Fermilab Quantum Science Program

Panagiotis Spentzouris

UK Quantum Workshop

October 16-17, 2018

Quantum Science Program

Exploit quantum properties (coherence, superposition, entanglement, squeezing, …) for acquiring, communicating, and processing information beyond classical capabilities.

Application areas
- **Sensing and metrology**
- **Communication**
- **Computing**

With potential (or already demonstrated) impact on many areas of basic research

These areas have natural overlaps: sensors as qubits, quantum communication for sensing and metrology, transduction for communication, computing algorithms for quantum system operations,…
- Leverage synergies to define a coherent R&D program

Why is Fermilab involved?

Fermilab is the primary U.S. lab for High Energy Physics (HEP)

Quantum Information Science in DOE-SC

ASCR
Quantum algorithms; uncertainty quantification and verification & validation methods; software stack; quantum networks

BES
Synthesis, characterization, theory, modeling, and instrumentation to advance quantum materials & chemical phenomena

HEP
Black hole physics; quantum gravity and quantum error correction; fundamental aspects of entanglement

NP
Isotopes and trapped ions for quantum devices; lattice quantum chromodynamics

Quantum Field Theory and Topology

Control of Quantum Phenomena

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

U.S. DEPARTMENT OF ENERGY | Office of Science

HEP and QIS - BESAC March 2018 12

Fermilab

Fermilab Quantum Information Science

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

Fermilab is engaging with the DOE-SC QIS Initiative in ways appropriate to our role as the main HEP lab:

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

Fermilab Quantum Science Program Thrusts

Superconducting Quantum Systems: Leverage Fermilab's world-leading expertise in SRF cavities to advance qubit coherence times, quantum memories, 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 and networks.

Quantum Sensors: Adapt quantum technologies including squeezing and entanglement to enable new fundamental physics experiments. Current activities:

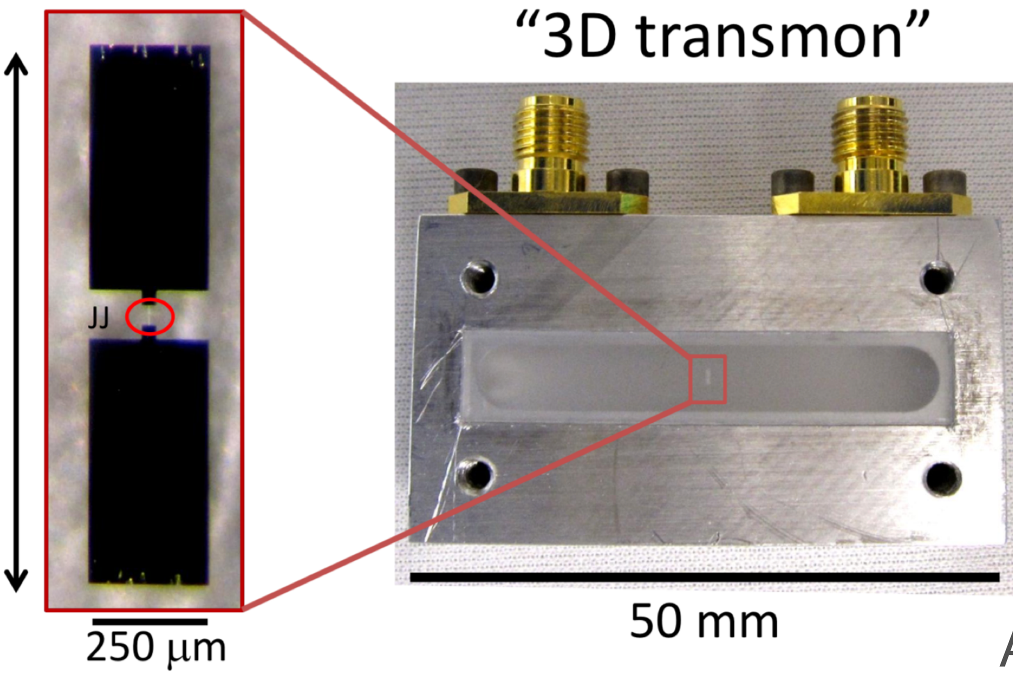
- Qubit-cavity systems for axion dark matter detection
- Cold atom interferometry
- Time-binned photon quantum teleportation for communication

Underpinning infrastructure: cold electronics, control systems; community building and workforce development

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

Superconducting 3D quantum computers

There are great advantages to coupling superconducting Josephson Junction qubits to superconducting microwave cavities



Good for:

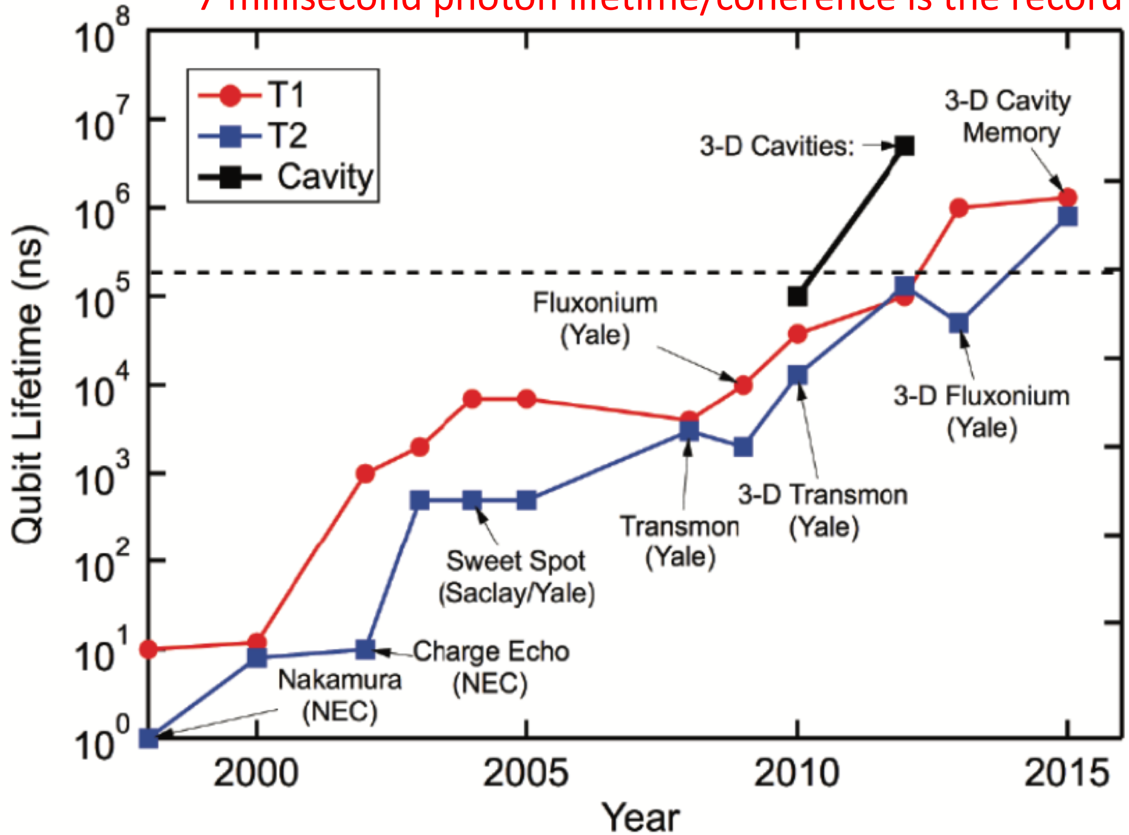
- Isolation
- Control
- Readout
- Coherence time

Achieved record long quantum coherence times, as measured by **T_2**, the dephasing time of superposition states

H. Paik et al, PRL 107, 240501 (2011)

3D qubits/cavities give the best quantum coherence

7 millisecond photon lifetime/coherence is the record



M. H. Devoret and R. J. Schoelkopf, *Science* 339, 1169–1174 (2013)

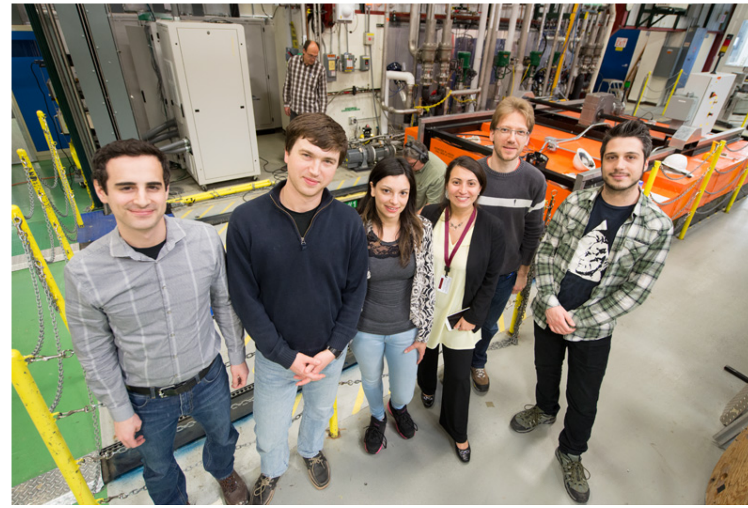
Long **quantum coherence time** is necessary for creating initial state, performing qubit gate operations, and measuring final state.

World record $\mathbf{T_2}$ **~** few milliseconds means we can start thinking about quantum computing circuits with depth ~ 10,000

Can we do better?

Fermilab superconducting cavities for accelerators

At Fermilab we make SRF cavities and assemble them into cryomodules for cutting-edge accelerators like LCLS-II and PIP-II



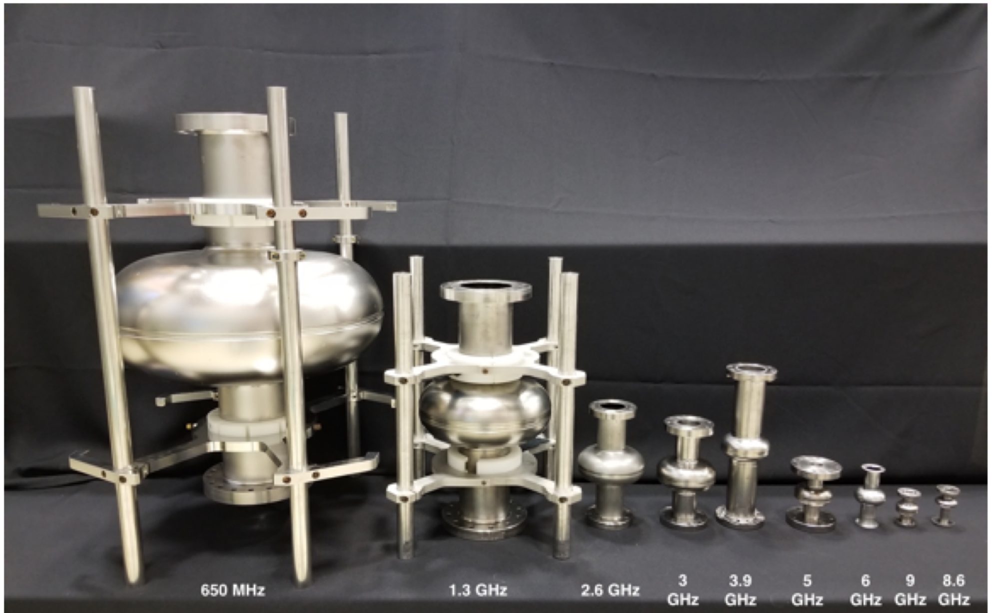
Alex Romanenko and Anna Grassellino lead the Fermilab SRF cavity program

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

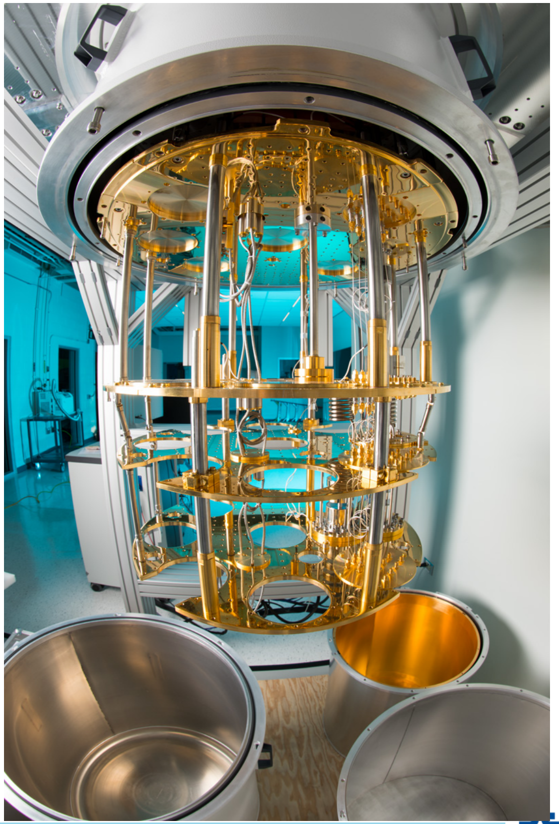
SRF cavities for quantum computers (QC)?

Challenges:

- For accelerators we want high gradients → as many photons as possible; for QC applications we want to manipulate cavity states at the **single photon** level
- Accelerators operate at temperatures around 2K, QC systems around 20 milliKelvin

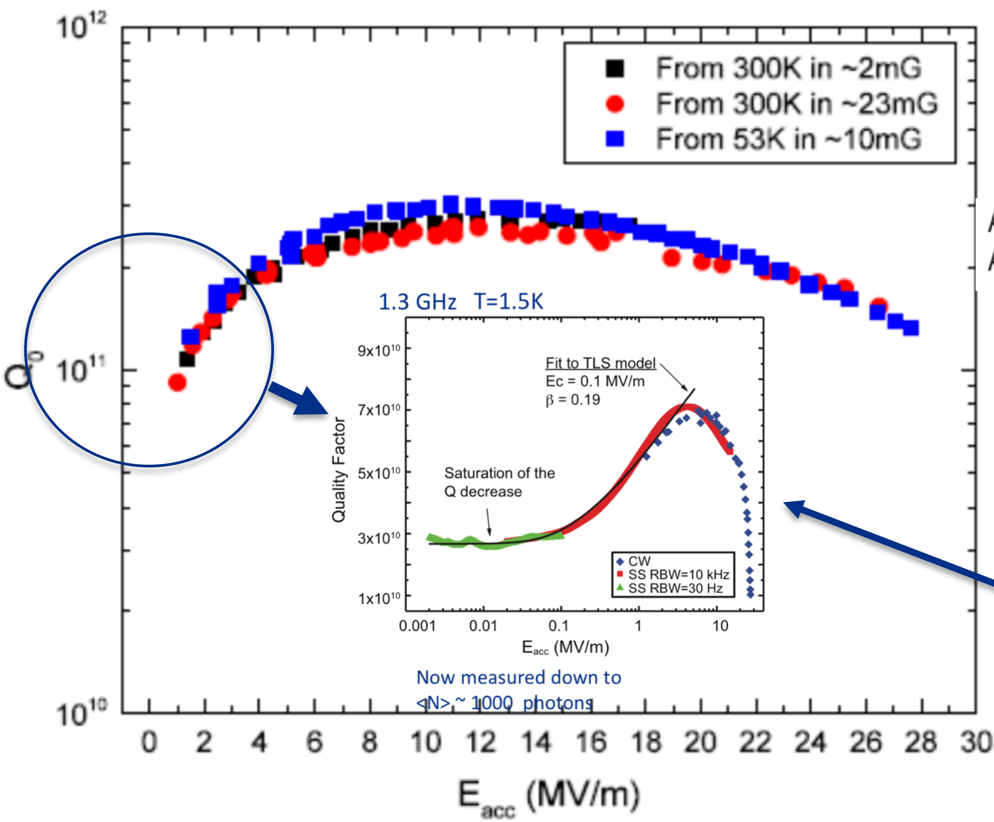


1-cell Fermilab cavities of various frequencies



The Q of superconducting cavities

For accelerators we want very high accelerating gradients and very high quality factor Q (high Q: resonant cavities "ring" longer, thus need less power)



Thanks to breakthroughs by Fermilab scientists, we now routinely achieve Q near or above 10^{11}

A. Romanenko, A. Grassellino et al. J. Appl. Phys. 115, 184903 (2014)
A. Romanenko, A. Grassellino et al. Appl. Phys. Lett. 105, 234103 (2014)

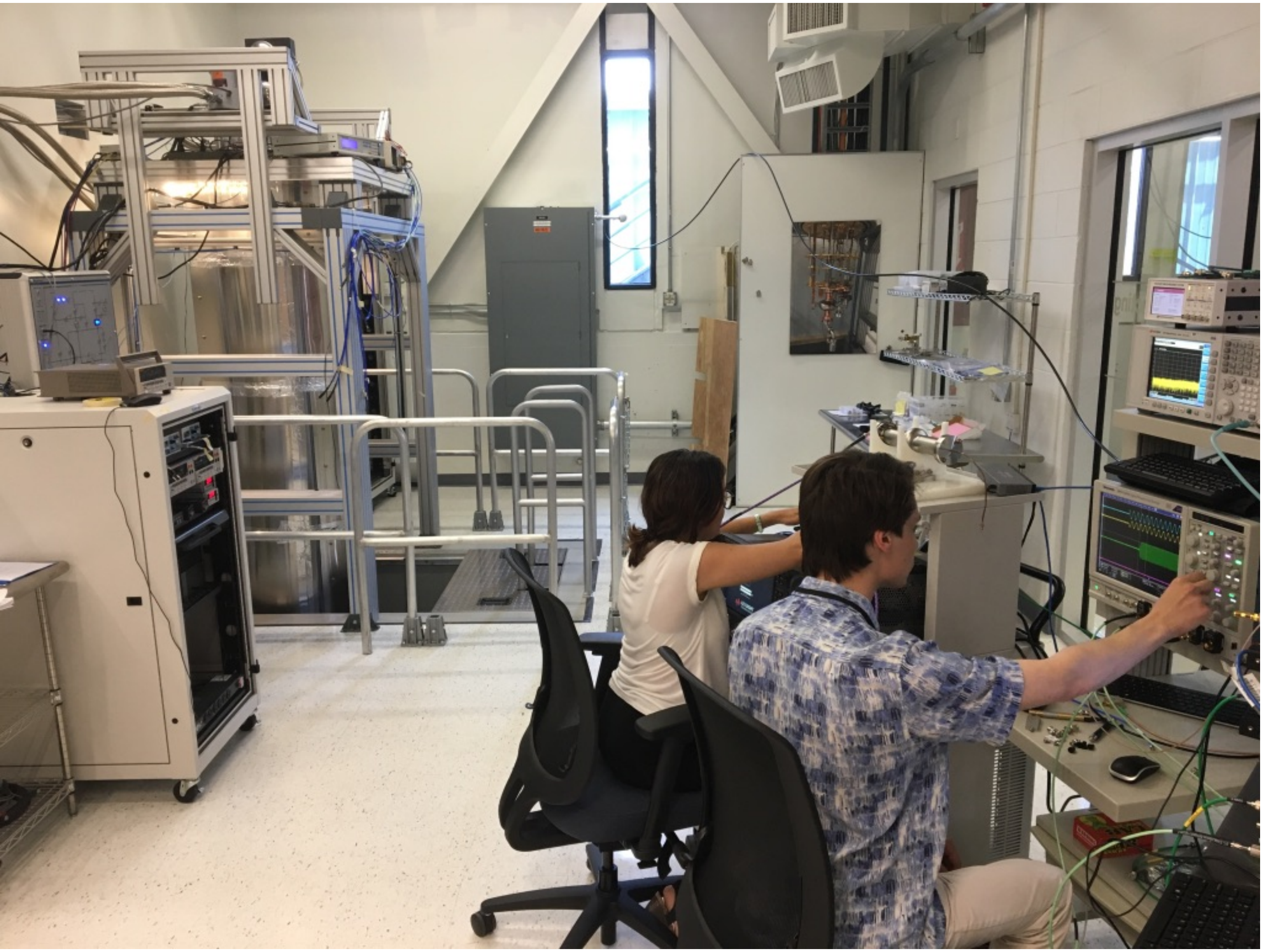
How will these cavities behave at ultralow fields for quantum science applications?

- Quantum computing/memory
- Dark sector searches
- Gravitational effects
- ....

Work at Fermilab and University of Chicago enhances understanding of Q at low field amplitude

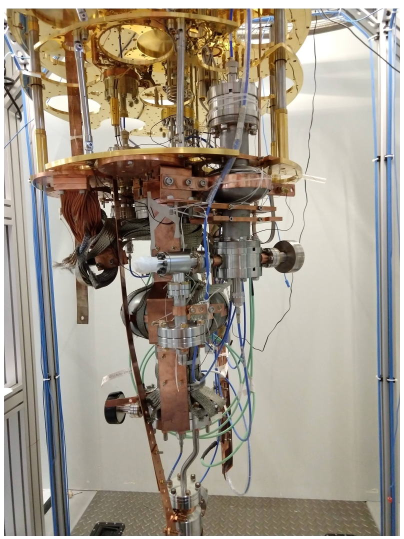
A. Romanenko and D. I. Schuster, Phys . Rev. Lett. **119**, 264801 (2017)

New SRF Quantum Lab operating at Fermilab now for R&D on qubits coupled to SRF cavities

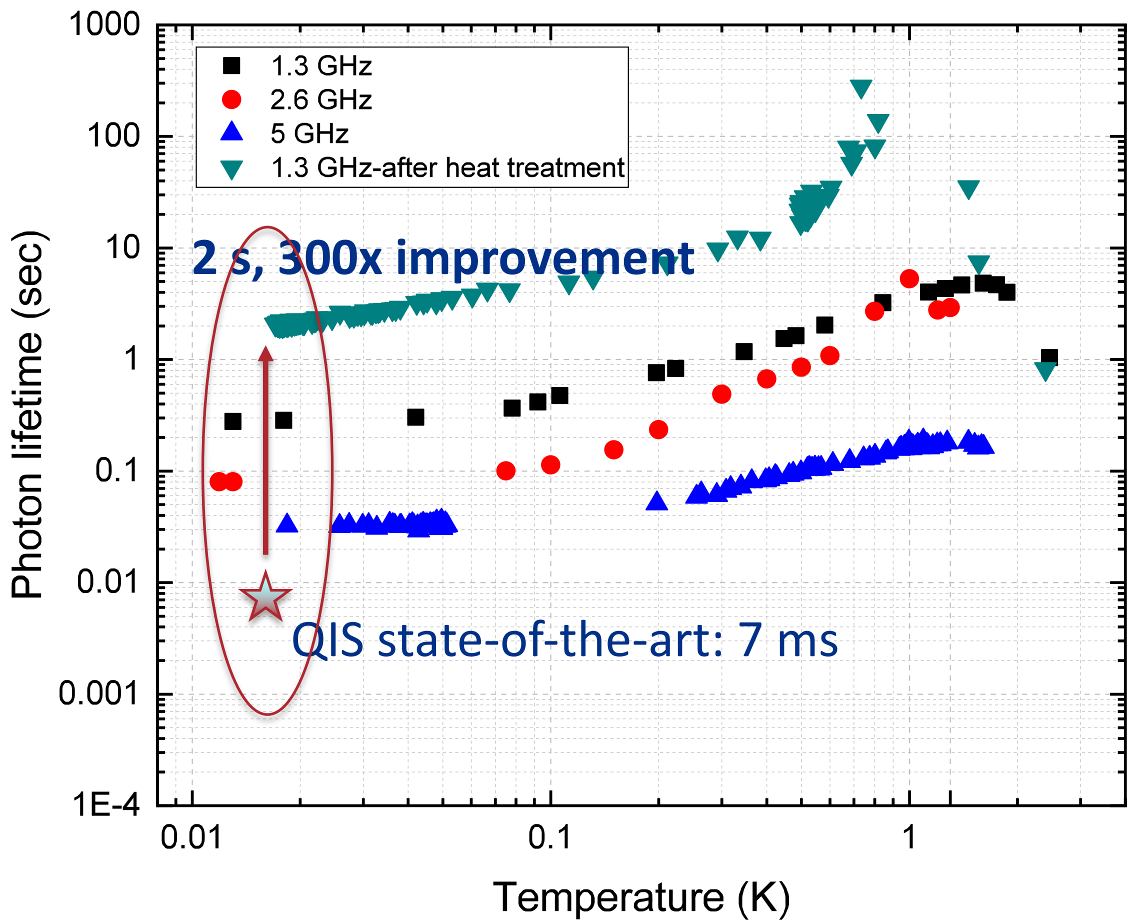


Superconducting qubits supplied by our partners at **NIST** and **UW Madison**

Record high photon lifetimes achieved at Fermilab



Accelerator cavities adopted for quantum regime



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

HEP applications of quantum computers

Long view:

- Most HEP applications will require thousands, if not millions, of error-corrected qubits, which won't be available for ~20 years
- However Fermilab is planning experiments that will be running 20 years from now, e.g. the DUNE neutrino experiment, and the CMS experiment at the HL-LHC

What can we do now?

- Identify scaled-down problems with elements of the applications we care about that can be addressed with near-term quantum technologies, and work on solving them!

Fermilab and Quantum Computing with Industry Partners

Goal is to gain experience with quantum algorithms relevant to HEP and understand application deployment on Quantum Computers (QCs)

Partnership with Google

- Become a gateway for the HEP community to access QC environment
- Build on partnership and host workshops, tutorials and training
  - First tutorial delivered, Fermilab Workshop on Sep 12-14, 2018 https://indico.fnal.gov/event/17199/
- Design "experiments" for Google QCs for algorithms we develop

Partnership with Rigetti

- Exploring Variational Eigenvalue solvers on Rigetti QC

Partnership with Lockheed Martin

- Access to D-Wave machine for quantum machine learning studies

HEP applications to today's quantum computers: from fermions to bosons to gauge theories

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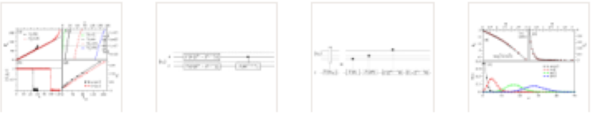
Electron-Phonon Systems on a Universal Quantum Computer

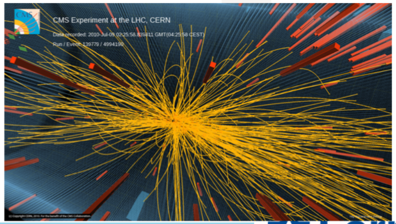
Alexandru Macridin, Panagiotis Spentzouris, James Amundson, and Roni Harnik
Phys. Rev. Lett. **121**, 110504 – Published 12 September 2018

Article | References | No Citing Articles | PDF | HTML | Export Citation

ABSTRACT

We present an algorithm that extends existing quantum algorithms for simulating fermion systems in quantum chemistry and condensed matter physics to include bosons in general and phonons in particular. We introduce a qubit representation for the low-energy subspace of phonons which allows an efficient simulation of the evolution operator of the electron-phonon systems. As a consequence of the Nyquist-Shannon sampling theorem, the phonons are represented with exponential accuracy on a discretized Hilbert space with a size that increases linearly with the cutoff of the maximum phonon number. The additional number of qubits required by the presence of phonons scales linearly with the size of the system. The additional circuit depth is constant for systems with finite-range electron-phonon and phonon-phonon interactions and linear for long-range electron-phonon interactions. Our algorithm for a Holstein polaron problem was implemented on an Atos quantum learning machine quantum simulator employing the quantum phase estimation method. The energy and the phonon number distribution of the polaron state agree with exact diagonalization results for weak, intermediate, and strong electron-phonon coupling regimes.

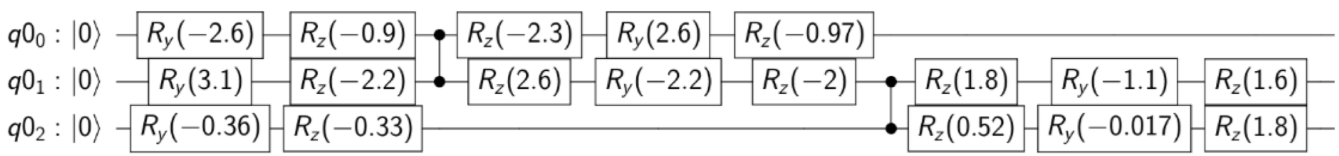




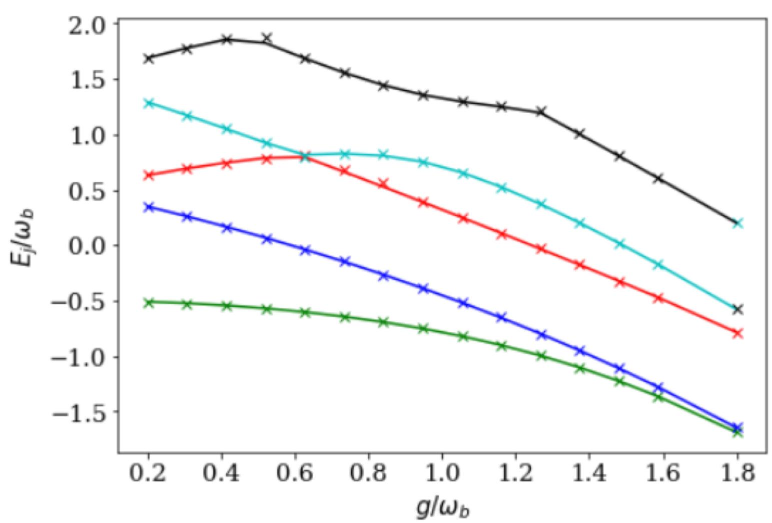
Fermilab

HEP applications of today's quantum computers: Variational Quantum Eigensolver

- Quantum-classical hybrid algorithm
  - quantum: efficient measurement of trial-state energy
  - classical: gradient-based algorithm to update trial state
- Trial state parameterized by a quantum circuit



- Implementation on Rabi-model (boson coupled to spin)



Algorithm verification
- simulate using Google's Cirq package
- tested on Rigetti's device

In progress:
- Preparing experiment on Google QPU
  - Understanding resource needs, optimizing circuit

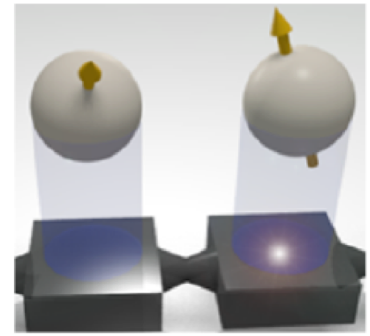
Andy Li et al, to be presented at QIP 2019

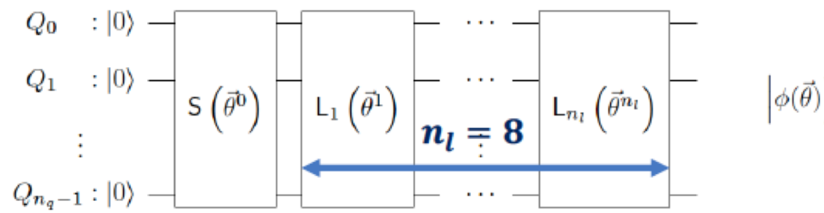
Running (experiments!) on Quantum Computers

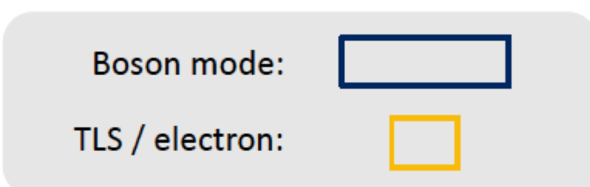
Proposal

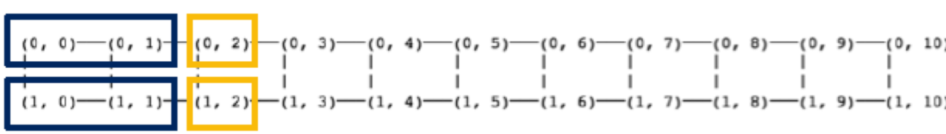
- Physical system to simulate:
  2 boson modes coupled to 2 TLSs or electrons
  (TLS = two-level system)

- Implementation:
  - Maximum of 3 bosons per mode
    → 2 qubits to encode 1 boson mode
  - Preparation circuit: 8 layers

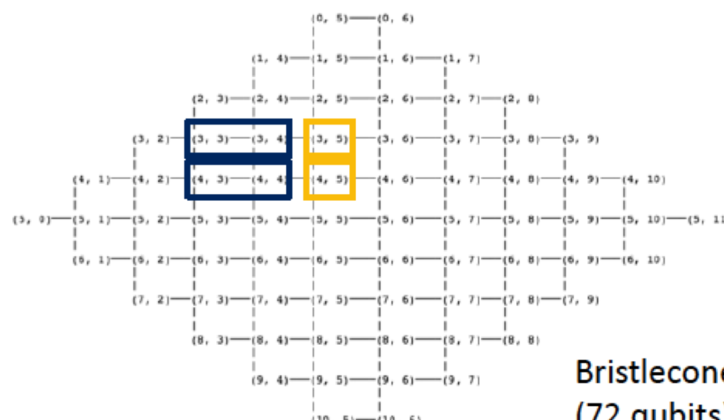








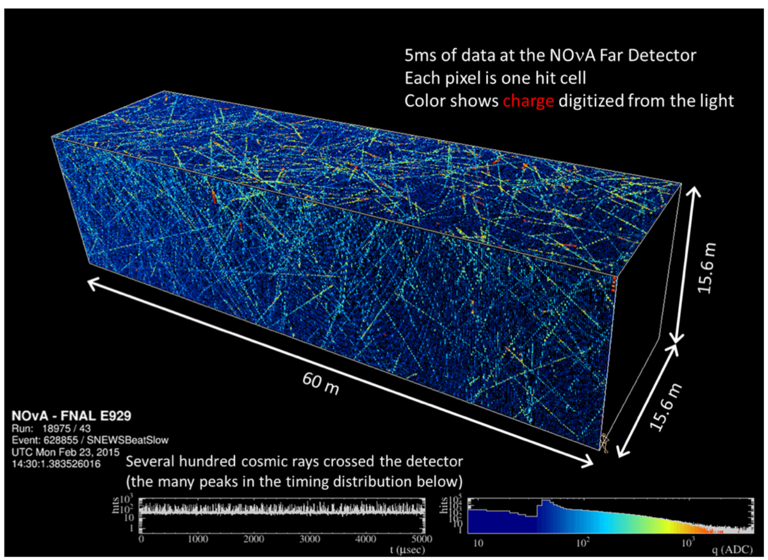
Foxtail (20 qubits)

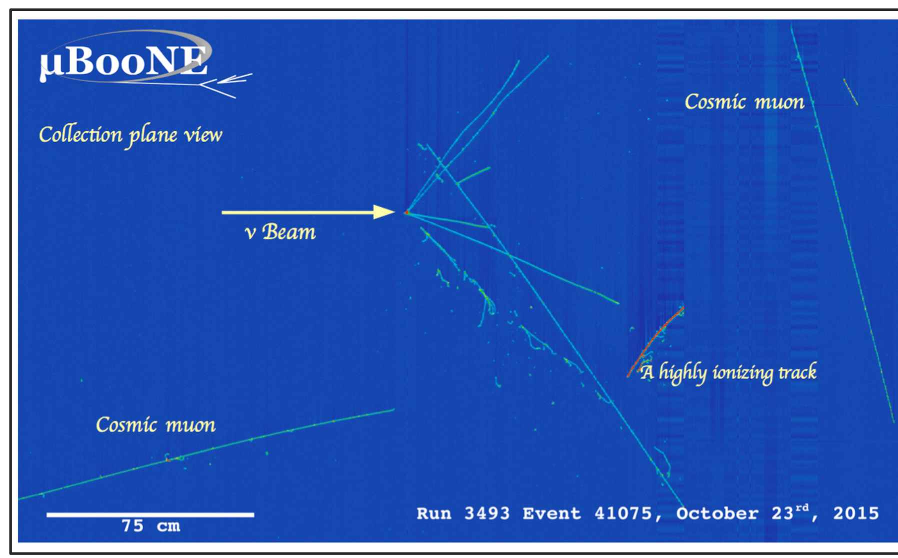


Bristlecone (72 qubits)

HEP applications on near-term Quantum Computers: Machine Learning (ML)

- Many experiments already using ML to better classify, e.g. neutrino-induced interactions in particle detectors. Fully quantum or hybrid (classical/quantum) approaches could improve performance.
- Some standard ML techniques, e.g. Boltzmann machines, involve estimating the ground state of a Hamiltonian that has many local minima; quantum ML may have advantages
- Quantum ML algorithms could be essential for “error correction” on sensor applications to improve sensitivity



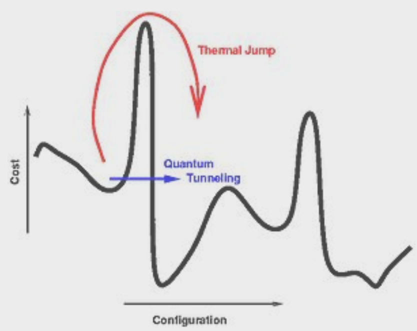


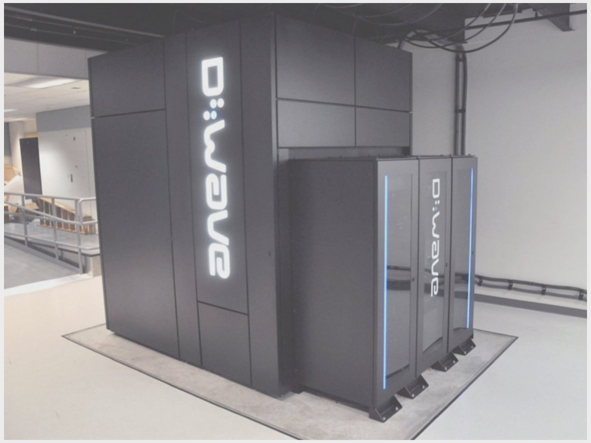
Astrophysics ML application using a Quantum Annealer

Partnering with Lockheed Martin and ORNL on ML problems in astrophysics:

- Several exploratory projects leveraging a D-Wave annealer: star/galaxy separation, anomaly detection, and autoencoders (for compression or simulation).
- Focus on exploring data representations (flexible resolution requirements, and multiple sorts of data for each object let us tune the inputs).
  - match the data representation to the hardware and understand trade-offs

- Annealing is a standard classical process for trying to avoid getting stuck in a local minimum
- **Quantum annealing** improves this by adding the possibility of quantum tunneling





D-Wave, a world leading quantum annealer (analog quantum computer)

Quantum Sensors for Dark Matter detection?

There are many plausible theories for the identity of dark matter

- Superpartner particles: Wino, Bino, Higgsino, sneutrino, …
- **Axions**
- Kaluza-Klein particles from extra dimensions
- Asymmetric dark matter
- WIMPzillas (??? talk to the theorists…)

Dark matter streaming in from space may interact very weakly with ordinary matter

But the details depend on the mass and other properties of the dark matter particles

Searching for axion dark matter

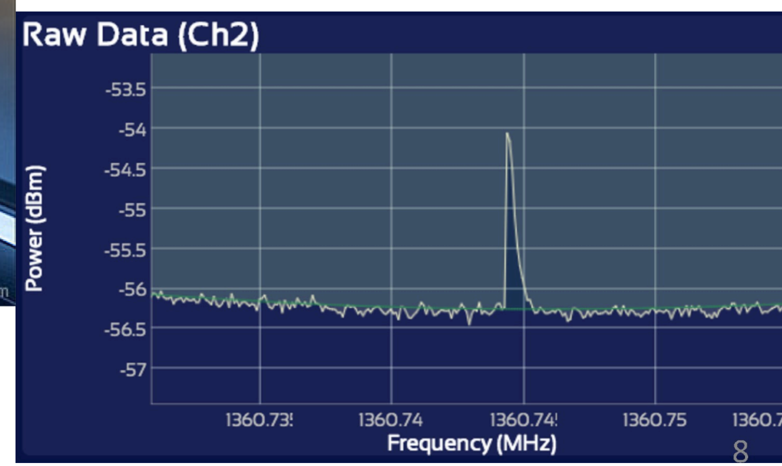
DOE Gen2 Dark Matter Project (Fermilab-managed)

A resonant cavity "axion" dark matter search proceeds by tuning the radio frequency of the cavity and checking to see if you can hear the dark matter "radio broadcast" above the static noise

- ☛ The "static" of the radio is thermal photons + quantum noise

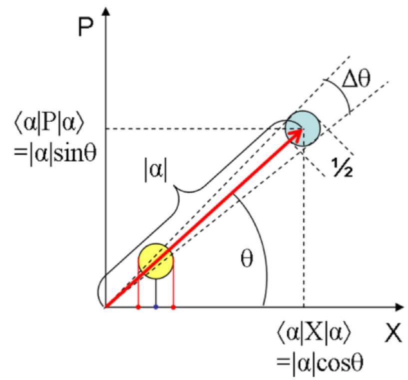
ADMX Experiment at U.Washington

Simulated axion signal from ADMX



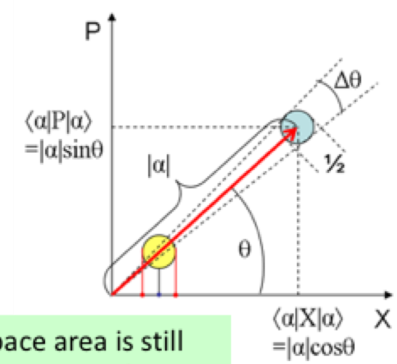
Can we improve measurement using quantum properties of sensors?

- Even at zero temperature readout amplifiers can't avoid quantum noise
  - Standard Quantum Limit (SQL)
- Quantum non-demolition (QND) single-photon detectors can do much better than SQL amplifiers
  - Measure photon number and put all backreaction into the unobserved phase of the wave



Heisenberg Uncertainty Principle
$\Delta X\, \Delta P = \Delta N\, \Delta\theta = ½\hbar$
(quantum of phase space area)

Quantum noise = 1 photon of "zero point" noise per mode in the T=0 limit.
(Caves, 1982)



Phase space area is still ½ħ but is **squeezed** in radial (amplitude) direction. Phase of wave is randomized.

Demonstrated with Rydberg atoms, (Serge Haroche Nobel Prize 2012)

Implementation using **superconducting qubits**, **D.Schuster et.al, 2007**

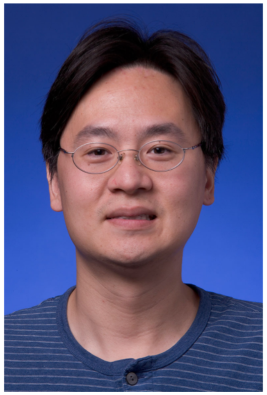
Proposed for axion search: Lamoreaux, Lehnert, et.al, 2013, Zheng, Lehnert, et.al, 2016

Improving the signal photon rate: superconducting qubits

- Increase the signal photon rate by using superconducting qubits as QND detectors and an ultra-high-Q cavity in a non-classical state
  - sensitive to incoming axion waves with any arbitrary phase
- Reduce error rate by incorporating multi-qubit readout system
- Challenges:
  - Integrating qubits with axion cavity (in strong magnetic field)
  - Cavity state preparation
  - Ultra-high-Q needed to hold cavity state for many QND measurements
  - Cavity tunability

Qubit-based single microwave photon sensors for axion detection

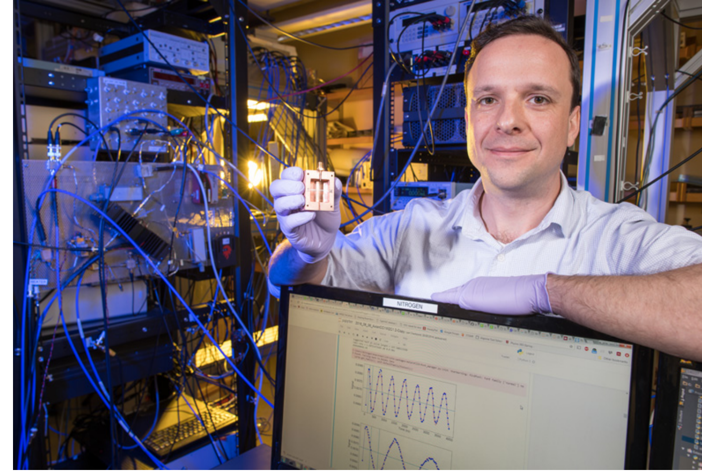
HEISING-SIMONS FOUNDATION



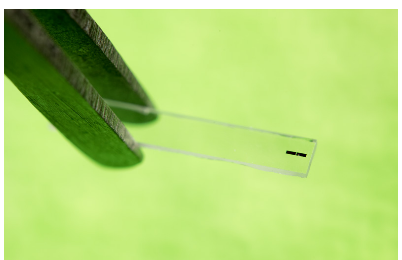
Aaron Chou

David Schuster(UC)

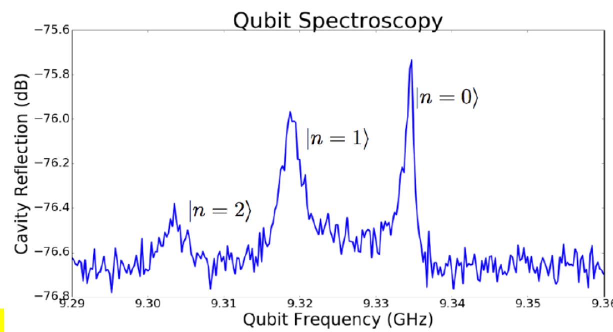
Konrad Lehnert U.Colorado/NIST



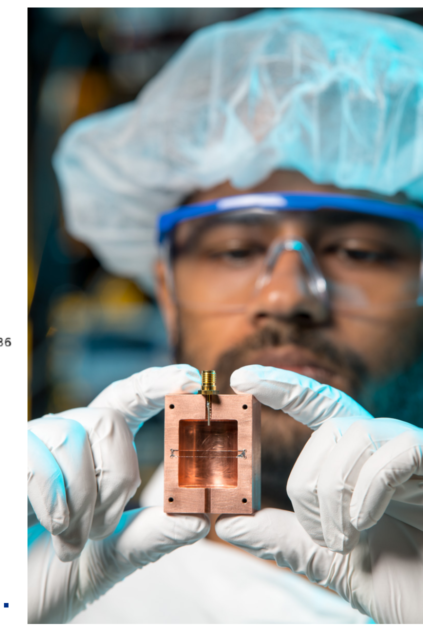
Daniel Bowring, Fermilab
2018 Early Career Award



New Fermilab test stand incorporates magnet into a dilution refrigerator for R&D on qubit-cavity systems for a next generation dark matter experiment.



Grad student Akash Dixit installing a prototype detector in a 10 mK test stand in the Schuster Lab.



Quantum Communication

- Quantum Communication R&D not only aims to deliver essential technologies for one of the main application areas of the Quantum Science ecosystem, but also drives R&D for the other two (sensors, computing).
- Objective is to develop the capabilities for high-fidelity long-range communication of quantum information, that will allow networking of quantum devices
- **Quantum Teleportation** is an enabling technology with applications for secure communications, quantum computing, and networking of sensors
- Using advanced photonics, long-rang quantum teleportation has been accomplished though space (China) and over telecom fiber (Canada)

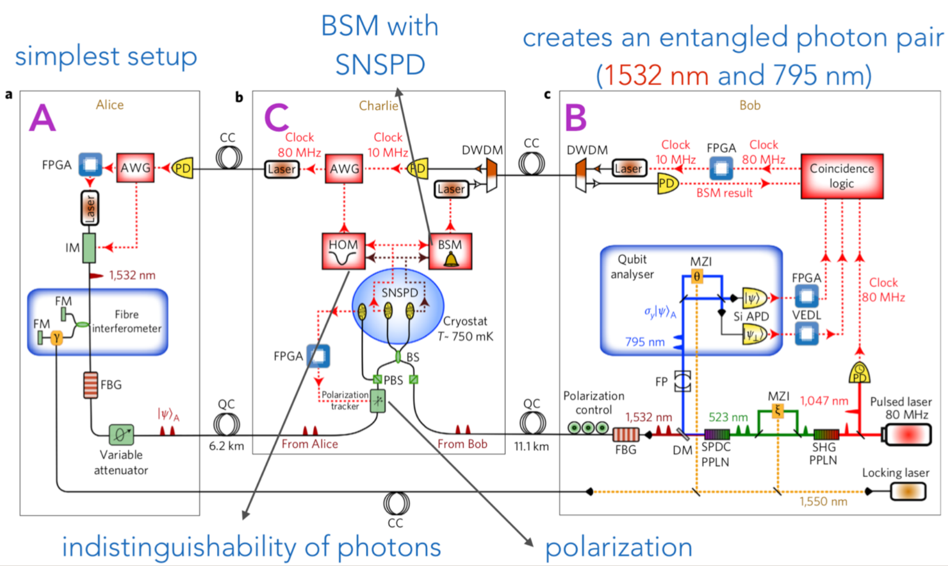
Fermilab quantum teleportation experiment (FQNET)

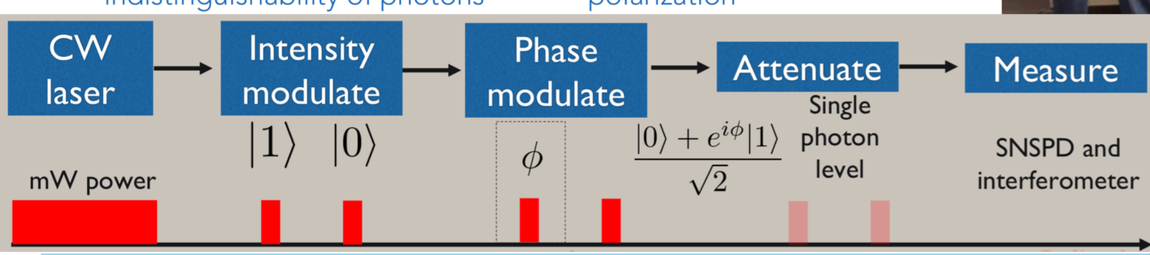
- Laser, attenuator, arbitrary waveform generator to make time-binned optical photonic qubits
- Spontaneous Parametric Down Conversion (SPDC) crystal, splitters, and other optics to entangle
- Transport the qubits over commercial telecom fiber
- Perform Bell-State-Measurement (BSM) with SNSPDs = Superconducting Nanowire Single Photon Detectors

Caltech

JPL Jet Propulsion Laboratory California Institute of Technology

AT&T





Fermilab

Current FQNET setup

Baseline equipment for teleportation in place

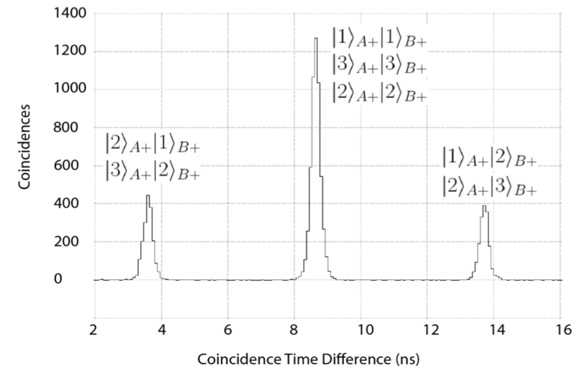
System commissioning underway

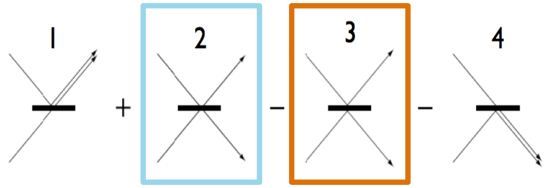
Challenges and the role of Fermilab competencies

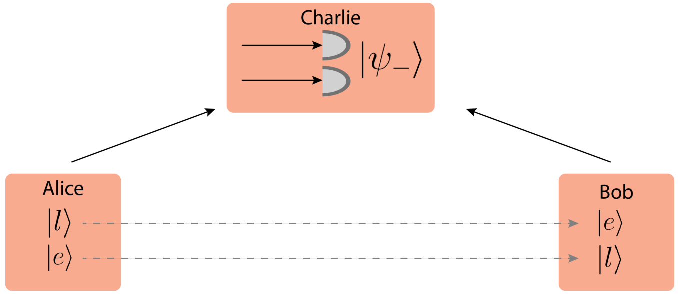
- Need to demonstrate (necessary conditions for teleportation):
  - Entanglement
  - Indistinguishability

- Several metrics to optimize:
  - Quantum teleportation fidelity & stability
  - Teleportation efficiency
  - Communication loss, bandwidth and rate

- Leveraging standard HEP technologies and tools at Fermilab:
  - Trigger, high-rate DAQ systems and controls
  - Software and computing infrastructure
  - Feedback, time synchronization
  - Lab infrastructure, fiber connectivity



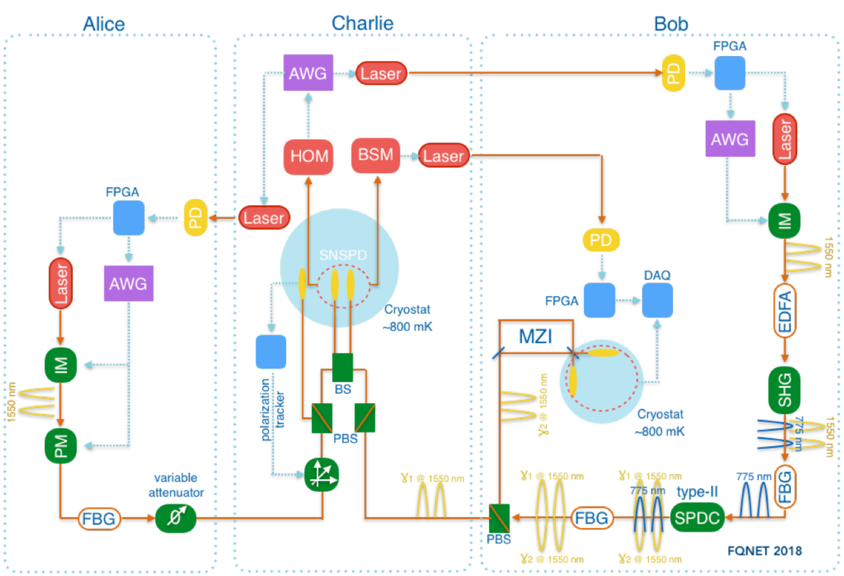




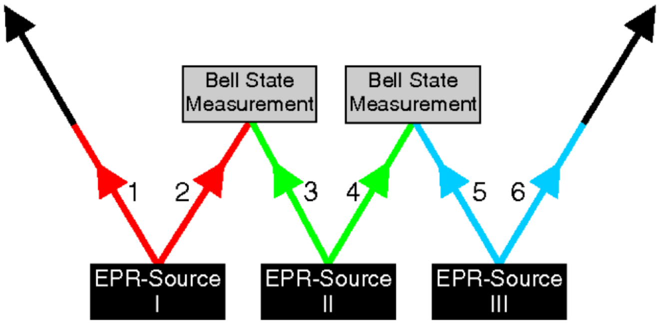
Next Step: Fermilab-Argonne Quantum Network

Leased telecom fiber between Fermilab and Argonne, ~30 miles apart, affords an opportunity to rapidly advance the science and technology of moving quantum information over long distances using entangled photons

Establish and maintain a state-of-the-art quantum network backbone while inviting the community at large to utilize it for testing a variety of quantum devices connected to the network



End-game vision and R&D drivers



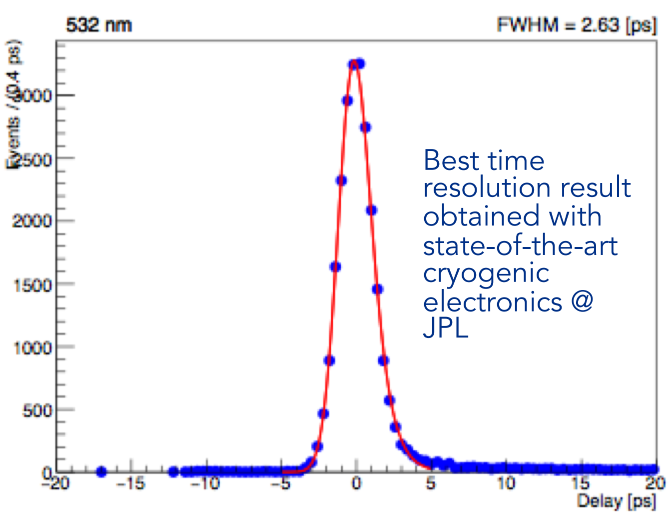
Entanglement Swapping

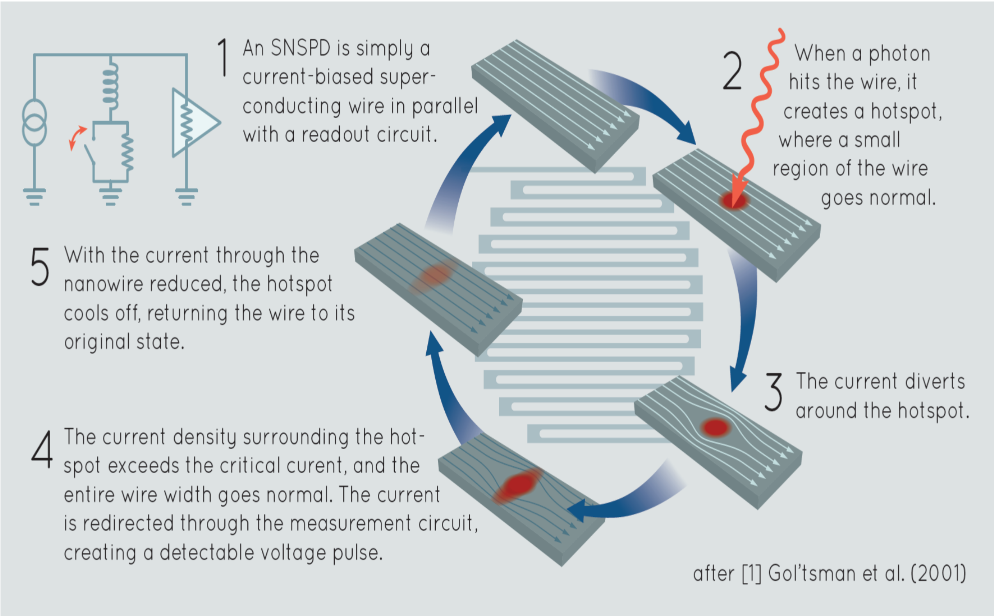
- Networks of quantum computers, quantum sensors, and other coupled physical systems (solids, trapped ions/atoms, phonons, polaritons)

- To enable a future quantum network, R&D is needed for:
  - High rate single and entangled photon sources
  - High efficiency, low noise, low jitter, photon-number resolving detectors
  - Quantum memories, quantum transducers
  - Quantum processors and algorithms

Driving HEP R&D: Cryogenic Electronics

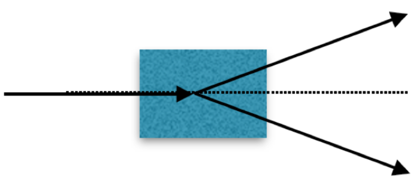
- Develop cryogenic amplifiers to reduce electronic noise and improve time resolution for SNSPDs
  - Low-noise cryogenic readout circuits based on state-of-the-art, commercially available SiGe heterojunction-bipolar-transistors integrated with cryogenic CMOS, operating at 1-4 Kelvin.
- Fermilab, JPL, Georgia Tech collaboration





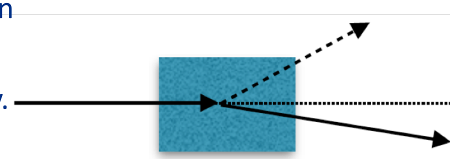
Driving HEP R&D: Dark Matter Detection

- Use high intensity entangled pair source to produce Photon-DarkPhoton pairs, and "image" them with Skipper CCDs
- Engineer SPDC crystals such that their properties are favorable for Photon-DarkPhoton discrimination
- Allows for background suppression via image patterning

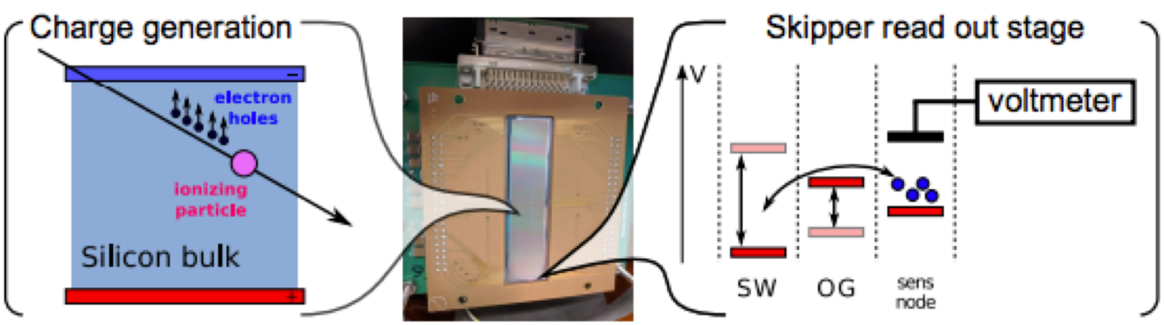


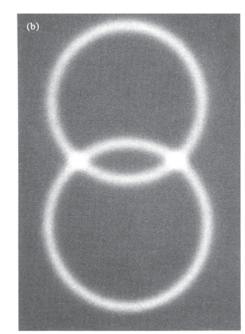
Spontaneous Parametric Down Conversion **(SPDC):** down-converted photons are entangled in angle and energy.

Emission angle and energy determined by the phase matching conditions and the crystal's index of refraction.



The index of refraction of the dark photon is significantly different, thus the angle of the visible photon is also significantly different for a given energy.

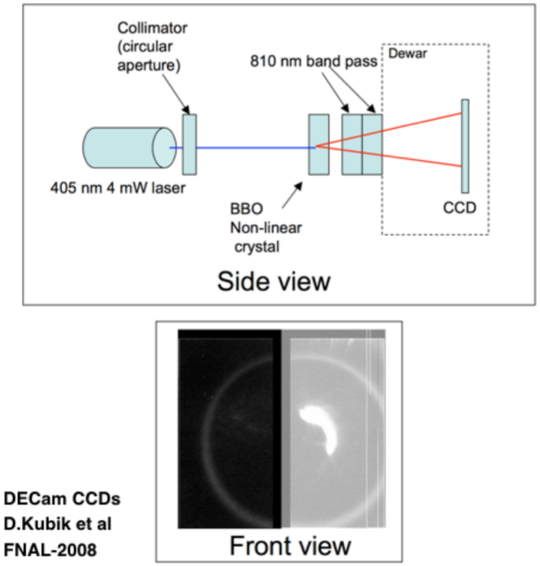




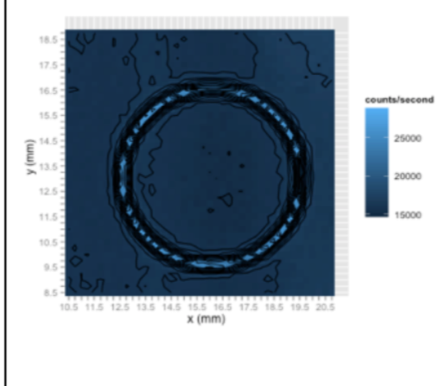
Fermilab

Driving HEP R&D: Dark Matter Detection

- Fermilab, LBNL, Caltech partnership
- Takes advantage of existing skipper-CCD R&D infrastructure at Fermilab and ongoing joint R&D with LBNL, and infrastructure developed for Quantum Communication activities (entangled photon-source, crystals)
- New project with goals to
  – demonstrate skipper-CCD technique for quantum imaging
    - demonstrate sub-shot noise fluctuations in a parametric down conversion experiment
  – develop new skipper-CCD design for quantum imaging
    - incorporate low-noise amplifier
    - higher readout speed



DECam CCDs
D.Kubik et al
FNAL-2008

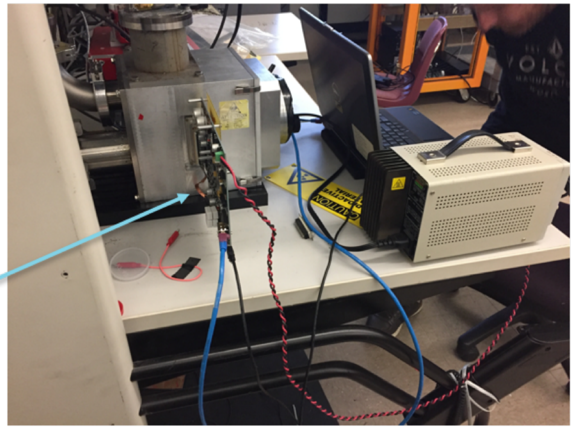


2015 — SPCM
Carlos Escobar et al

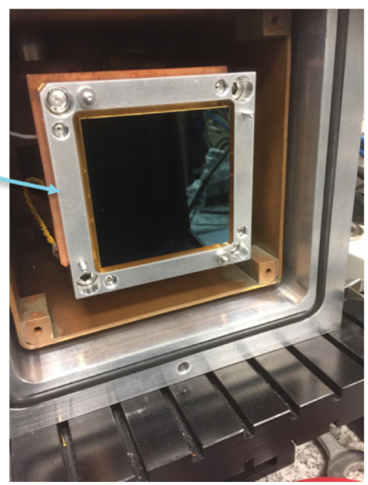
Quantum Imaging Setup

Adapting source of entangled photons built for use with SiPMs, for the skipper-CCD setup.

CCD test vessel

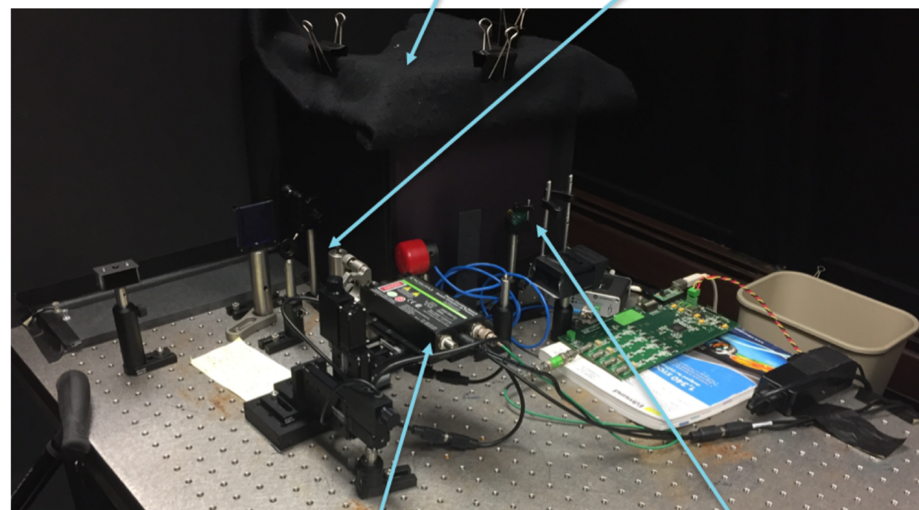


CCD inside test vessel



405nm Laser

BBO holder + filters

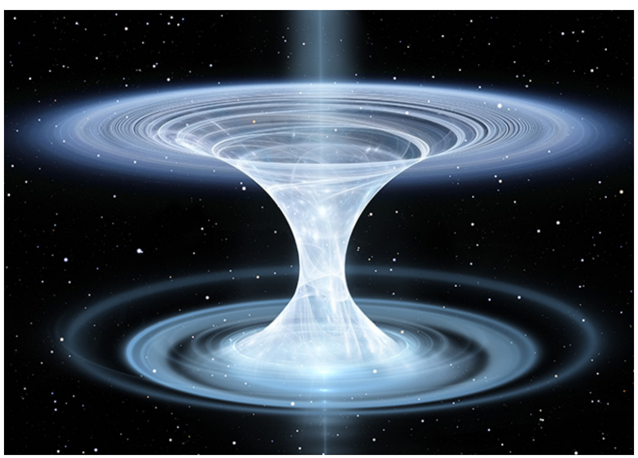


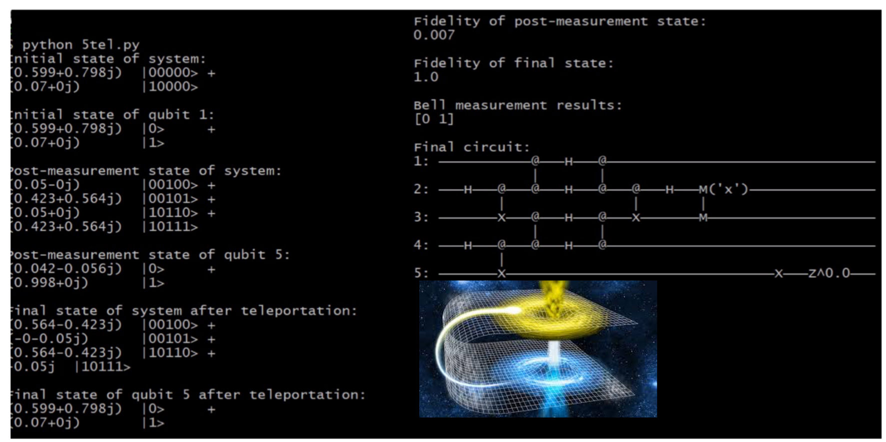
beam dump

single photon counter

Driving HEP Science: Entanglement as Probe of Space-Time

- Recent HEP theoretical work shows that a pair of entangled black holes can be connected by a **wormhole**
- This has been shown to be **a special kind of quantum teleportation**, that should be reproducible for smaller quantum systems in the lab
  - Implementation of protocols on available quantum computers
  - FQNET is developing the technology required for to perform the first experiments with wormhole teleportation protocols





MAGIS Collaboration

Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS-100)

Phil Adamson[1], Swapan Chattopadhyay[1,2], Jonathon Coleman[5], Peter Graham[3], Steve Geer[1], Roni Harnik[1], Steve Hahn[1], Jason Hogan[†3], Mark Kasevich[3], Jeremiah Mitchell[2], Rob Plunkett[1], Surjeet Rajendran[4], Linda Valerio[1] and Arvydas Vasonis[1]

[1] *Fermi National Accelerator Laboratory; Batavia, IL 60510, USA*
[2] *Northern Illinois University; DeKalb, Il 60115, USA*
[3] *Stanford University; Stanford, California 94305, USA*
[4] *University of California at Berkeley; Berkeley, CA 94720, USA*
[5] *University of Liverpool; Merseyside, L69 7ZE, UK*

STANFORD

UNIVERSITY OF CALIFORNIA BERKELEY

NIU Northern Illinois University

UNIVERSITY OF LIVERPOOL

Fermilab

Physics Motivation

Dark matter and new forces

- Time-dependent signals caused by ultra-light dark matter candidates (dilaton, ALP, relaxion …)
- Dark matter that affects fundamental constants: electron mass, fine structure constant
- Time-dependent EP violations from B-L coupled dark matter
- New forces

Advancing quantum science

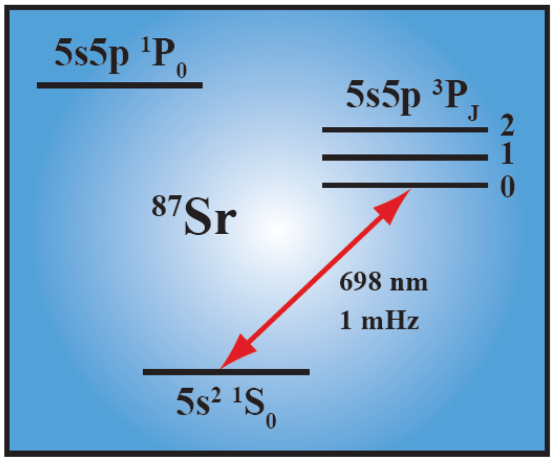
- Atom de Broglie wavepackets in superposition separated by up to 10 meters
- Durations of many seconds, up to 9 seconds (full height launch)
- Quantum entanglement to reduce sensor noise below the standard quantum limit

Gravitational wave detector development

- Probe for studying cosmology
- Explores range of frequencies not covered by other detectors
- LIGO sources before they reach LIGO band
- Optimal for sky localization: predict when and where events will occur (for multi-messenger astronomy)

Leverage atomic clock technology and quantum metrology for fundamental physics experiments

- Best clocks in the world now lose <1 second in 10^{18} seconds
- MAGIS utilizes physics of atomic clocks and atom interferometers

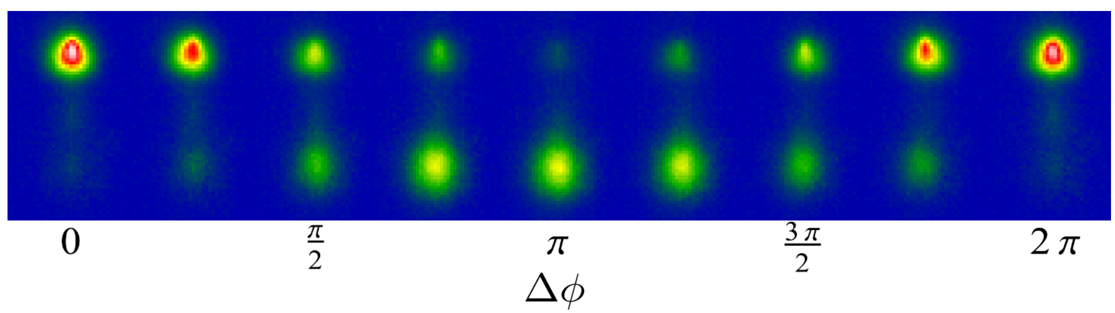


Strondium clock transition

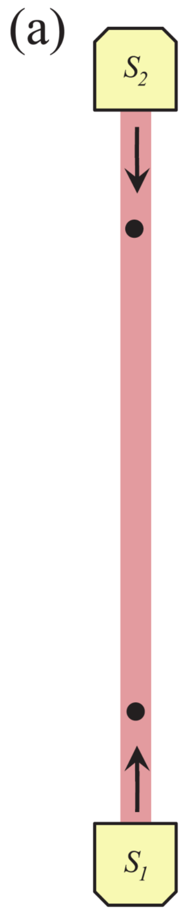
Data from world record atom interferometer duration (>2 seconds) at Stanford

Dickerson, et al., PRL **111**, 083001 (2013).

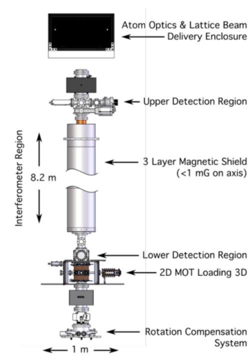
Science signal (CCD images):

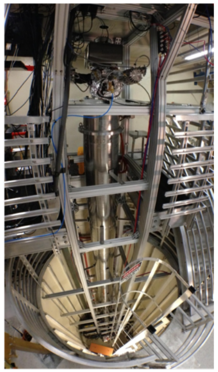


Gradiometer sensor design



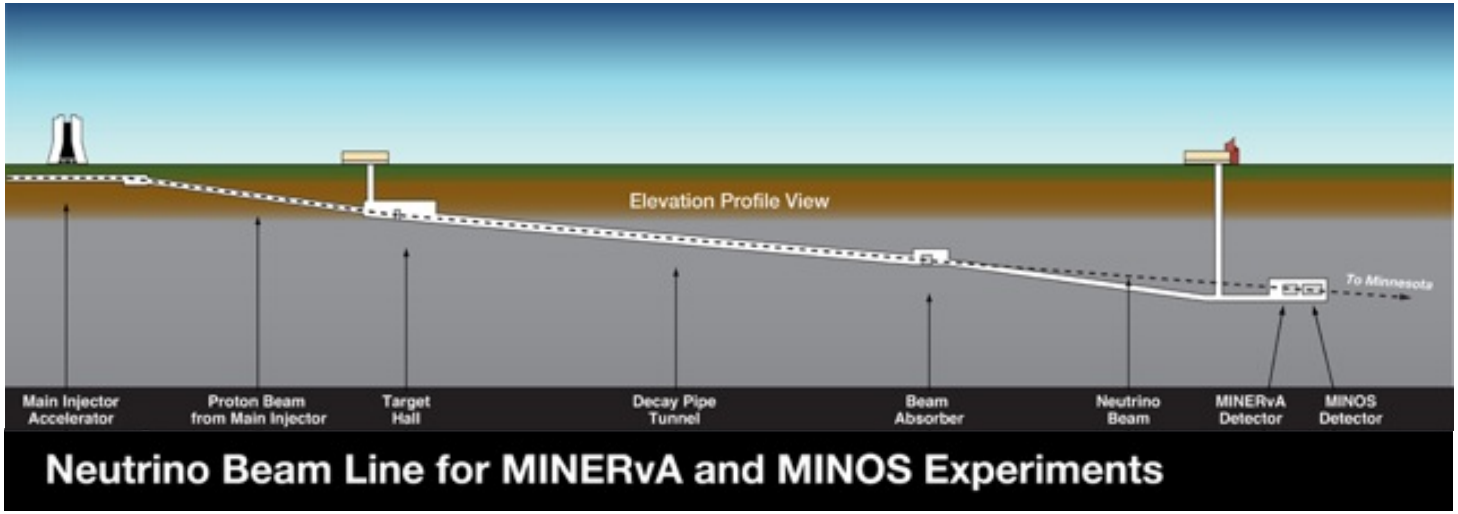
- Compare two (or more) ultra-cold atom ensembles separated by a **large baseline**
  - Laser pulses implement light-pulse atom interferometry at each end
- Science signal is **differential phase** between interference patterns
- Differential measurement suppresses many sources of common noise and systematic errors
- Proof-of-concept using the Stanford 10 m scale prototype

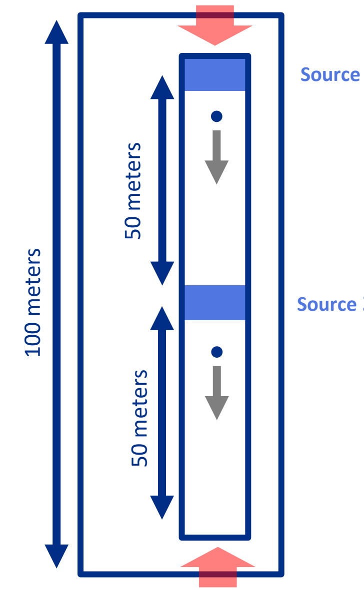




Science signal strength is proportional to baseline length (DM, GWs).

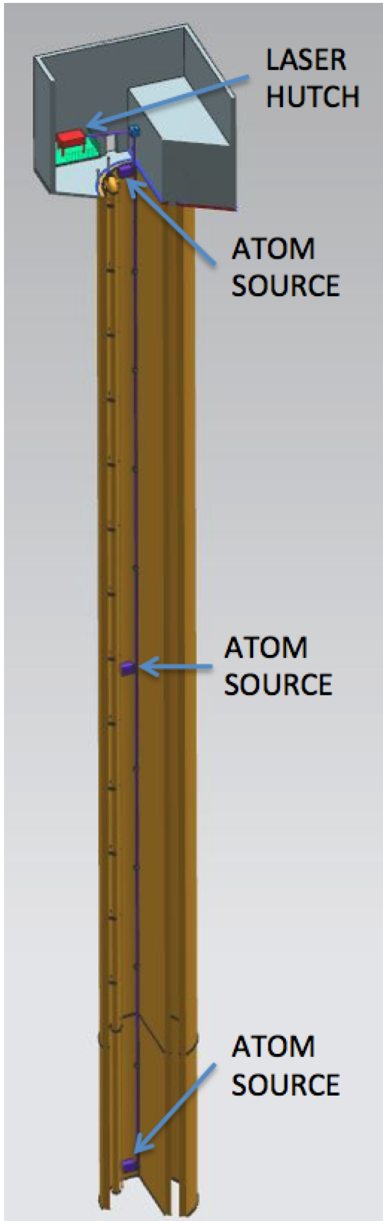
MAGIS-100 detector at Fermilab





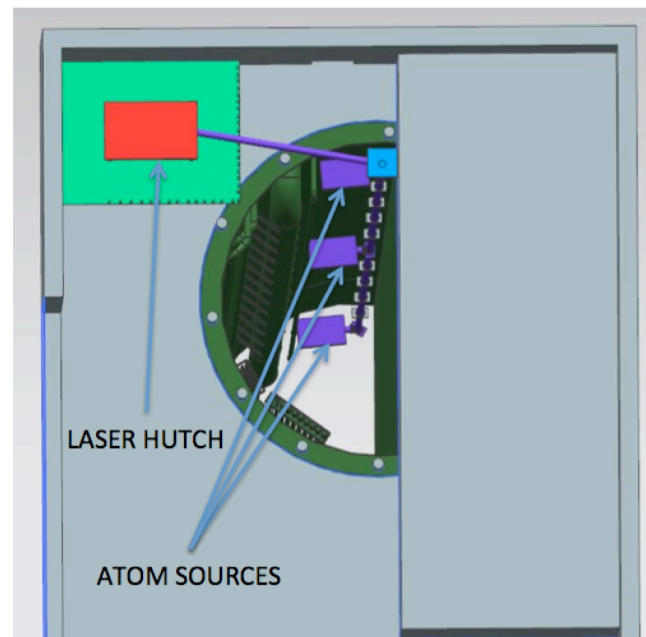
- MINOS, MINERvA, NOvA experiments use NuMI beam
- 100 meter access shaft – 100 meter atom gradiometer
- Search for dark matter coupling in the Hz range
- Intermediate step to full-scale detector for GWs
  - Aim to retire technical risk associated with scaling up:
    - Vacuum, trajectory control, alignment tolerances, …

MAGIS-100 design



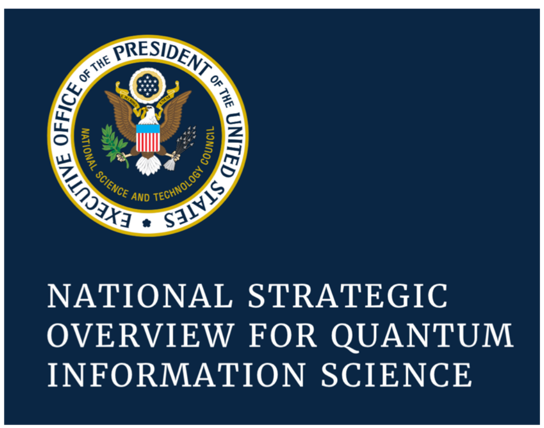
System Components:

- ~90 meter vacuum tube (vertical)
- Atom sources (three, attached to tube)
- Laser system for implementing atom interferometry (hutch at top)



Outlook

- We are building a Quantum Science Program leveraging Fermilab's competencies and targeting HEP long-term needs
  - Our Quantum Science initiatives are already producing results
- The community of HEP scientists engaging with QIS is growing
- We are establishing collaborations with universities, industry, and labs
- The US is developing a national approach to QIS R&D
  - We are in the process of developing long term strategy and objectives in this context



Fermilab quantum collaborations

Collaborations are for non-proprietary basic research in quantum science.
Strategy: engage with major U.S.-based companies, other labs, and university groups with QIS expertise.

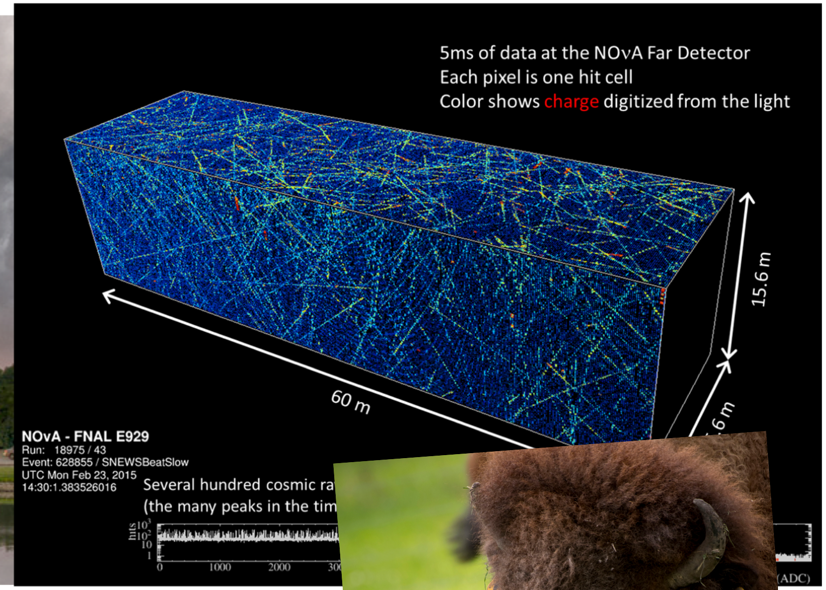
Argonne National Laboratory
Lockheed Martin
The University of Chicago
NIST
Oak Ridge National Laboratory
Yale
Google
University of Liverpool
University of Washington
Caltech
The University of Wisconsin Madison
Berkeley
inqnet Alliance for Quantum Technologies
JPL Jet Propulsion Laboratory California Institute of Technology
AT&T
Leland Stanford Junior University

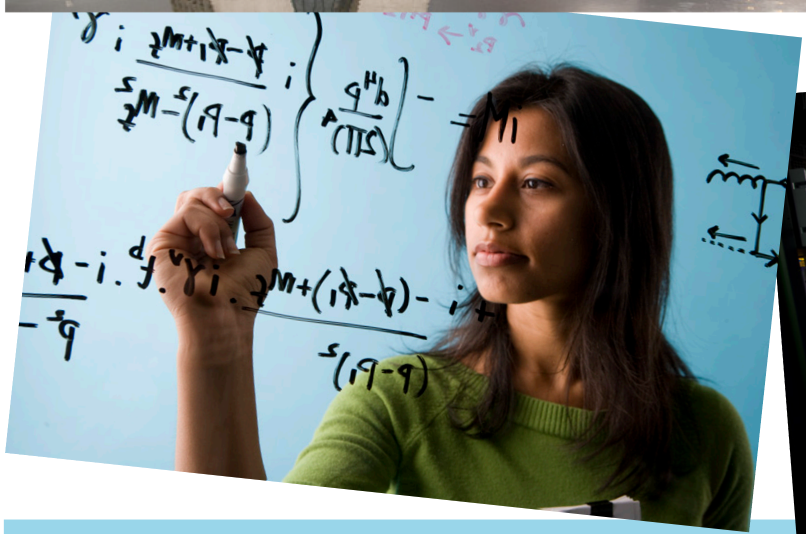
Fermilab

EXTRAS

Why is Fermilab involved?

Fermilab is the primary U.S. lab for High Energy Physics (HEP)





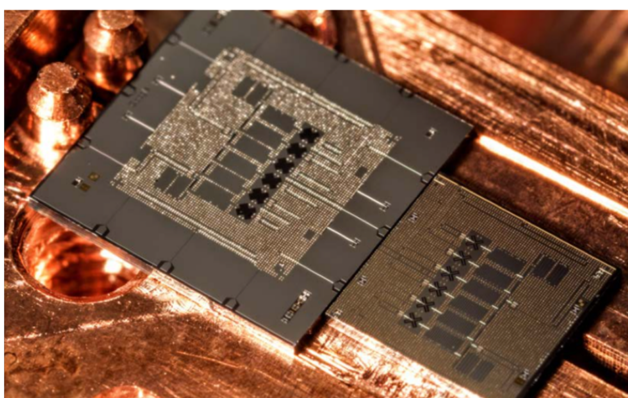
From qubits to quantum systems

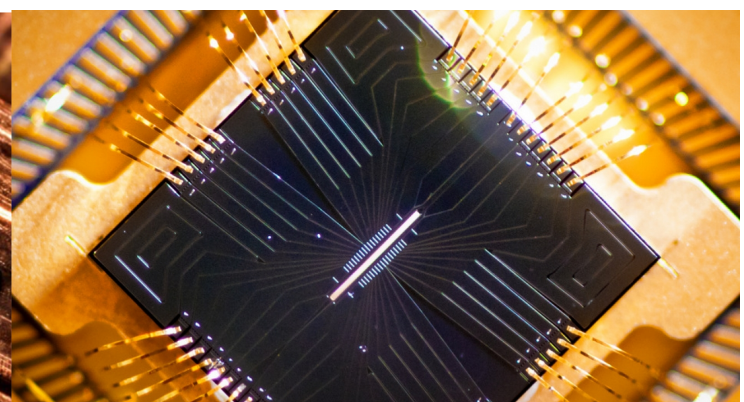
For useful qubits we need

- Ability to create initial state, perform qubit gate operations, and measure final state
- Maintain **quantum coherence** long enough to do all this
- Low rate of errors; ability to detect errors and do **error correction**

Then scale this all up to a large quantum system

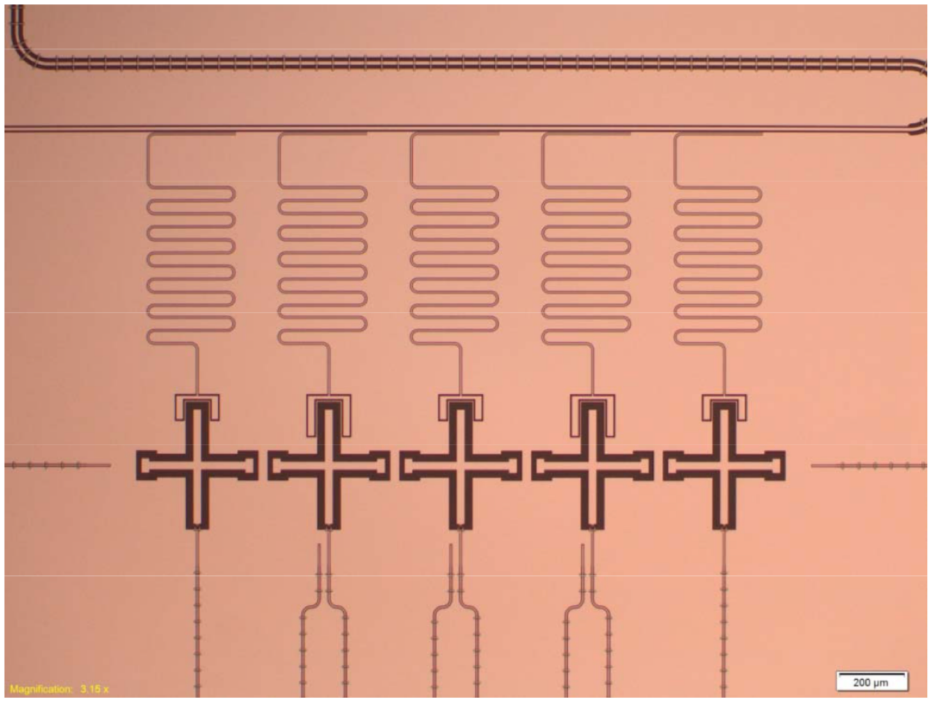
Extra challenge: no-cloning theorem (no copying of quantum info!)





Quantum computers with superconducting cirquits

Many groups working with variations on superconducting Josephson Junction circuits, in some cases with very fast and very high fidelity (low error rate) gate operations

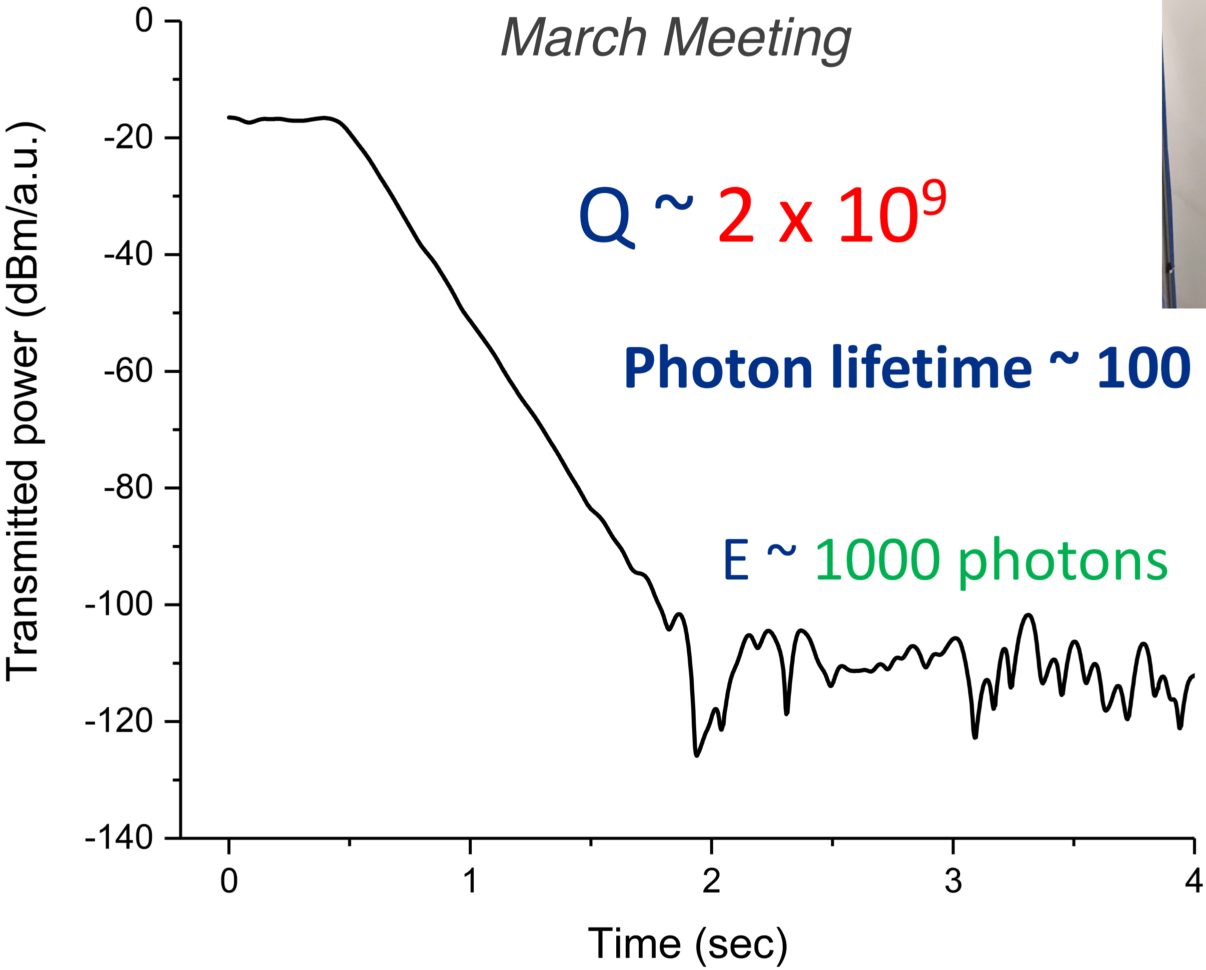


superconducting Xmon qubits

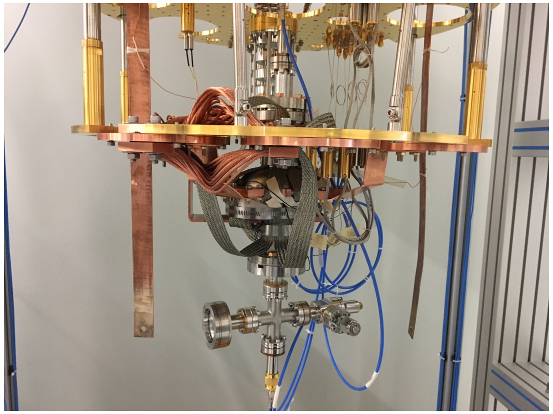
Gate	Fidelity (%)	Gate Time
X	99.95	20ns
Y	99.95	20ns
X/2	99.93	20ns
Y/2	99.93	20ns
-X	99.92	20ns
-Y	99.90	20ns
-X/2	99.93	20ns
-Y/2	99.93	20ns
H	99.91	40ns
Z	99.97	10ns
Z/2	99.98	10ns

Similar performance with 2-qubit gates: 99.4%, 40 ns

First try at T ~ 12 mK, down to ~1000 photons



Presented at the APS March Meeting



Q ~ 2 x 10^9

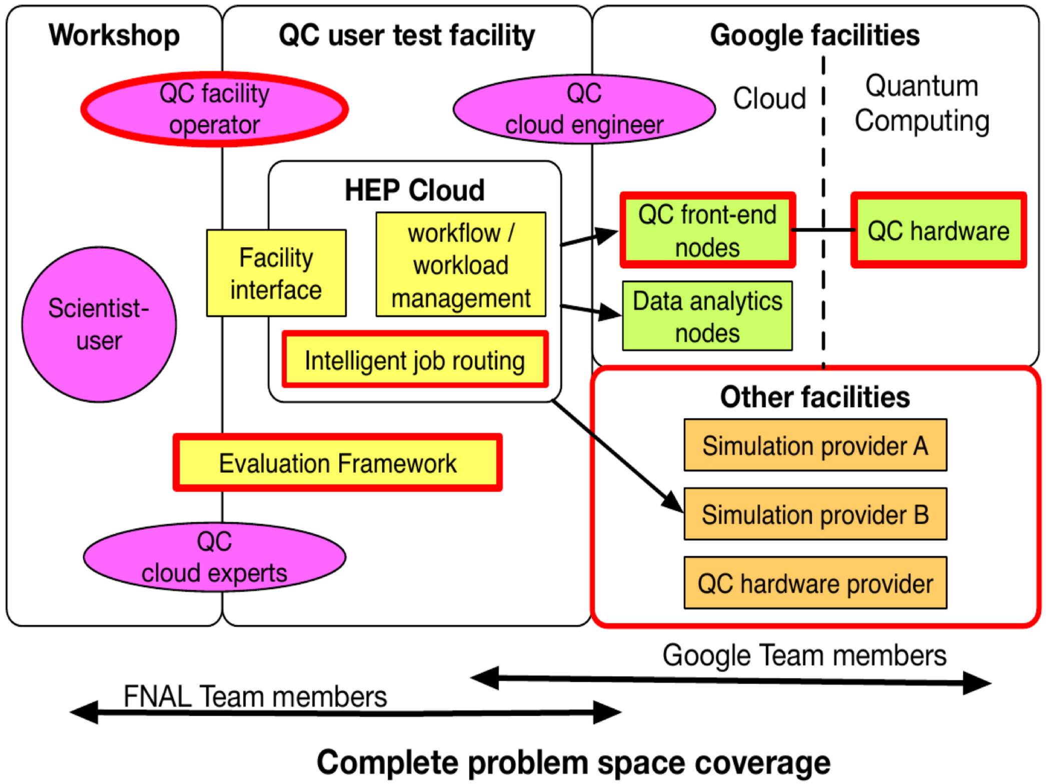
Photon lifetime ~ 100 milliseconds

E ~ 1000 photons

Next step: couple a very high Q SRF cavity with a transmon qubit & probe achievable coherence times

Fermilab

Quantum Computing Infrastructure



HEPCloud is the Fermilab gateway to heterogeneous computing resources:

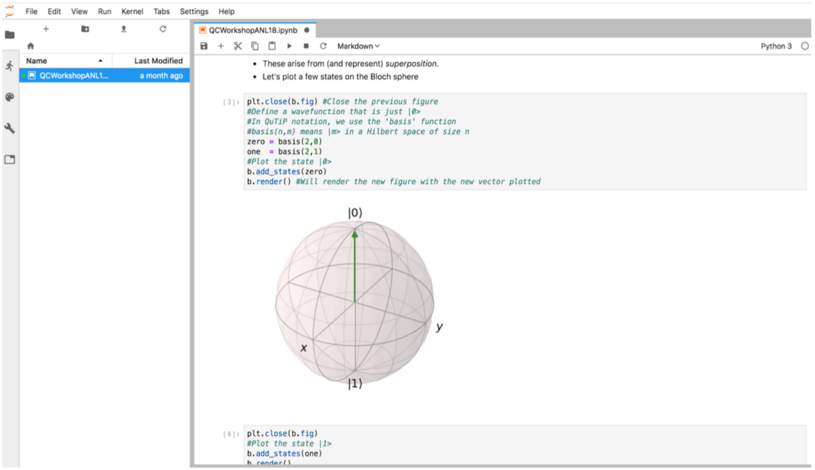
- Local and remote Grid clusters, commercial clouds (AWS, Google, …), and HPC Centers (NERSC, ALCF, …)

Utilize HEPCloud to provide QC access to HEP Scientists (and accelerate adoption through familiar environment). Working to:

- Connect HEPCloud to Quantum Computing Resources (e.g. Google QC via Google Cloud)
- Optimize Classical – Quantum Execution Engine

Workforce Development

- Workshops and tutorials the first step for workforce development
- Co-developed and delivered first tutorial with Google
  - Container with most utilized QC environments
  - Jupyter notebooks for exercises



docker

Google

ProjectQ
Powerful open source software for quantum computing

rigetti
pyQuil

jupyter

Cirq
OpenFermion

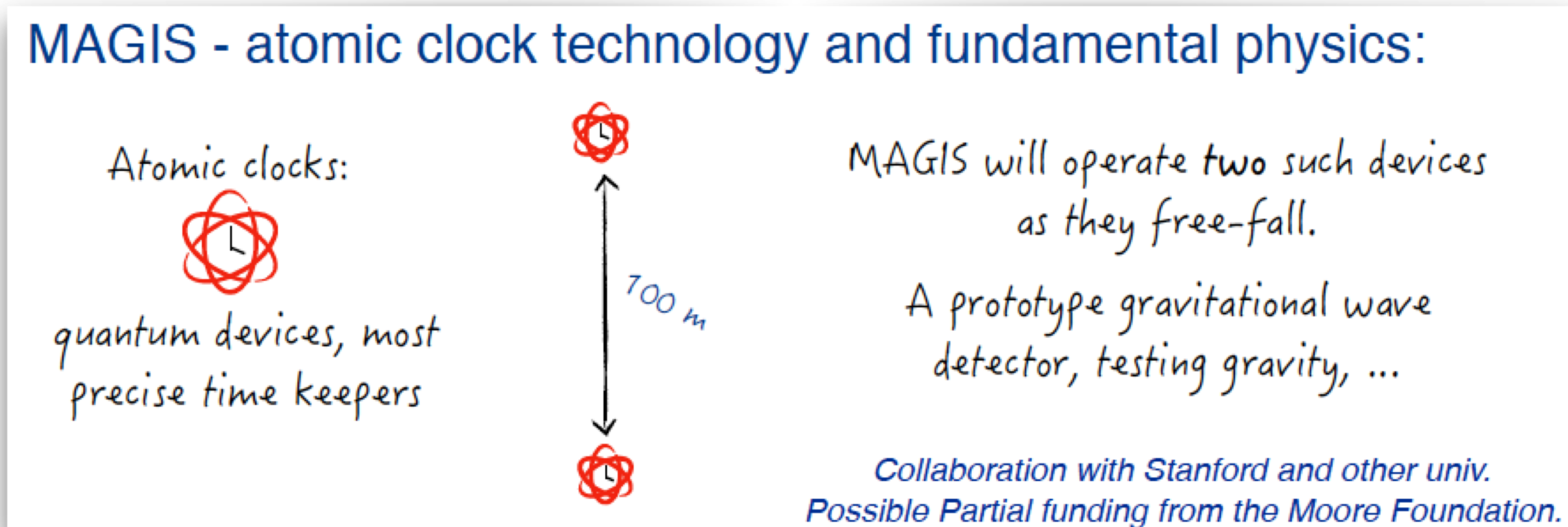
Microsoft | Quantum
Q#

IBM
QISKit

QuTiP
Quantum Toolbox in Python

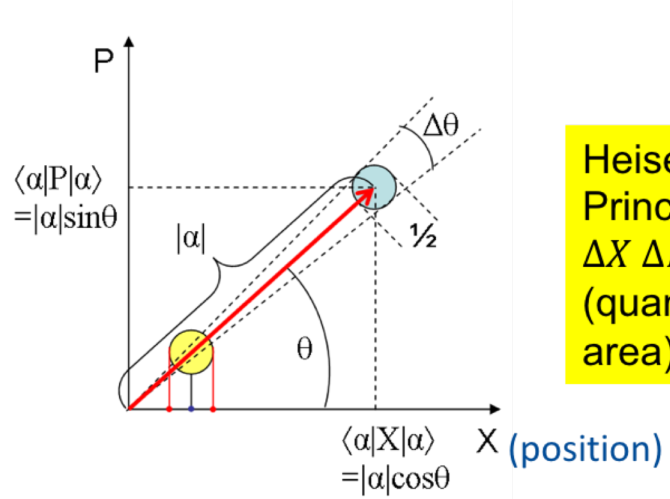
Quantum Sensors: an appealing technology to explore the Universe

- Major questions in High Energy Physics:
  - Are there new forces on nature we do not know about?
  - What makes up the Dark Matter in the Universe?
  - What can we learn with gravitational waves? ... etc
- We are leveraging quantum technology to explore these questions (and stretching it to the limit).



Can we improve measurement using quantum properties of sensors?

- Even at zero temperature readout amplifiers can't avoid quantum noise
  - A result of the Uncertainty Principle (can't simultaneously know with arbitrary precision both amplitude and shape)
- Zero-point readout noise: Standard Quantum Limit (SQL)

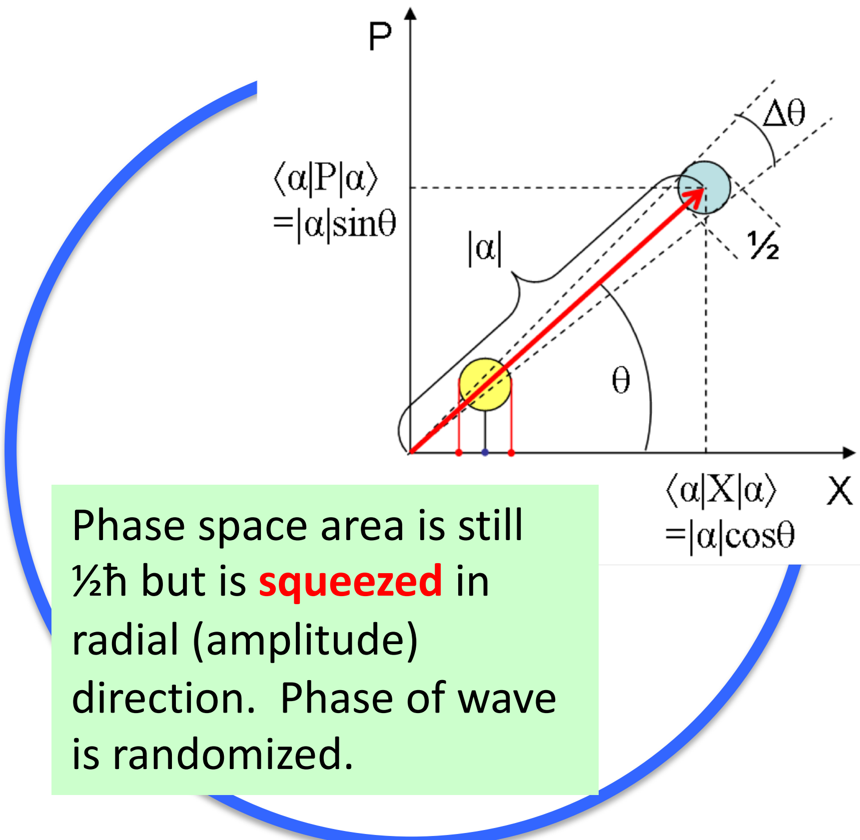


Heisenberg Uncertainty Principle
$\Delta X \, \Delta P = \Delta N \, \Delta\theta = ½ \, \hbar$
(quantum of phase space area)

Quantum noise = 1 photon of "zero point" noise per mode in the T=0 limit.
(Caves, 1982)

Quantum non-demolition single-photon detectors can do much better than SQL amplifiers

Measure photon number and put all backreaction into the unobserved phase of the wave – which we don't care about...



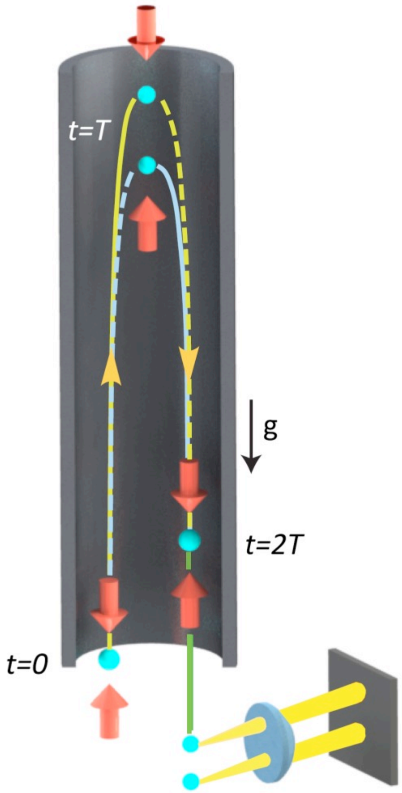
Phase space area is still ½ħ but is **squeezed** in radial (amplitude) direction. Phase of wave is randomized.

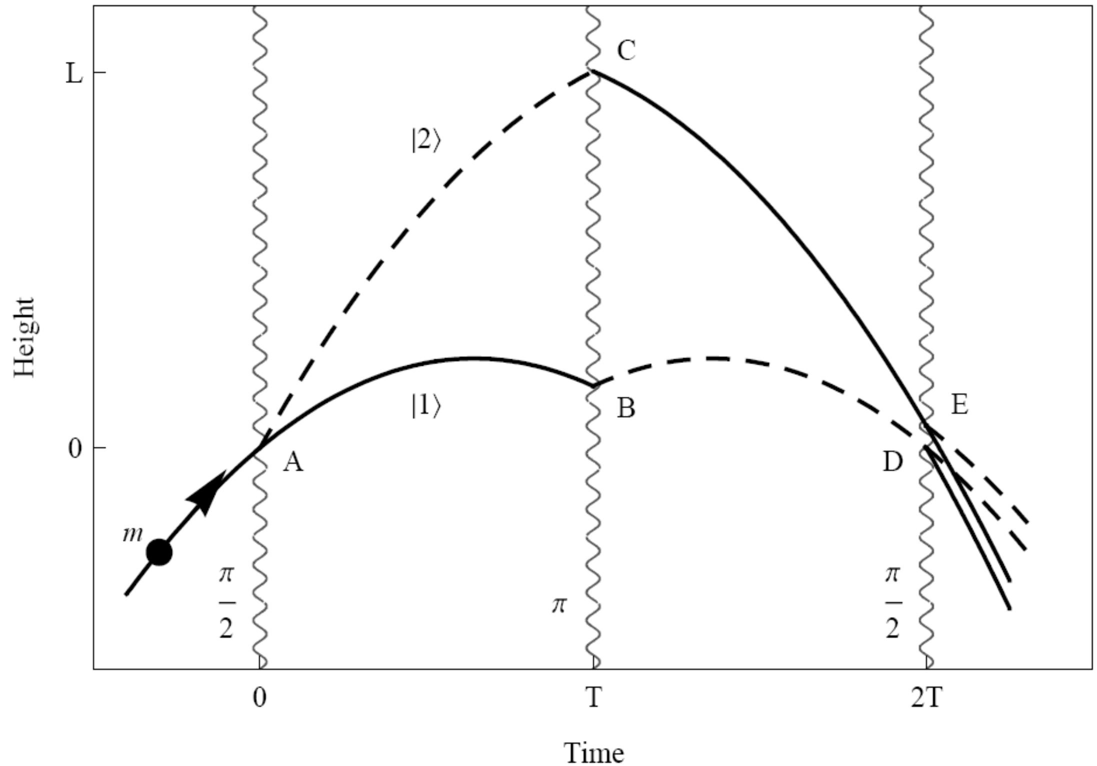
Demonstrated with Rydberg atoms, (Serge Haroche Nobel Prize 2012)

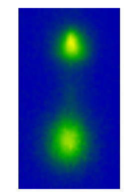
Implementation using **superconducting qubits**, **D.Schuster et.al, 2007**

Proposed for axion search: Lamoreaux, Lehnert, et.al, 2013, Zheng, Lehnert, et.al, 2016

Light pulse atom interferometry



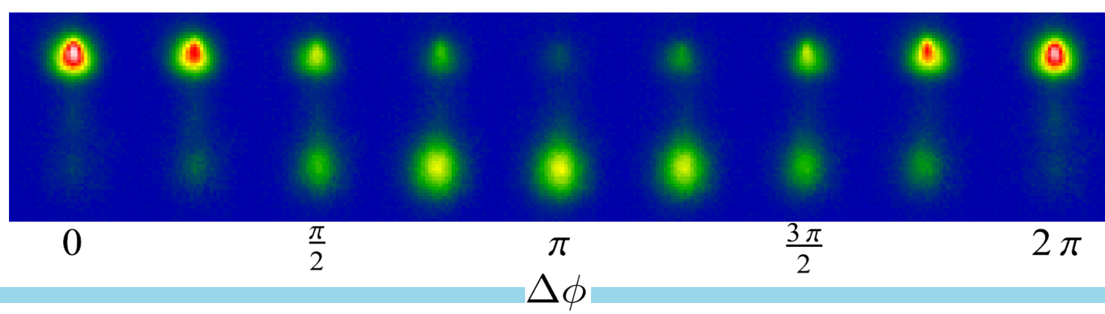




Dickerson, et al., PRL **111**, 083001 (2013).

Images of atom port populations vs phase

Science signal (CCD images):



Data from world record atom interferometer duration (>2 seconds) at Stanford

Stanford 10 m scale