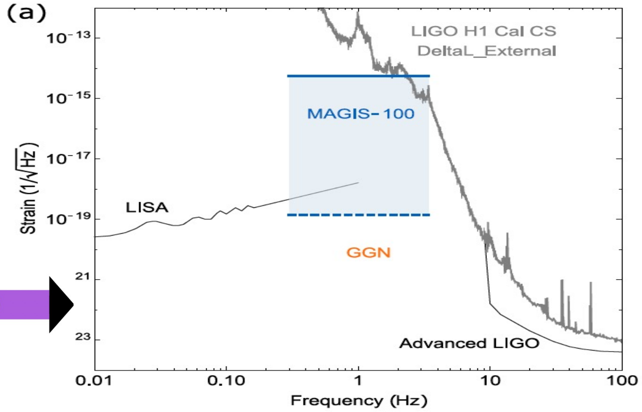
Expected MAGIS-100 B-L dark matter sensitivity

More info at Phys. Rev. D93, 075029 (2016)

Gravitational Wave sensitivity in 1 Hz range


Gravitational Waves

MAGIS-100



QUANTUM SCIENCE

- Atom wave packets in superposition separated by ~10 m
- Durations up to 9 seconds
- Entanglement to reduce noise
- Sequential transitions for Large Momentum Transfer

MAGIS-100 project

- Working on detailed system/integration engineering
- Study of noise mitigation strategies (e.g., spatially resolved detection to reduce influence of laser wavefront errors, multiloop interferometers to reduce effects from Earth rotation and gravity gradients)
- In the process of building parts of the system and planning installation

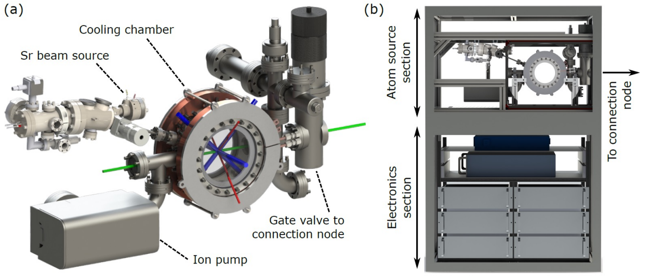


Figure 10. Atom source CAD model. (a) The atom source vacuum assembly. The Sr beam source

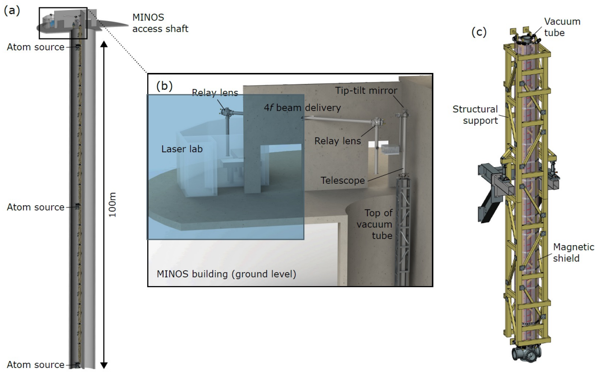
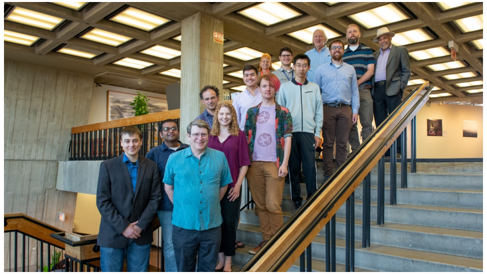


Figure 7. MAGIS-100 detector layout. (a) CAD model of the 100 m interferometer region installed





Exploring quantum computing and quantum simulation for HEP

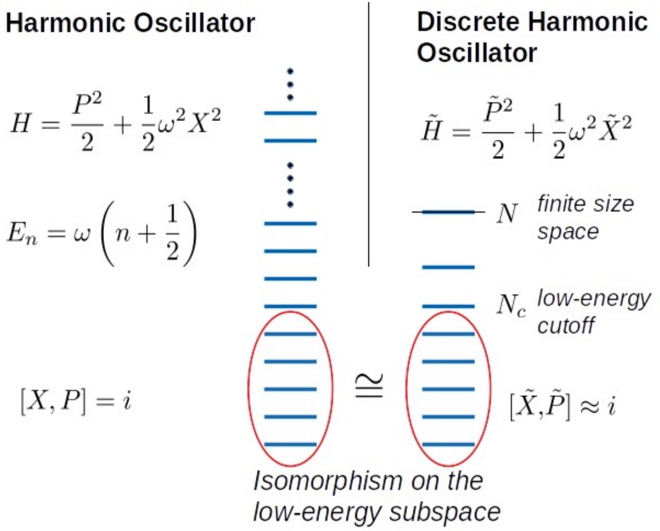
- **Long term goals**
  - Theory: real-time evolution for QCD, jet physics, QCD string fragmentation, quantum parton showers, multiparticle scattering…
  - Computation: event classification, optimization, QML
- **Challenges**
  - Breaking down big problems into small enough problems that can run on near-term quantum processors (QPUs) and remain useful (provide insight)
  - Rethinking HEP algorithmic formalisms and approaches to be optimal for QPUs, not just mapping classical approaches
    - Understand optimal applicability of digital QPUs vs simulators

Boson encoding and fermion-boson interactions

- Simulation of fermion-boson systems
  - **Challenge**: interaction term in the evolution acts as a displacement operator on the bosonic part of the Hilbert space

$$H_{fb} = \sum_{ijn} g_{ijn}(c_i^\dagger c_j + c_i^\dagger c_j)(b_n^\dagger + b_n)$$

    - Difficult to implement using the occupation number basis
- Algorithm using **coordinate basis**, achieves **exponential precision** for digitization!
  - Directly from the Nyquist-Shannon theorem



$$\epsilon < 10e^{-(0.51N_x - 0.76N_{ph})}$$

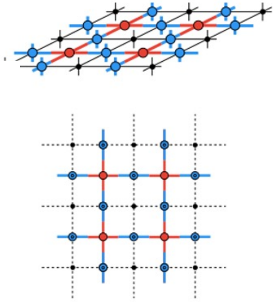
$$n_{boson\ qubits} = O\left(\log\left(\log \epsilon^{-1}\right)\right)$$

PRL 121, 110504 and PRA 98, 042312

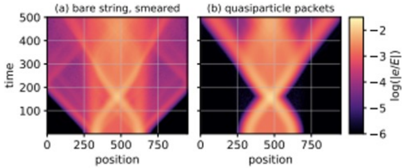
Quantum Information for Theoretical Particle Physics

Lead PI: Marcela Carena (Fermilab)
Lead lab: Fermilab
Partners: Caltech, LANL, MIT, Purdue U., UIUC, U. of Washington - INT.

[1] Ji, Lamm, Zhuo, Phys.Rev.D 102 (2020), 114513
[2] Estrada, Harnik, Rodriguez, Senger, arXiv: 2012.04707
[3] Ciavarella, Klco, Savage, arXiv: 2101.10227
[4] Milsted, Liu, Preskill, Vidal, arXiv: 2012.07243
[5] Meurice, Sakai, Unmuth-Jockey, arXiv: 2010.06539
[6] Carena, Lamm, Li and Liu, to appear

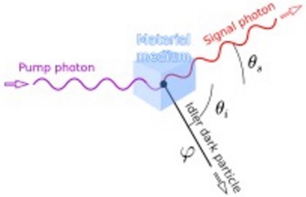


n [5], The magnetic layer of the transfer matrix for
3 in a time slice (top) and "from above" (bottom).



From [4], Evolution of the excess energy density e (relative to vacuum), as a fraction of total excess energy E, in a spin chain for two initial states: (a) created by applying a spatially smeared string operator to the vacuum and (b) constructed from MPS tensors to contain kink and antikink quasiparticle wavepackets

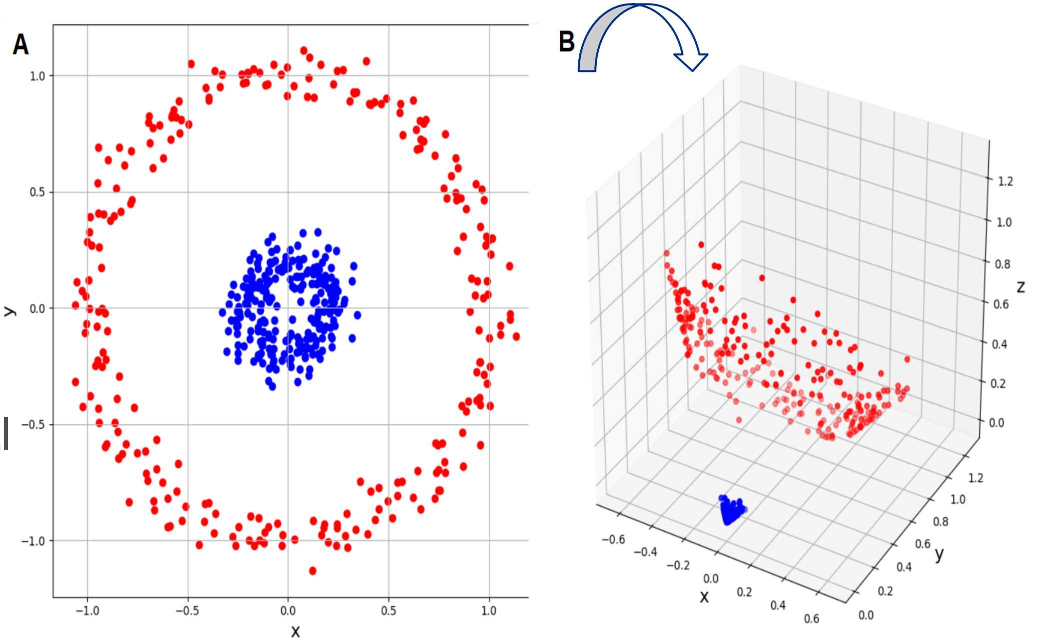
Consortium under HEP QuantISED



From [2], a sketch of the dark SPDC process in which a pump photon converts to a signal photon plus an axion or dark photon. This process may open new opportunities to search for new physics with tools used in quantum communication.

Quantum Machine Learning

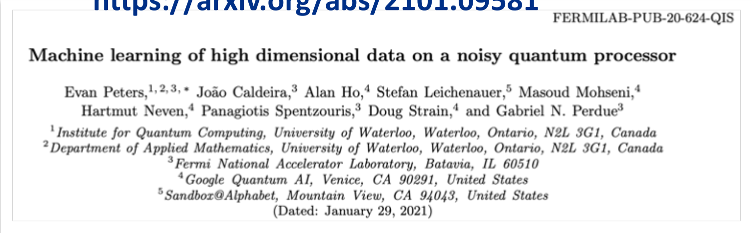
- Motivation for using quantum computing to construct feature maps (quantum kernel in a classical SVM):
  - We want non-linear classification in low dimensional space to become linear separation in high dimensional space
  - quantum circuit could provide a convenient, linear boundary in high-dimensional Hilbert space



Quantum Machine Learning for HEP

- Use Sycamore (Google supremacy chip) for binary classification of Type II vs Type I supernovae.
- Encode each event using qubit rotations, scramble with entangling gates.
- Compute UU✝️ → effectively an overlap measure (probability of all 0's bitstring).
- Event vs event computation (O(N2) with dataset size).
- Resulting matrix fed to a classical SVM.

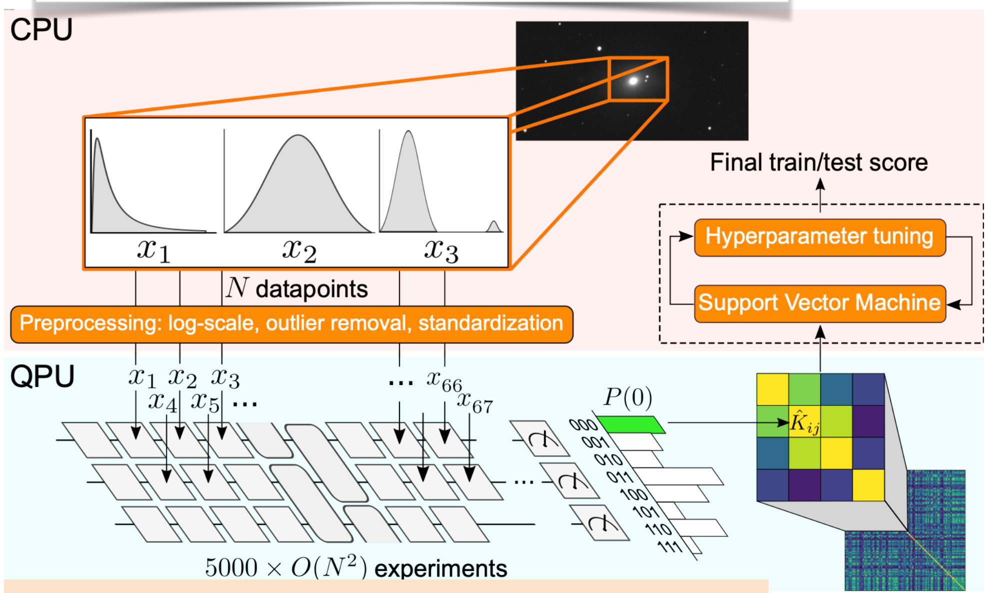
https://arxiv.org/abs/2101.09581



FERMILAB-PUB-20-624-QIS

Machine learning of high dimensional data on a noisy quantum processor

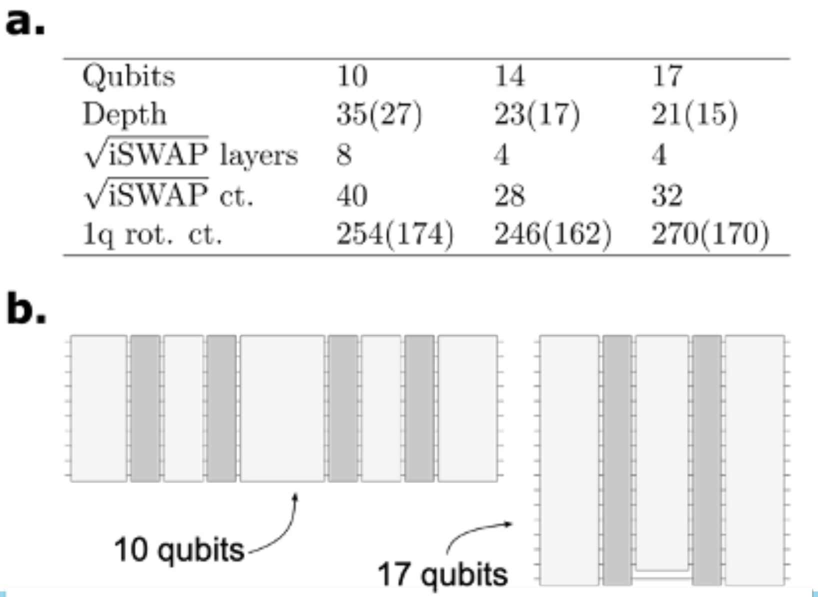
Evan Peters,[1, 2, 3, *] João Caldeira,[3] Alan Ho,[4] Stefan Leichenauer,[5] Masoud Mohseni,[4]
Hartmut Neven,[4] Panagiotis Spentzouris,[3] Doug Strain,[4] and Gabriel N. Perdue[3]
[1] *Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada*
[2] *Department of Applied Mathematics, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada*
[3] *Fermi National Accelerator Laboratory, Batavia, IL 60510*
[4] *Google Quantum AI, Venice, CA 90291, United States*
[5] *Sandbox@Alphabet, Mountain View, CA 94043, United States*
(Dated: January 29, 2021)



npj Quantum Inf **7,** 161(2021).

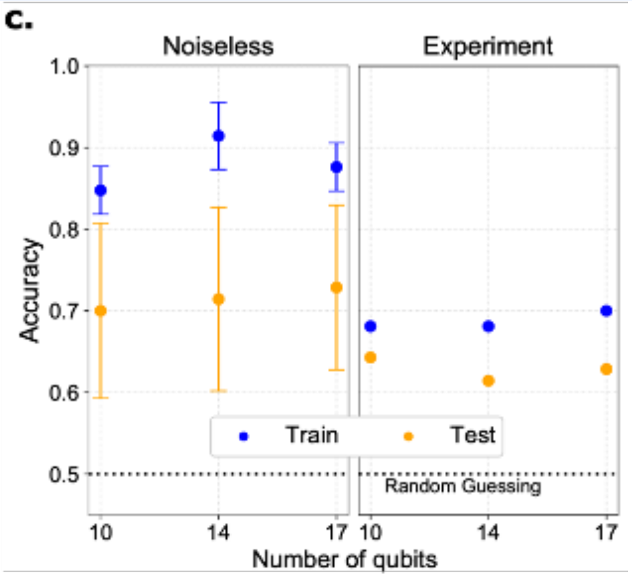
Quantum Machine Learning for HEP

- Largest qubit count for a quantum kernel classifier to date.
- Highest dimension dataset for a quantum kernel classifier to date.
- No classical pre-processing, use the same dataset as is in classical approaches.
- No quantum advantage but the algorithm is competitive with classical solutions.



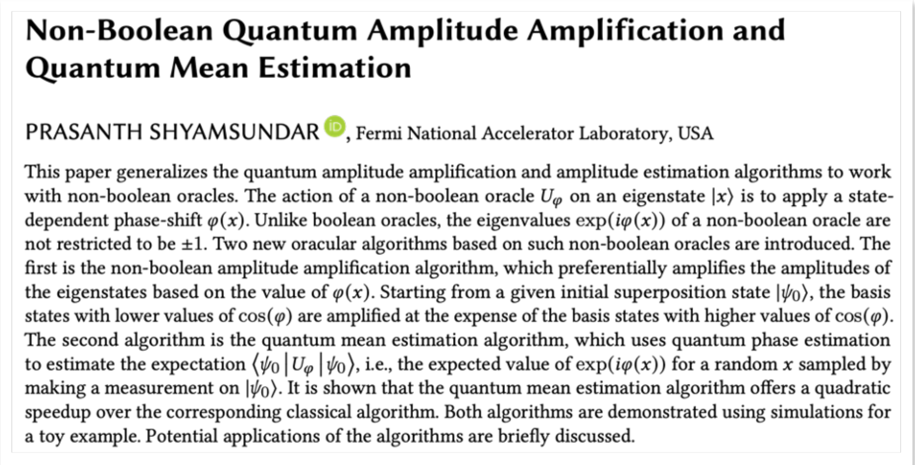
a.

Qubits	10	14	17
Depth	35(27)	23(17)	21(15)
$\sqrt{\text{iSWAP}}$ layers	8	4	4
$\sqrt{\text{iSWAP}}$ ct.	40	28	32
1q rot. ct.	254(174)	246(162)	270(170)



Quantum Algorithms

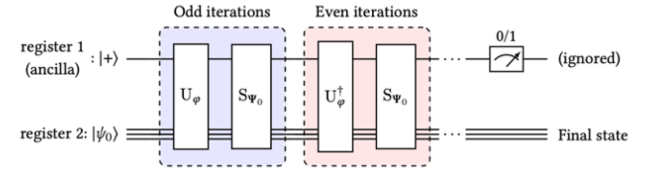
- Generalized Grover's search algorithm into an optimization algorithm for non-boolean objective functions.
- Generalized the quantum counting algorithm into a quantum mean estimation algorithm.
- Very general algorithm developed in the context of QML but with multiple potential applications:
  - Approximate optimization
  - Simulating probability distributions
  - Estimating the overlap between states
  - Meta-oracles to evaluate the superposition of a wave function and a unitary.

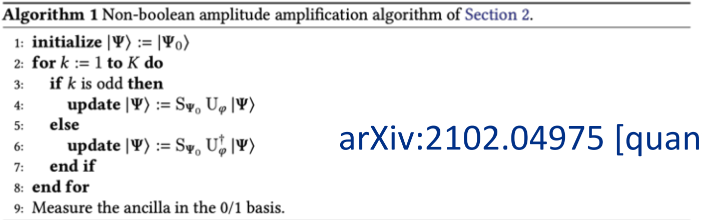


Non-Boolean Quantum Amplitude Amplification and Quantum Mean Estimation

PRASANTH SHYAMSUNDAR, Fermi National Accelerator Laboratory, USA

This paper generalizes the quantum amplitude amplification and amplitude estimation algorithms to work with non-boolean oracles. The action of a non-boolean oracle U_φ on an eigenstate $|x\rangle$ is to apply a state-dependent phase-shift $\varphi(x)$. Unlike boolean oracles, the eigenvalues $\exp(i\varphi(x))$ of a non-boolean oracle are not restricted to be ± 1. Two new oracular algorithms based on such non-boolean oracles are introduced. The first is the non-boolean amplitude amplification algorithm, which preferentially amplifies the amplitudes of the eigenstates based on the value of $\varphi(x)$. Starting from a given initial superposition state $|\psi_0\rangle$, the basis states with lower values of $\cos(\varphi)$ are amplified at the expense of the basis states with higher values of $\cos(\varphi)$. The second algorithm is the quantum mean estimation algorithm, which uses quantum phase estimation to estimate the expectation $\langle\psi_0|U_\varphi|\psi_0\rangle$, i.e., the expected value of $\exp(i\varphi(x))$ for a random x sampled by making a measurement on $|\psi_0\rangle$. It is shown that the quantum mean estimation algorithm offers a quadratic speedup over the corresponding classical algorithm. Both algorithms are demonstrated using simulations for a toy example. Potential applications of the algorithms are briefly discussed.





Algorithm 1 Non-boolean amplitude amplification algorithm of Section 2.

```
initialize $|\Psi\rangle := |\Psi_0\rangle$
for $k := 1$ to $K$ do
    if $k$ is odd then
        update $|\Psi\rangle := S_{\Psi_0} U_\varphi |\Psi\rangle$
    else
        update $|\Psi\rangle := S_{\Psi_0} U_\varphi^\dagger |\Psi\rangle$
    end if
end for
Measure the ancilla in the 0/1 basis.
```

arXiv:2102.04975 [quant-ph]

Quantum Computing challenges: noise and decoherence

We don’t want qubits to interact with the environment.

- Decoherence: relaxation, pure dephasing, correlated noise, …

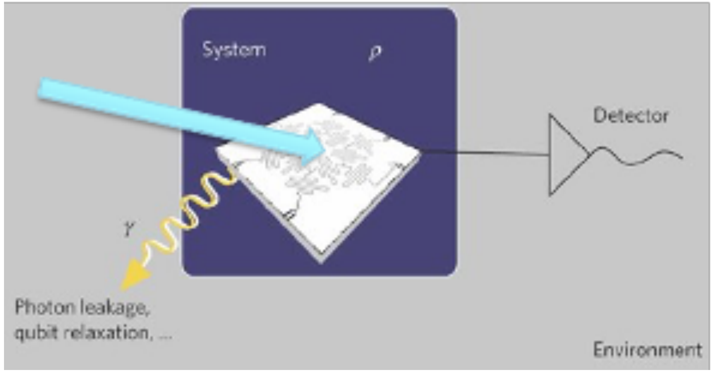
  → device loses ‘quantumness’

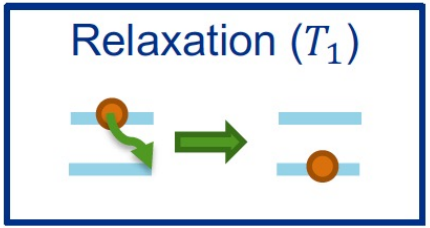
- Control error: inaccurate gate implementation due to imperfect calibration, qubit drift, …

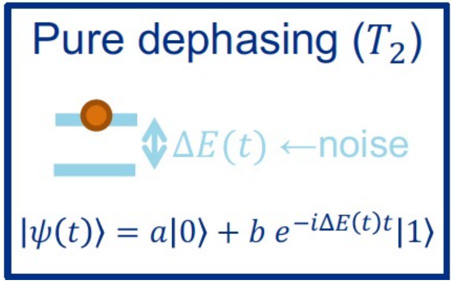
  → reliable result only within a limited number of gate operations

- Limits **useful circuit “depth”**

A. A. Houck *et al*, *Nat Phys* **8**, 292 (2012)




Relaxation (T_1)

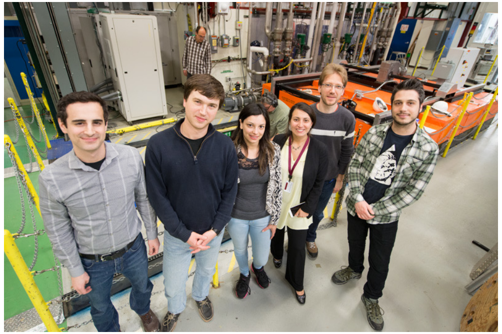

Pure dephasing (T_2)

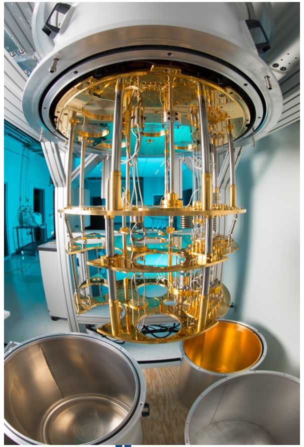
$$|\psi(t)\rangle = a|0\rangle + b\, e^{-i\Delta E(t)t}|1\rangle$$

Superconducting RF technology for quantum applications

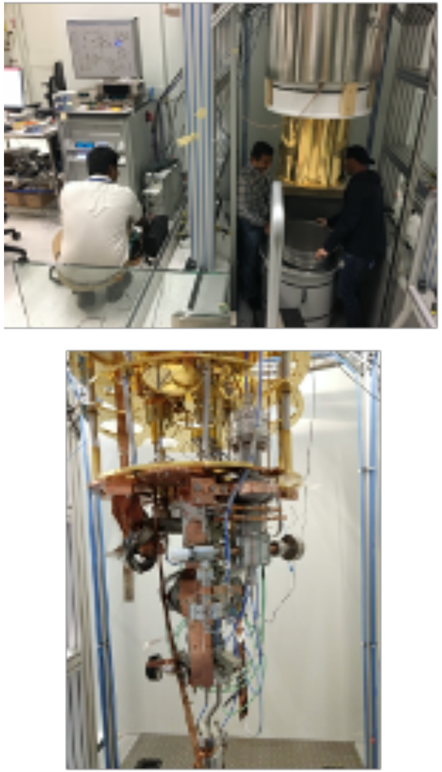
- Central component of our program
  - Leverage world leading lab competencies
    - world’s best SRF cavities for cutting-edge accelerators like LCLS-II and PIP-II
- Successfully adapt to the quantum regime
- Drives multiple quantum applications, engaging theorists and experimentalists
  - SRF cavity-based quantum computers
  - sensors for the detection of dark matter and other exotic particles

Cryomodule built at Fermilab for the new LCLS-II free electron laser light source at SLAC

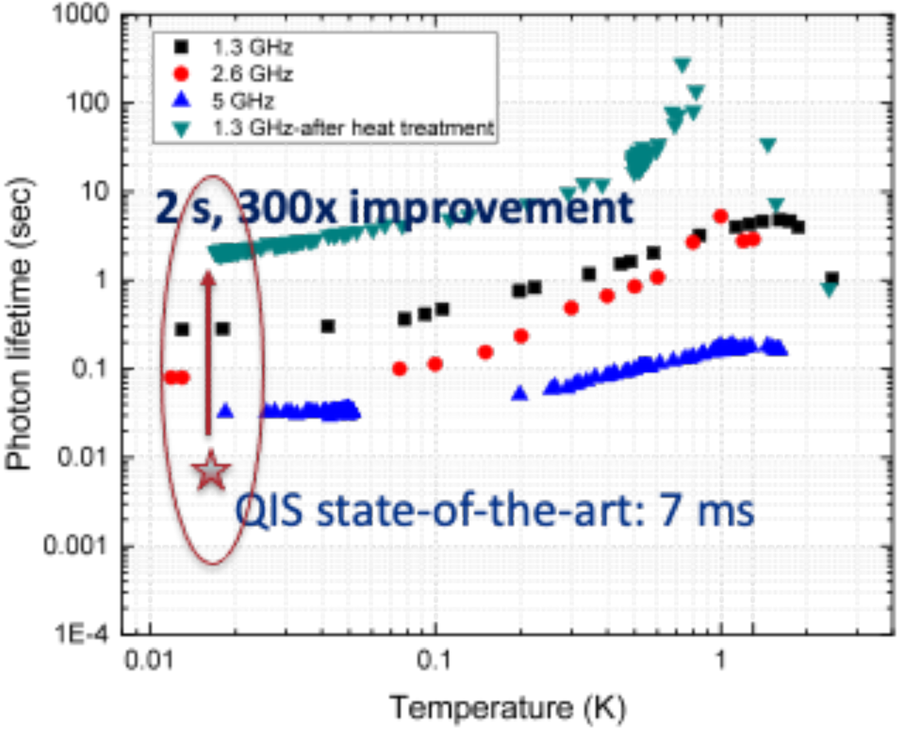




Record high photon lifetimes achieved at Fermilab



Accelerator cavities adopted for quantum regime



2 s, 300x improvement

QIS state-of-the-art: 7 ms

A. Romanenko, R. Pilipenko, S. Zorzetti, D. Frolov, M. Awida, S. Posen, A. Grassellino, arXiv:1810.03703

Super Conducting Quantum Materials and Systems (SQMS) NQI Center

SQMS is using ultraefficient superconducting radio-frequency (SRF) resonators to significantly increase coherence of quantum systems.

SQMS leverages decades of expertise in materials, radio frequency superconductivity and surface engineering that has already demonstrated ultrahigh-quality-factor 3D resonators, which achieved world record coherence times of 2s— orders of magnitude longer than previously possible.

SQMS aims to push quantum coherence even further to tens of seconds.

Host institution

Fermilab

Core partners

rigetti

Northwestern University

NASA Ames Research Center

AMES LABORATORY
Creating Materials & Energy Solutions
U.S. DEPARTMENT OF ENERGY

Contributing partners

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

Goldman Sachs

Università degli Studi di Padova

NIST National Institute of Standards and Technology U.S. Department of Commerce

INFN Istituto Nazionale di Fisica Nucleare

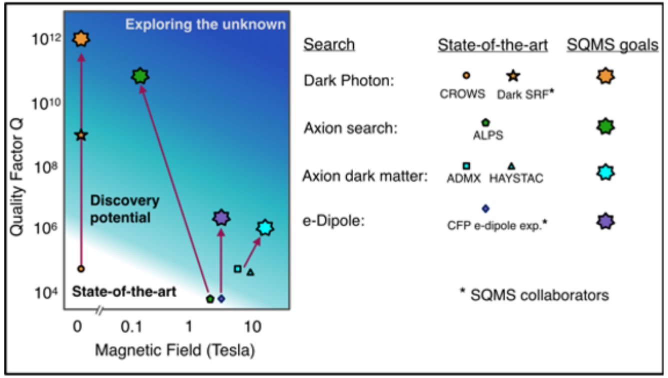
Unitary Fund

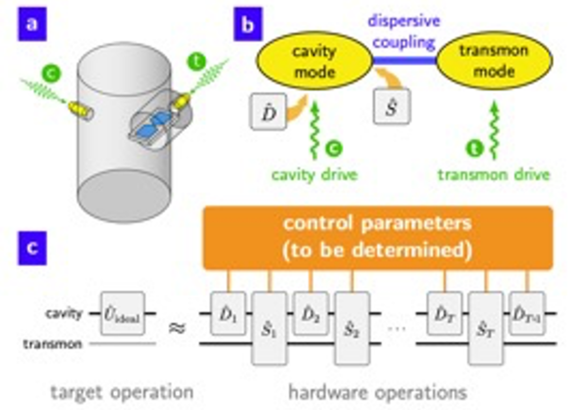
JANIS Cryogenic Research Equipment

Lockheed Martin

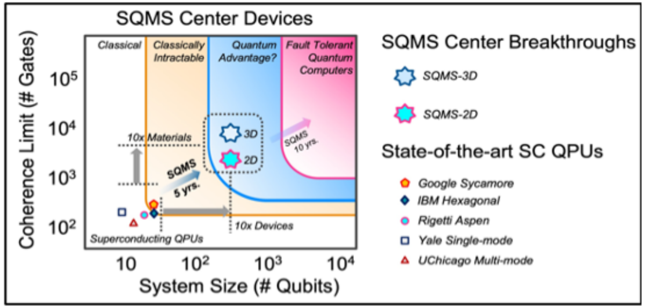
3D devices: better coherence, multi-level systems (qudits)

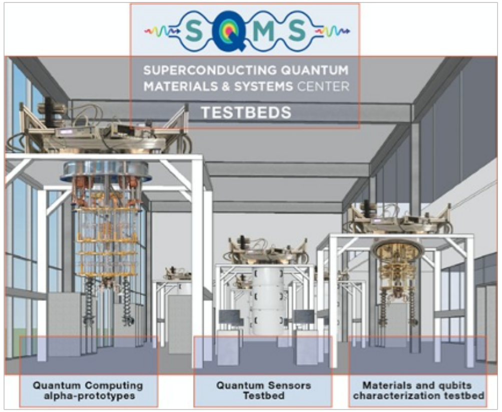
https://sqms.fnal.gov

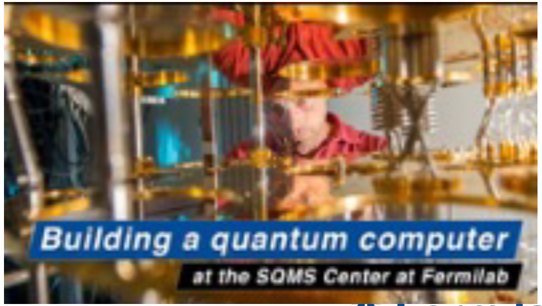


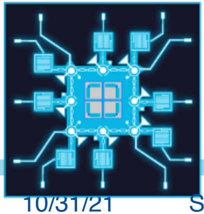


Fösel et al, arXiv:2004.14256







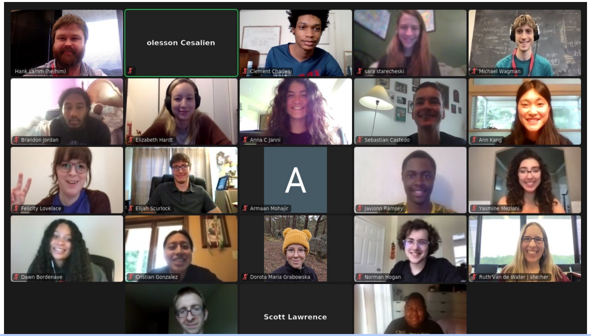


Education and Outreach

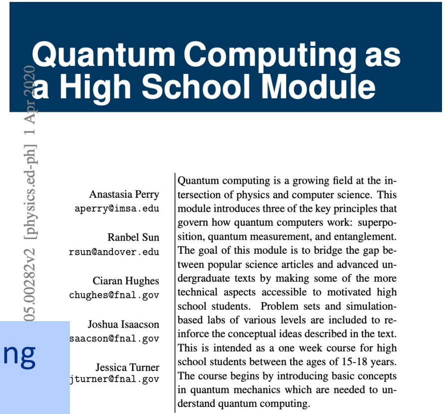
- Tutorials and courses (working with academic and industry partners)
- Training material
  - Including for high-school students!
- Seminars & Lectures
- Seasonal student programs
- Graduate students engaged in our R&D projects

➢ The NQI Centers are now having a strong presence in this domain, working on creating an ecosystem with industry and academia

First ever public Google Quantum Computing tutorial (FNAL, 2018)



Theory Division Undergraduate Quantum Computing Internship & School (July 6 – July 23, 2021)



Quantum Computing as a High School Module

05.00282v2 [physics.ed-ph] 1 Apr 2020

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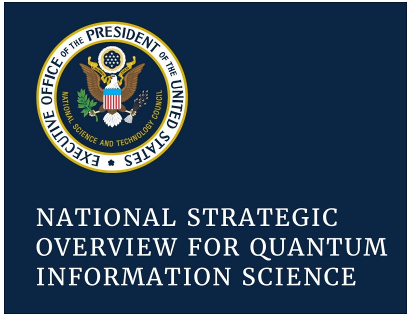
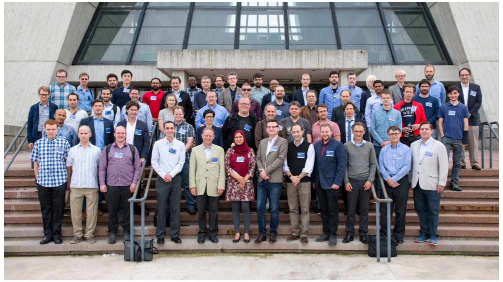
Quantum computing is a growing field at the intersection of physics and computer science. This module introduces three of the key principles that govern how quantum computers work: superposition, quantum measurement, and entanglement. The goal of this module is to bridge the gap between popular science articles and advanced undergraduate texts by making some of the more technical aspects accessible to motivated high school students. Problem sets and simulation-based labs of various levels are included to reinforce the conceptual ideas described in the text. This is intended as a one week course for high school students between the ages of 15-18 years. The course begins by introducing basic concepts in quantum mechanics which are needed to understand quantum computing.

Summary

- We are building a Quantum Science & Technology Program targeting HEP long-term needs by leveraging Fermilab's competencies and infrastructure
  - Initiatives are already producing scientific results and are leading to major projects
  - Engagement of the HEP community is growing
- Establishing collaborations with QIS experts from universities, industry, labs
- Developing long term strategy in the context of the National approach to QIS and leveraging the opportunities it provides



NATIONAL STRATEGIC
OVERVIEW FOR QUANTUM
INFORMATION SCIENCE

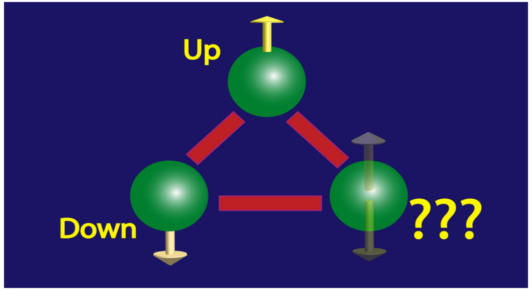


Backups

Science motivation and a little history

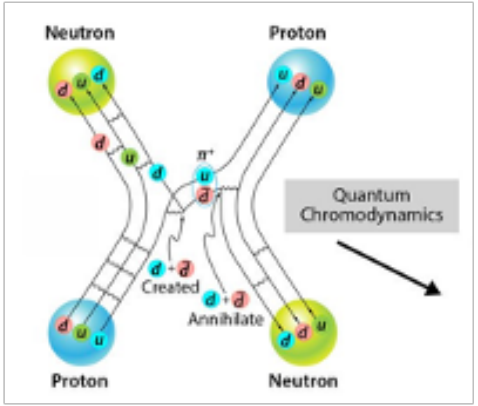
- In the early 1980’s became clear that first principles calculation of properties and behavior of quantum mechanical systems is extremely challenging
  - The **number of parameters** required to describe a quantum system grows **exponentially** with the size of the system (think number of degrees of freedom, number of particles, …)
  - The **number of operations** required for the temporal evolution of the system also increases **exponentially** with the size of the system

- This leads us to use approximations (e.g. Monte Carlo) for doing calculations on classical computers, but these approximations don’t work for all problems
  - Polynomial scaling for Monte Carlo phase-space integrals of many-body systems (good!)
  - But only works when the integrant changes slowly and doesn’t change sign (not good…)
    - The “sign-problem”, bad for fermionic and frustrated systems



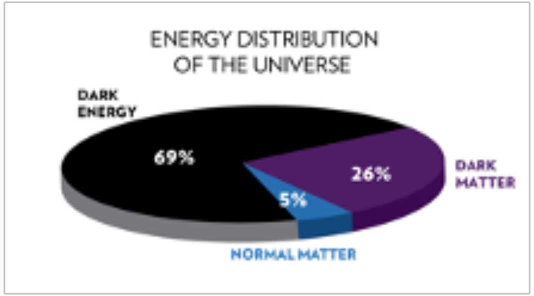
HEP (and Fermilab's) Quantum Drivers

Simulation



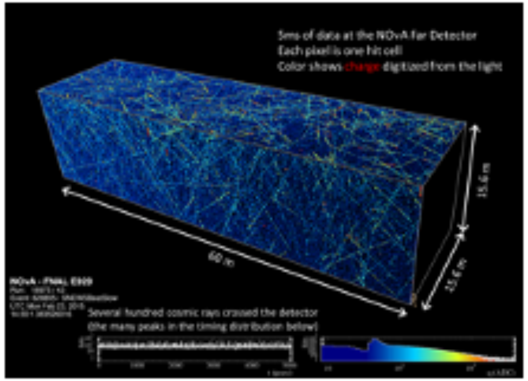
First principles simulation of the universe. QCD and Quantum Gravity

Sensing



Discover the new physics particles that make up ~95% of the universe

Data Processing

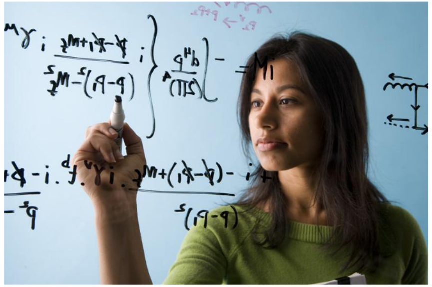


Current and future HEP experiments generate >exabyte of data per year

Science goals drive technology innovation

All the easy experiments have been done already

Pushing the boundaries of technology enables new experiments… and our science goals drive technology innovation!



US Particle Physics Project Prioritization Panel (P5) science drivers:

- Higgs boson
- Neutrinos
- Dark matter, dark energy
- Exploring the unknown

FQNET

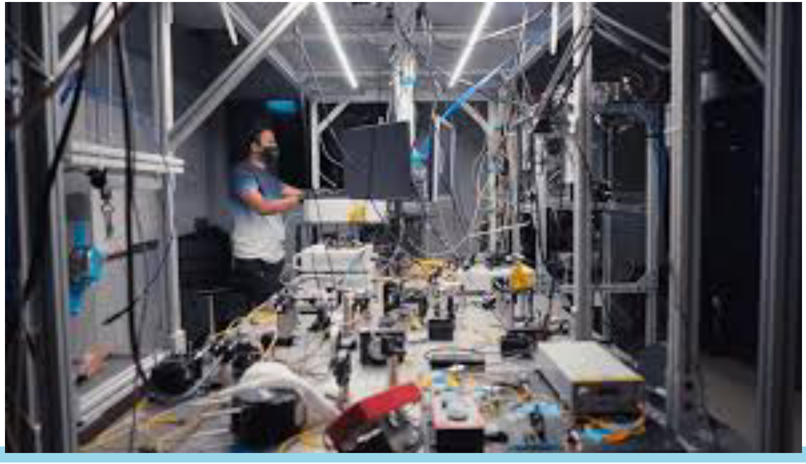
inqnet
ALLIANCE FOR QUANTUM TECHNOLOGIES
ə'kyo͞ot :: AQT
in'kyo͞onet :: inqnet

Caltech

NASA JPL

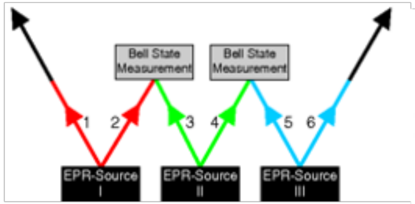
Fermilab
U.S. DEPARTMENT OF ENERGY
Office of Science

CQNET



Quantum links to quantum networks to the quantum internet

- Networks of quantum computers, quantum sensors, and other coupled physical systems (solids, trapped ions/atoms, phonons, polaritons)



Entanglement Swapping

Four priority directions:
- Foundational building blocks
  - …, teleportation systems ✓
- Device integration
- Network functionality for distributed entanglement ✓
- Error correction

Report of the DOE
Quantum Internet
Blueprint Workshop

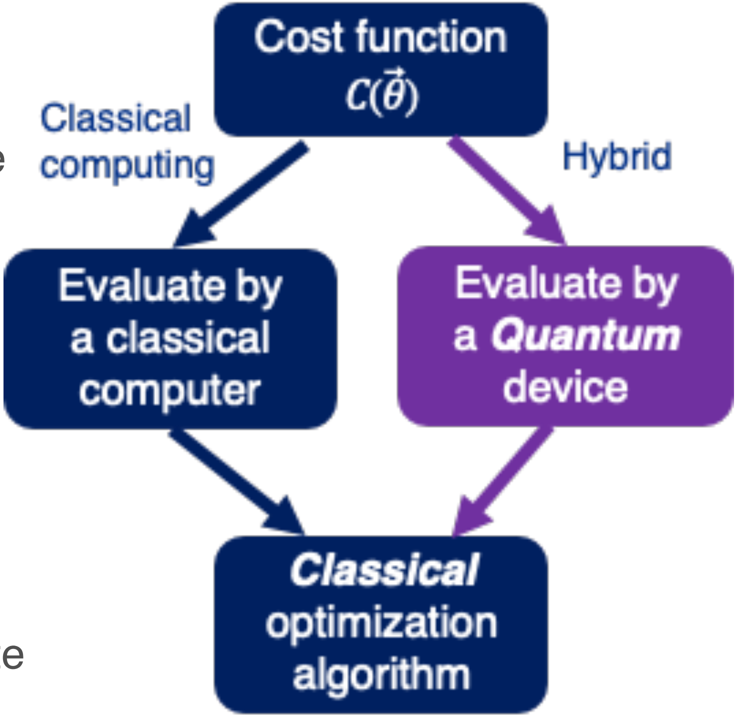
From Long-distance Entanglement to
Building a Nationwide Quantum Internet

February 5-6, 2020

https://www.energy.gov/sites/prod/files/2020/07/f76/QuantumWkshpRpt20FINAL_Nav_0.pdf

Quantum-classical hybrid variational algorithms

- Quantum Approximate Optimization Algorithm (QAOA)
  - Approximated solutions for combinatorial optimization problems through a series of classically optimized gate operations
- Quantum kernel method
  - Support vector machine (SVM) with kernel function evaluated by quantum devices
- Quantum autoencoder
  - encoding in Hilbert space with encoder trained classically
- Variational quantum eigensolver (VQE)
  - Variational ansatz represented by a list of quantum gate and optimized by a classical optimizer



Cost function $C(\vec{\theta})$

Classical computing

Hybrid

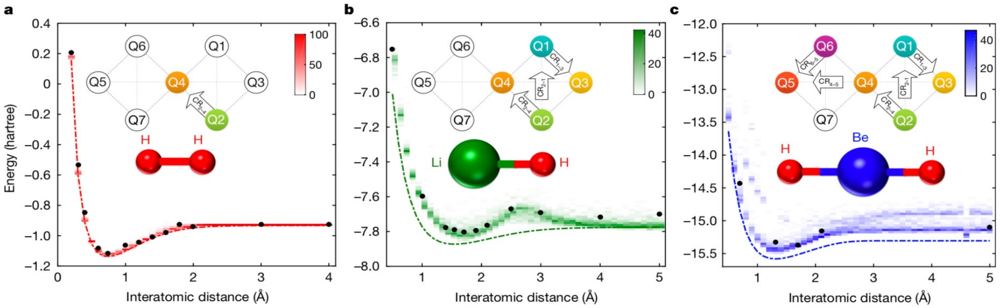
Evaluate by a classical computer

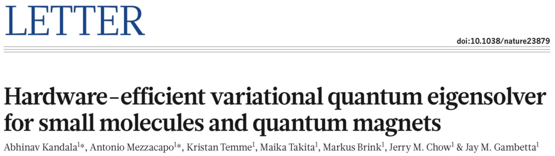
Evaluate by a ***Quantum*** device

Classical optimization algorithm

VQE for science applications

- Fermions ↔ Qubits
  - – Jordan-Wigner transformation





LETTER

doi:10.1038/nature23879

Hardware-efficient variational quantum eigensolver for small molecules and quantum magnets

Abhinav Kandala[1]*, Antonio Mezzacapo[1]*, Kristan Temme[1], Maika Takita[1], Markus Brink[1], Jerry M. Chow[1] & Jay M. Gambetta[1]

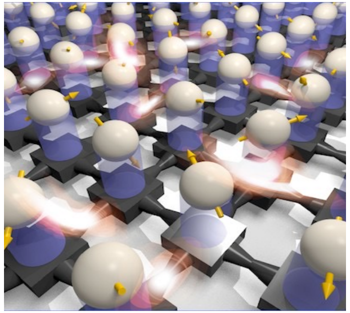
- But many models in high-energy and condensed-matter involve non-fermionic degrees of freedom

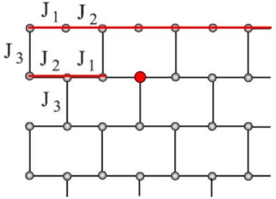
Jordan-Wigner Transformation

$$\sigma^{+}_{i,j} = 2a^{+}_{i,j} e^{i\pi\left(\sum_{k<j,l} a^{+}_{l,k} a_{l,k} + \sum_{l<i} a^{+}_{l,j} a_{l,j}\right)}$$

$$\sigma^{z}_{i,j} = 2a^{+}_{i,j} a_{i,j} - 1$$

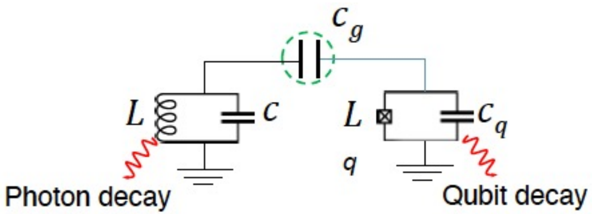
- Goal: many-body systems with bosons
  - light-matter interaction
  - electron-phonon coupling





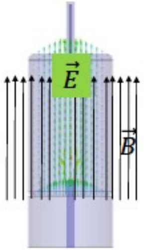
Represent spin operators by spinless fermion operators

Quantum non-demolition measurements using cavities and qubits



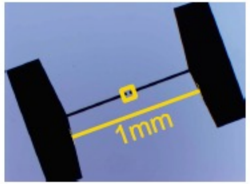
$$\hat{\mathcal{H}} = \boxed{\omega_c a^\dagger a} + \boxed{\omega_q \frac{\sigma_z}{2}} - \boxed{\chi a^\dagger a \sigma_z}$$

Quantized Field | Qubit | Dispersive Coupling



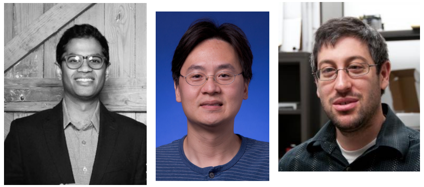
Maximum overlap between the applied magnetic field and the cavity mode (TM_{010})

$$\omega_{010} = 2\pi\, 9.56\ GHz$$



χ set by:

1. Dipole arm geometry
2. Qubit location in cavity
3. Qubit-cavity frequency detuning
4. Qubit anharmonicity



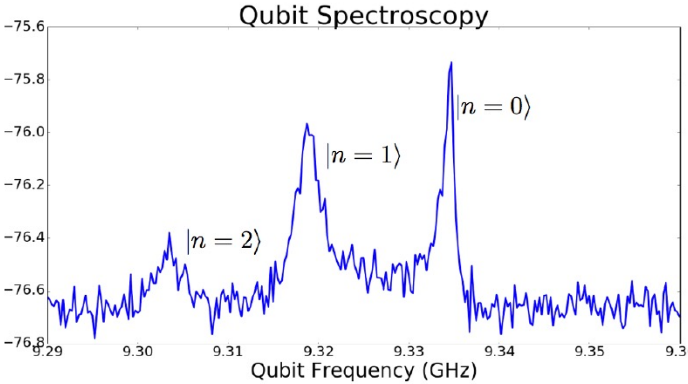
Searching for Dark Matter with a Superconducting Qubit

Akash V. Dixit, Srivatsan Chakram, Kevin He, Ankur Agrawal, Ravi K. Naik, David I. Schuster, Aaron Chou

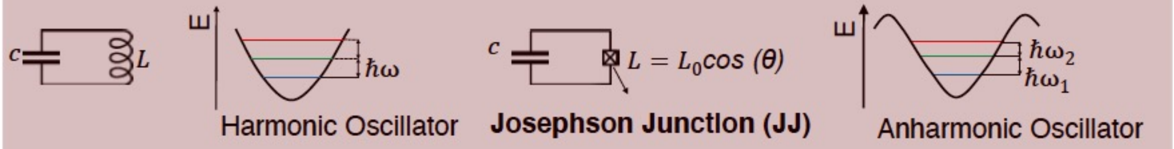
Quantum Non-demolition (QND) Measurement

Triggering a click without destroying the photon

$$\hat{\mathcal{H}} = \omega_c a^\dagger a + (\omega_q - 2\chi a^\dagger a)\frac{\sigma_z}{2} \qquad \hat{\mathcal{H}} = (\omega_c - 2\chi \tfrac{\sigma_z}{2})\, a^\dagger a + \omega_q \sigma_z$$



Qubit



Quantum non-demolition (QND) measurement, by example

- Consider the position measurement **x** of a free particle with mass **m**, with precision Δx_1, thus $\Delta p > \bar{h}/\Delta x_1$
  → After time t: $\Delta x_2 \cong \Delta x_1 + t\,\Delta p/m$, thus the **predictability** of the position is demolished

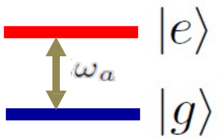
- QND is all about the **predictability of subsequent measurements**, thus ensuring the back-action doesn't affect the time evolution of the variable *Q* we interrogate:

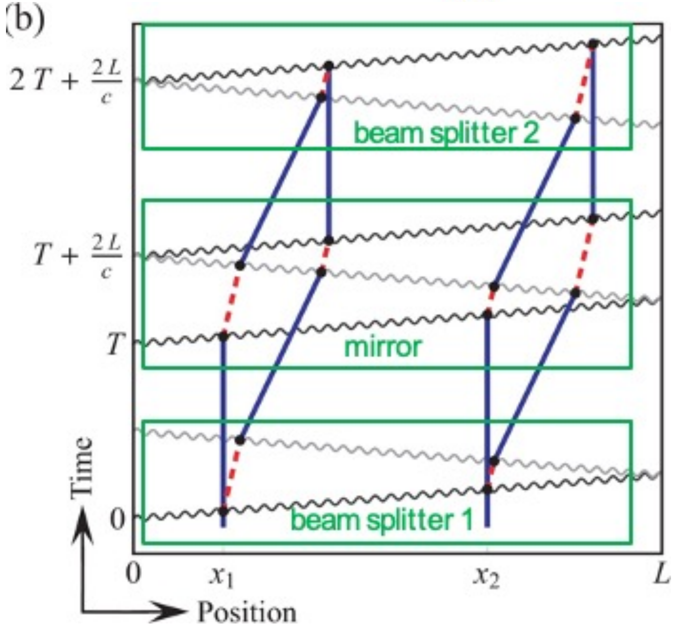
$$-i\,\bar{h}\,\frac{d\bar{Q}}{dt} = [\bar{Q}, \bar{H}]$$

- For our example, $\bar{H} = \bar{P}^2/2m$ and if we measure **p** with precision Δp, although $\Delta x > \bar{h}/\Delta p$ subsequent measurements of **p** will still have precision Δp
  - Of course, the details of the measurement are important, e.g., if we obtain the momentum measurement through measurements of the track of a particle, then back-action will be relevant

Gradiometer Signal

- Phase shift determined by difference in times spent in excited clock state for arm 1 vs arm 2
- Look at difference in phase shifts for two interferometers separated by baseline ~L (gradiometer phase shift)
- Magnitude of contribution to gradiometer phase shift from each interferometer zone: $\Delta\phi \sim \omega_A\,(2L/c)$
- For constant (or linearly drifting) L and transition frequency, gradiometer phase shift cancels
- **To have a nonzero phase shift, need transition frequency or L to vary on a time scale T (time between each zone)**



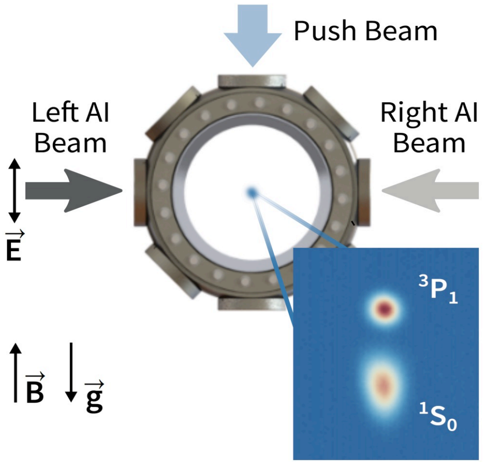


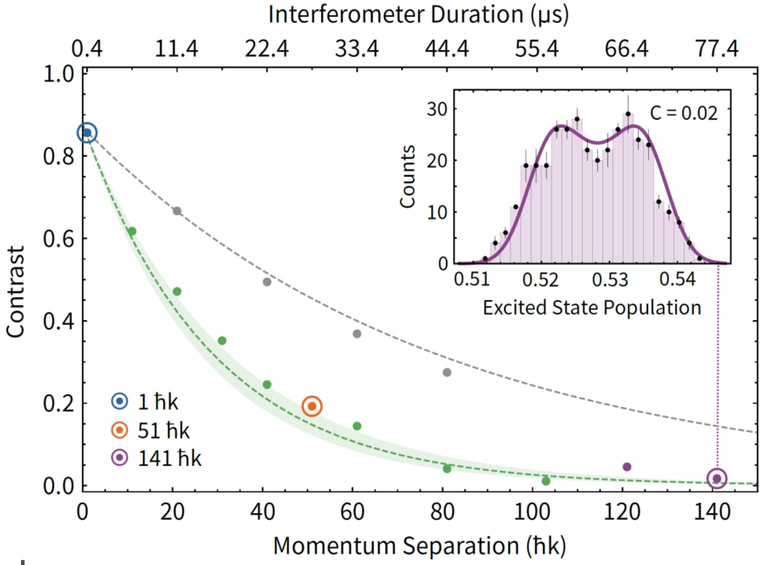
Two ways to get a signal:

$\delta\omega_A$	*Dark matter*
$\delta L = hL$	*Gravitational wave*

Graham et al., PRL **110**, 171102 (2013).
Arvanitaki et al., PRD **97**, 075020 (2018).

MAGIS R&D: Clock Atom Interferometry





First Large Momentum Transfer (LMT) clock interferometers using sequential single-photon transitions

Record LMT interferometer (141 ħk)

Demonstrated 81 ħk gradiometer (power limited); T > 1 ms (>> lifetime)

Ongoing upgrade to 1000 ħk

Stanford team:J. Rudolph, PRL **124**, 083604 (2020)

Boson encoding using coordinate basis

$$H = H_f + H_b + H_{fb}$$

fermion
(*second quantized*)

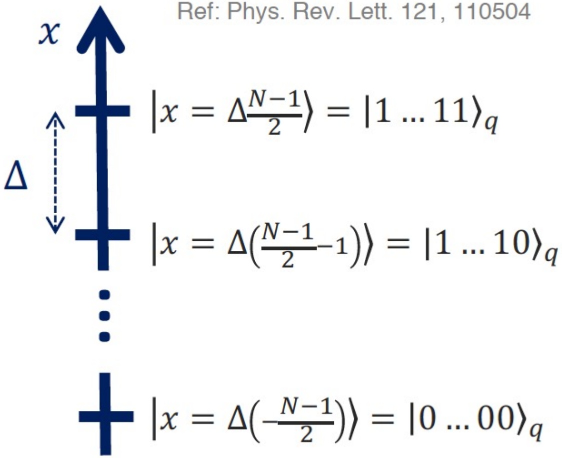
$$H_f = \sum_{ij} t_{ij} \left(c_i^\dagger c_j + c_j^\dagger c_i \right) + \sum_{ijkl} U_{ijkl} c_i^\dagger c_j^\dagger c_k$$

boson
(*first quantized*)

$$H_b = \sum_{n\nu} \frac{P_{n\nu}^2}{2M_\nu} + \frac{1}{2} M_\nu \omega_{i\nu}^2 X_{n\nu}^2 + \sum_{n\nu m\mu} K_{n\nu m}$$

fermion-boson

$$H_{fb} = \sum_{ijn\nu} g_{ijn\nu} \left(c_i^\dagger c_j + c_j^\dagger c_i \right) X_{n\nu}$$



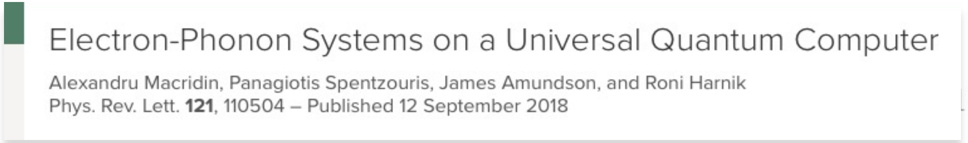
Ref: Phys. Rev. Lett. 121, 110504

- Bosons are described by a set of harmonic oscillators
- Harmonic oscillators discretized and expressed as a superposition of {Ix>} states stored on N qubits

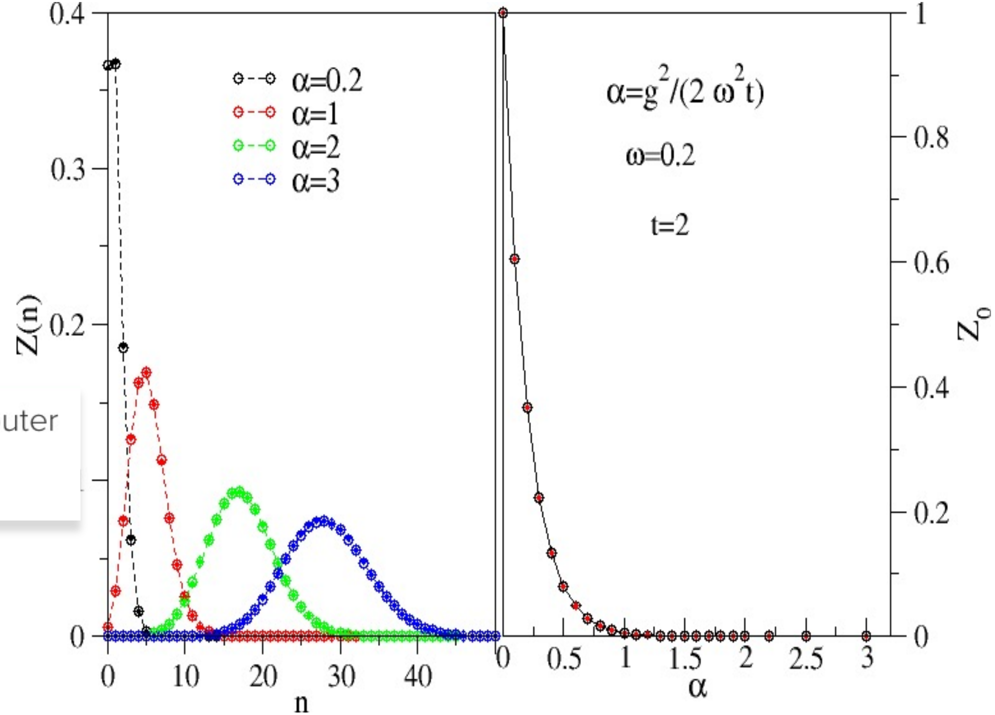
Application: Holstein polaron

Polaron

- One electron interacting with the vibrations of the lattice
- Can be viewed as an electron dressed by phonons


Electron-Phonon Systems on a Universal Quantum Computer

Alexandru Macridin, Panagiotis Spentzouris, James Amundson, and Roni Harnik
Phys. Rev. Lett. **121**, 110504 – Published 12 September 2018



$$|\Phi\rangle = \sum_{n=0,r} a_{nr}|n,r\rangle$$ ground state

$$Z(n) = \sum_{r} |a_{nr}|^2$$ phonon distribution