Fermilab Quantum Science Program

Panagiotis Spentzouris

CERN openlab Quantum Computing for HEP

November 5-6, 2018

Quantum Science Program

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

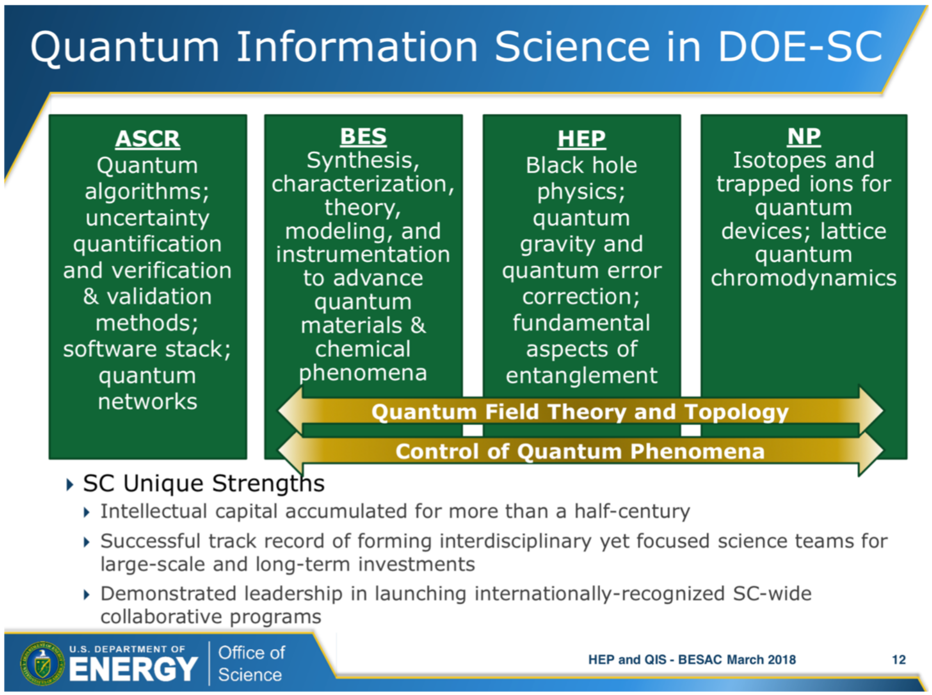
Application areas
- **Sensing and metrology**
- **Communication**
- **Computing**

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

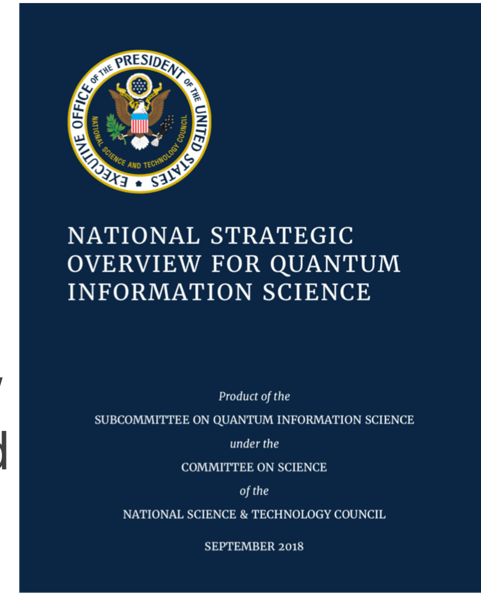
These areas have natural overlaps: sensors as qubits, quantum communication for sensing and metrology, transduction for communication, computing algorithms for quantum system operations,…
- Leverage synergies to define a coherent R&D program

Why is Fermilab involved?

Fermilab is the primary U.S. lab for HEP



We are part of the National Quantum Initiative → Strategic Overview document released in September



A new program: DOE awards, including 8 for Fermilab, announced at White House summit September 24

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:

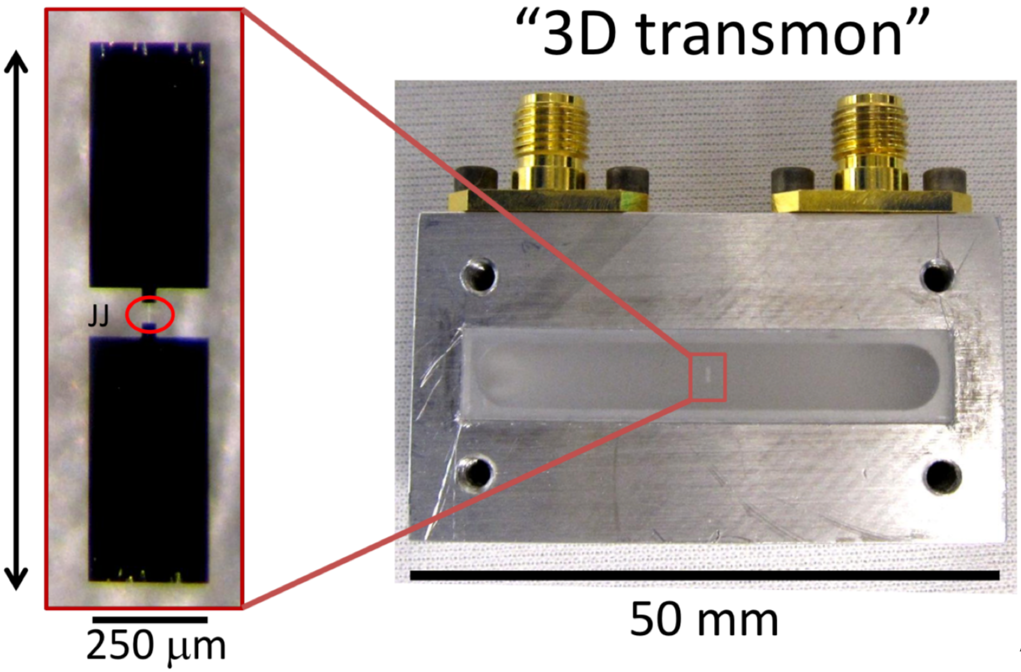
- Time-binned photon quantum teleportation for communication
- Qubit-cavity systems for axion dark matter detection
- Cold atom interferometry

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:

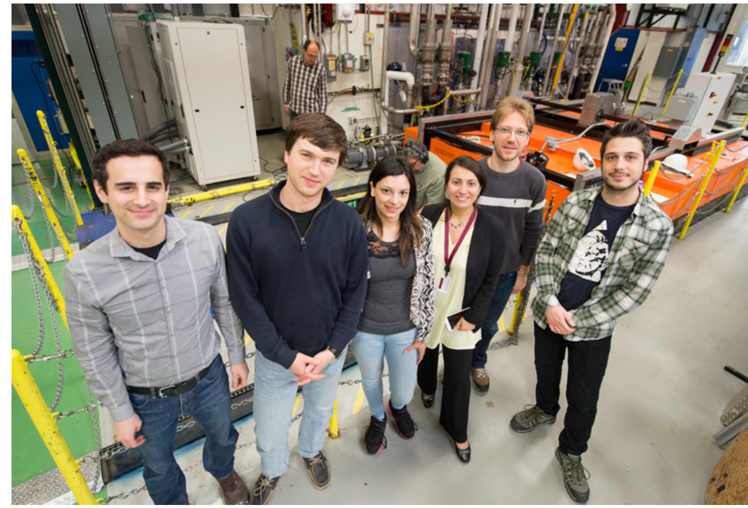
- Isolation
- Control
- Readout
- Coherence time

Achieved record long quantum coherence times of **7 ms**, as measured by $\mathbf{T_2}$, the dephasing time of superposition states

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

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



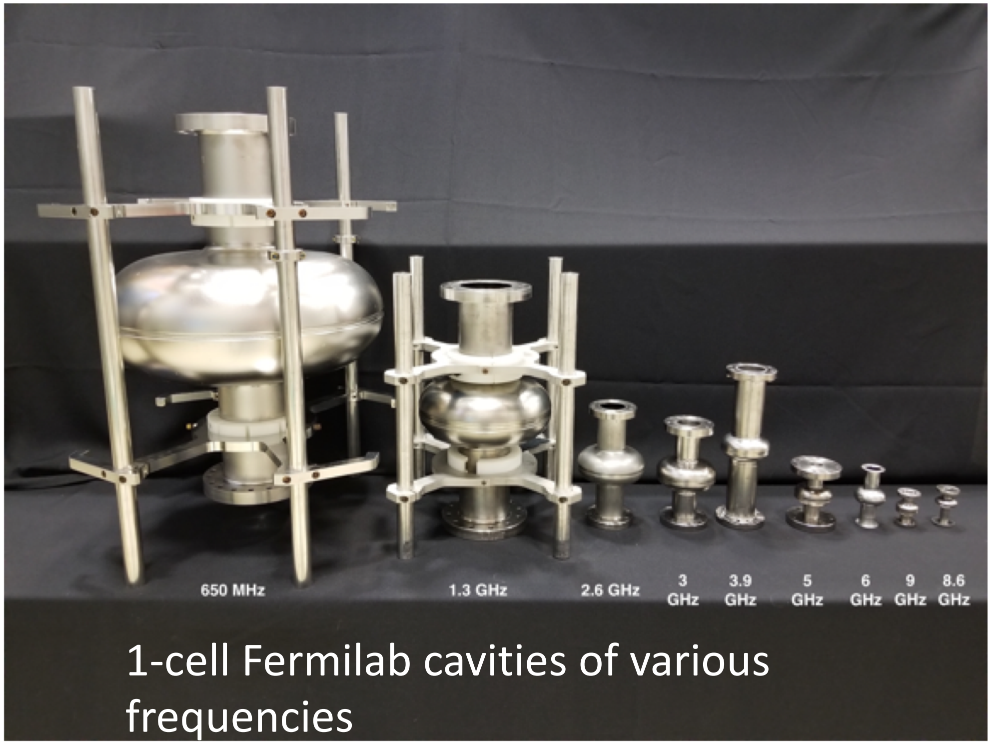
Alex Romanenko and Anna Grassellino lead the Fermilab SRF cavity program

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

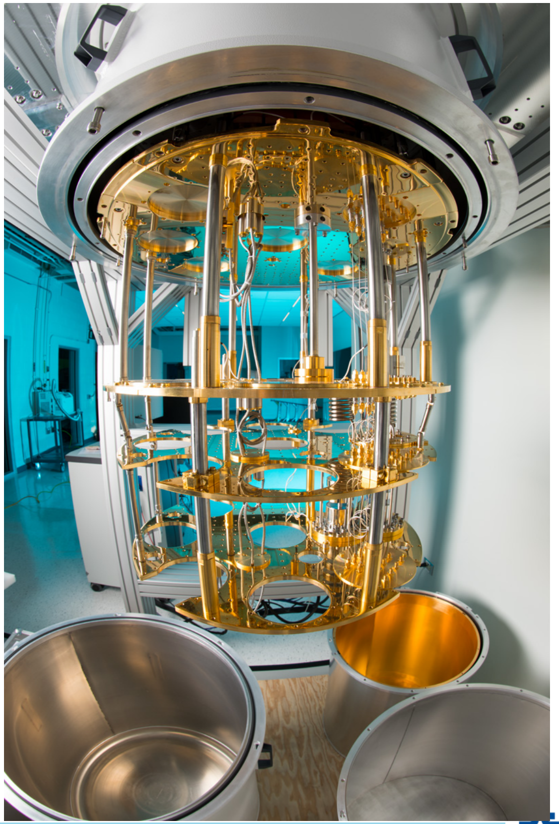
SRF cavities for quantum computers (QC)?

Challenges:

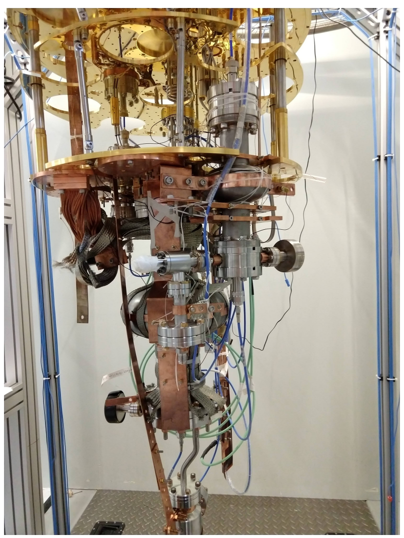
- For accelerators we want high gradients → as many photons as possible; for QC applications we want to manipulate cavity states at the **single photon** level
- Accelerators operate at temperatures around 2K, QC systems around 20 milliKelvin



1-cell Fermilab cavities of various frequencies

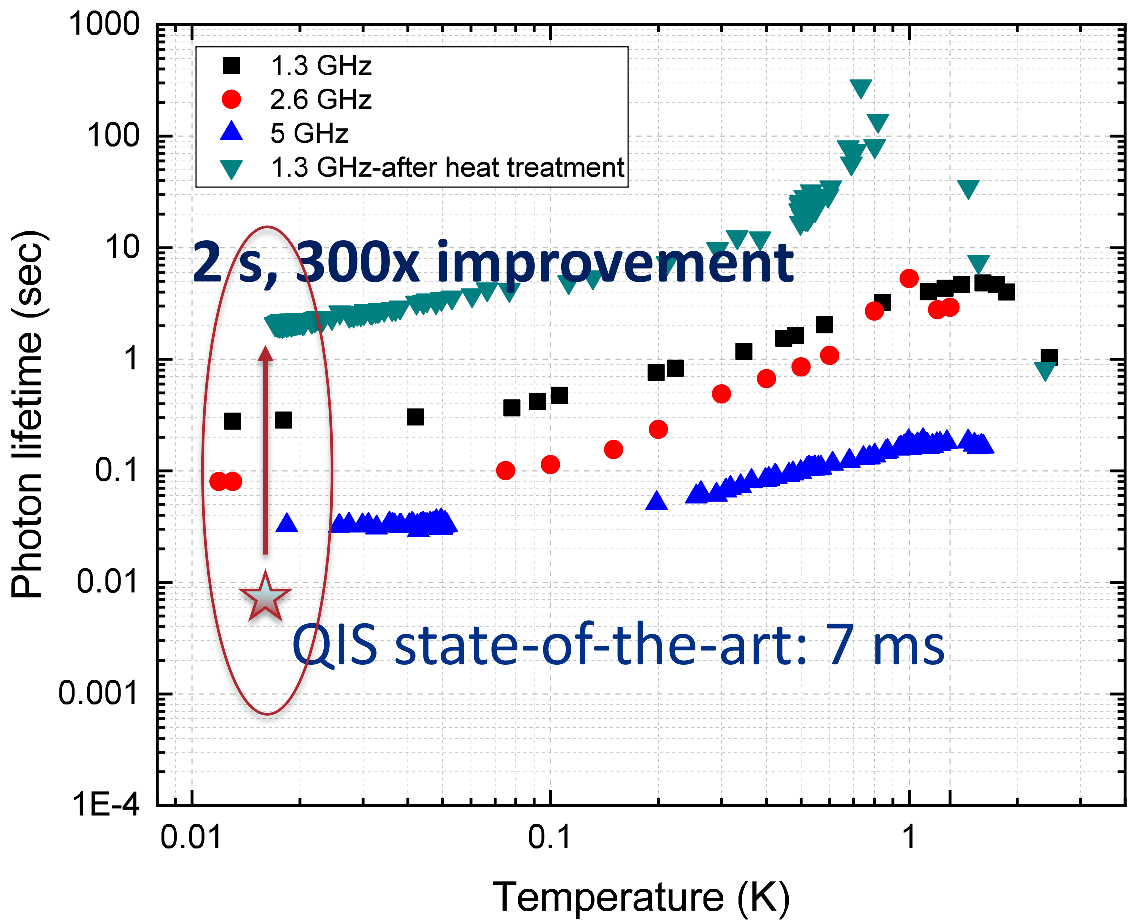


Record high photon lifetimes achieved at Fermilab



Integration with **transmon qubits** successful, measurements underway

Accelerator cavities adopted for quantum regime



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

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

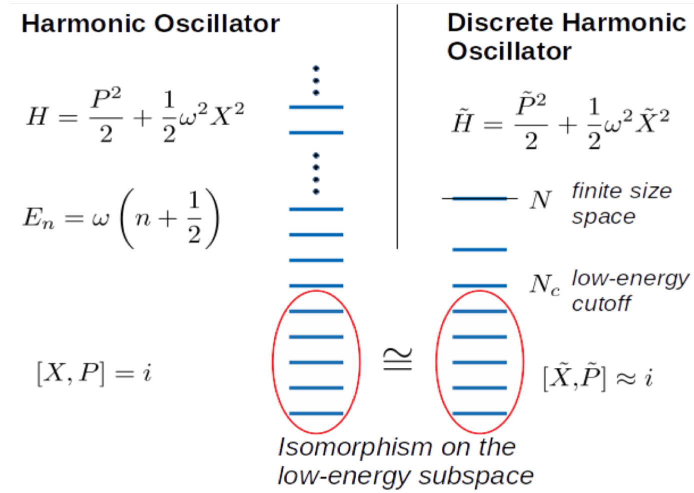
- Exploring Variational Eigenvalue solvers on Rigetti QC

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

- **New approach** for fermion-boson interacting systems: boson representation in the coordinate basis (exponential accuracy!)
  - → efficient on quantum computers!
  - – tested using **Quantum Phase Estimation** on the ATOS & Google simulators for a polaron model.

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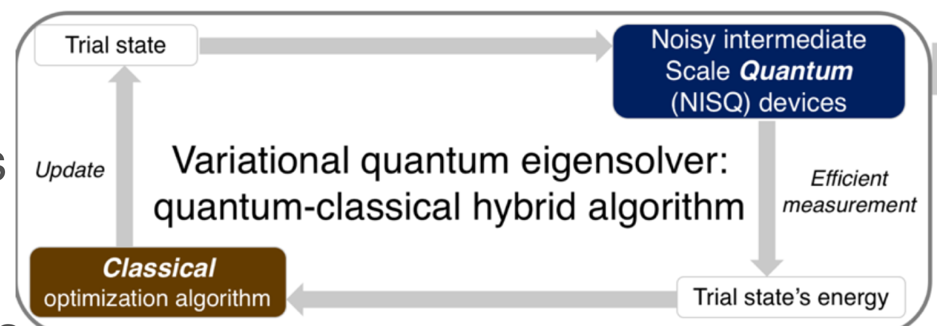
Electron-Phonon Systems on a Universal Quantum Computer

Alexandru Macridin, Panagiotis Spentzouris, James Amundson, and Roni Harnik

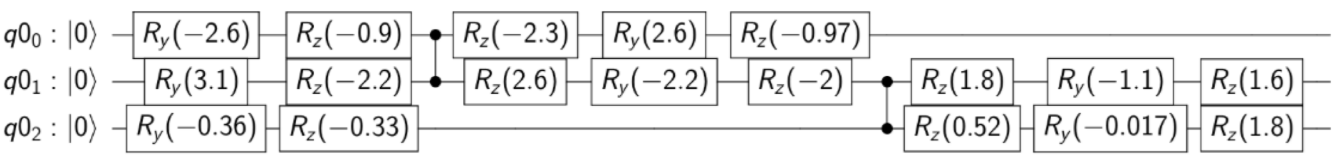
Phys. Rev. Lett. **121**, 110504 – Published 12 September 2018

- **Experiments** on *Noisy Intermediate Scale Quantum* devices (Google, Rigetti), using **Variational methods**
  - – Use coordinate or occupation number basis for bosons
  - – Simple models for the experiments
    - Rabi model (two level atom interacting with photons)
    - Polaron model (one electron on a 1D lattice interacting with phonons)

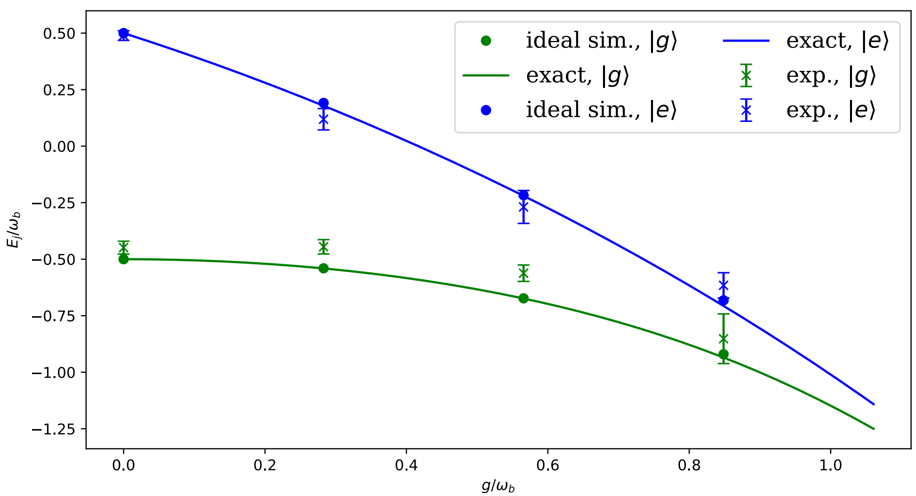


HEP applications of today's quantum computers: Variational Quantum Eigensolver

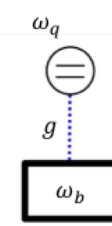
- Quantum-classical hybrid algorithm
  - quantum: efficient measurement of trial-state energy
  - classical: gradient-based algorithm to update trial state
- Trial state parameterized by a quantum circuit

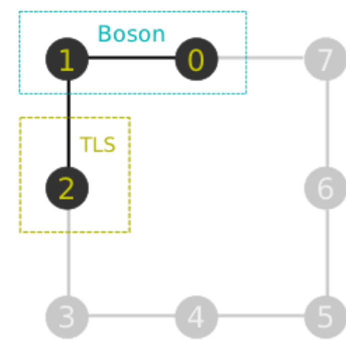


- Implementation on Rabi-model (boson coupled to spin)



- Rabi model: bosons with interaction mediated by a two-level system (TLS)
- Encoding of the boson model and TLS on the Rigetti's 8Q device



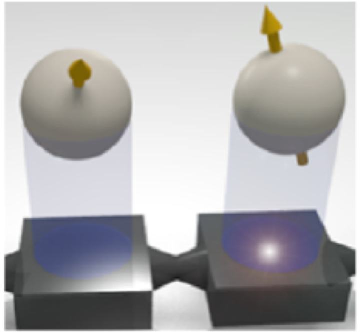


Algorithm verification using simulators, also tested on Rigetti's 8Q device

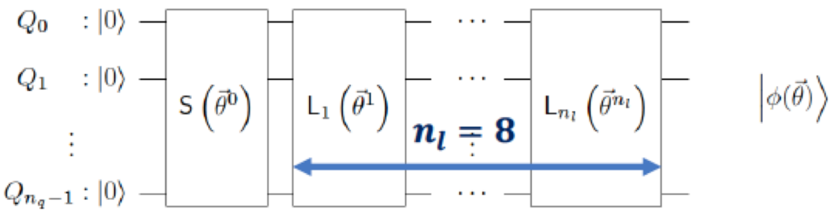
Running (experiments!) on Quantum Computers

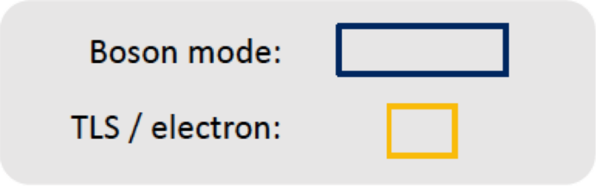
Proposal

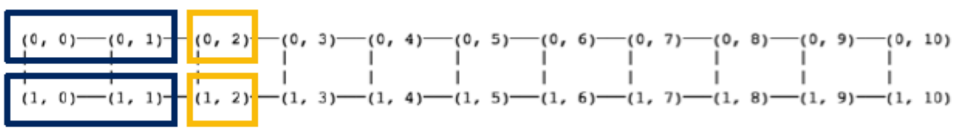
- Physical system to simulate:
  2 boson modes coupled to 2 TLSs or electrons
  (TLS = two-level system)



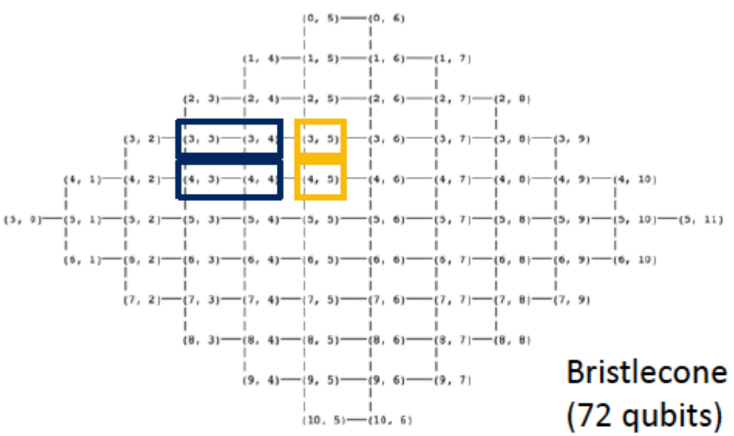
- Implementation:
  - Maximum of 3 bosons per mode
    → 2 qubits to encode 1 boson mode
  - Preparation circuit: 8 layers







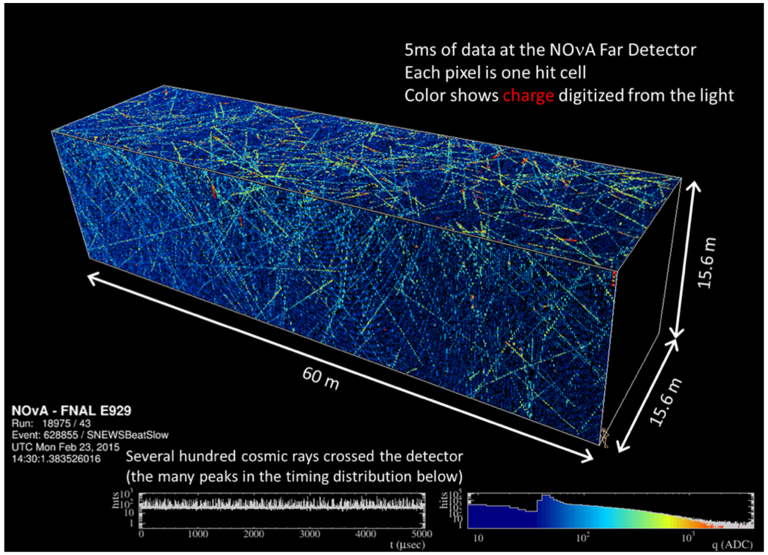
Foxtail (20 qubits)

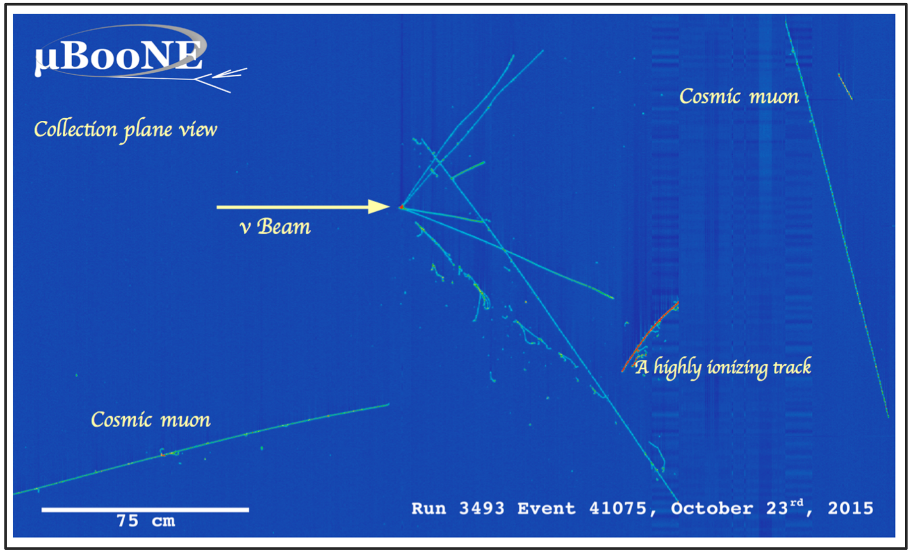


Bristlecone
(72 qubits)

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 to improve sensitivity for sensor applications



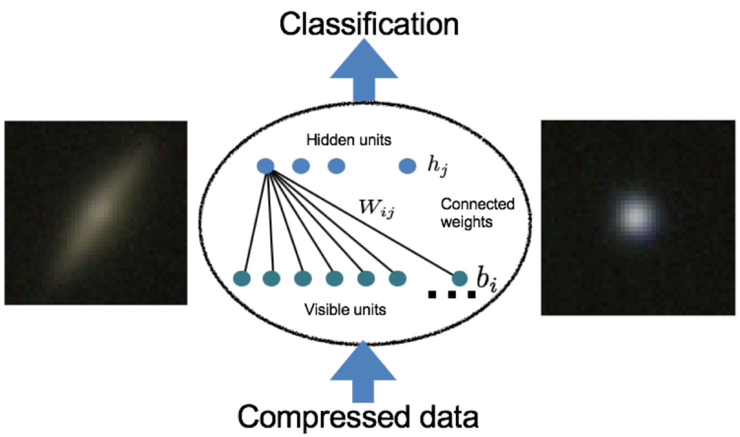


Astrophysics ML application using a Quantum Annealer

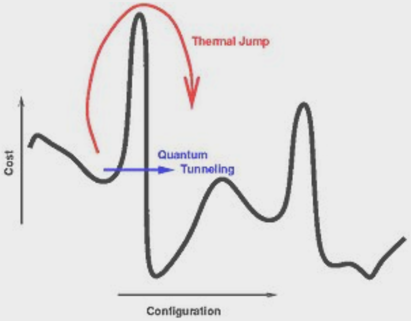
Partnering with Lockheed Martin and ORNL on ML problems in astrophysics:

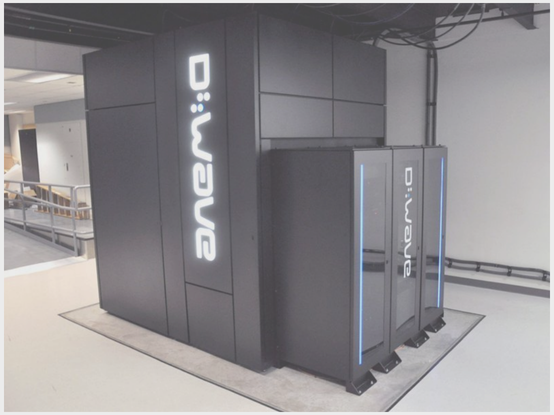
- Several exploratory projects leveraging a D-Wave annealer: star/galaxy separation, anomaly detection, and autoencoders (for compression or simulation).

- Focus on exploring data representations and understanding tradeoffs



- Annealing is a standard approach for finding minima
- **Quantum annealing** improves this by adding the possibility of quantum tunneling





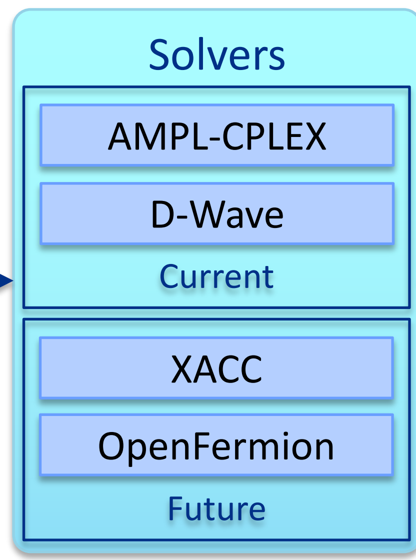
D-Wave, a world leading quantum annealer (analog quantum computer)

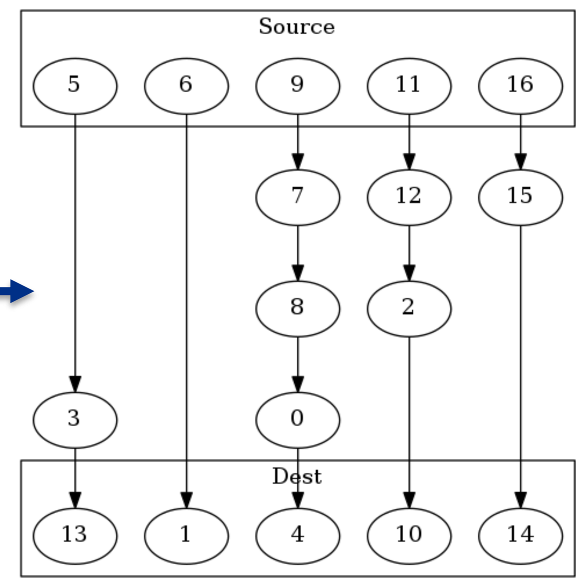
Quantum optimization for LHC physics

- Employ a quantum annealer to estimate systematics due to Color Recombination models
  - Winner takes all approach settles to local minima
- Formulate the energy minimization as a binary constraint satisfaction problem, amenable to quantum annealers
  - Solve for realistic partonic configurations aiming to find a **global** minimum
- Compare results with best-known classical solutions
  - Evaluate impact on measurements such as the top quark mass.

$$
\begin{aligned}
H = {} & A\sum_{i\in\mathcal{N}}\Big(1-\sum_{r\in\mathcal{S}}x_{i,r}\Big)^2 + A\sum_{r\in\mathcal{S}}\Big(1-\sum_{i\in\mathcal{N}}x_{i,r}\Big)^2 \\
& + A\Big(1-\sum_{k\in\mathcal{O}}x_{k,1}\Big)^2 + A\Big(1-\sum_{l\in\mathcal{D}}x_{l,s}\Big)^2 + A\sum_{r=2}^{s-1}\Big(\sum_{l\in\mathcal{D}}x_{l,r}-\sum_{k\in\mathcal{O}}x_{k,r+1}\Big)^2 \\
& + B\sum_{(i,j)\in\mathcal{A}}\lambda_{ij}\sum_{r=1}^{s-1}x_{i,r}x_{j,r+1} - B\sum_{(k,l)\in O\times D}\lambda_{ij}\sum_{r=1}^{s-1}x_{l,r}x_{k,r+1}
\end{aligned}
$$

For a given set of quarks and antiquarks, find the arrangement of gluons that minimizes the λ measure





Quantum Optimization

- For a given set of quarks and antiquarks, find the arrangement of gluons that minimizes the **λ measure:**

$$\lambda = \sum_{\substack{i=1 \\ j=i+1}}^{n+1} ln \frac{m_{ij}^2}{m_0^2} = \prod_{\substack{i=1 \\ j=i+1}}^{n+1} ln \frac{m_{ij}^2}{m_0^2}$$

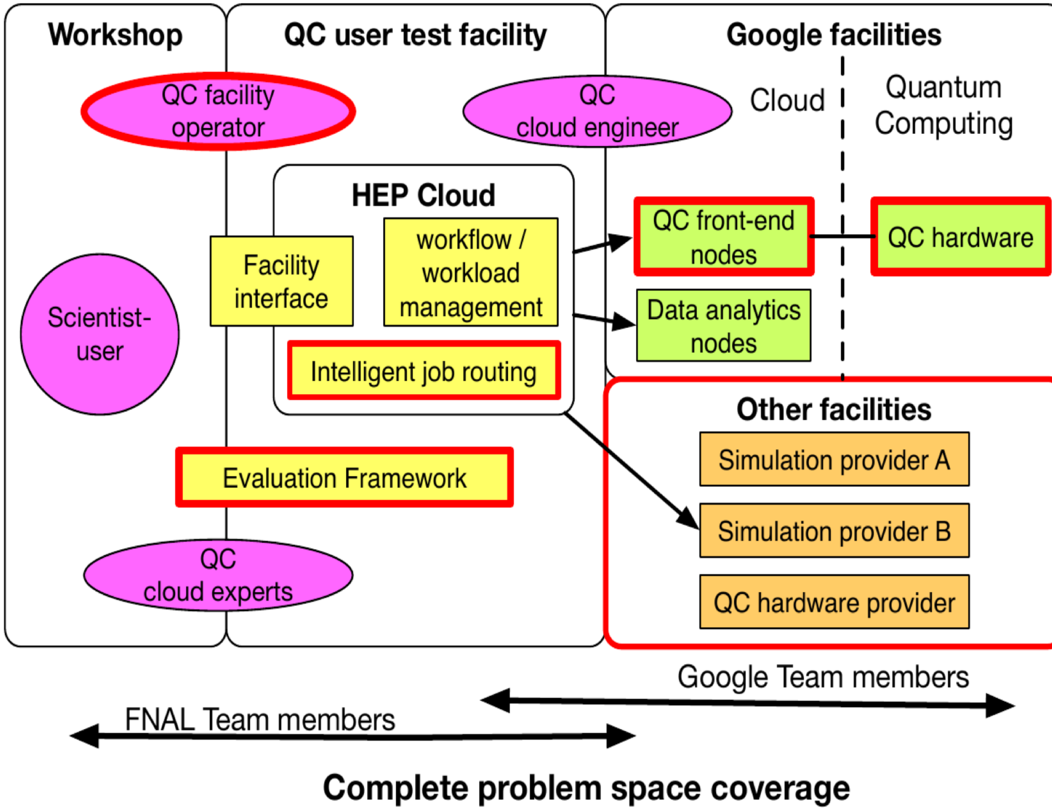
- Constraints:
  - Every node is in only one position
  - Only one node can fill one position
  - An origin must be in the first position
  - A destination node must be in the last position
  - An origin node comes after a destination node

- This is a graph theory problem where we embed the particles into a graph G(V;E), each node representing a particle. An edge between two nodes exists if an interaction between these particles exist. The node sets:
  - quarks: origin nodes O,
  - gluons: intermediate nodes I, and
  - antiquarks: destination nodes D.
  - The distance between two nodes is the m_{ij} in the λ measure

Fermilab

Quantum Computing (QC) Infrastructure

- Make state-of-the-art toolkits transparently available to HEP in the cloud
- Use familiar technologies, such as notebooks and containers
- Solve collaborative access and authentication issues



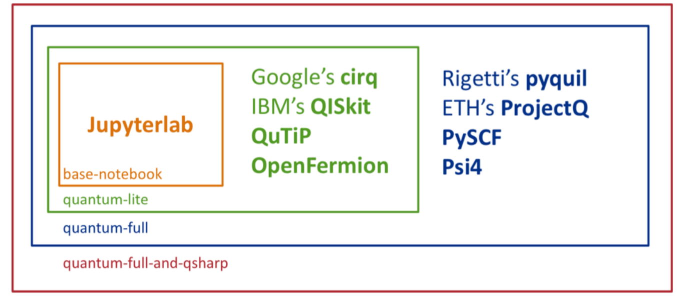
HEPCloud is the Fermilab gateway to heterogeneous computing resources:

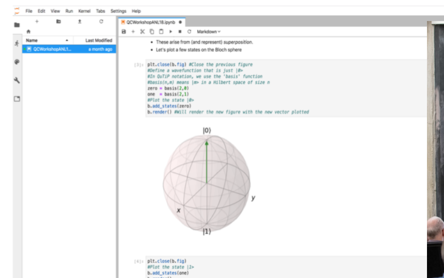
– Local and remote Grid clusters, commercial clouds (AWS, Google, …), and HPC Centers (NERSC, ALCF, …)

Utilize HEPCloud to provide QC access and accelerate adoption.

Training and tutorials for HEP

- Workshops and tutorials the first step for workforce development
- Co-developed and delivered first tutorial with Google (Sep 2018)
  – Container with most utilized QC environments
  – Serves Jupyter notebooks
    - Runs on laptops with Docker, cloud with Jupyter-Hub





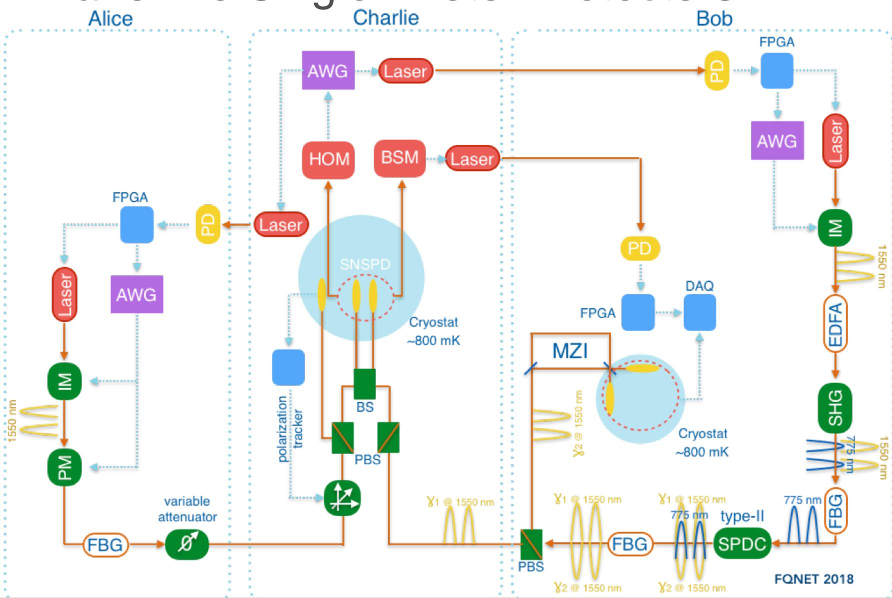
Quantum Communication

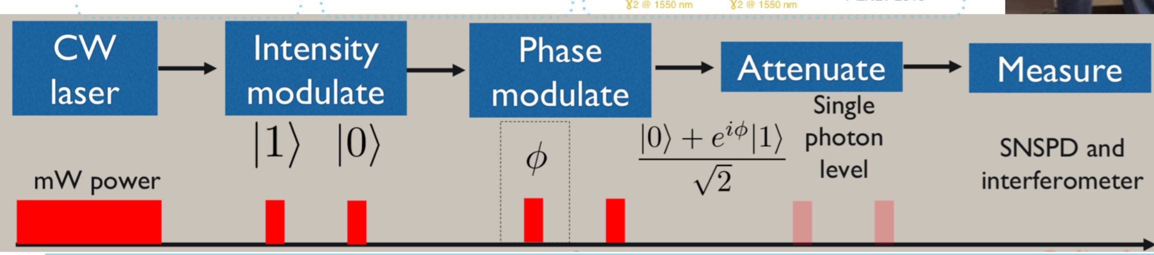
- Quantum Communication R&D not only aims to deliver essential technologies for one of the main application areas of the Quantum Science ecosystem, but also drives R&D for the other two (sensors, computing).
- Objective is to develop the capabilities for high-fidelity long-range communication of quantum 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 precision optics and controls to implement teleportation
- 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

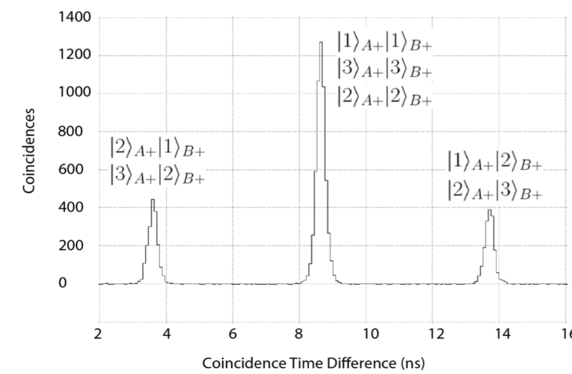
Current FQNET setup

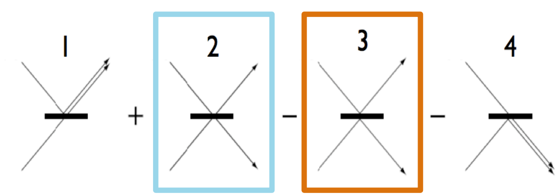
Baseline equipment for teleportation in place

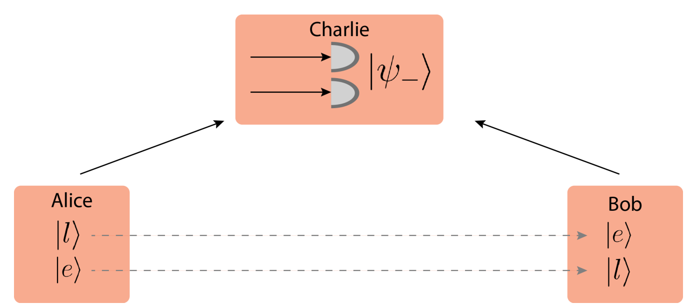
System commissioning underway

Challenges and leveraging HEP 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







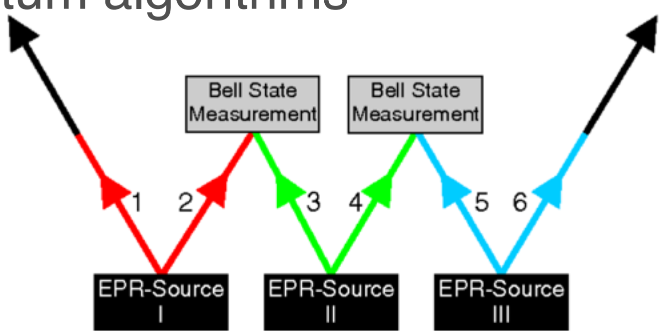
Fermilab

Next Step: Fermilab-Argonne Quantum Network

Telecom fiber between Fermilab and Argonne (~30 miles), affords an opportunity to advance science and technology for quantum communication over long distances using entangled photons.

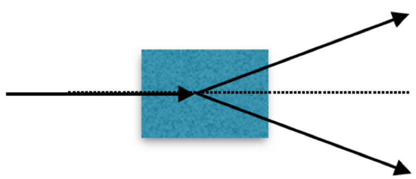
Establish a state-of-the-art quantum network backbone while inviting the community to utilize it for testing a variety of quantum devices connected to the network. R&D focus areas:

- High rate photon sources
- High efficiency, low noise and jitter, photon-number resolving detectors
- Quantum memories and transducers
- Quantum algorithms



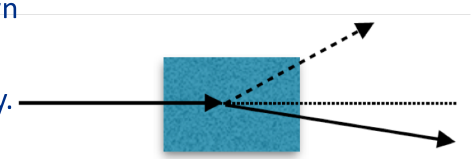
Driving HEP R&D: Dark Matter Detection

- 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

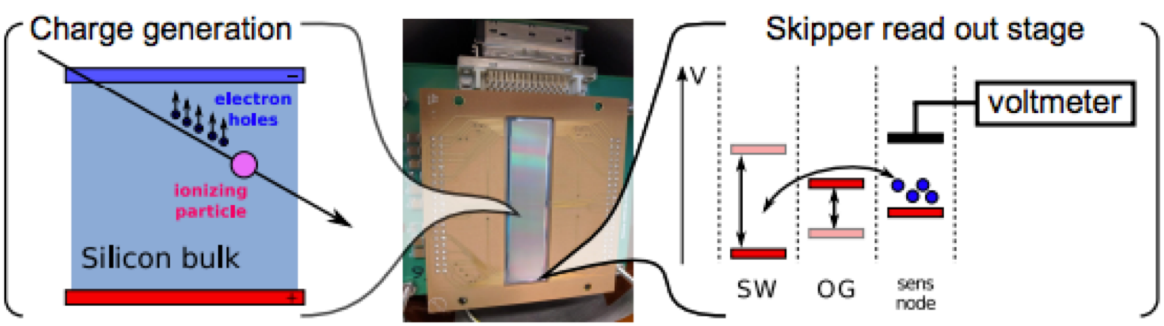


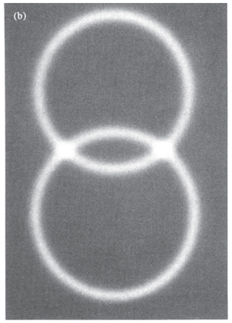
Spontaneous Parametric Down Conversion **(SPDC):** down-converted photons are entangled in angle and energy.

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.

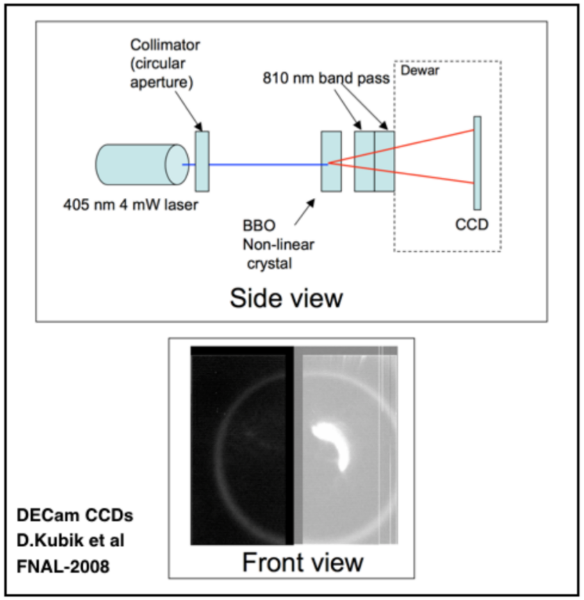


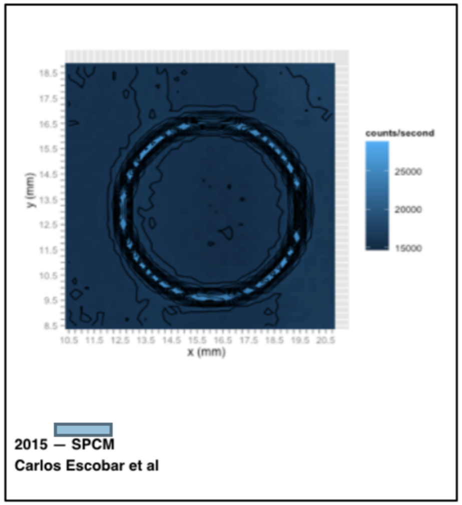


Fermilab, LBNL, Caltech partnership

Driving HEP R&D: Dark Matter Detection

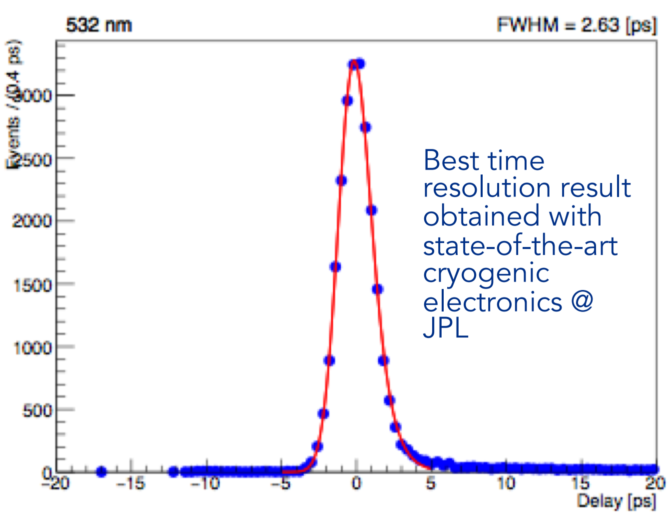
- Fermilab, LBNL, Caltech partnership
- Takes advantage of existing skipper-CCD R&D infrastructure at Fermilab and ongoing joint R&D with LBNL, and infrastructure developed for Quantum Communication activities (entangled photon-source, crystals)
- New project with goals to
  - demonstrate skipper-CCD 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

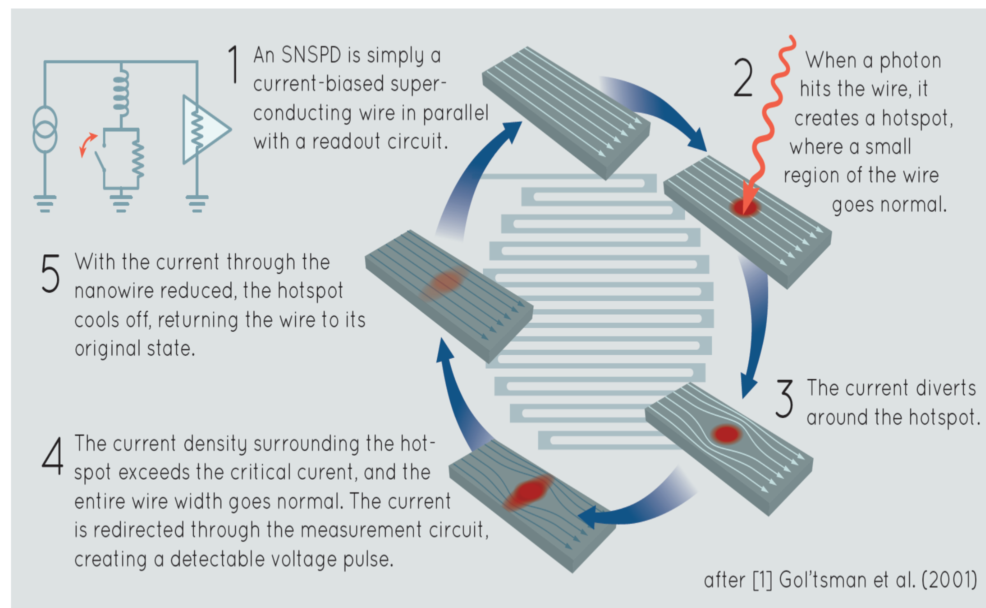




Driving HEP R&D: Cryogenic Electronics

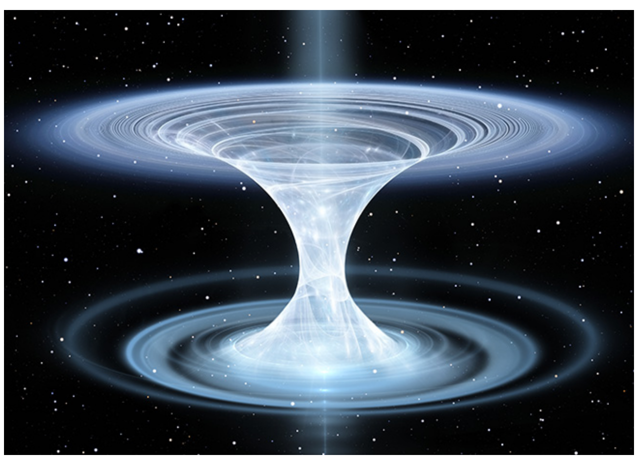
- Develop cryogenic amplifiers to reduce electronic noise and improve time resolution for SNSPDs
  - Low-noise cryogenic readout circuits based on state-of-the-art, commercially available SiGe heterojunction-bipolar-transistors integrated with cryogenic CMOS, operating at 1-4 Kelvin.
- Fermilab, JPL,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

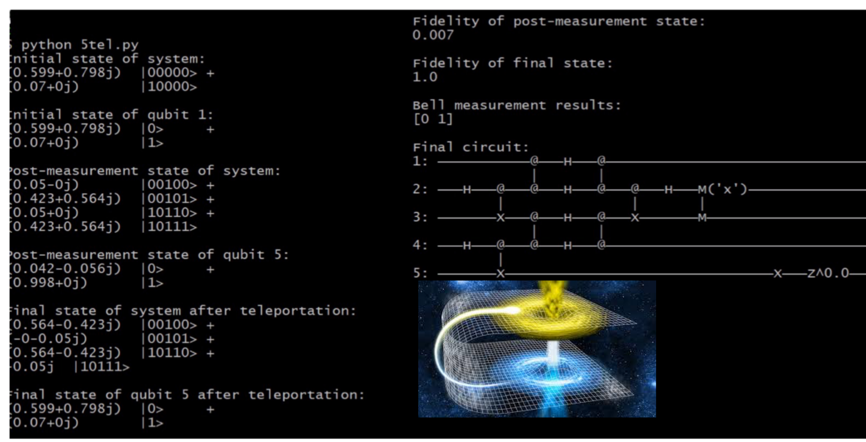




Driving HEP Science: Entanglement as Probe of Space-Time

- 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





Searching for axion dark matter

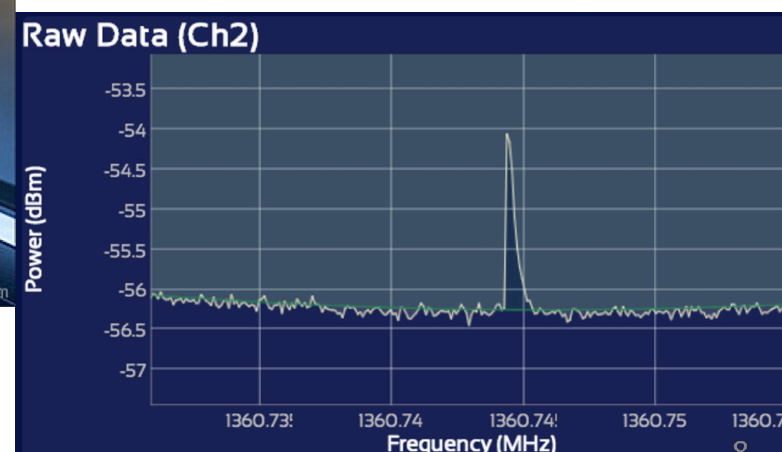
DOE Gen2 Dark Matter Project (Fermilab-managed)

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

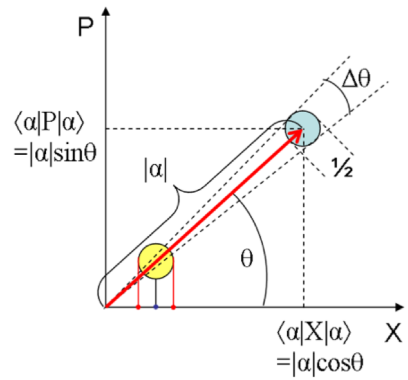
ADMX Experiment at U.Washington

Simulated axion signal from ADMX



Can we improve measurement using quantum properties of sensors?

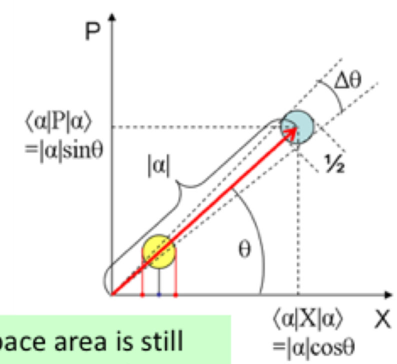
- Even at zero temperature readout amplifiers can't avoid quantum noise
  - Standard Quantum Limit (SQL)
- Quantum non-demolition (QND) single-photon detectors can do much better than SQL amplifiers
  - Measure photon number and put all backreaction into the unobserved phase of the wave



(position)

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)

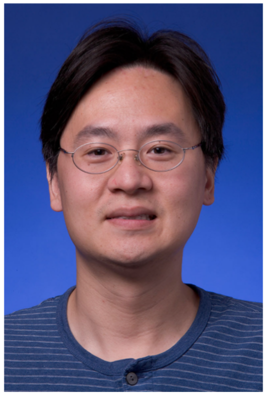
Implementation using **superconducting qubits**, **D.Schuster et.al, 2007**

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 impact of read errors by incorporating multi-qubit readout system
  - Possibly further improving by preparing them in an entangled state and utilizing quantum ML
- 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

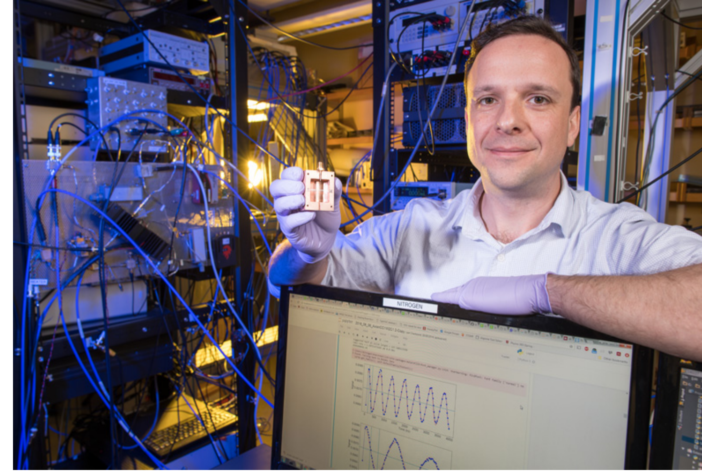
Qubit-based single microwave photon sensors for axion detection



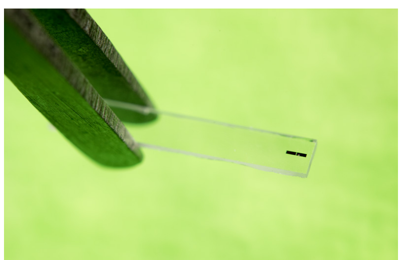
Aaron Chou

David Schuster(UC)

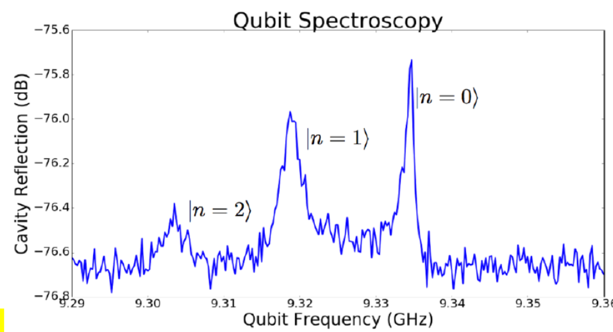
Konrad Lehnert U.Colorado/NIST



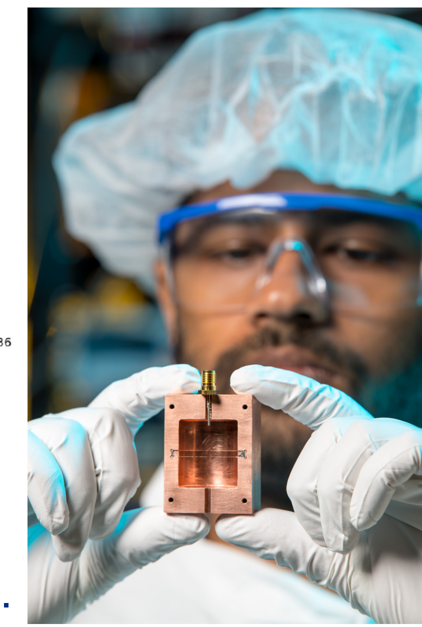
Daniel Bowring, Fermilab
2018 Early Career Award



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

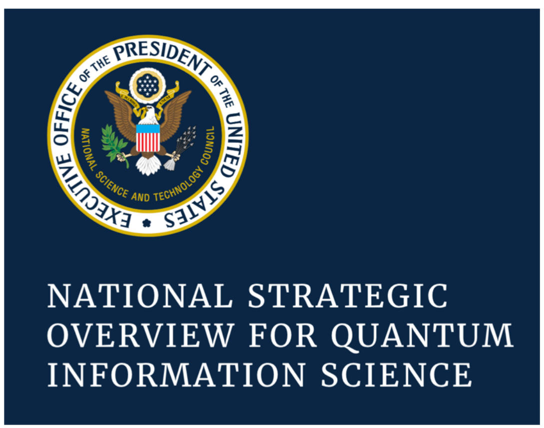


Grad student Akash Dixit installing a prototype detector in a 10 mK test stand in the Schuster Lab.



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

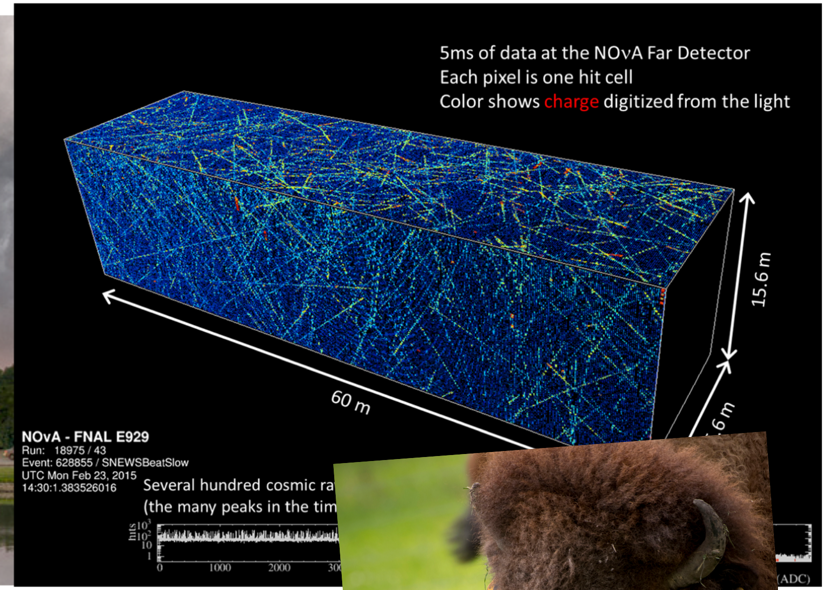
Fermilab quantum collaborations

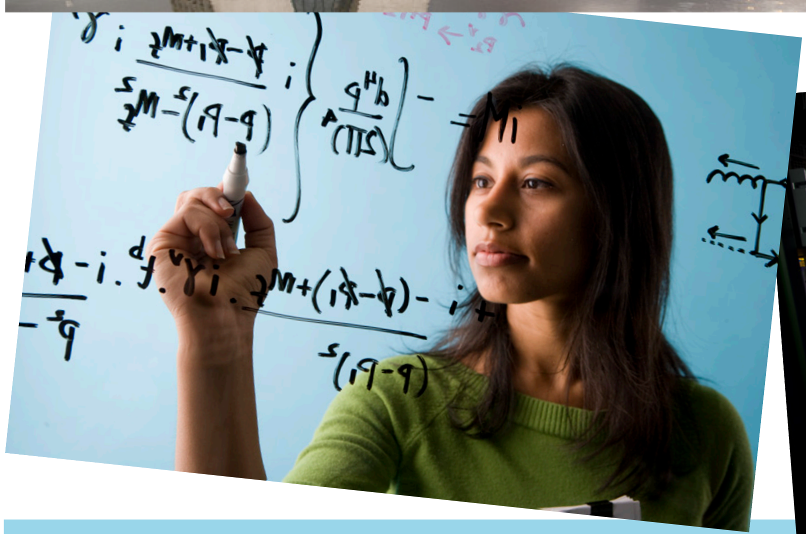
Collaborations are for non-proprietary basic research in quantum science.
Strategy: engage with major U.S.-based companies, other labs, and university groups with QIS expertise.

EXTRAS

Why is Fermilab involved?

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





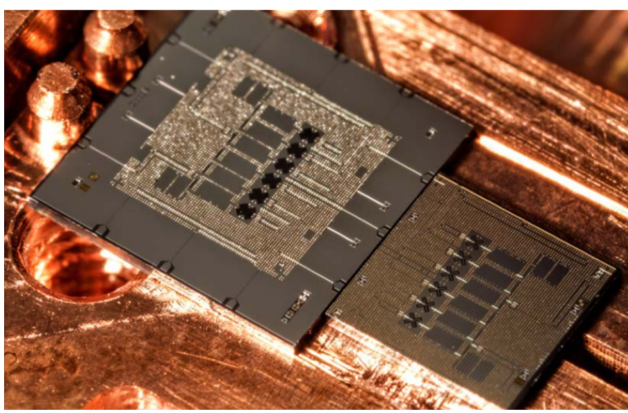
From qubits to quantum systems

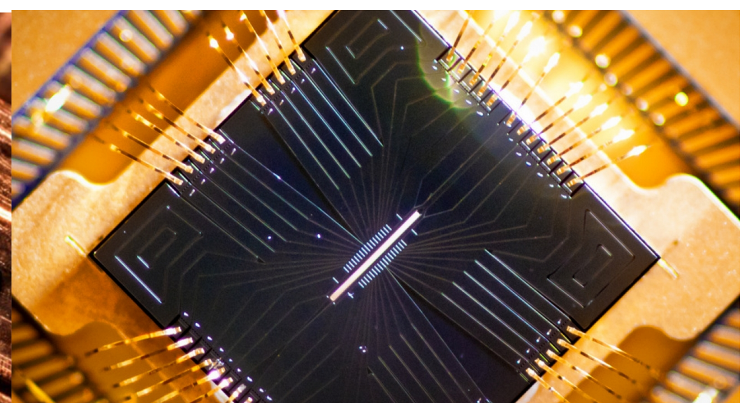
For useful qubits we need

- 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

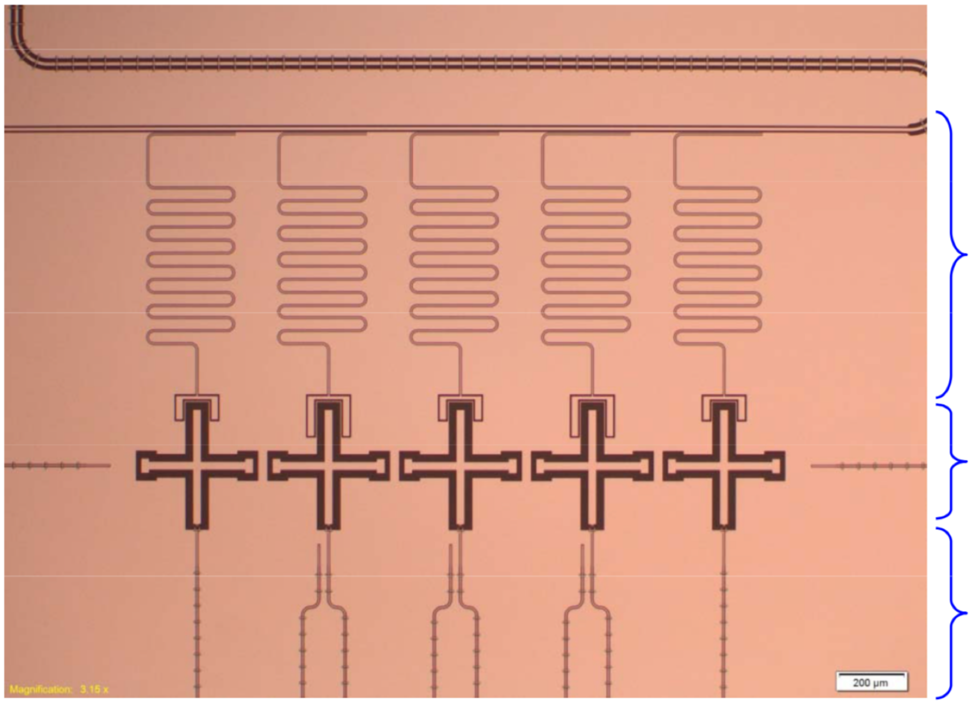
Extra challenge: no-cloning theorem (no copying of quantum info!)





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

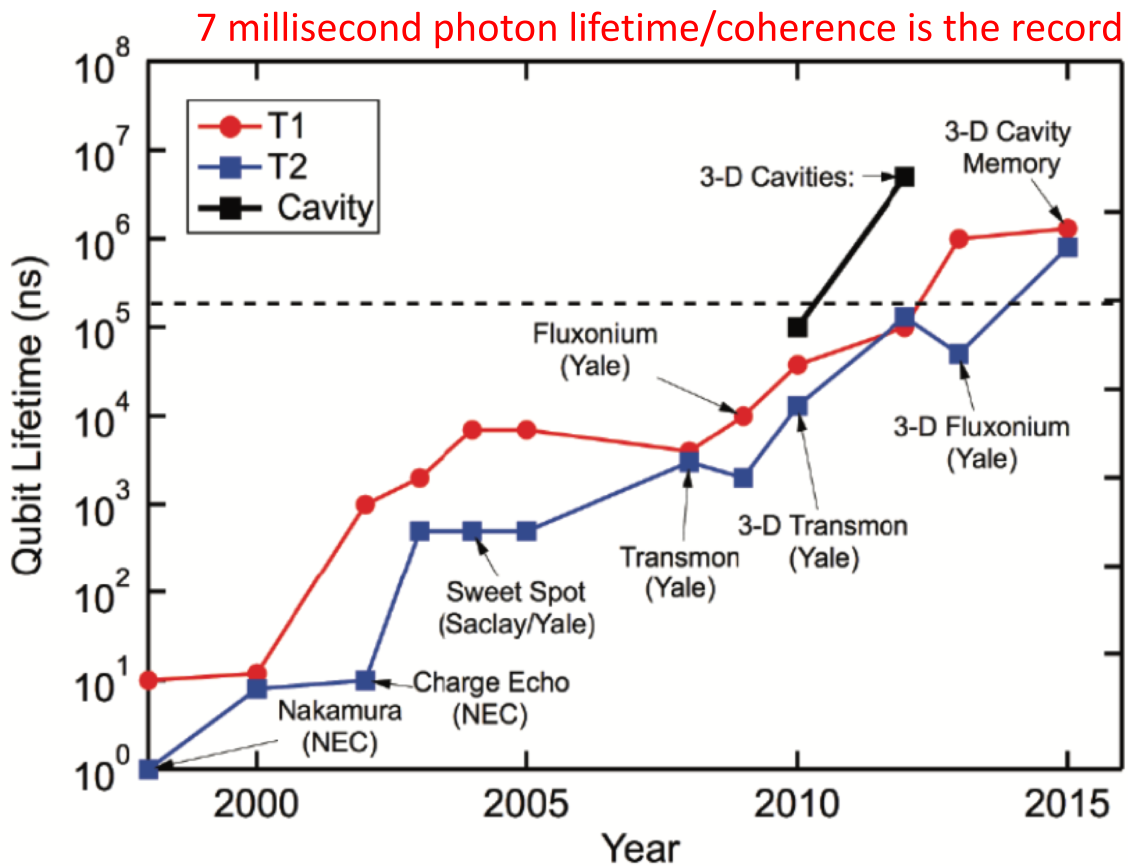


superconducting Xmon qubits

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

3D qubits/cavities give the best quantum coherence



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

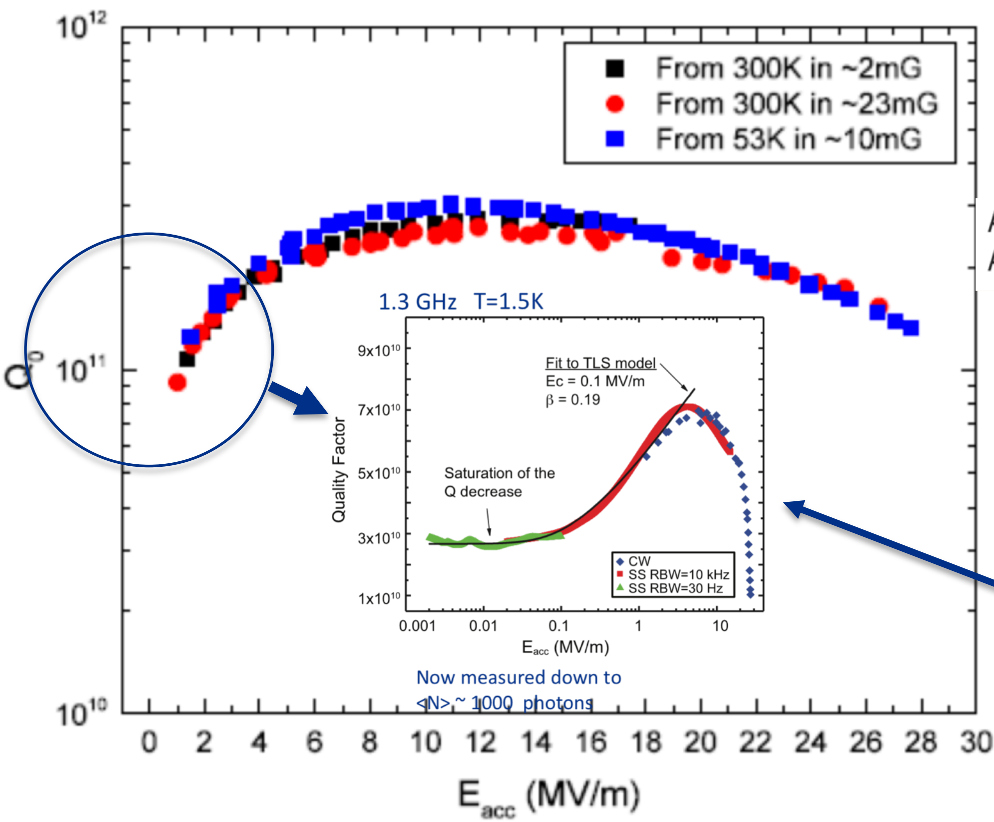
Long **quantum coherence time** is necessary for creating initial state, performing qubit gate operations, and measuring final state.

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

Can we do better?

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)

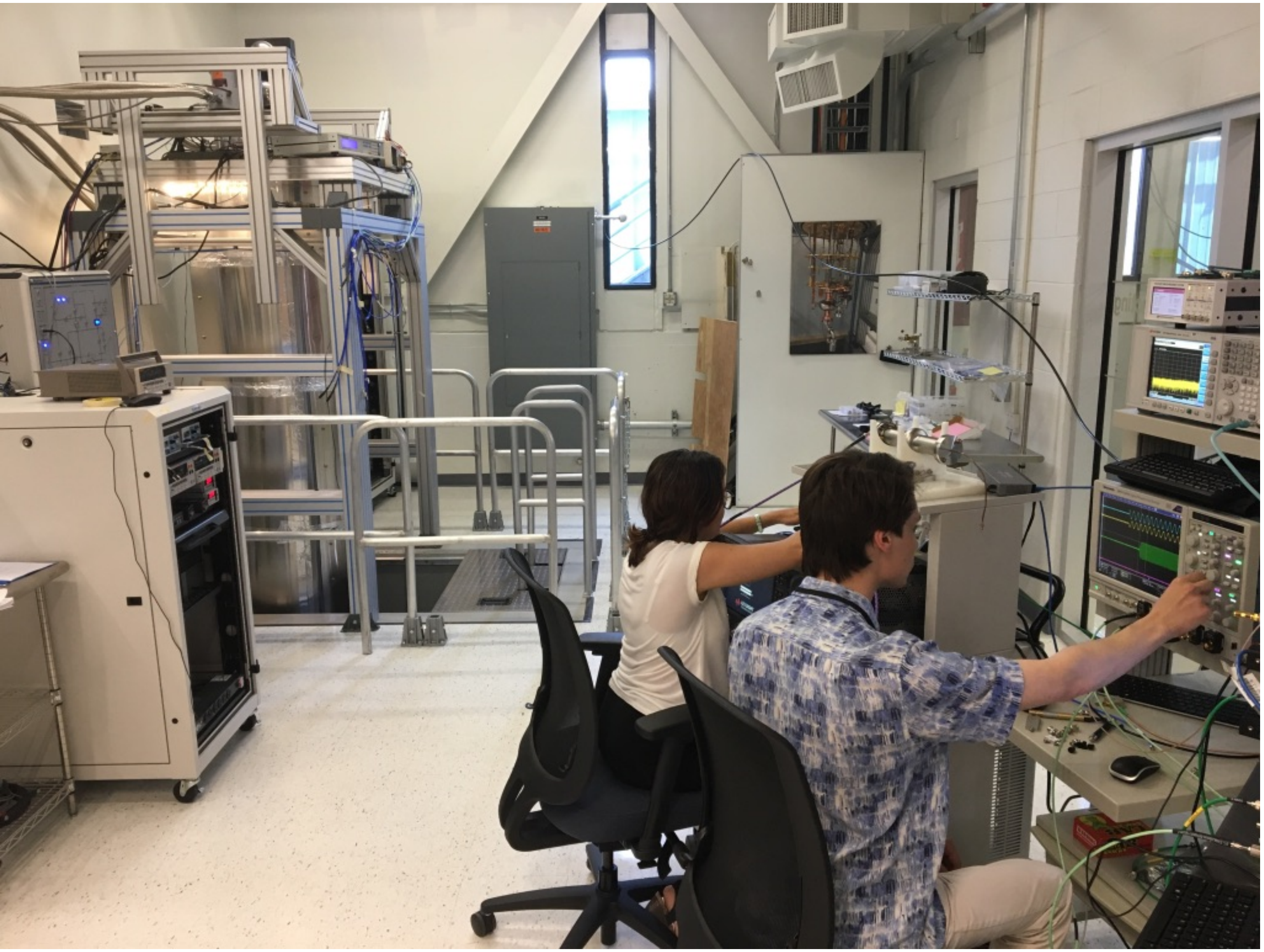
How will these cavities behave at ultralow fields for quantum science applications?

- 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**

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!

Restricted Boltzmann Machines (RBM)

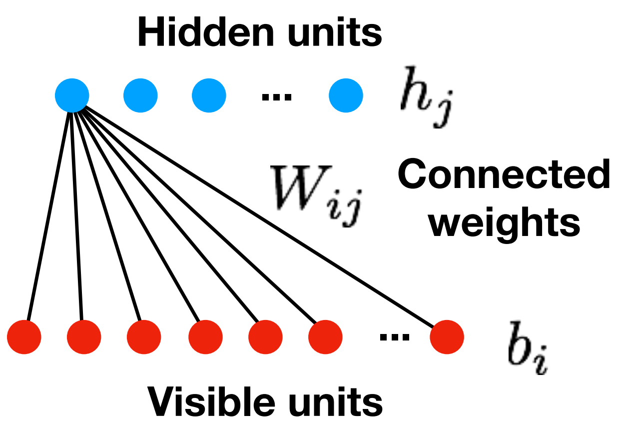
- The probability of a configuration is modeled with the Gibbs distribution.

$$P(v,h) = \frac{1}{Z} e^{-E(v,h)}$$

- Energy function - Ising model: $$E(v,h) = -\sum_{i=1}^{n} b_i v_i - \sum_{j=1}^{n} c_j h_j - \sum_{i=1}^{n}\sum_{j=1}^{m} W_{ij} v_i h_j$$
  - Partition function: $$Z = \sum_{v_k}\sum_{h_l} \exp\left(\sum_k b_k v_k + \sum_l c_l h_l + \sum_{kl} W_{kl} v_k h_l\right)$$

- The energy function is difficult to evaluate (NP-hard) because of the partition function.

- RBMs do not feature hidden-hidden or visible-visible connections.
  - Other connectivity strategies exist.
  - Long-term quantum advantage will be rooted in very high connectivity within the hidden nodes (including multiple layers).



RBMs on the D-wave

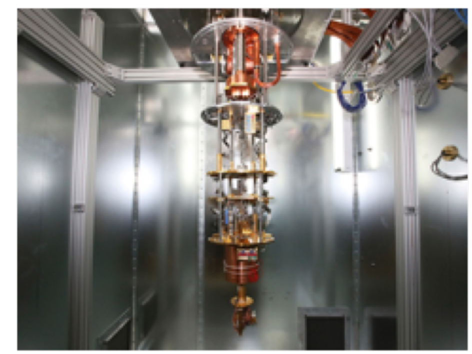
- Quantum annealing utilizes adiabatic computation.

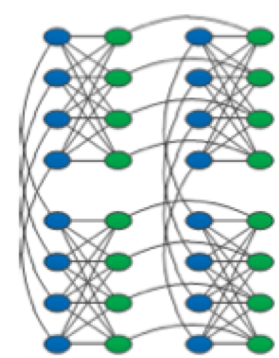
$$\mathcal{H}(t) = (1 - s(t))\,\mathcal{H}_i + s(t)\mathcal{H}_f$$

- Distribution of final states on real-world hardware is also modeled by the Boltzmann distribution.

- Therefore, we can use the quantum computer as a sampling engine to perform the RBM optimization very quickly as compared to Markov Chain MC or other methods.

- Chimera graph connectivity between qubits on D-wave 2000Q restricts us to ~64 visible and 64 hidden nodes in the RBM.





Quantum Optimization

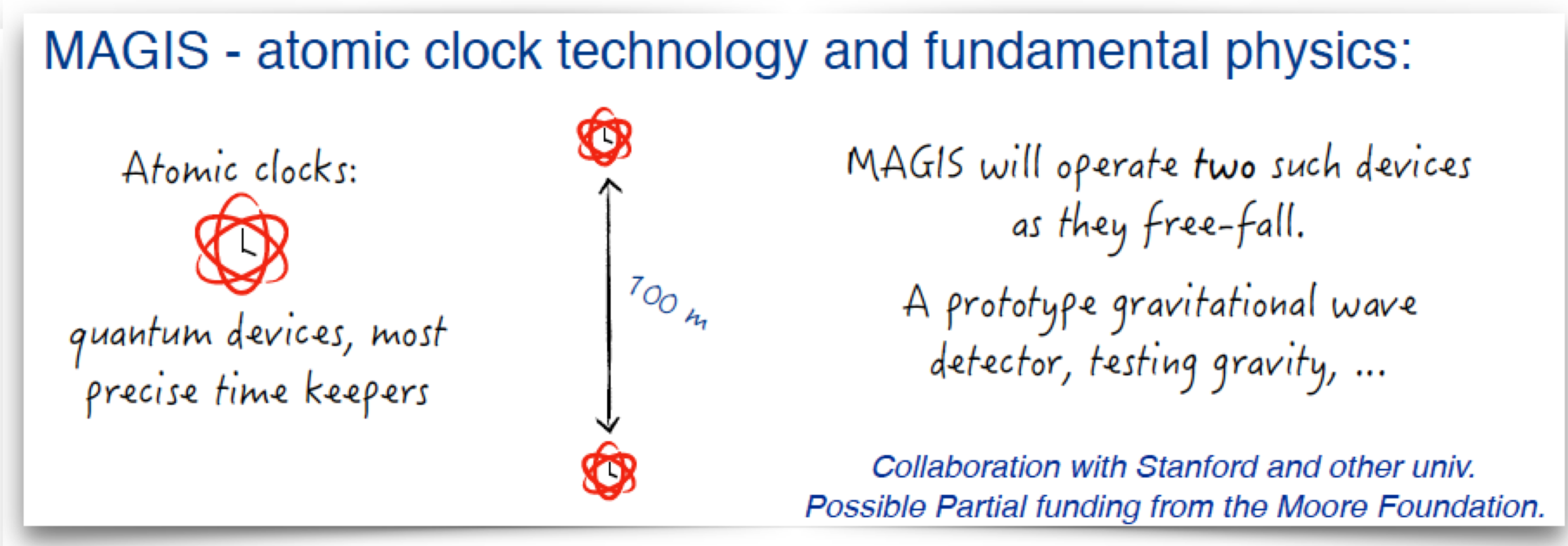
- Confinement of colored partons into colorless particles may be described with the Lund string model.
- However, the full complexity of hadron collisions cannot be described by simple combination of the perturbative color flow with the string model.
- Color recombination (CR) models change the color connections before hadronization - and therefore, change the formation of strings.
- CR models minimize a free energy computed from the strings - since the number of color combinations can be very large, current models employ a winner-takes-all algorithm to find local minima

Quantum Optimization

- Three main goals:
  - Formulate the energy minimization over colored partons as a binary constraint satisfaction problem - amenable to quantum annealers.
  - Solve the problem for realistic partonic configurations to find a global minimum with quantum simulators and existing hardware.
  - Study the phenomenological impact of the global solutions, and identify modifications to the underlying model to account for them.
- Knowing the phenomenological impact is important for extracting science at the LHC. No studies of these global minima are available and CR uncertainties, for example, are limiting systematics in computing the top quark mass from data.

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).



Quantum Sensors for Dark Matter detection?

There are many plausible theories for the identity of dark matter

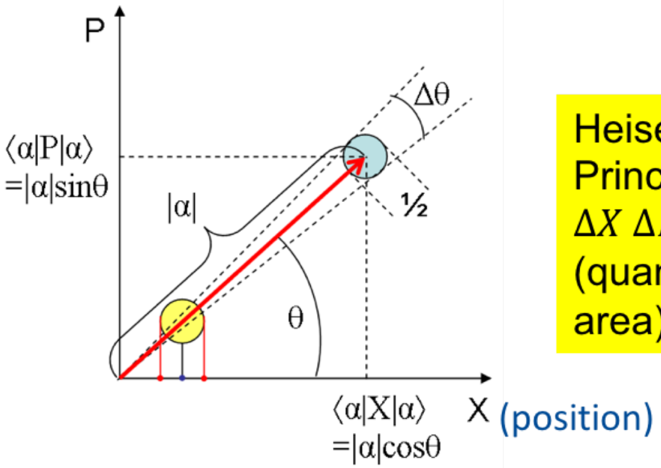
- Superpartner particles: Wino, Bino, Higgsino, sneutrino, …
- **Axions**
- Kaluza-Klein particles from extra dimensions
- Asymmetric dark matter
- WIMPzillas (??? talk to the theorists…)

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

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)

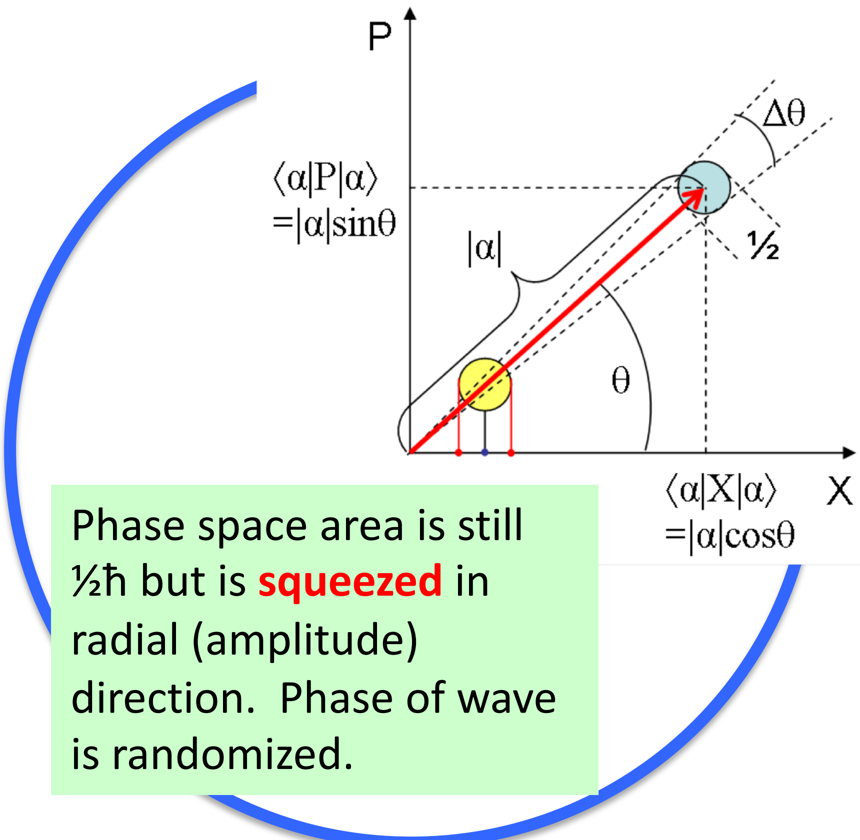


Heisenberg Uncertainty Principle
$\Delta X\, \Delta P = \Delta N\, \Delta\theta = ½\, \hbar$
(quantum of phase space area)

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...



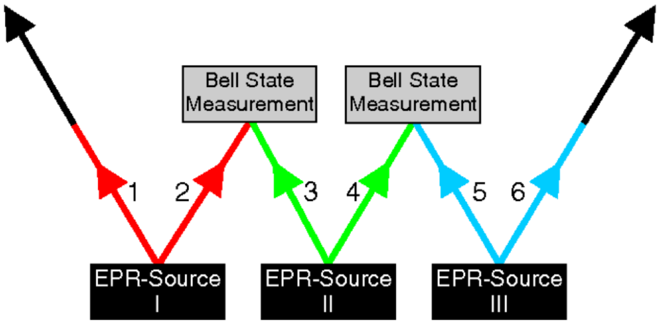
Phase space area is still ½ħ but is **squeezed** in radial (amplitude) direction. Phase of wave is randomized.

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

End-game vision and R&D drivers



Entanglement Swapping

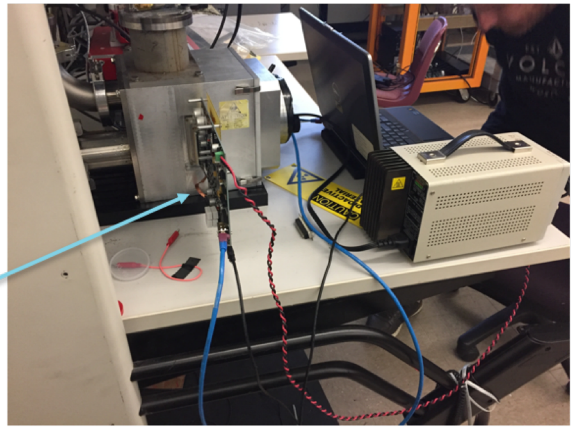
- Networks of quantum computers, quantum sensors, and other coupled physical systems (solids, trapped ions/atoms, phonons, polaritons)

- 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

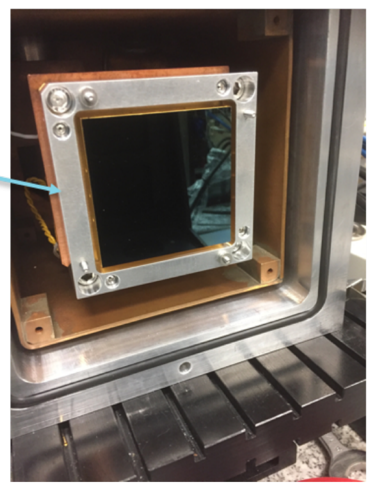
Quantum Imaging Setup

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

CCD test vessel

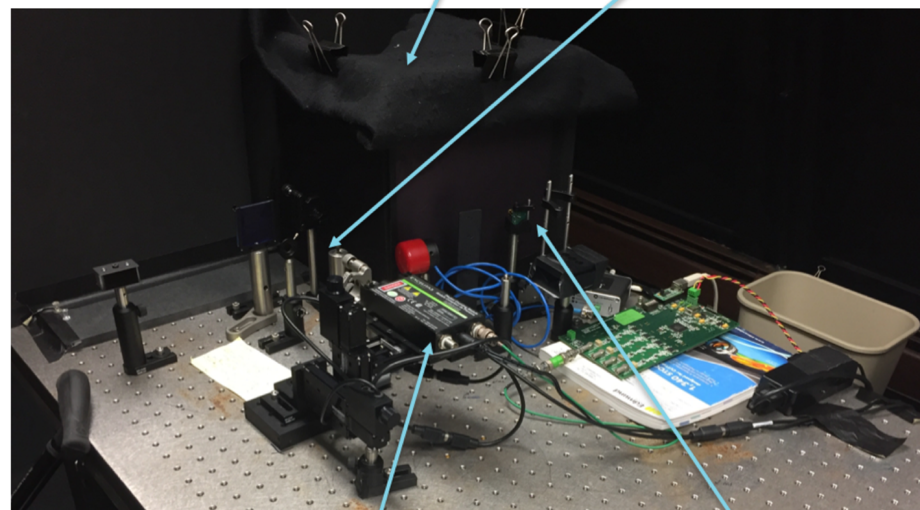


CCD inside test vessel



405nm Laser

BBO holder + filters

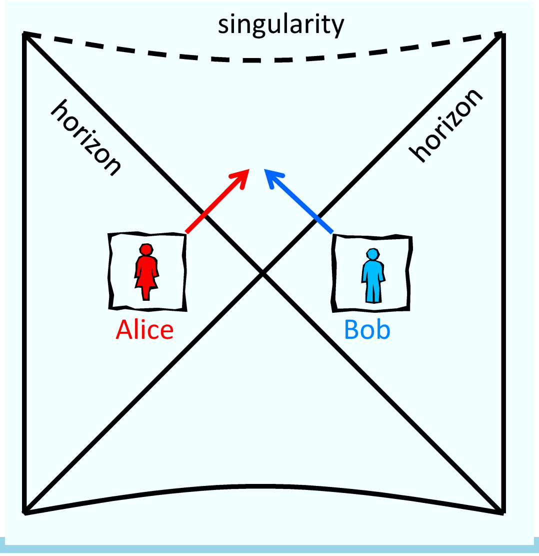


beam dump

single photon counter

Quantum teleportation through a wormhole

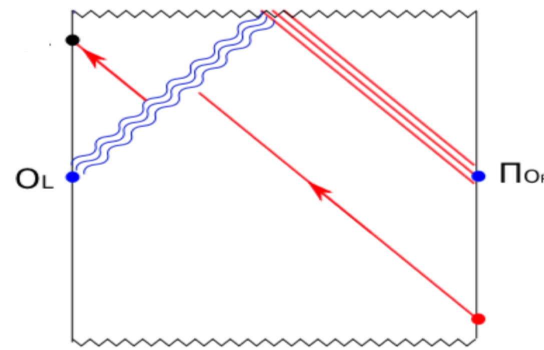
- It has been known for decades that the full Schwarzschild geometry describes a pair of black holes connected via a **wormhole**, known as the **Einstein-Rosen (ER) bridge**.
- This wormhole is non-traversable, in the sense that anyone jumping into one black hole, and attempting to get to the horizon of the second black hole, instead ends up at the singularity.
- One can make a similar pair of black holes in Anti-de-Sitter space; in this case the AdS/CFT correspondence gives a powerful relation between the bulk gravitational physics and the physics of quantum entanglement



Quantum teleportation through a wormhole

- In 2016 Jafferis et al showed that the AdS version contains a **traversable wormhole** when perturbed by a simple unitary operator.
- Maldacena, Stanford and Yang have shown the required perturbation can be mapped into the standard operations of quantum teleportation.
- Thus, in this particular kind of semi-classical system, ***quantum teleportation has an equivalent AdS/CFT description as a qubit physically moving through a wormhole.***

Maldacena and Susskind have speculated quantum teleportation in general is some kind of **"quantum" wormhole**



P. Gao, D. Jafferis, A. Wall, "Traversable wormholes via a double trace deformation", arXiv:1608.05687.
J. Maldacena and L. Susskind, "Cool horizons for entangled black holes", arXiv:1306.0533.
J. Maldacena, D. Stanford, Z. Yang, "Diving into traversable wormholes", arXiv:1704.05333.
L. Susskind and Y. Zhao, "Teleportation through the wormhole", arXiv:1707.04354.

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)

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

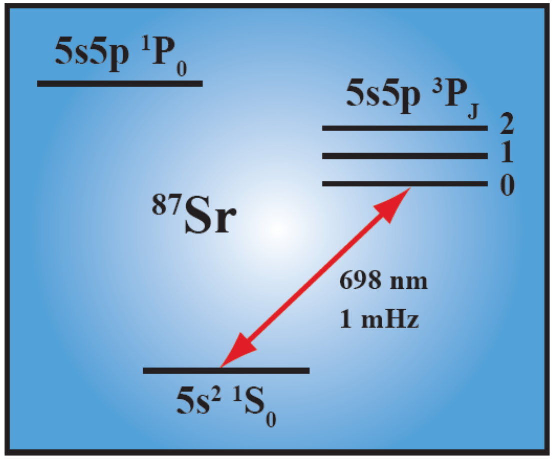
Northern Illinois University

UNIVERSITY OF LIVERPOOL

Fermilab

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

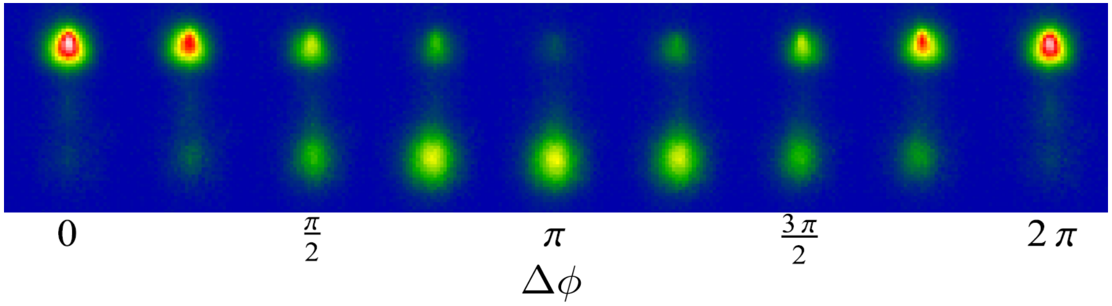


Strondium clock transition

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

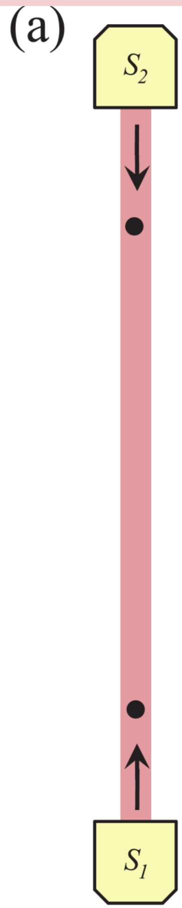
Dickerson, et al., PRL **111**, 083001 (2013).

Science signal (CCD images):



Gradiometer sensor design

Leverage **atomic clock** technology and **quantum metrology** for fundamental physics experiments

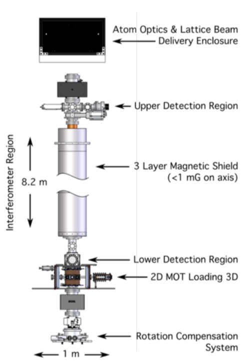


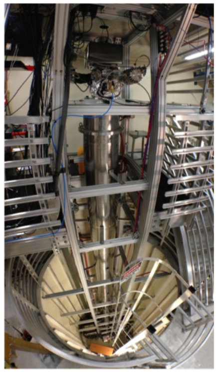
- Compare two (or more) ultra-cold atom ensembles separated by a **large baseline**
  - Laser pulses implement light-pulse atom interferometry at each end

- Science signal is **differential phase** between interference patterns

- Differential measurement suppresses many sources of common noise and systematic errors

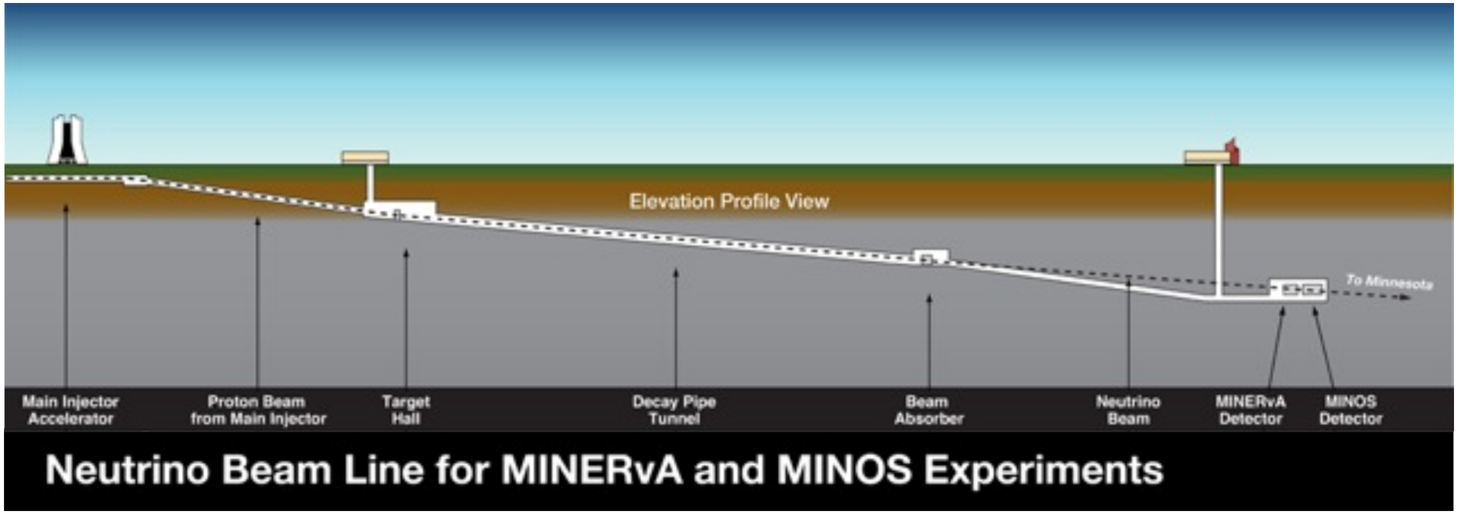
- Proof-of-concept using the Stanford 10 m scale prototype

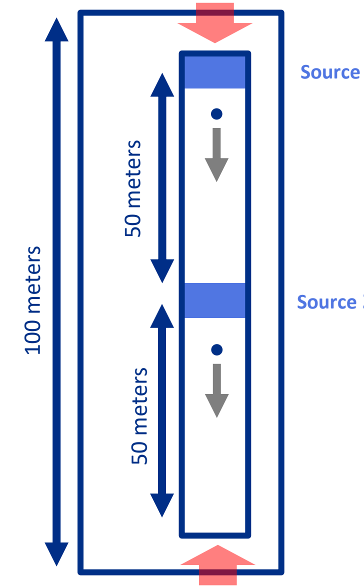




Science signal strength is proportional to baseline length (DM, GWs).

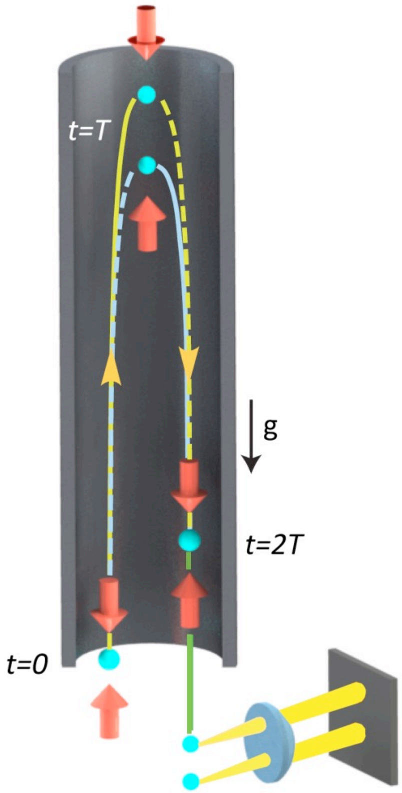
MAGIS-100 detector at Fermilab

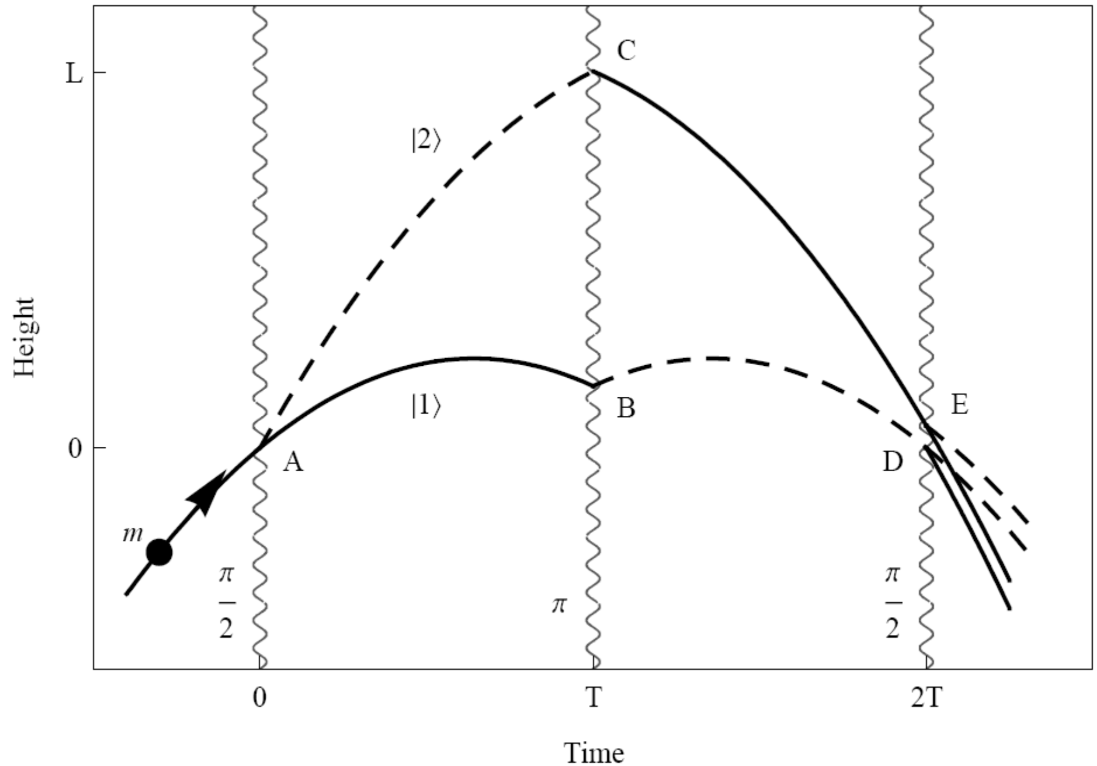


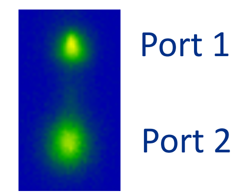


- MINOS, MINERvA, NOvA experiments use NuMI beam
- 100 meter access shaft – 100 meter atom gradiometer
- Search for dark matter coupling in the Hz range
- Intermediate step to full-scale detector for GWs
  - Aim to retire technical risk associated with scaling up:
    - Vacuum, trajectory control, alignment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

Light pulse atom interferometry



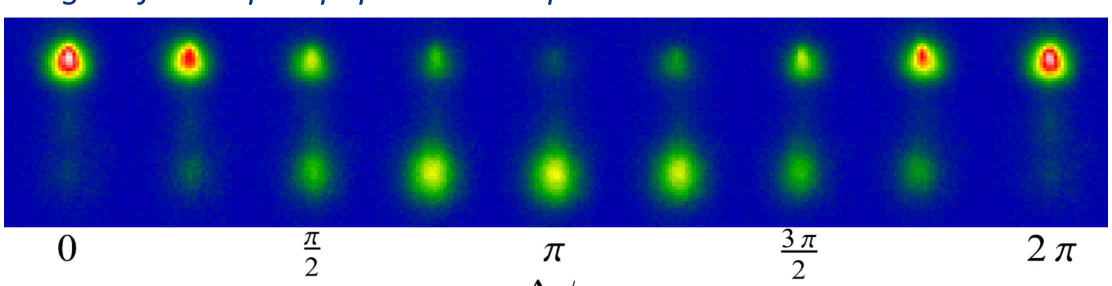




Dickerson, et al., PRL **111**, 083001 (2013).

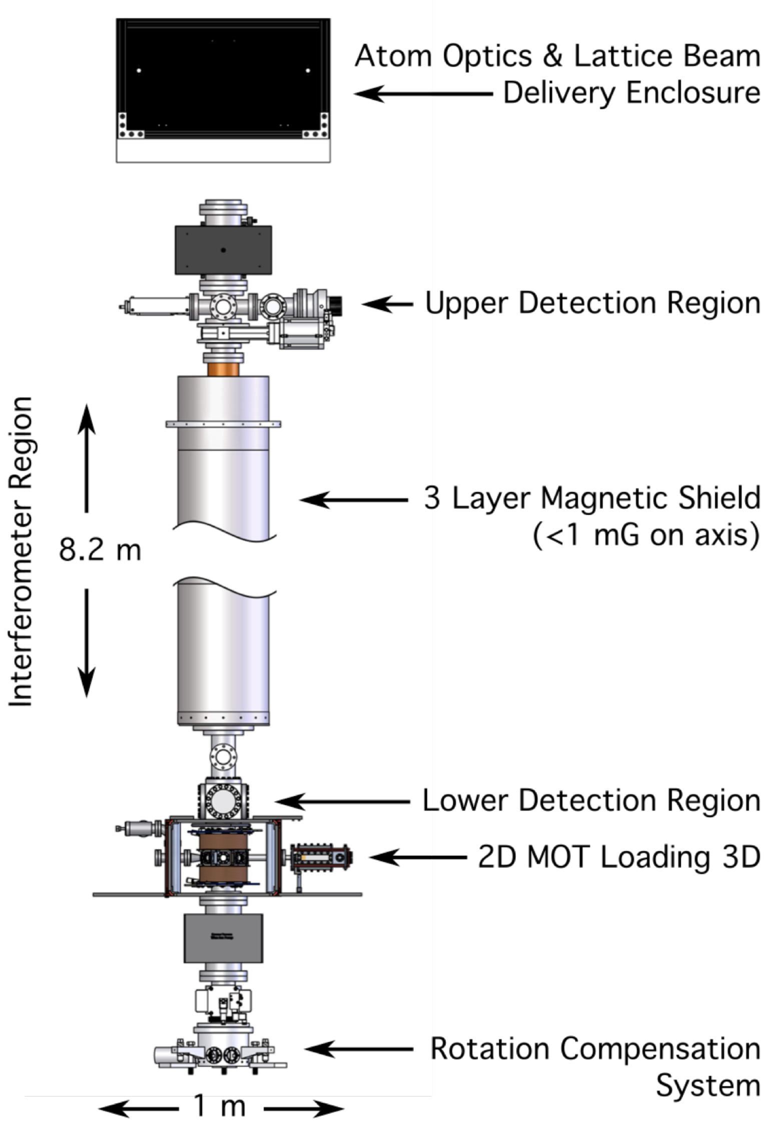
Images of atom port populations vs phase

Science signal (CCD images):



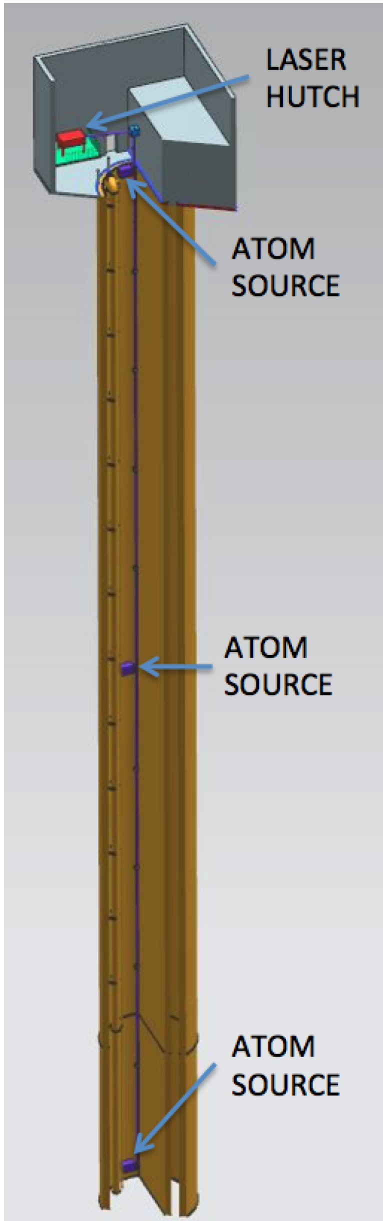
Data from world record atom interferometer duration (>2 seconds) at Stanford

Stanford 10 m scale



Fermilab

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)