Vision and Strategy for QIS at Fermilab

Panagiotis Spentzouris

Fermilab PAC Meeting

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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**

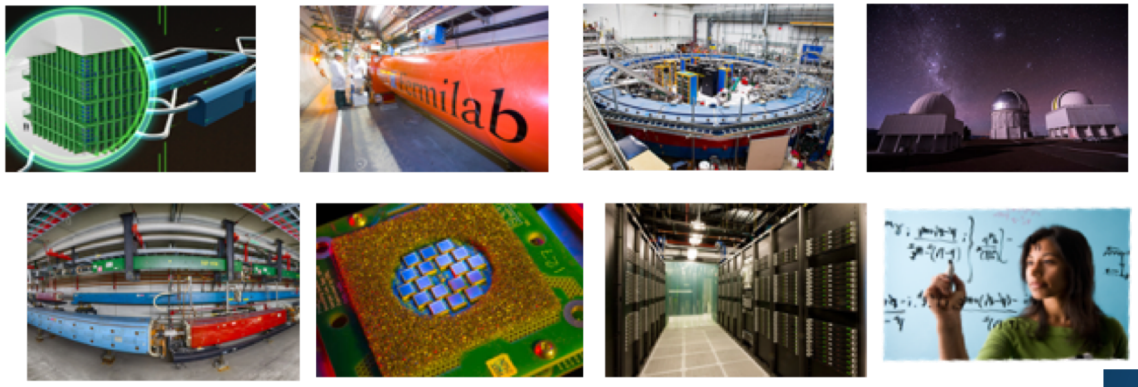
With potential (or already demonstrated) impact in many areas of basic research

These areas have natural overlaps, e.g. sensors as qubits, quantum communication for sensing and metrology, transduction for communication, algorithms for quantum systems…

Fermilab and Quantum Science & Technology

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

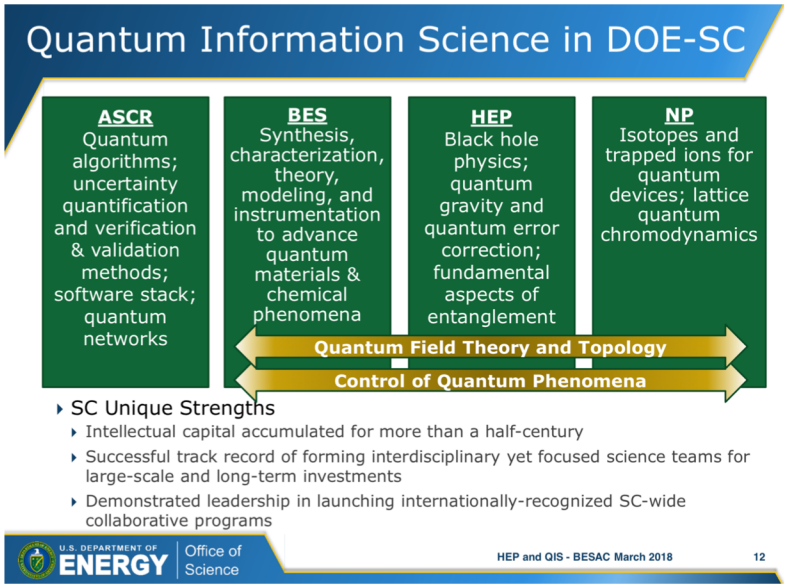
HEP science with neutrinos, the LHC, muons, and the cosmos



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

Many fundamental HEP research areas can benefit from successful quantum S&T applications and many HEP competencies and technologies that can advance quantum S&T

A new and rapidly advancing program: DOE/HEP QuantISED awards (September 2018), LDRD, Early Career Awards



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 as the main 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

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.

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

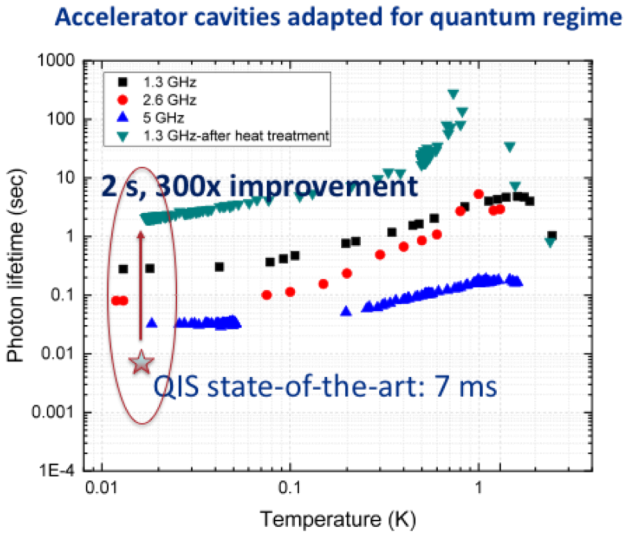
Enabling technologies: cold electronics, control systems; access to quantum resources for community building and workforce development

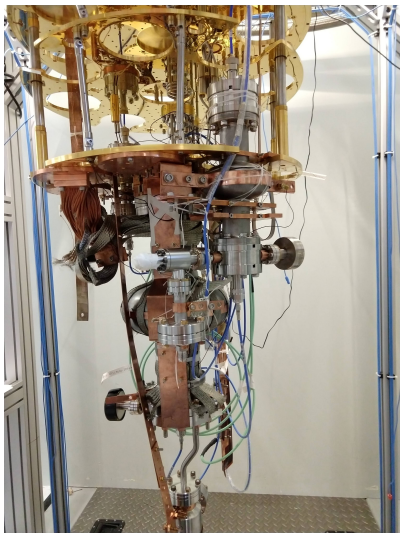
Foundational Quantum Science connections to HEP: quantum field theory, black holes, wormholes, emergent space-time.

Superconducting RF technology for quantum applications

See also Anna's and Roni's talks

- Major component of our program
  - Leverages core lab competencies and infrastructure, engaging partners with leading expertise where needed
- Drives multiple applications, engaging theorists and experimentalists
  - SRF-based qubit technology
  - sensors for the detection of dark matter and other exotic particles
- Could help catalyze research in areas such as quantum memories, controls, algorithms, transduction, …





WISCONSIN UNIVERSITY OF WISCONSIN-MADISON NIST

HEP theory and applications on quantum computers

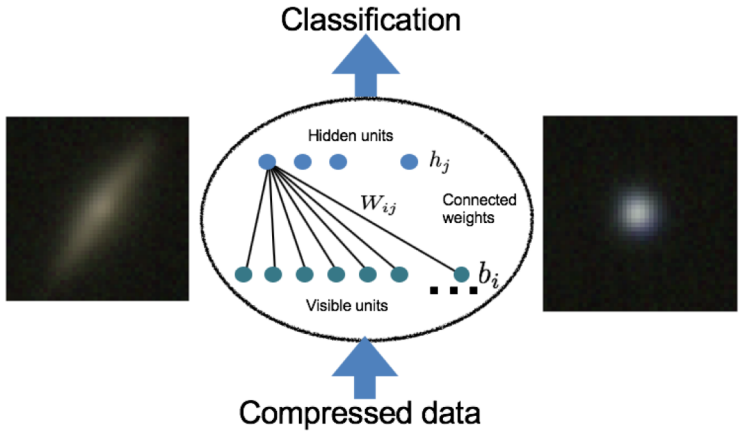
- Collaboration with Caltech and University of Washington
- Current focus on **quantum simulations** of particle physics
  - Seek **efficient** and **accurate** (digitization) field representations for near and intermediate term machines
- New approach on simulation of fermion-boson interacting systems
  - Overcomes the c**hallenge** of efficiently representing the interaction term
  - Develop algorithm using **coordinate basis**, achieve exponential precision for digitization!

    Macridin et al: PRL, 121, 110504 and PRA, 98, 042312
  - Result used by our UW collaborators in arXiv:1808.10378 further advancing investigations for HEP applications on near term quantum computers

Optimization and ML applications

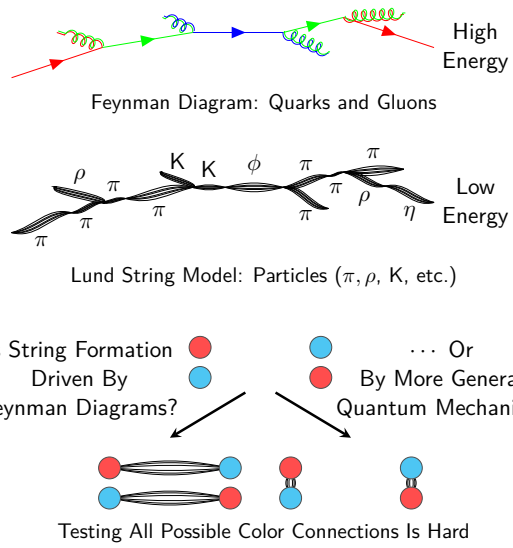
Partnering with Lockheed Martin and ORNL on **ML** problems in **astrophysics**

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



Partnering with ORNL on **optimization** problems for **LHC physics**

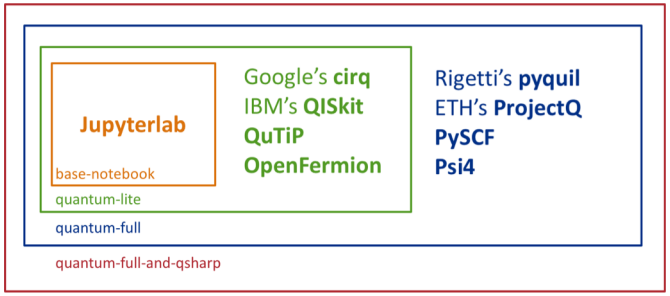
- Employ a quantum annealer to estimate systematics due to Color Recombination models
  - Formulate as a binary constraint satisfaction problem
- Compare results with best-known classical solutions
  - Evaluate impact on current measurements



Fermilab

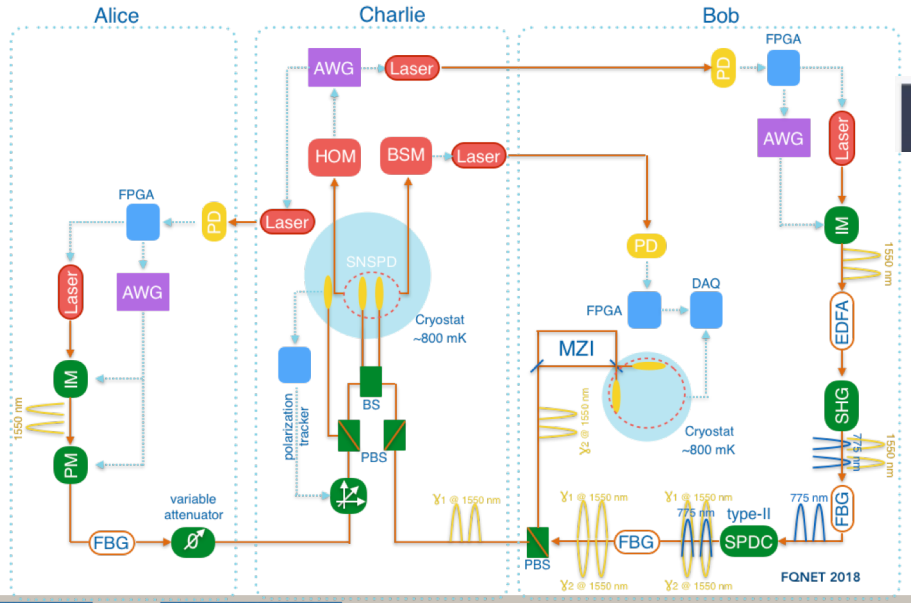
Providing access and training for HEP

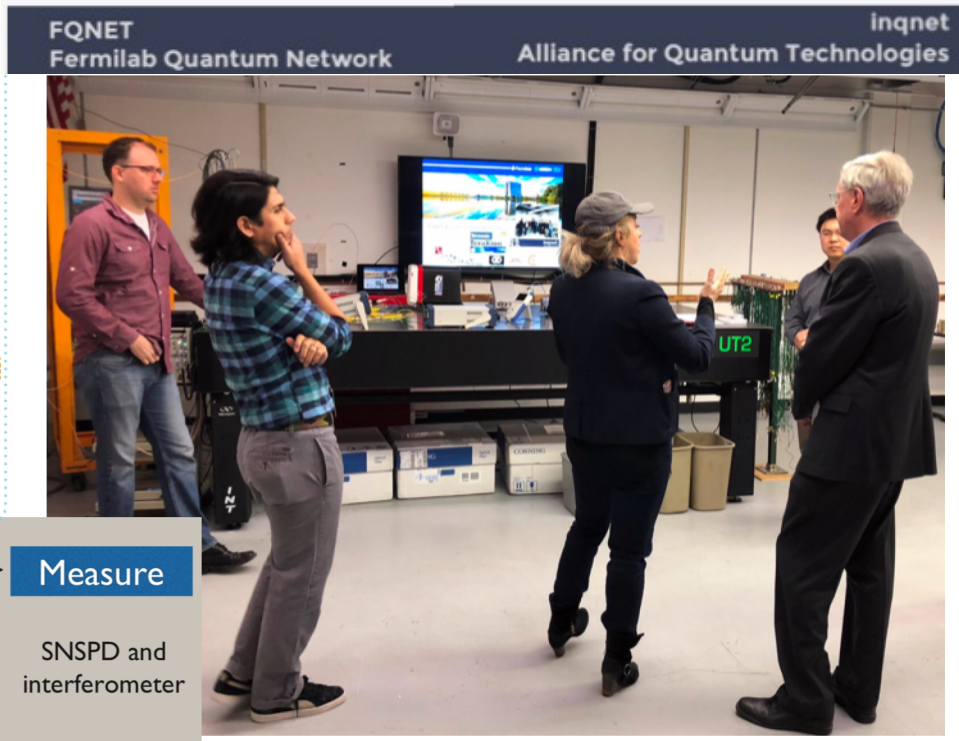
- Workshops and tutorials, first step for community engagement and workforce development
- Partnership with Google; Co-developed and delivered first tutorial with (Sep 2018)
  - Container with most utilized QC environments
- Joined IBM Q ORNL hub (Dec 2018)

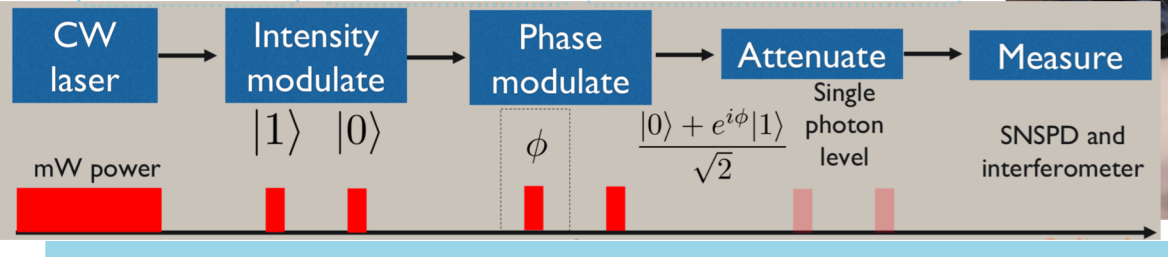


Fermilab quantum teleportation experiment (FQNET)

- **Time-binned optical photonic qubits** over commercial telecom fiber
- Build and commissioned over the past 15 months and has achieved quantum teleportation
- Working on optimizing teleportation fidelity, stability & overall efficiency
- Next step to distribute quantum info between nodes across Fermilab

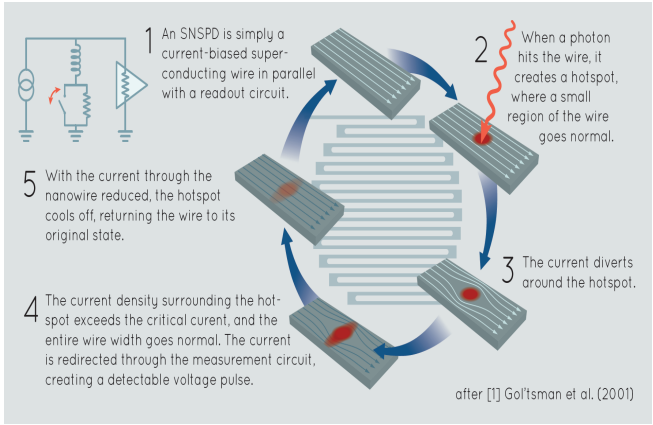


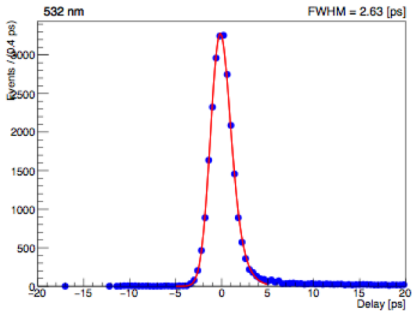


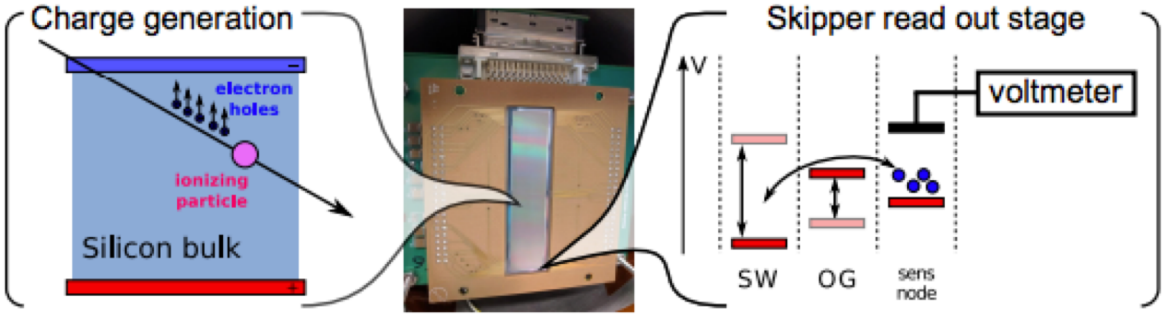


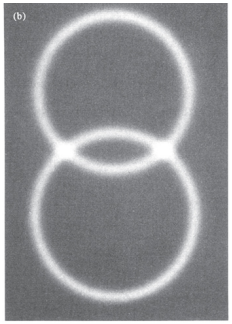
R&D driven by quantum communication

- Develop **cryogenic electronics** to reduce electronic noise and improve time resolution for SNSPDs
  - Fermilab, JPL, Georgia Tech
- **Dark matter detection**: use high intensity entangled pair source to produce photon—dark-photon pairs, and "image" them with Skipper CCDs



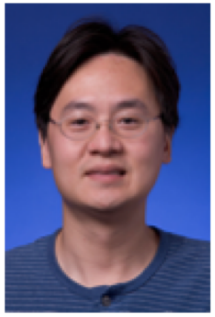






Fermilab, LBNL, Caltech partnership

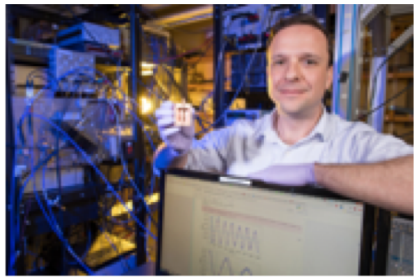
Qubit-based single microwave photon sensors for axion detection



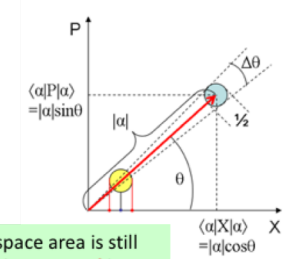
Aaron Chou

David Schuster(UC)

Konrad Lehnert U.Colorado/NIST

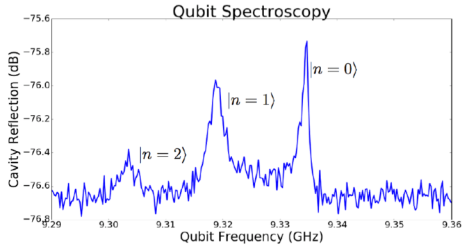


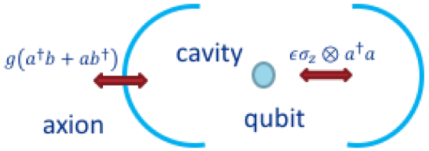
Daniel Bowring, Fermilab
2018 Early Career Award

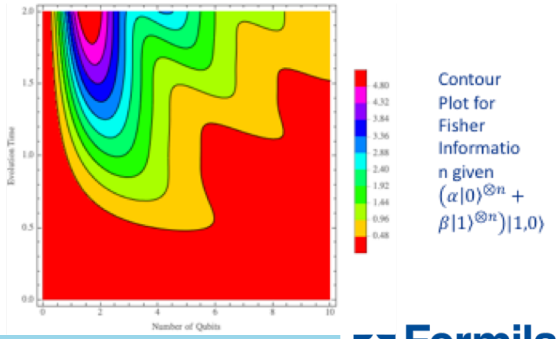


Phase space area is still ½ħ but is **squeezed** in radial (amplitude) direction. Phase of wave is randomized.

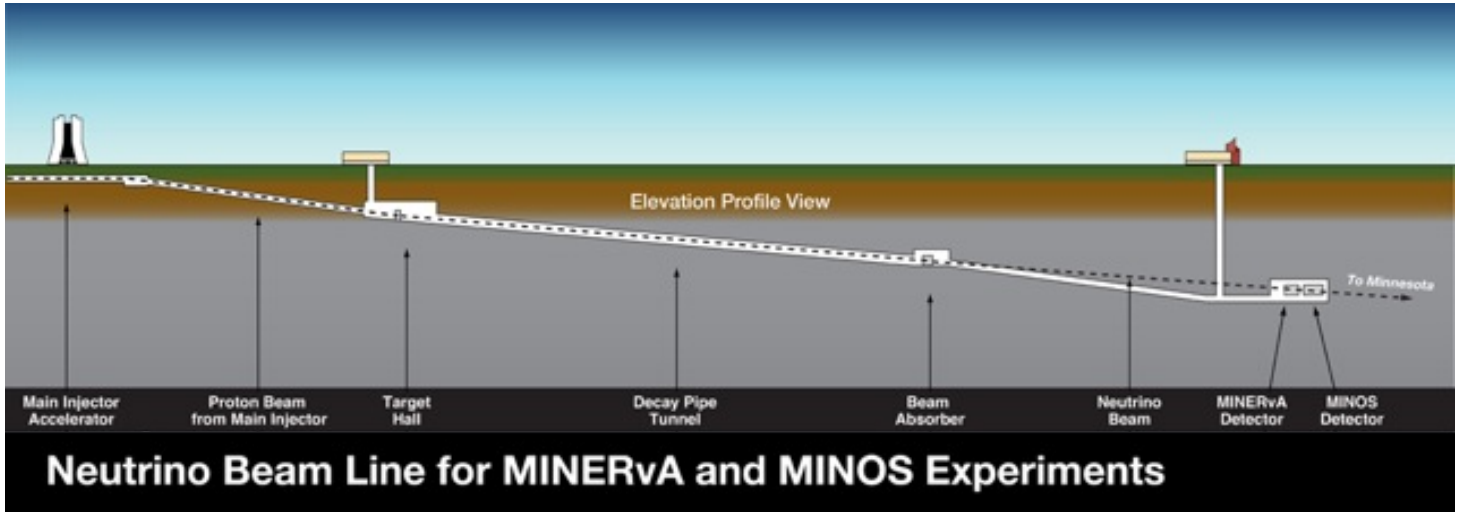
- Increase the signal photon rate by using superconducting qubits as QND detectors and an high-Q cavity in a non-classical state
  - sensitive to incoming axion waves with any arbitrary phase
- Reduce impact of read errors by incorporating multi-qubit readout
  - Possibly further improving by preparing them in an entangled state and even utilizing quantum ML

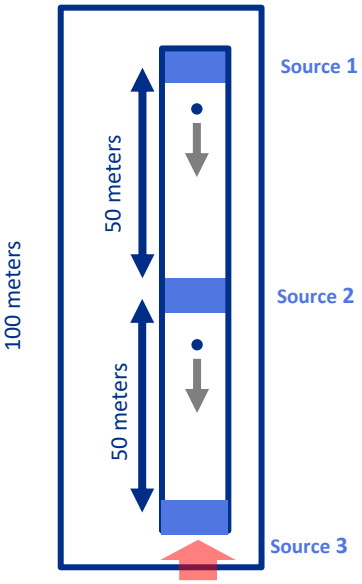




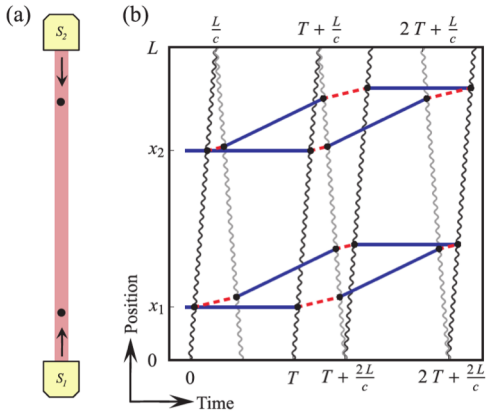


MAGIS-100 detector at Fermilab





STANFORD BERKELEY Northern Illinois University NIU UNIVERSITY OF LIVERPOOL Fermilab



- 100 meter access shaft – 100 meter atom gradiometer
- Search for ultra-light dark matter coupling
- Step toward full-scale detector for Gravitational Waves from Stanford 10 m prototype (Hz range)
  - Aim to retire technical risk associated with scaling up: Vacuum, trajectory control, alignment tolerances, …

The next phase of the program

- Continue to exploit complementarity and overlaps to increase program coherence.
- Continue to leverage Fermilab competencies for new projects
  - Controls, MAGIS-100, …
- Working with local institutions to establish a platform for taking advantage of the collective Chicagoland QIS expertise
- Preparing to compete for a National QIS Research Center
  - SC operated centers to conduct basic research for scientific breakthrough

We want Fermilab to be the place that HEP and QIS folks come to do research that enables HEP science applications, doing cutting-edge science at the same time

Summary

- We are building a Quantum Science Program targeting HEP long-term needs by leveraging Fermilab's competencies and infrastructure
  - Our initiatives are already producing results
  - The engagement of the HEP community is growing
- We are establishing collaborations with universities, industry, and labs
- We are developing our long term strategy leveraging opportunities of the National approach to QIS R&D

NATIONAL STRATEGIC OVERVIEW FOR QUANTUM INFORMATION SCIENCE