The Fermilab Quantum Program

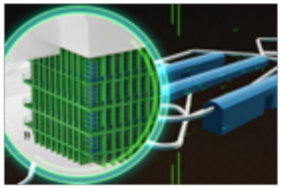
Panagiotis Spentzouris

International Workshop on Cryogenic Electronics for Quantum Systems

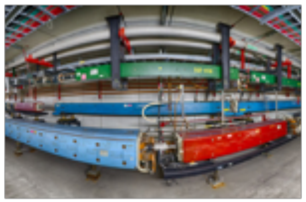
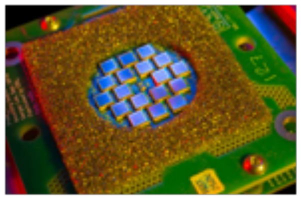
June 17th, 2019

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

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

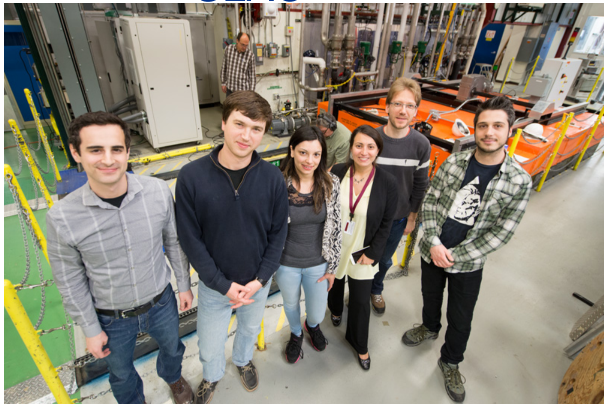
Many fundamental **HEP** research areas can **benefit** from successful Quantum Science and Technology **(S&T) applications** and many **HEP competencies** and **technologies** can **advance quantum S&T**

→ Establishing a new and rapidly advancing program (first awards received Sep 2018, DOE/HEP QuantISED)

Superconducting RF technology for quantum applications

- Central component of our program
  - Leverage world leading lab competencies engaging partners where necessary
- Drives multiple applications, engaging theorists and experimentalists
  - SRF-based qubit technology
  - sensors for the detection of dark matter and other exotic particles
- Could catalyze research in areas such as quantum memories, controls, algorithms, transduction, …

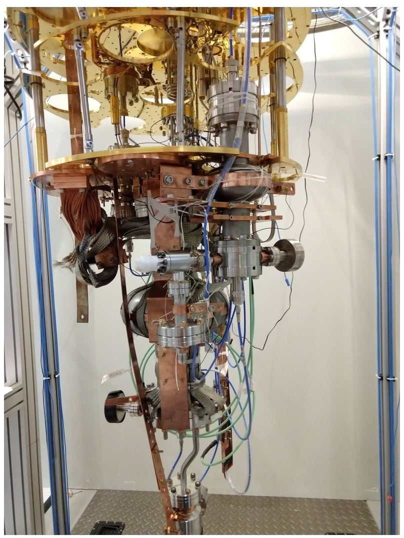
Cryomodule built at Fermilab for the new LCLS-II free electron laser light source at SLAC



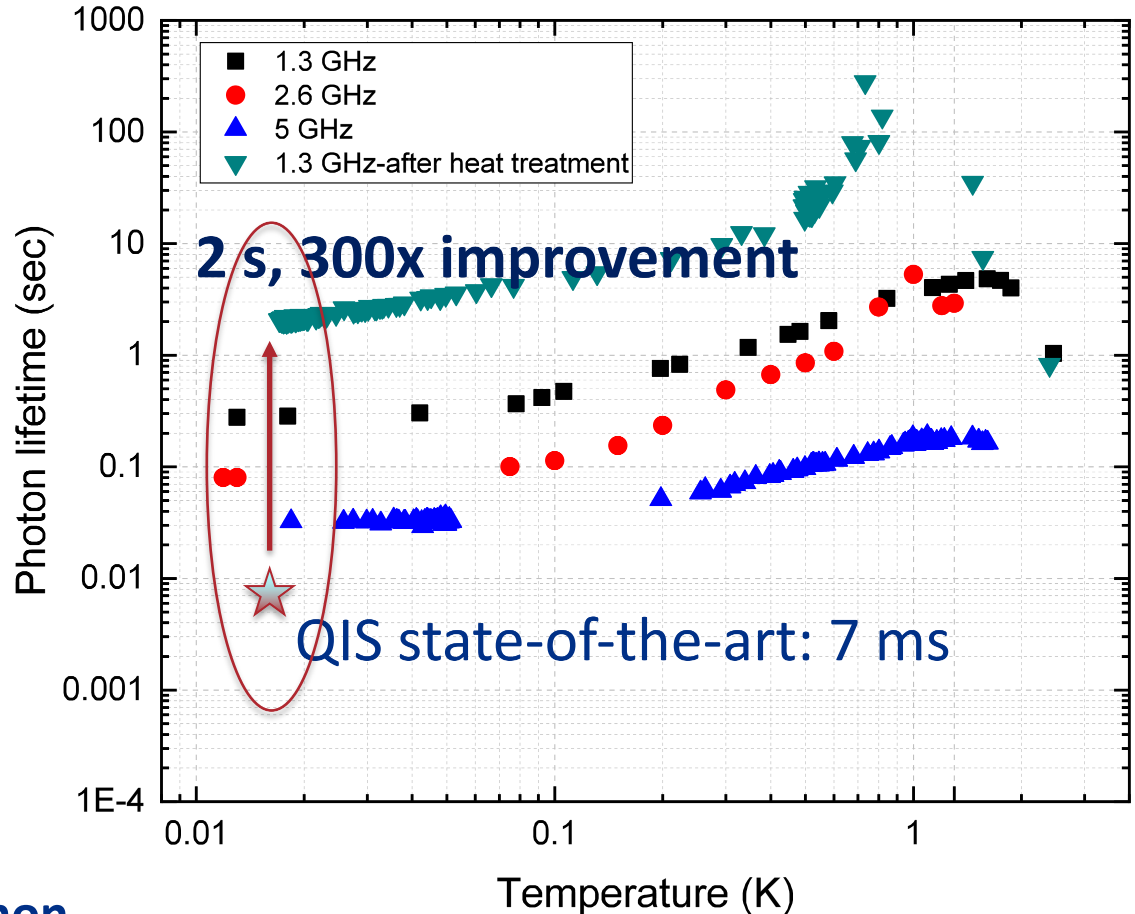
QIS PI Alex Romanenko and Anna Grassellino lead the Fermilab SRF cavity program

partners WISCONSIN UNIVERSITY OF WISCONSIN–MADISON NIST

Record high photon lifetimes achieved at Fermilab



Accelerator cavities adopted for quantum regime



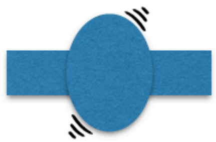
Integration with **transmon qubits** (built by UW Madison) underway

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

Early Returns: Dark Photon Searches with SRF cavities

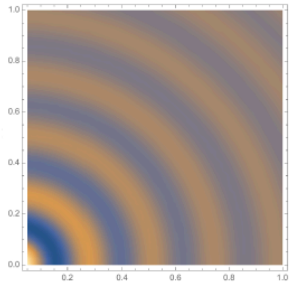
Dark Photon Search

The first simple setup:



Emitter Cavity

Frequency of 1.3 GHz, excited to ~ 35 MV/m. Thats ~ 10^{25} Photons!



a dark photon field is radiated at 1.3 GHz.

Receiver Cavity

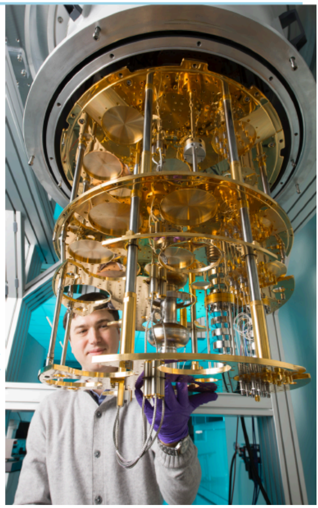
Tuned to 1.3 GHz. Responds to dark field. Contains only thermal noise (T=1.4 K).

Vertical cavity test Facility at APS-TD (VTS)

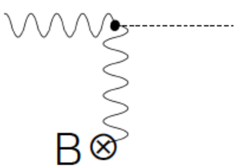
Ready now
T= 1.4K
~1000 photons

Dilution Fridge at APS- TD Quantum Lab (QCL)

More prep required
T~20 mK
NO thermal photons

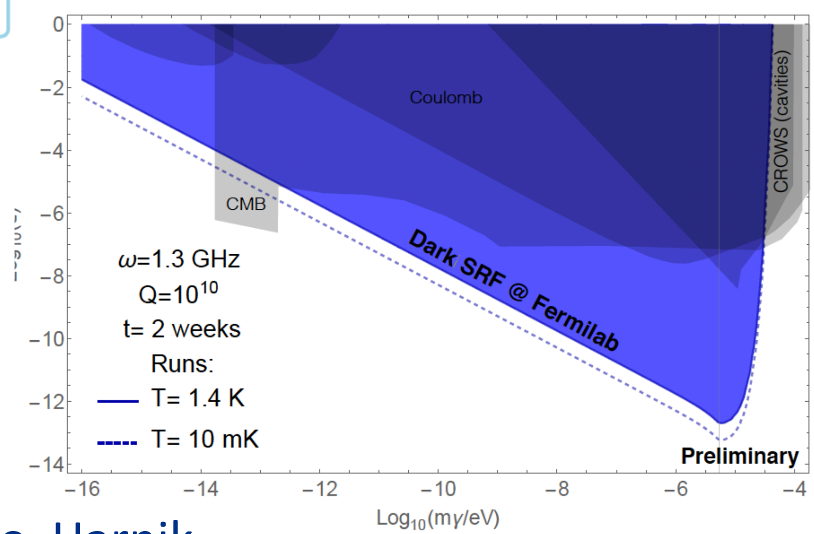


$$\mathcal{L} = \frac{\alpha}{f} a F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$



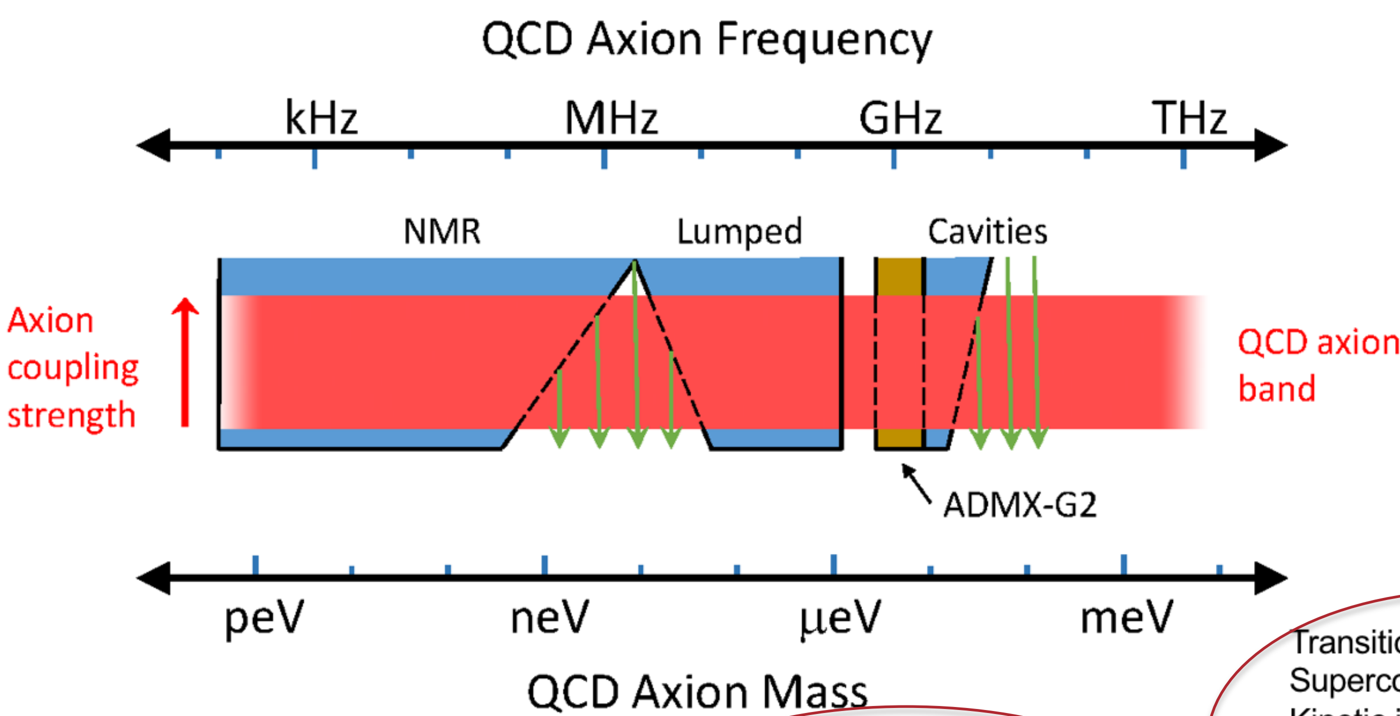
Axions and photons mix in a magnetic field.

An oscillating E·B is a source of dark photons.



Grasselino, Romanenko, Harnik

Strategy to cover 10 orders of magnitude in axion mass



BOLD = funded by 2018 DOE QuantISED program

Quantum nondemolition with aluminum qubits (A.Chou, K.Lehnert, D.Schuster)

Transition edge sensors, Superconducting nanowire, Kinetic inductance detectors, Quantum capacitance det. (C.Chang, S.Nam, A.Sonnenschein)

Noiseless photon upconvertors, spin-squeezing (K.Irwin, A.Sushkov)

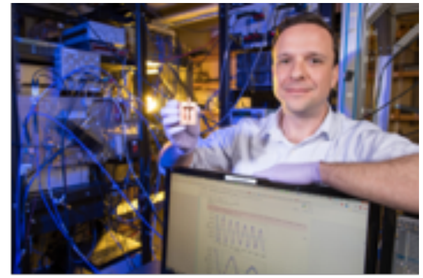
High-Tc qubits/amps (C.Chang, A.Chou)
Rydberg atoms (R.Maruyama, A. Chou),
Graphene-JJs (KC Fong, A.Chou)

Qubit-based single photon sensors for axions

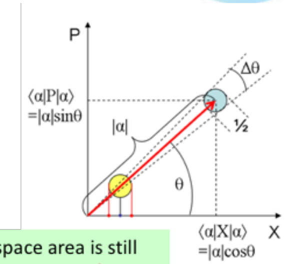
Aaron Chou

David Schuster(UC)

Konrad Lehnert U.Colorado/NIST

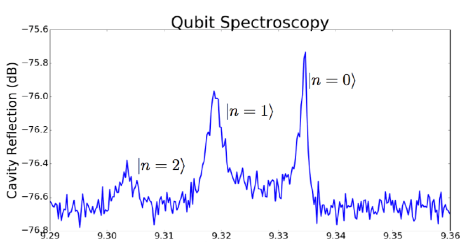


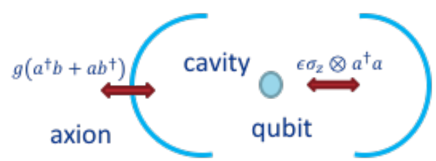
Daniel Bowring, Fermilab
2018 Early Career Award

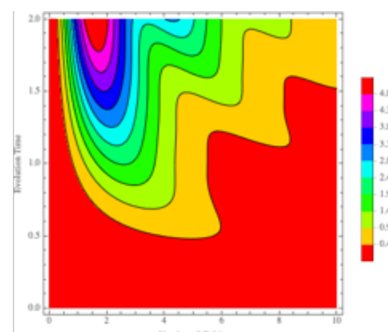


Phase space area is still ½ħ but is **squeezed** in radial (amplitude) direction. Phase of wave is randomized.

- Increase signal photon rate with superconducting qubits as Quantum Non-Demolition detectors and high-Q cavity in non-classical states
  - sensitive to incoming axion waves with any arbitrary phase
- Reduce impact of read errors by incorporating multi-qubit readout
  - Possible further improvements by preparing qubits in an entangled state and even utilizing quantum ML

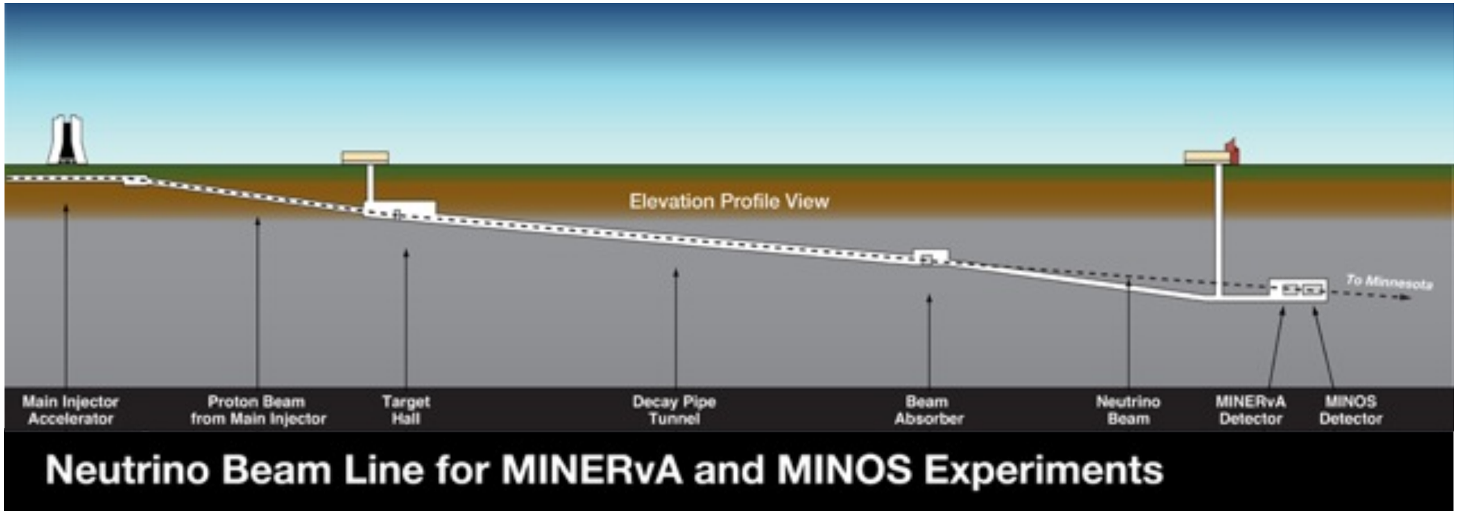


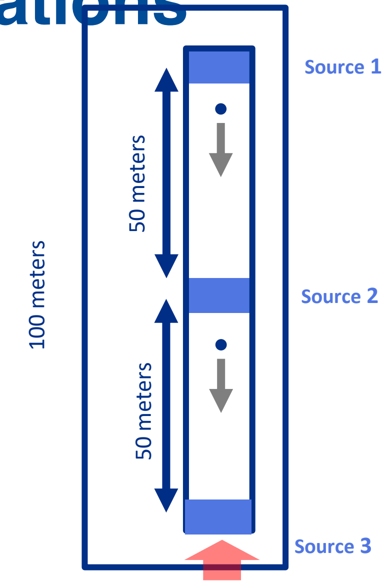




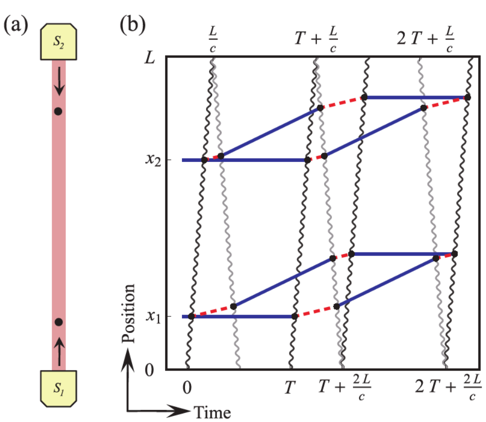
Contour Plot for Fisher Informatio n given $(\alpha|0\rangle^{\otimes n} + \beta|1\rangle^{\otimes n})|1,0\rangle$

MAGIS-100: leveraging Fermilab infrastructure and competencies toward full scale sensor applications





Plunkett, Fermilab PI



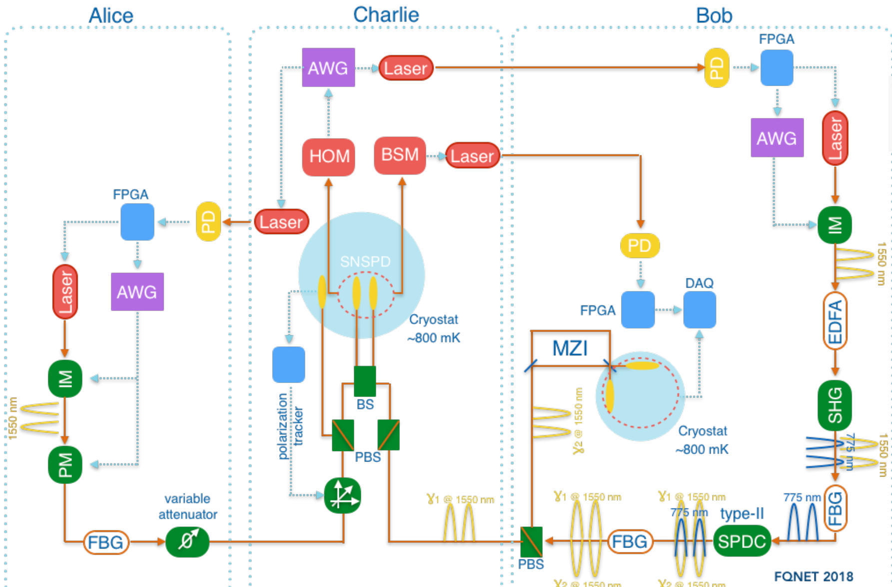
- 100 meter access shaft – 100 meter **atom gradiometer**
- Search for **ultra-light dark matter** coupling
- Step toward full-scale detector for **Gravitational Waves** from Stanford 10 m prototype (Hz range)
  - **retire technical risk** associated with scaling up: Vacuum, trajectory control, alignment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

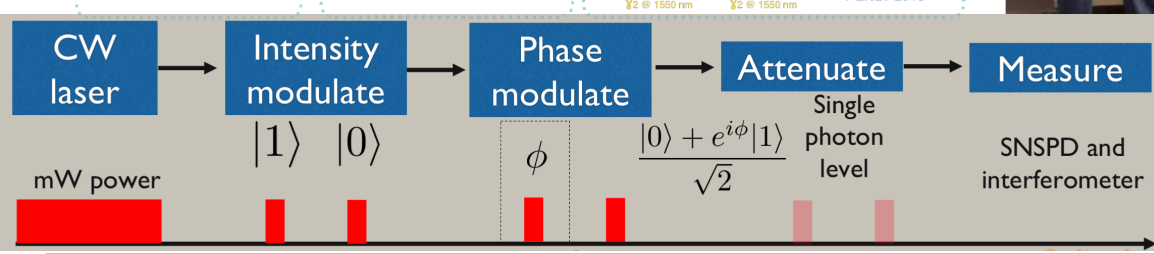
Fermilab quantum teleportation experiment (FQNET)

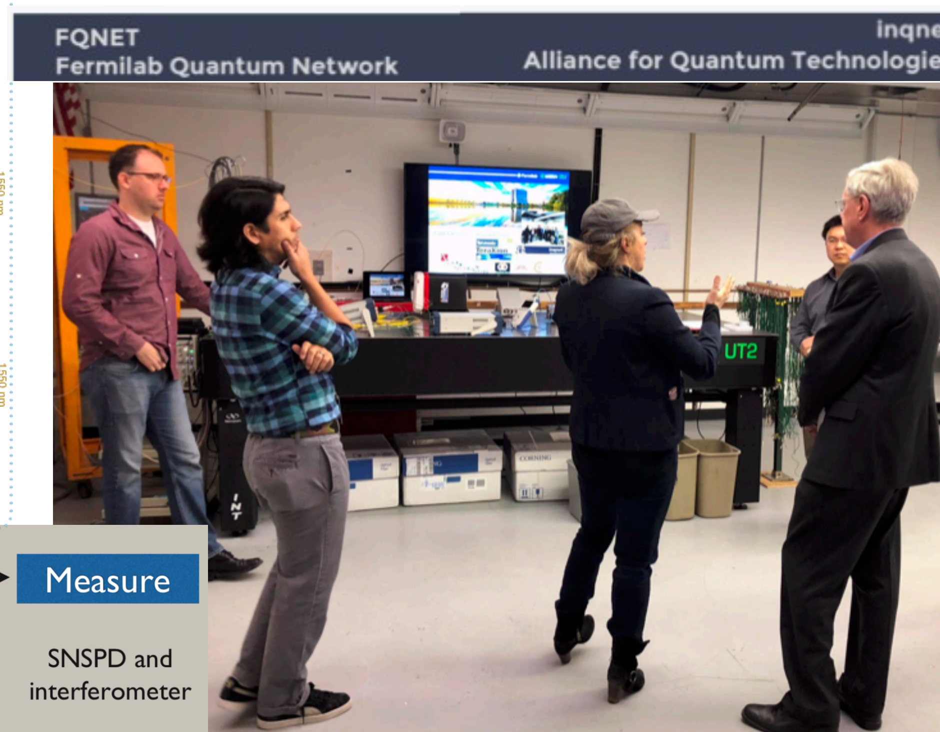
- **Time-binned optical photonic qubits** over commercial telecom fiber
- Built and commissioned over the past ~2 years, achieved **teleportation**
- Optimizing teleportation fidelity, stability & overall efficiency
- Next step to distribute quantum info between nodes across Fermilab
- Mid-term goal: entanglement distribution for non-trivial topologies

Caltech JPL AT&T

Spiropulu, PI

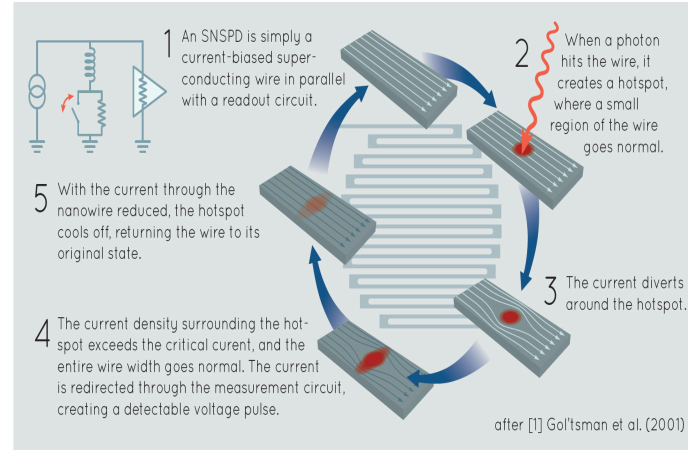




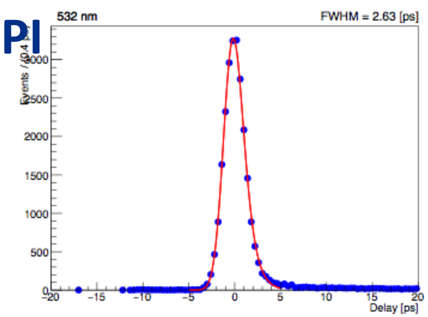


R&D driven by quantum communications

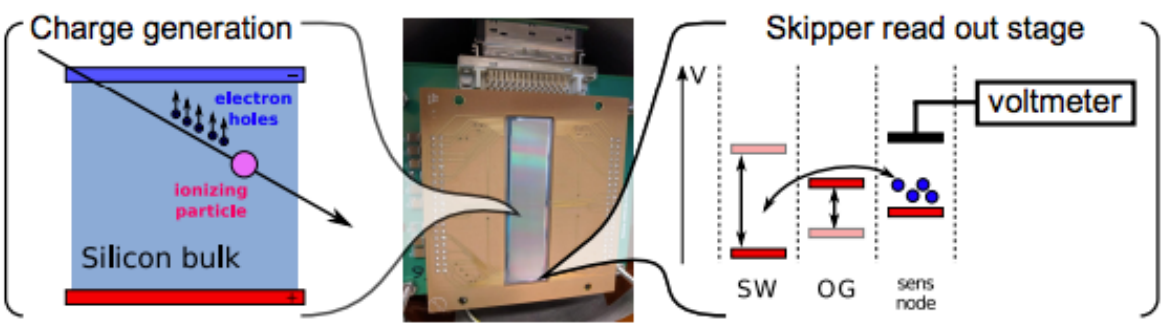
- Develop **cryogenic electronics** to reduce electronic noise and improve time resolution for SNSPDs
  - Fermilab, JPL, Georgia Tech
- **Dark matter detection**: use high intensity entangled pair source to produce photon—dark-photon pairs, and “image” them with Skipper CCDs

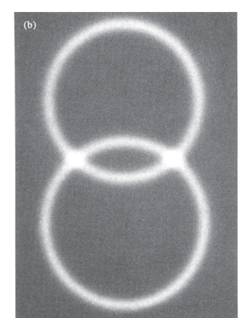


Braga, PI



Estrada, PI





Fermilab, LBNL, Caltech partnership

HEP quantum computing applications

Long view:

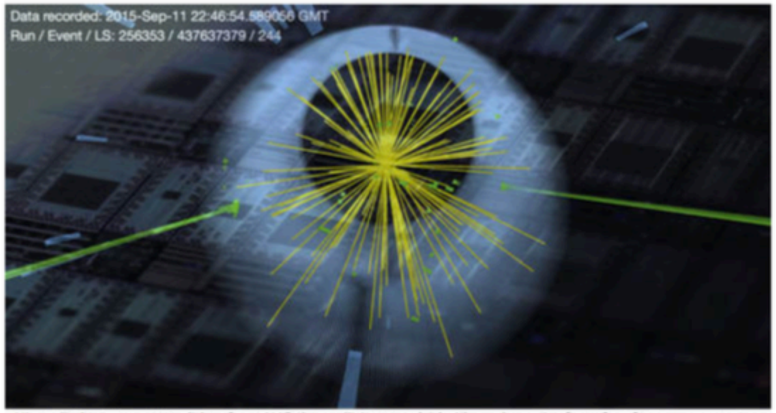
- Most HEP applications will require thousands, if not millions, of error-corrected qubits, which won't be available for ~20 years
- However HEP is planning experiments that will be running 20 years from now, e.g. the DUNE neutrino experiment, the LHC experiments, …

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!
- Extra credit: specific algorithms relevant to specific applications in ~5 years

Solving a Higgs optimization problem with quantum annealing for machine learning

October 18 2017 | Nature Paper Summary



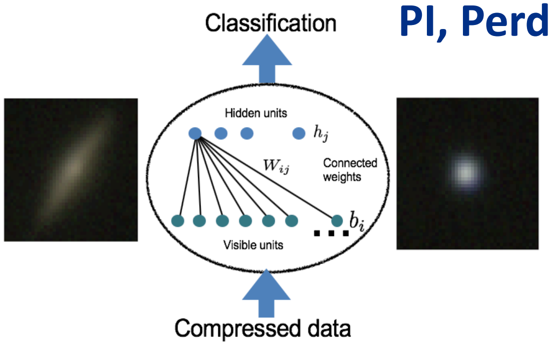
Higgs di-photon event candidate from LHC data collisions overlaid with a schematic of a wafer of quantum processors

HEP quantum computing applications

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

- star/galaxy separation, anomaly detection, autoencoders (for compression or simulation).

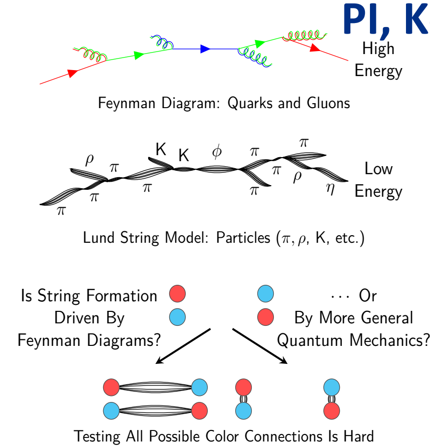
PI, Perdue



Partnering with ORNL on **optimization** problems for Large Hadron Collider **(LHC) physics**

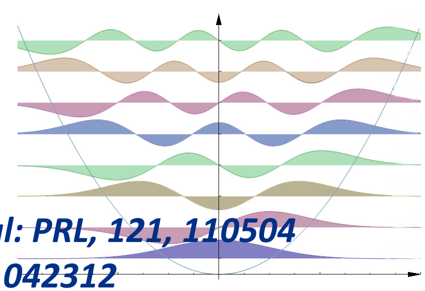
- Estimate hadronization model systematics
  - Formulate as a binary constraint satisfaction problem

PI, Kowalkoski



Partnership with Caltech and University of Washington for **Quantum Field Theory Simulation**

- Seek efficient and accurate **field digitization** and **Hilbert space representations** for near term quantum computers
  - First results, achieve exponential precision for digitization of boson fields



Macridin et al: PRL, 121, 110504 and PRA, 98, 042312

Summary

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