FQI program status

Panagiotis Spentzouris
Fermilab PAC
18 January 2023

Overview

The Fermilab Quantum Institute (**FQI**) **hosts** or **manages** all QIS&T activities except SQMS and provides **support** to all (leveraging resources across lab organizations)

QIS&T @Fermilab started in 2016 (LDRD, HEP pilot projects) and got established with the HEP QuantISED program. Success of these activities supported successful NQI center bids (SQMS –lead, QSC major part) and attracting non-HEP projects.

2016
First engagement (dark matter, algorithms, networking/foundational physics, srf tech, ...)

2017
SRF LDRD; HEP QIS first pilot
Google engagement: procurement co-design proposal

2018
LDRDs: FQNET and "Establish Quantum Center"
Lockheed and Caltech CRADAs; **IBM** agreement
CQE founding member

2018 late
QuantISED-I; MAGIS
Proto-FQI (in directorate)

2019
ASCR funds IEQNET
FQI formal org

2020
NQI centers
Quantum Internet Blueprint
Engage MIT/LL optical atomic clocks (cryoelectronics)
QuantISED-II

2021
ASCR funds IEQNET+ (1 year) towards testbeds

2022
Second successful HEP/QIS experiment (GQuEST)

The FQI program includes the HEP **QuantISED consortia** (sensors for dark matter, theory and algorithms) and **experiment pathfinders** (MAGIS-100 –dark matter, gravitational waves); **quantum network** R&D (capabilities developed under QuantISED – now ASCR funded); the **FNAL/QSC** activities (sensors & electronics; competencies developed under QuantISED –Aaron's talk); and microelectronics for QIS (Farah's talk)

Overview

- **Program motivation:** advance HEP science through QIS&T (ever increasing precision needs drive the need for innovative techniques and technologies), while leveraging Fermilab's S&T competencies and infrastructure to advance QIS&T.
- **Goal:** Produce high impact quantum science results in the near term, while building capacity for HEP discovery in the long term.
- **Approach:** Build/leverage strategic partnerships and collaborations with experts to advance our know-how and build a HEP QIS& community
- **Next steps: QuantISED** and **quantum network** projects end FY24Q1. Defining focus/goals for next phase of our program, preparing for (expected in FY23) HEP & (early summer CY23) ASCR **BRN** workshops**,** and for anticipated next major project in quantum networks **(CHIPS and Science Act** authorizes $100M/year for R&D and infrastructure deployment)

Current FQI Thrusts

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

Quantum Sensors: adapt quantum technologies to enable new fundamental physics experiments, with focus on dark matter detection

- Qubit-cavity systems, cold atom interferometry

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

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

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

Quantum Computing in FQI

Focus on **exploring use cases, establishing expertise, and forming partnerships.**

- **Quantum simulation for field theory:** Foundational work on digital quantum simulation of bosons, fermion-boson interactions — *PRL 121, 110504; PRA 98.042312 and 105.052405*
- **Quantum computing for data analysis:** Quantum annealing for galaxy morphology classification with Lockheed Martin — *https://arxiv.org/abs/1911.06259*
- **Quantum computing for data analysis:** Machine learning classifiers applied to high dimensional science data with Google, Sandbox@Alphabet, University of Waterloo — *Nature (npj) Quantum Information 7, 161 (2021)*
- **Theory inputs for DUNE:** Quantum simulation for neutrino scattering — first comprehensive resource estimate with U. of Washington (-> U. Trento), Los Alamos — *PRD 101, 074038 (2020)*
- **Advance QIS to enable HEP applications:** Qubit assignment problem (quantum computers for quantum program compilation) on Google hardware, with U. of Waterloo — *under review at PRX, https://arxiv.org/abs/2201.00445*
- **Quantum simulation for field theory:** Large scale simulation of Z2 gauge theory with Google, Sandbox@Alphabet, U. of Waterloo — *Supercomputing 2021, https://arxiv.org/abs/2110.07482*
- **Quantum simulation for hadronization:** classically simulated integration of a hadronization model, based on a two-leg ladder configuration of neutral Rydberg atoms, with PYTHIA arXiv:2212.02476

npj Quantum Information 7, 161 (2021)

https://arxiv.org/abs/2101.09581

FERMILAB-PUB-20-624-QIS

Machine learning of high dimensional data on a noisy quantum processor

Evan Peters,[1,2,3,*] João Caldeira,[3] Alan Ho,[4] Stefan Leichenauer,[5] Masoud Mohseni,[4]
Hartmut Neven,[4] Panagiotis Spentzouris,[3] Doug Strain,[4] and Gabriel N. Perdue[3]
Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada
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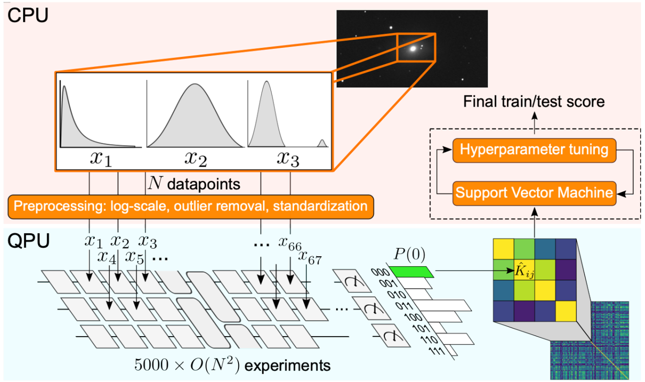
[5]*Sandbox@Alphabet, Mountain View, CA 94043, United States*

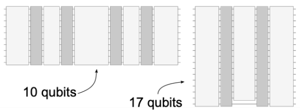
- Binary classification: Type II vs Type Ia supernovae (balanced 50/50 in this dataset).
- Dataset is time series values in different astronomical observational bands.
- These are Fourier transformed, and paired with distribution statistics (mean, skew, etc.) - 67 floating point numbers with some renormalization.
- **Same starting point as a science analysis -** ***no preprocessing for dimensionality reduction.***
- **(Hybrid) Quantum kernel method - compute a kernel on the QPU and fit a Support Vector Machine on a classical computer.**



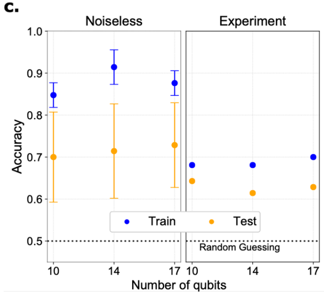
a.

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

b.



c.



DOE: Quantum Information Science Enabled Discovery (QuantISED)

- **Key funding support driving pioneering investigations of quantum information in High Energy Physics**

Fermilab

Google

Sandbox @Alphabet

Results for 10, 14, 17 qubit circuits.

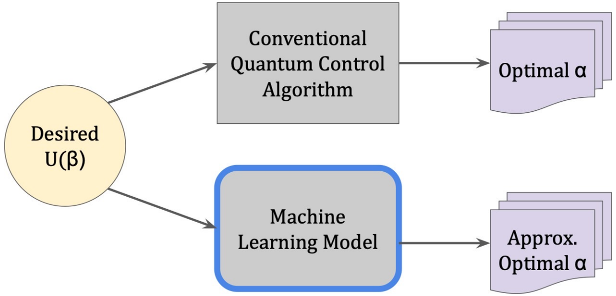
Noise mitigation techniques extended in https://arxiv.org/abs/2105.08161

- Final classifier accuracy not driven by the number of qubits.
- **Main advantage of higher qubit count (and increased depth) - encode data of higher dimension.**
- Kernel classifier method shows **intriguing intrinsic robustness against noise** - even in cases where circuit fidelity was low we were able to achieve interesting classification accuracies.
- Competitive with noiseless simulation and classical benchmarks.

Experiment conducted as part of the Google Quantum AI Early Access Partners program - one of the very first applications from outside Google to run on their quantum advantage platform.

Practical quantum AI/ML

- With current hardware, best applications of "QML" are classical AI/ML for **quantum control** and for running **quantum algorithms on quantum data** (sensors or the outputs of a quantum computer).
- E.g., ML algorithm trained to produce a qubit rotation gate running on FPGA – investigating possible solutions to low-latency, automated quantum error correction.
- Other activity areas:
  - Classical AI for de-noising theory calculations.
  - Classical AI for predicting circuit fidelity (important for the very deep circuits required in HEP).
  - Quantum AI to enhance distributed, entangled quantum sensor data analysis - the ultimate application for HEP discovery



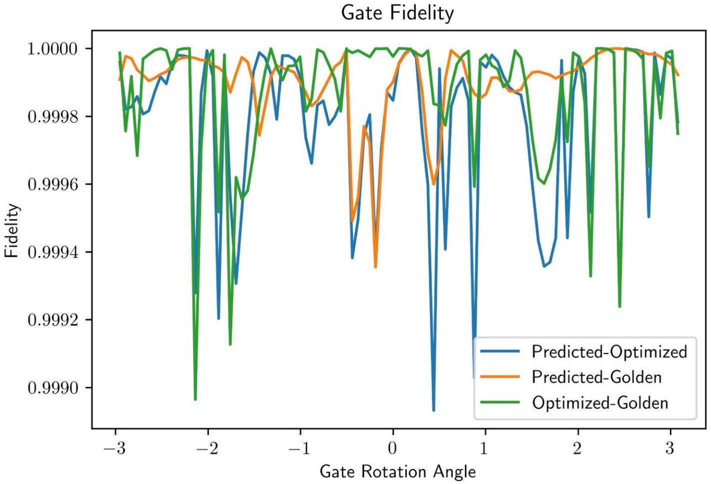
Desired U(β)

Conventional Quantum Control Algorithm

Optimal α

Machine Learning Model

Approx. Optimal α



Predicted - ML model output

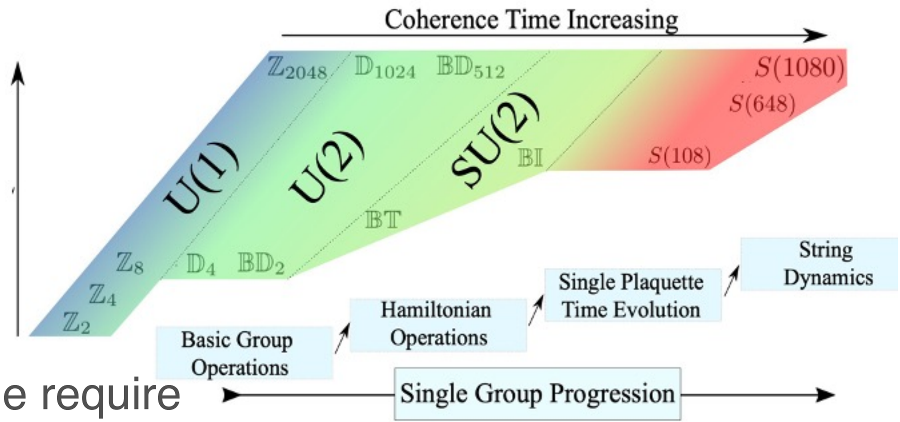
Optimized - from simulation optimizer

Golden - mathematically derived

https://arxiv.org/abs/2208.02645

Simulating Z2 gauge theory

- Aim to understand potential for “scientific advantage.”
- Studied **Z2 gauge theory on a simulated Google Sycamore QPU** with a large noise scan - one of the largest NOISY quantum circuit simulations ever performed



- Observables of interest for quantum advantage require resources at the edge of what we can simulate exactly with exascale computing.

Goal is to better understand the interplay between inexact simulation and theory errors

- Noise errors became comparable to physics theory errors for roughly x10-100 better qubit noise parameters, as compared to today’s state of the art.
- Collaboration with scientists at Google and Sandbox@Alphabet

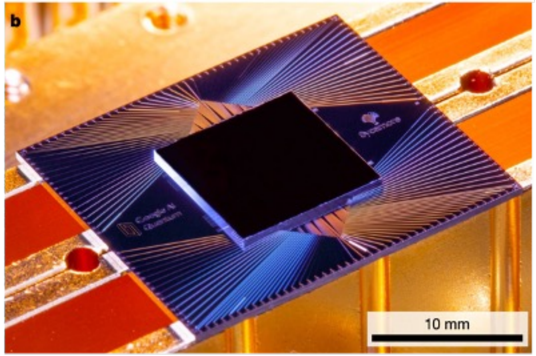


Fig. 1 | The Sycamore processor. a, Layout of processor, showing a rectangular array of 54 qubits (grey), each connected to its four nearest neighbours with couplers (blue). The inoperable qubit is outlined. **b,** Photograph of the Sycamore chip.

FQI Quantum Algorithms, next 5-year goals

- Advance capabilities for quantum simulation of field theories, with data analysis for quantum sensors (possibly distributed & entangled) a new focus area
- Analogous to the early days of lattice computing, aim to engage in a co-design process to define the QC requirements for HEP physics and find and explore the “boundaries” of quantum advantage with current (and near future) hardware
- Explore the interplay between algorithm development for quantum sensing and computation (similar devices, different operational conditions/constraints)

These goals leverage Fermilab’s competencies in quantum field theory, quantum algorithms, and quantum sensing and networking, and support our science objectives for new physics searches.

QuantISED Consortium: Quantum Sensing for Dark Matter:

Engage neighboring fields to adapt quantum technology to HEP science targets


Aaron Chou (Lead PI, FNAL)


Dave Schuster (Stanford)


Konrad Lehnert (Colorado)


Reina Maruyama (Yale)


Pierre Echternach (JPL)


Robert McDermott (Wisconsin)


Rakshya Khatiwada (IIT/FNAL)


Karl Berggren (MIT)


Sae Woo Nam (NIST)


Juan Estrada (FNAL)

Bold = PD alumni, now faculty


Danielle Speller (JHU)


Akash Dixit (GS → NIST)


Ankur Agrawal (GS → AWS)


Fang Zhao (FNAL)


Morgan Lynn (Chicago)


Yue Jiang (Colorado)


Liz Ruddy (Colorado)


Sumita Ghosh (Yale)


Dave Harrison (Wisconsin)

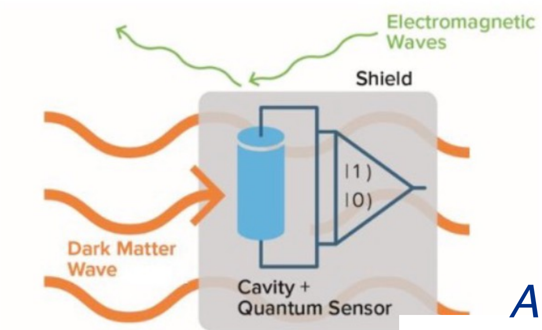

Jialin Yu (IIT)


Tony Zhou (MIT)


Stewart Kopell (MIT)

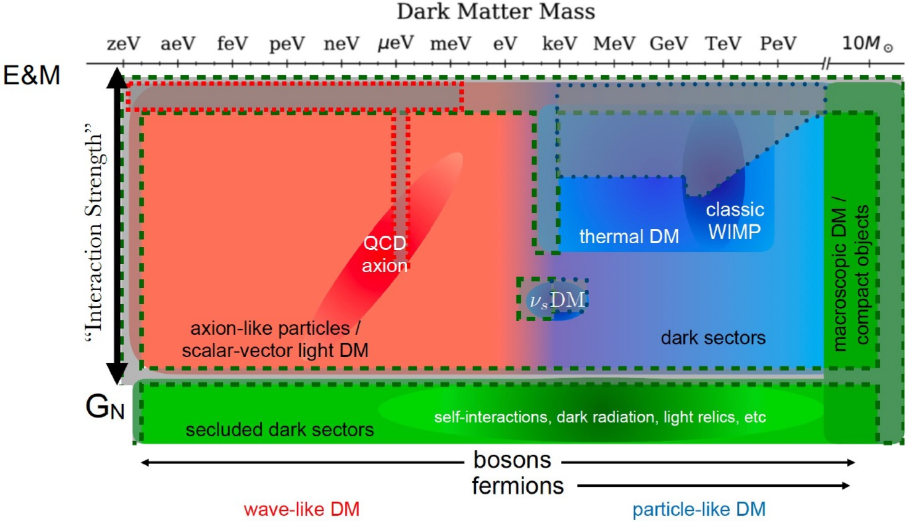
Motivation: improve sensitivity for DM searches

DOE-OHEP
Basic Research Needs
white paper, 2018



Develop experimental techniques using single-photon counting quantum devices to evade quantum back-action noise of conventional techniques

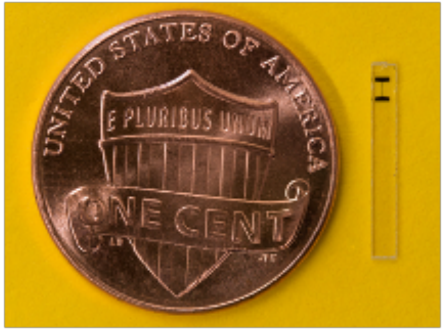
APS-DPF Snowmass Study, July 2022



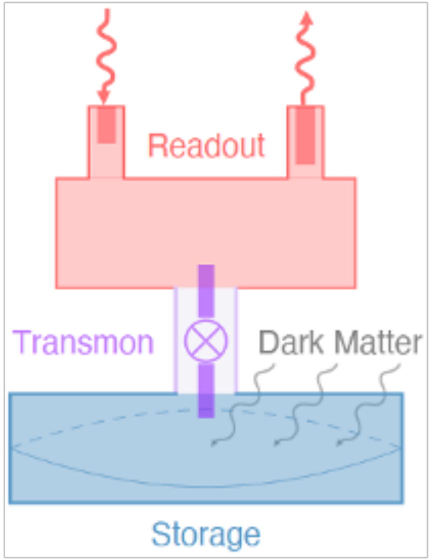
A winning strategy: utilization of diverse variety of experimental techniques necessary to cover every decade of possible dark matter mass.

Detecting Dark Matter with a Superconducting Qubit

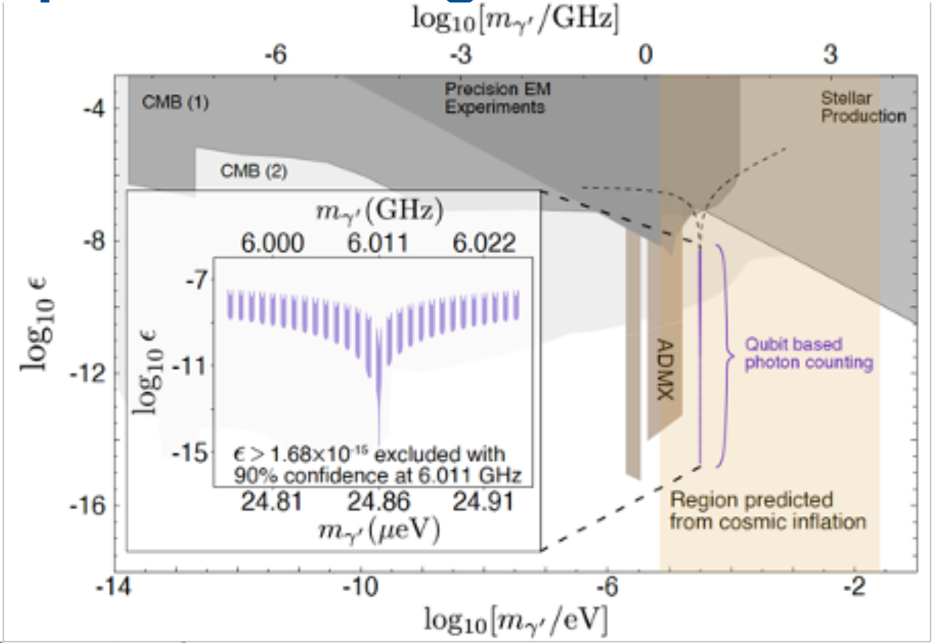
Transmon qubit = artificial atom with large antennae to efficiently couple to signal photons captured in microwave cavities



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



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



Results:

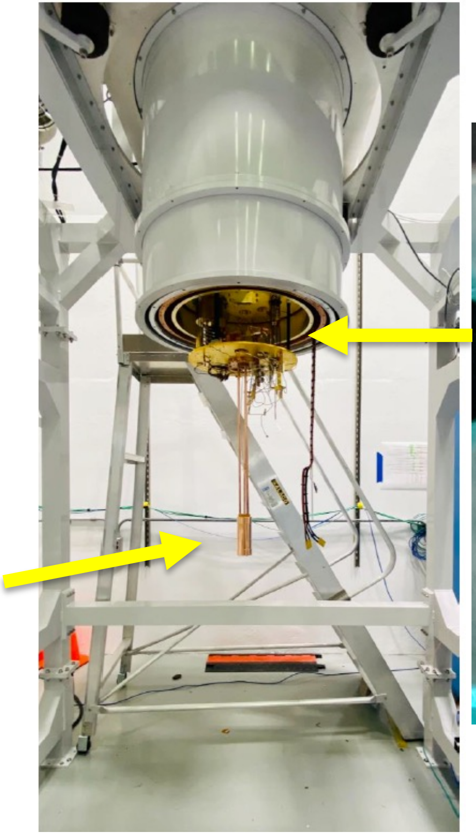
- World record quantum sensor noise suppression - **15.7 dB below standard quantum limit**
- World-leading dark photon sensitivity
- 1300x speed-up of future dark matter experiments

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

QuantISED axion dark matter search:

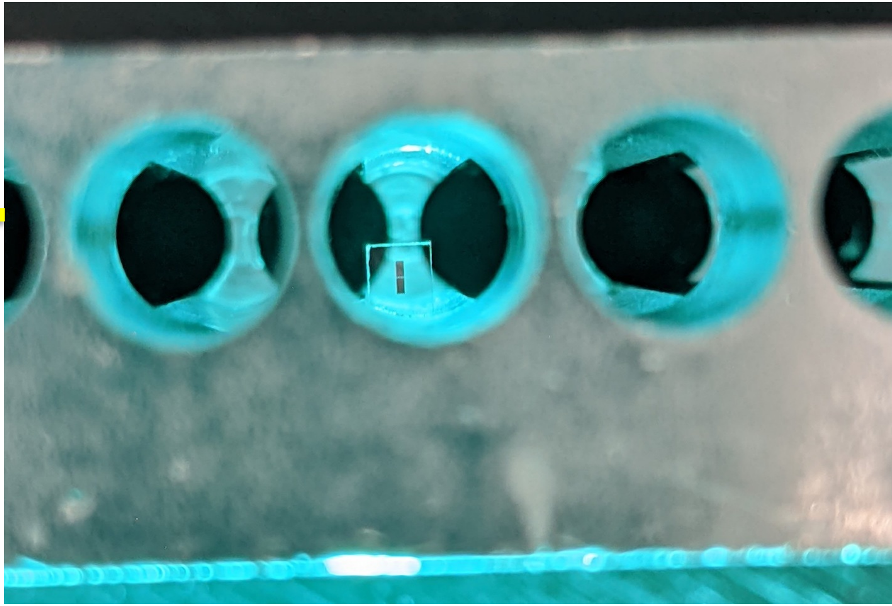
Nested sapphire cavity compatible with high B field needed for axion search:
$Q > 10^6$,
¼-wave layers reflect photon waves back to center

(based on design from INFN)



Installed in 10 mK dilution refrigerator and 14T solenoid magnet at SiDet Lab B.

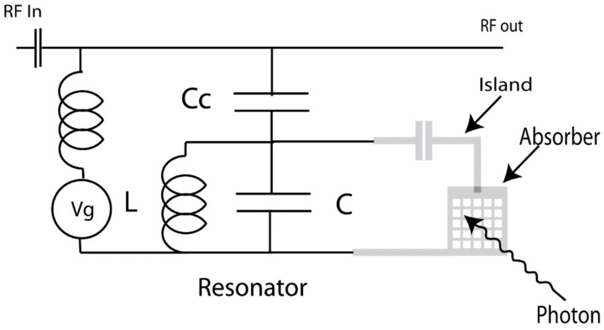
Quantum readout electronics in remote, magnetically-shielded region



Transmon qubit performs quantum non-demolition single photon counting with noise 40x lower than zero-point noise.

To do: cavity tuning, signal photon transport. Targeting FY24 operations.

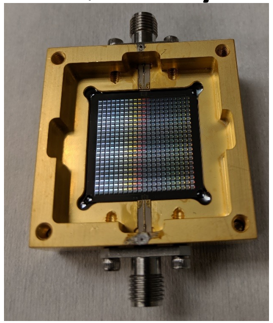
Quantum Capacitance Detector (QCD) for Dark Matter



- Based on cooper pair box (charge qubit)
- Used in Far infrared spectroscopic missions (space telescope) Caltech/JPL
- Photon => superconducting absorber => broken cooper pairs => tunnel into a small capacitive island => causes non equilibrium quasiparticle population to increase
- **NEP < 10^{-20} W/Sqrt Hz at 1.5 THz** – most sensitive far IR detector!
- Applications for > 100 GHz (Aluminum cooper pair breaking energy/bandgap)

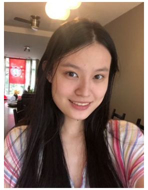
https://doi.org/10.1117/1.JATIS.7.1.011003

QCD array



Fabrication Andrew Beyer

QCD mounted in FNAL QuantiSED fridge

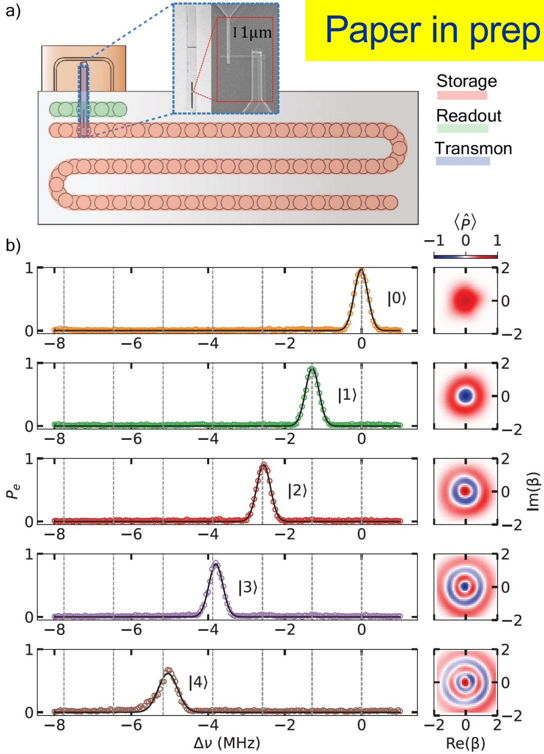


Jialin Yu
IIT PhD student

- Currently, IIT/FNAL integrating QCD with a Josephson Junction based weak photon source (fab by U Wisconsin) to characterize a 25-qubit array for dark matter detector development
- Currently, IIT/FNAL developing capability to readout multiple detectors with a Zurich UHF Arbitrary Waveform Generator and Radio Frequency System on Chip (RFSoC) platform
- Plans to:

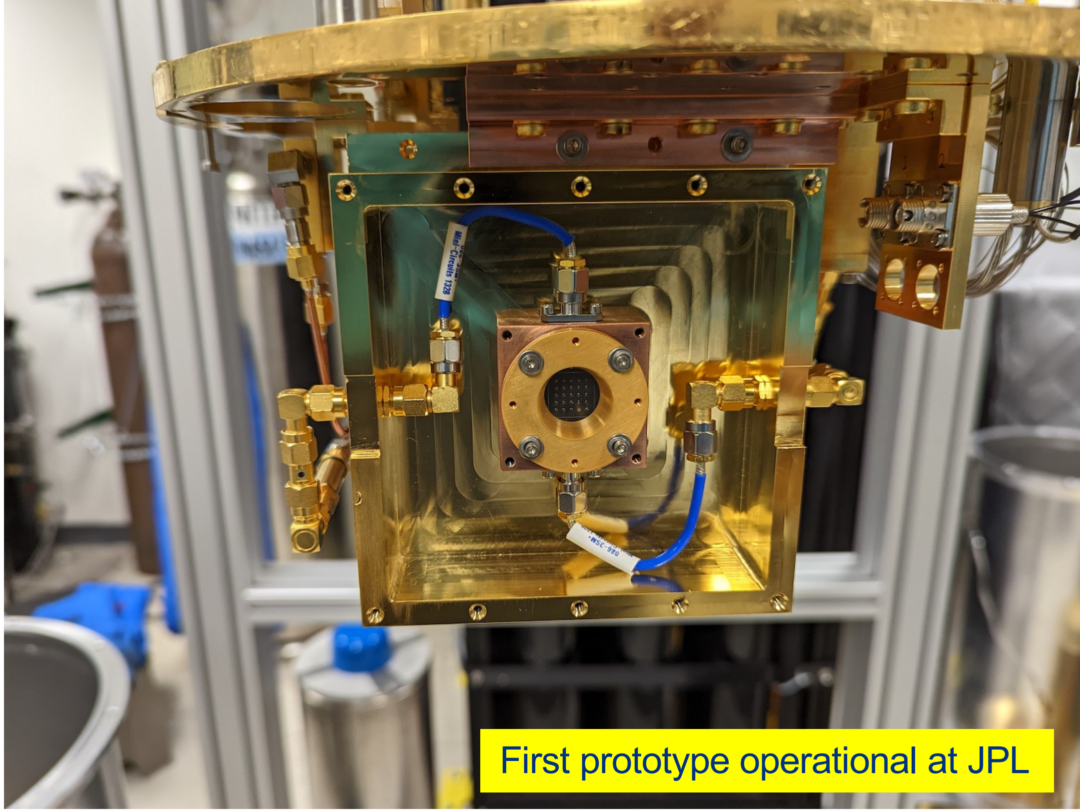
→ demonstrate single photon detection sensitivity
→ Implement techniques to reduce dark count rate

Qubit Stark shifts for Fock states



Paper in prep.

Measured Wigner functions



First prototype operational at JPL

SQuAD experiment: Prepare cavity mode in Fock state to stimulate the emission of signal photons from classical dark matter waves.

LADERA experiment: Use Cooper pair-breaking qubit-based detectors to search for THz dark radiation generated by dynamical friction on the rolling dark energy field (FNAL, JPL)

FQI quantum sensors: next 5 years (and beyond) goals

- Quantum sensing for HEP science a major focus of FQI
- Deliver successful experiment demonstrators; provide the technology and leadership to establish science collaborations to bid for projects that will transition the concepts to science operations
- Continue to explore quantum sensing technologies to generate experiment demonstrators

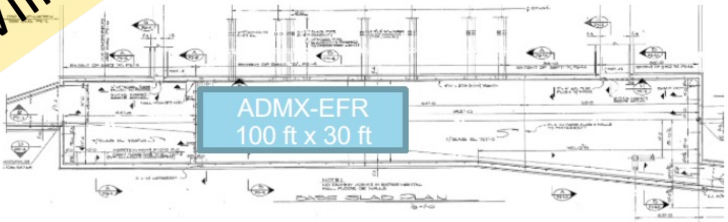
  Leveraging infrastructure from all FQI projects, aspire to develop capabilities that can support a “user program” for dark matter technology development

- Provide the quantum technology and competencies to underpin a future “Dark Wave Laboratory” (Andrew's talk)

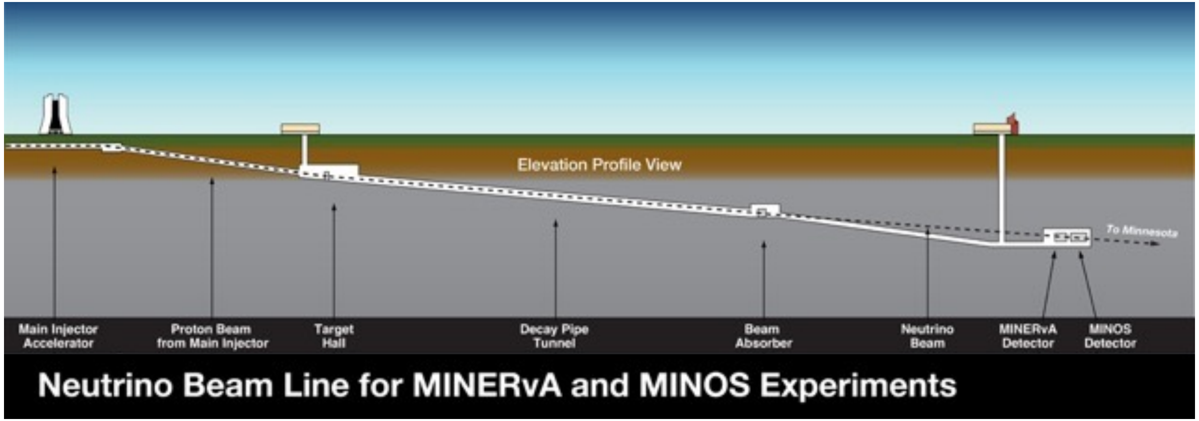
Dark Wave Laboratory

- ***Vision: host several experiments which could support a new dark matter user program over the next decade, with many students/postdocs potentially being stationed at Fermilab***
- Will convert an underused 7000 sq. ft high-bay facility + 6500 sq ft of shop and office space into a dedicated “Dark Wave Quantum Sensor Laboratory” .
  - Good place to run large magnets – will have helium recovery and other cryo infrastructure, magnetic shielding.
  - Initially will install ADMX-EFR in half the space.
  - Renovation of this space has been proposed as General Plant Project (GPP)

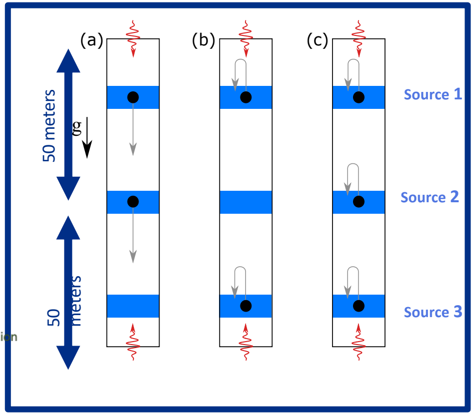
Will be discussed in Andrew’s talk



MAGIS-100 experiment at Fermilab



STANFORD
Fermilab
Northwestern University
UNIVERSITY OF LIVERPOOL
Northern Illinois University
JOHNS HOPKINS UNIVERSITY
SLAC
UNIVERSITY OF OXFORD
UNIVERSITY OF CAMBRIDGE
THE UNIVERSITY OF CHICAGO
GORDON AND BETTY MOORE FOUNDATION
GBMF7945
QuantiSED 2019
UKRI Science and Technology Facilities Council
UK STFC
Kavli Foundation



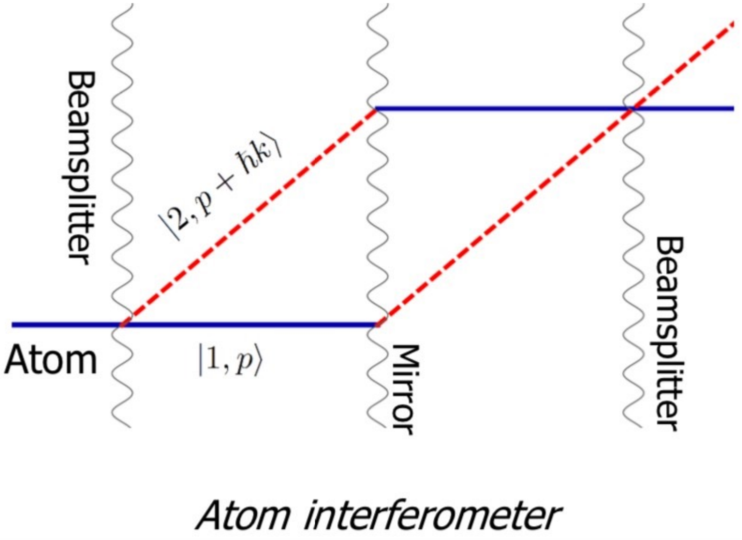
- Major **technological advance** for studying very **low mass dark matter.**

  100 m baseline – order of magnitude better than current state-of-the-art

  Uses ultra-precise Strontium clock transition.

- **Pathfinder** for longer baselines, sensitive to **~1 Hz gravitational waves.**

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

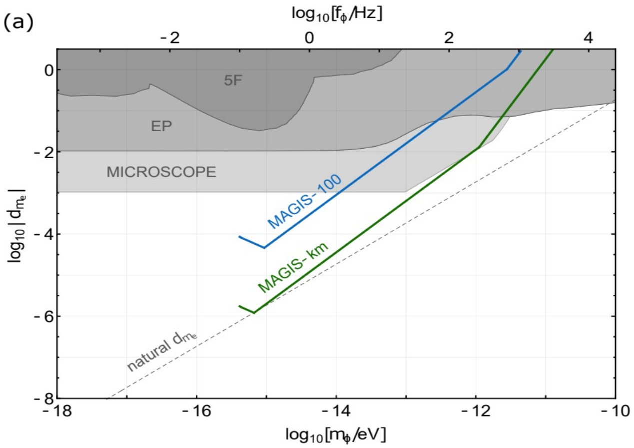


Atom interferometer

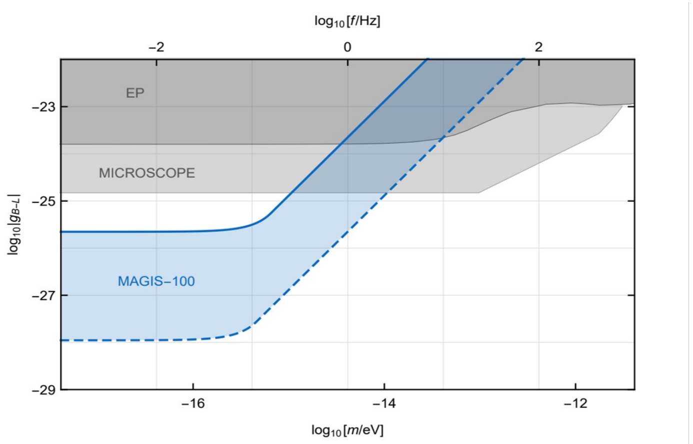
- Cold atoms in free fall
- Use lasers to split and recombine the wavefunction of single atoms
- Compare differential acceleration
- Sensitivity scales like the space-time area
  - ➢ Goal is 10^{-13} g/Hz$^{1/2}$
- Advancing R&D for entangled atom sources

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

Diverse MAGIS-100 Science Program



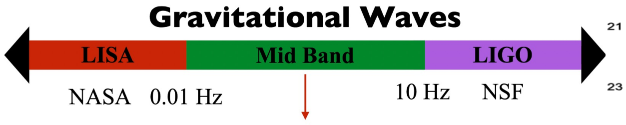
Ultralight Dark Matter Sensitivity – Electron Coupling



Expected MAGIS-100 B-L dark matter sensitivity

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

Gravitational Wave sensitivity in 1 Hz range

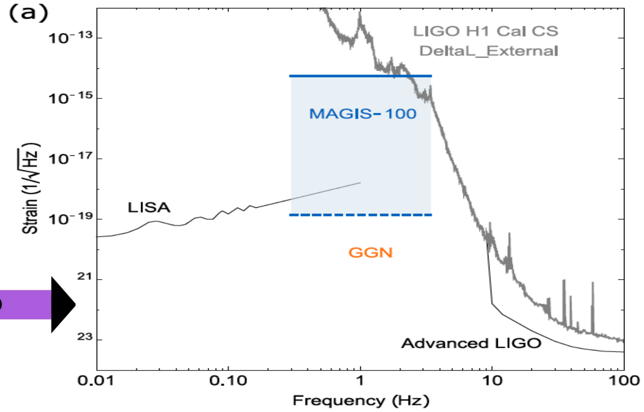


Gravitational Waves

LISA | Mid Band | LIGO

NASA 0.01 Hz | 10 Hz NSF

MAGIS-100

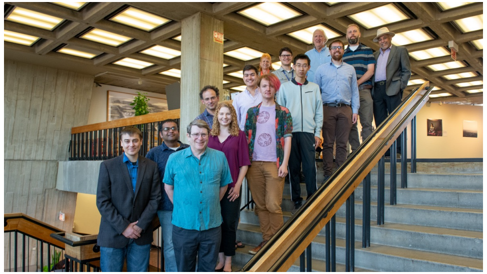


QUANTUM SCIENCE

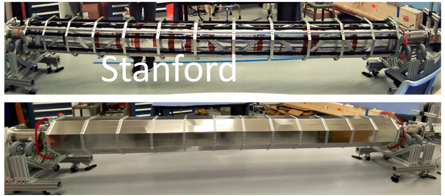
- Atom wave packets in superposition separated by ~10 m
- Durations up to 9 seconds
- Entanglement to reduce noise
- Sequential transitions for Large Momentum Transfer

MAGIS-100 project

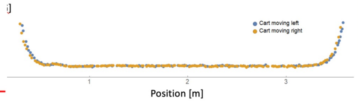
- Final stretch for baselining the project (aim April ‘23)
- Excellent progress on system/integration engineering
- Noise mitigation strategies and systems under development (e.g., laser wavefront errors, Earth rotation and gravity gradients, etc.)
- Building components, installation planning in progress

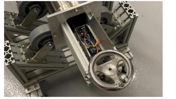


Assembled prototype MAGIS module with horizontal bias coils and magnetic shield



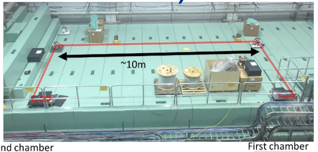
After degauss, magnetic shield meets specifications:

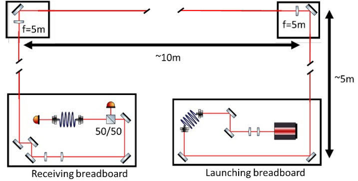


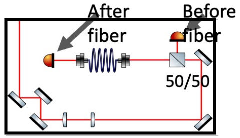


Magnetometer shuttle on suspension wires

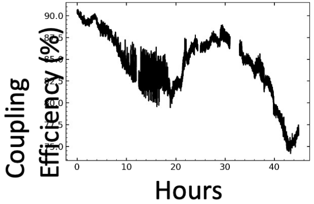
NU, FNAL





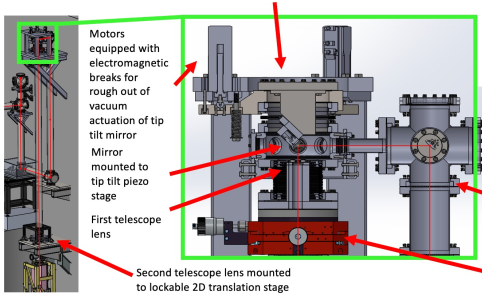


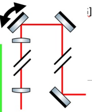
Receiving breadboard



NU, Liverpool, FNAL

Telescope Region





Advanced design, early machining and parts procurement, extensive vacuum tests of materials

Quantum Systems

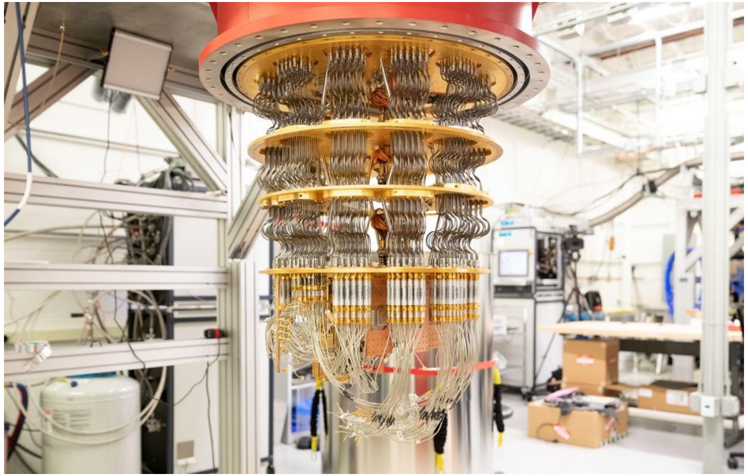
Classical input (controls) →

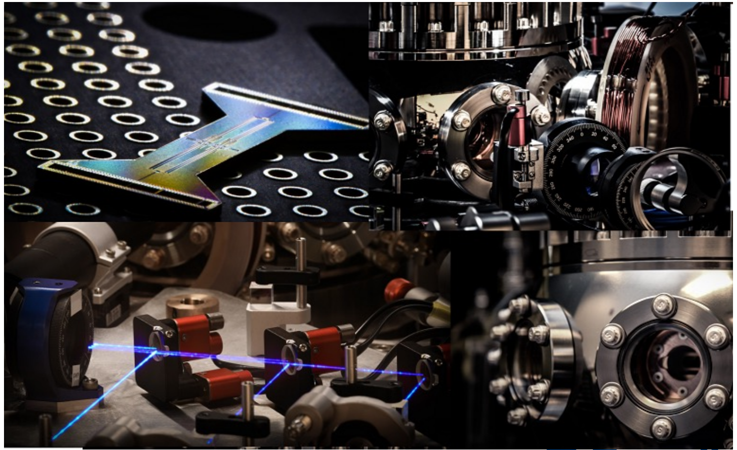
FNAL competency

→ Classical output (measurements)

FNAL competency

Quantum System (qubits, gates)





Challenges:

Controllability, coherence, scalability

Open-source Quantum Instrumentation Control Kit (QICK)

- Utilize major Fermilab competency in FPGA controls & readout electronics
- Started as a pilot QuantISED project, transitioned to become a major component of the Fermilab QSC program (facilitated by early success of the project)
- QICK's success and utilization goes beyond the QSC program → investigating options for establishing a QICK "consortium"

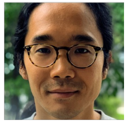
Neal Wilcer (FNAL)

Ken Treptow (FNAL)

Leo Stefanazzi (FNAL)

Shefali Saxena (QuantiSED at ANL)

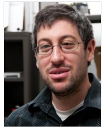
Sho Uemura(FNAL)



Sara Sussman (U. Princeton)

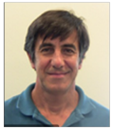
Chris Stoughton (FNAL)

David Schuster (U.Chicago)



Martin Di Federico (FNAL)

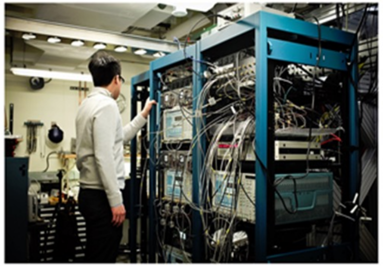
Gustavo Cancelo(FNAL)



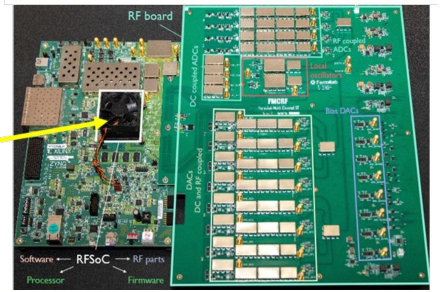
The goal for QICK was to improve cost and increase scalability and performance vs commercial systems; **the project delivered**

Review of Scientific Instruments **93**, 044709 (2022); https://doi.org/10.1063/5.0076249

Replaces ~$1M, full rack, off-the-shelf → **with $20K, single pair of boards**

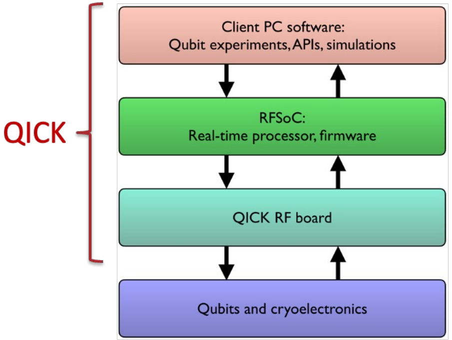


RFSoc FPGA



Broad user base

Jan 12th, 2023, QICK workshop @Fermilab: over 135 participants from over 30 universities, 10 companies



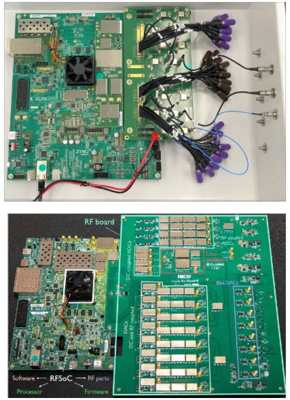
QICK

Client PC software:
Qubit experiments, APIs, simulations

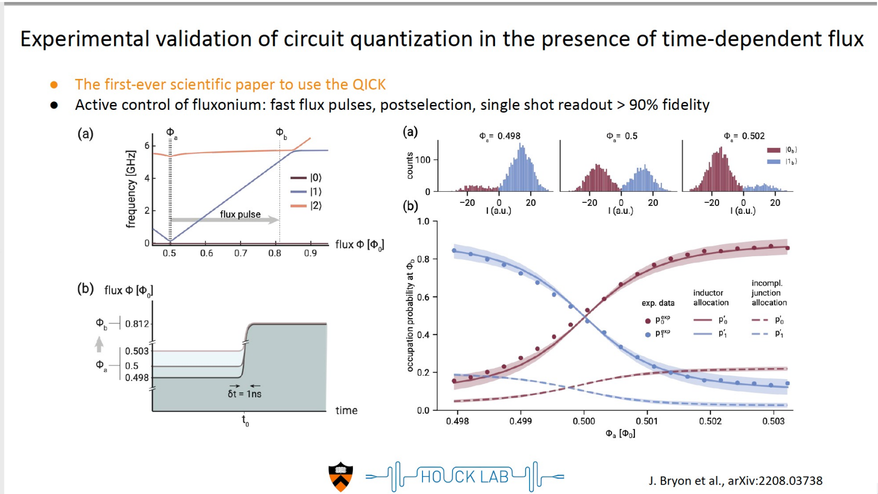
RFSoC:
Real-time processor, firmware

QICK RF board

Qubits and cryoelectronics



Complete system



Experimental validation of circuit quantization in the presence of time-dependent flux

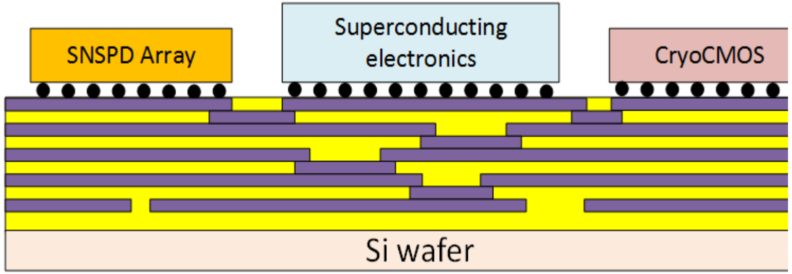
- The first-ever scientific paper to use the QICK
- Active control of fluxonium: fast flux pulses, postselection, single shot readout > 90% fidelity

J. Bryon et al., arXiv:2208.03738

Cryogenic electronics: major FNAL competency

Objectives:

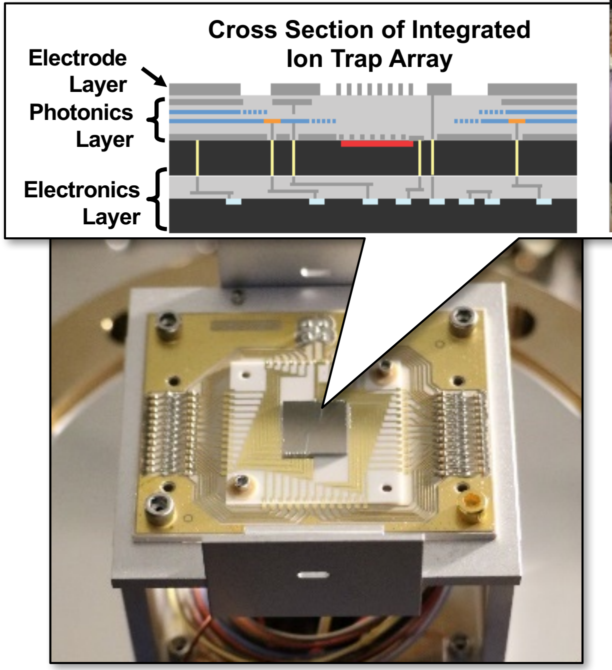
- Scalability of control electronics
  - On-chip, integration
- Scalability of the system
  - From ~100 to 1M qubits
- Performance (gate timing, …)

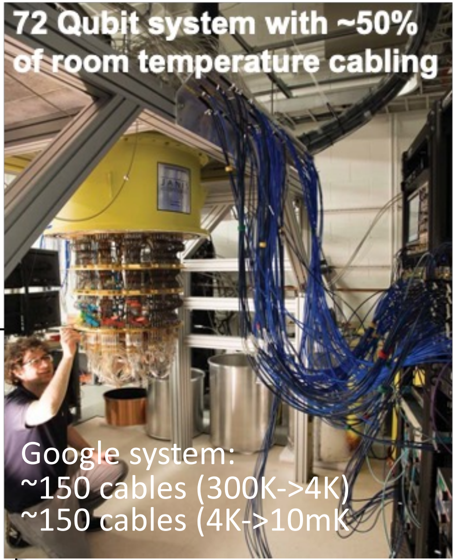


Super Conducting Multi Chip Module carrier

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

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


Cross Section of Integrated Ion Trap Array


72 Qubit system with ~50% of room temperature cabling

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

Quantum ASICs for HEP science –strategic partnerships

QUANTUM COMMUNICATION

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

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

JPL
Jet Propulsion Laboratory
California Institute of Technology

SNSPD: 4M pixel cryogenic readout at 4K

Georgia Tech

photon counting and picosecond timing (detector R&D): (**space science applications, dark matter & sterile neutrino searches**)

QUANTUM SENSING

Portable optical atomic clocks (Joint DOE-DOD development) (QuantISED)

MIT
LINCOLN
LABORATORY

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

cryoCMOS for Quantum

cryoCMOS tool-kit (100mK – 4K) GF 22 FDX (LDRD)
cryoCMOS workshop @ IEEE Quantum week - Oct 2020

EPFL
GLOBALFOUNDRIES

QUANTUM IMAGING

SiSeRo CCD: Novel Devices

MIT
LINCOLN
LABORATORY

Sub-electron noise, MHz – Non-destructive read

Skipper CCD in CMOS

SLAC
Tower Semiconductor

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

QUANTUM COMPUTING

Beyond NISC era scalable QC

Microsoft

Cryoelectronics testbed for 100 – 1000 quantum dots (LDRD)

NQI – Quantum Science Center

Control Cryoelectronics for Ion-Trap based QC

Co-design system for Spin-Liquid simulations

OAK RIDGE
National Laboratory

Quantum networks bring new capabilities and enable new applications

Crypto functions

Quantum Key Distribution
Leader election
Byzantine agreement
…

Low bandwidth

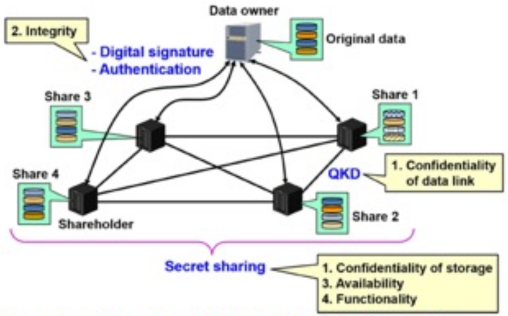


Image from Quantum Sci. Technol. 2 (2017) 020501

Sensing

Distributed clocks
Interferometry
- optical and IR telescope arrays
- Cosmology

…

High bandwidth

Quantum Computing (QC)

Blind QC
Client-server QC
Distributed QC
…

High to very high bandwidth

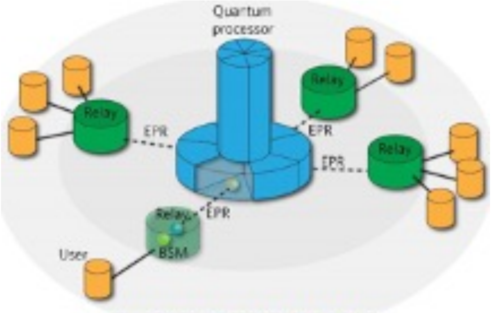


Image from *Nature Photon* **10**, 671–675 (2016).
https://doi.org/10.1038/nphoton.2016.179

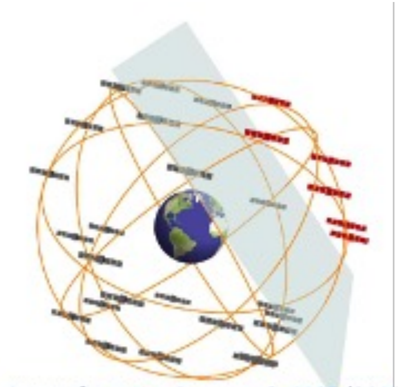


Image from Nat Commun **8**, 1195 (2017).

Foundational physics studies using QIS

Use a Quantum Computer (QC) as an experimental apparatus to probe connections between spacetime and quantum entanglement

Utilize a highly entangled quantum system and implement a protocol to **measure properties consistent with descriptions of a traversable wormhole** (in a very simple model)

Demonstrate for the first-time the potential of quantum-scale experiments that could probe fundamental physics and could be possible as quantum technology evolves.

Future experiments with better QC and with QCs connected through quantum networks, such as those under development at Fermilab, could provide better insight through better resolution and adding non-trivial spatial separation of the two systems

The international journal of science / 1 December 2022

nature

HOLOGRAPHIC WORMHOLE

A step towards investigating quantum gravity using quantum computers

Carbon conundrum
EU climate plan sacrifices biodiversity and carbon storage

Integrated circuit
Global supply chain promises cheaper path to solar energy

The beak that was
Cretaceous bird fossil casts doubt on avian evolutionary tree

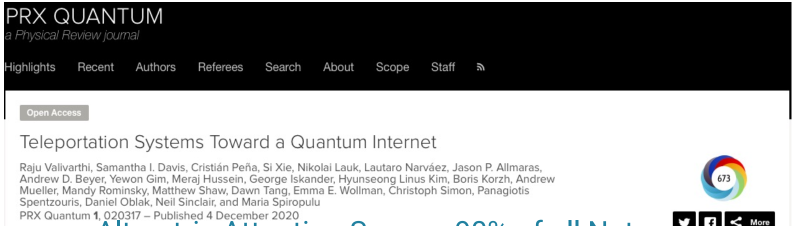
Harvard, Caltech, MIT, Google, and Fermilab

"wormhole teleportation" protocols part of the original motivation for Quantum Network R&D

Fermilab Quantum Network Labs

The FQNET/CQNET collaboration

FQNET@DAB commissioned 2018



PRX QUANTUM

a Physical Review journal

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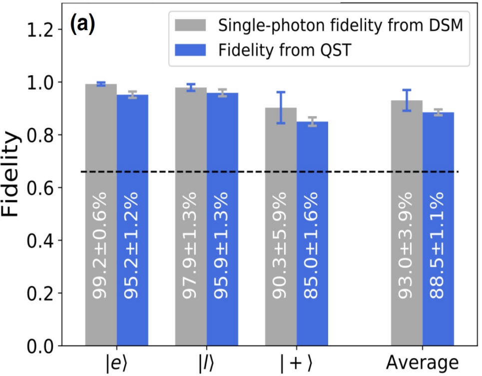
Teleportation Systems Toward a Quantum Internet

Raju Valivarthi, Samantha I. Davis, Cristián Peña, Si Xie, Nikolai Lauk, Lautaro Narváez, Jason P. Allmaras, Andrew D. Beyer, Yewon Gim, Meraj Hussein, George Iskander, Hyunseong Linus Kim, Boris Korzh, Andrew Mueller, Mandy Rominsky, Matthew Shaw, Dawn Tang, Emma E. Wollman, Christoph Simon, Panagiotis Spentzouris, Daniel Oblak, Neil Sinclair, and Maria Spiropulu

PRX Quantum **1**, 020317 – Published 4 December 2020

Altmetric Attention Score > 90% of all Nature Papers, @ 99% percentile of all papers ever scored

CQNET/FQNET 2020

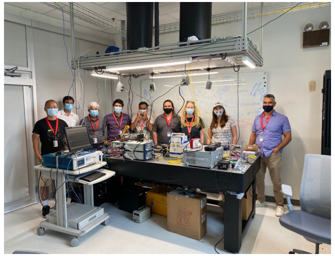


High-fidelity teleportation over 44 km

Sustained 24/7 operation for ~week duration

Sustained teleportation rate of ~1Hz

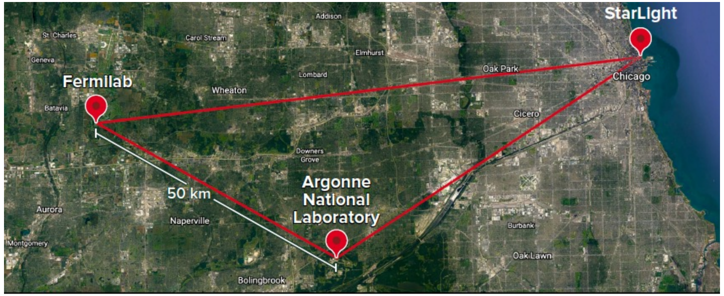
FQNET@FCC commissioned 2020



Quantum Networks: towards a Quantum Internet

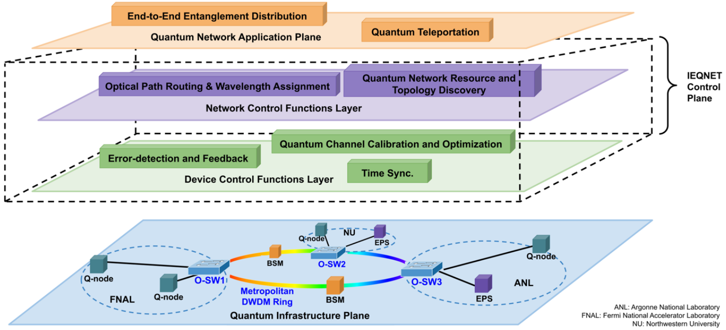
Current focus: deploy a **multi-node, multi-user metropolitan scale quantum network** in the greater Chicago area.

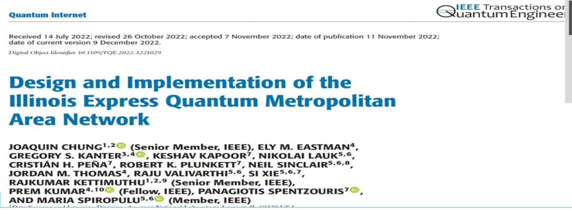
Leveraging Fermilab competencies in precision timing, controls, network architecture, and systems integration



The IEQNET collaboration

Fermilab
Argonne National Laboratory
Caltech
Northwestern University
HYPERLIGHT
NuCrypt





Quantum Internet

IEEE Transactions on Quantum Engineering

Received 14 July 2022; revised 26 October 2022; accepted 7 November 2022; date of publication 11 November 2022; date of current version 9 December 2022.

Digital Object Identifier 10.1109/TQE.2022.3221029

Design and Implementation of the Illinois Express Quantum Metropolitan Area Network

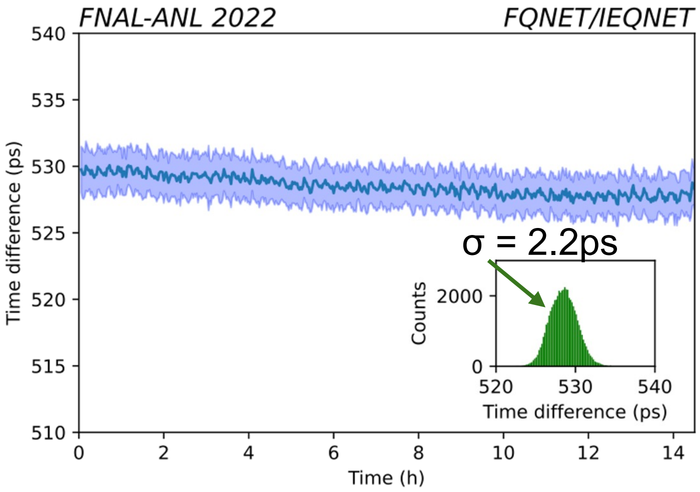
JOAQUIN CHUNG[1,2] (Senior Member, IEEE), ELY M. EASTMAN[4], GREGORY S. KANTER[3,4], KESHAV KAPOOR[7], NIKOLAI LAUK[5,6], CRISTIÁN H. PEÑA[7], ROBERT K. PLUNKETT[7], NEIL SINCLAIR[5,6,8], JORDAN M. THOMAS[4], RAJU VALIVARTHI[5,6], SI XIE[5,6,7], RAJKUMAR KETTIMUTHU[1,2,9] (Senior Member, IEEE), PREM KUMAR[4,10] (Fellow, IEEE), PANAGIOTIS SPENTZOURIS[7], AND MARIA SPIROPULU[5,6] (Member, IEEE)

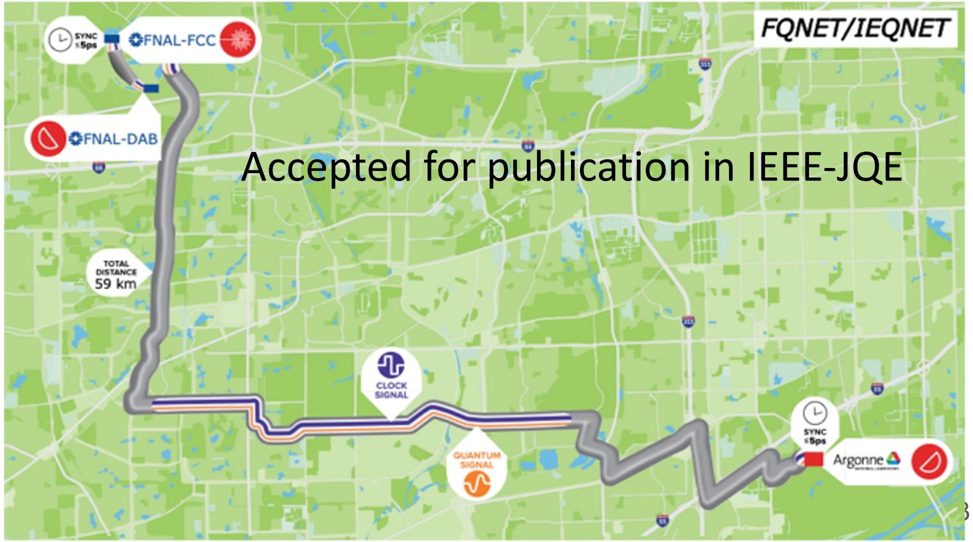
Long-term vision: support security, sensor, and computing applications, following the **DOE Quantum Internet Blueprint**

Entanglement distribution between FNAL and ANL

Synchronization of the photon pair

- Using 2 pairs of 59 km fiber links, classical clock and quantum photon pair signals multiplexed and sent along the same fibers (coexistence)
- Achieved time-jitter of 2.2 ps on link



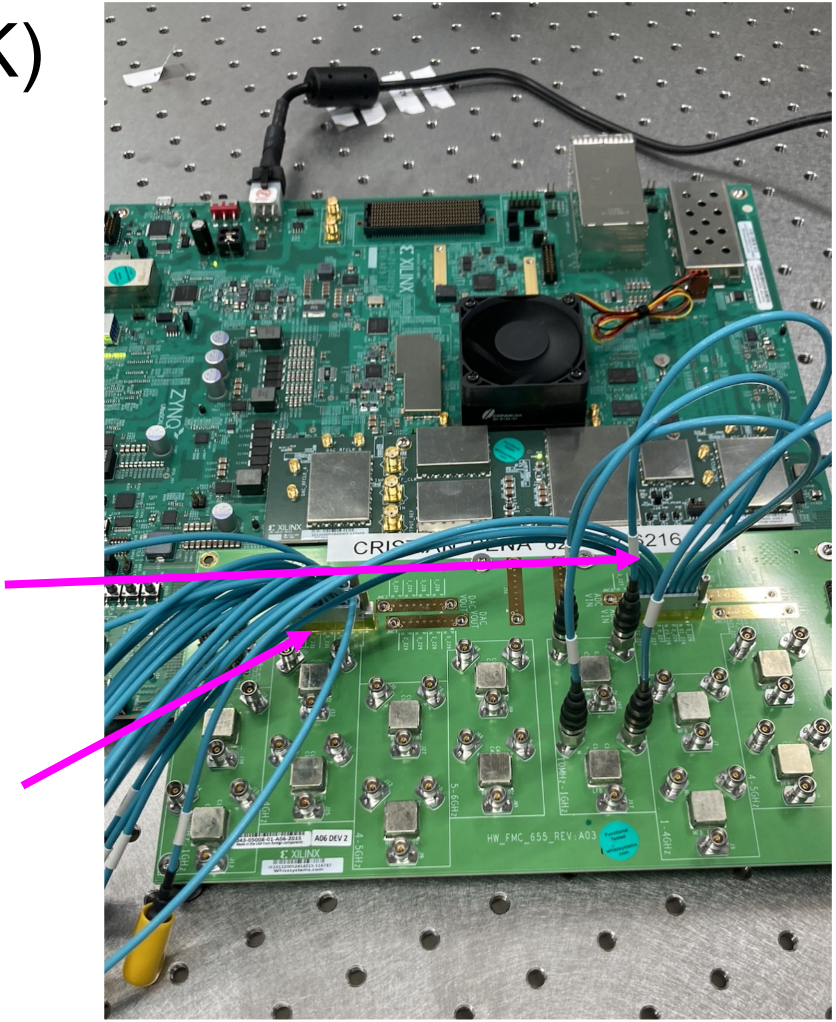


Accepted for publication in IEEE-JQE

RFSoC FPGA Controls (QICK)

- Firmware to simultaneously produce qubits (150ps wide pulses) and read out SNSPD detection signals. Time-bin separation is 2 ns

- Replaces conventional setup of AWG driver + Commercial TDC readout
  - **Reduce cost from ~$200K to ~$15K**

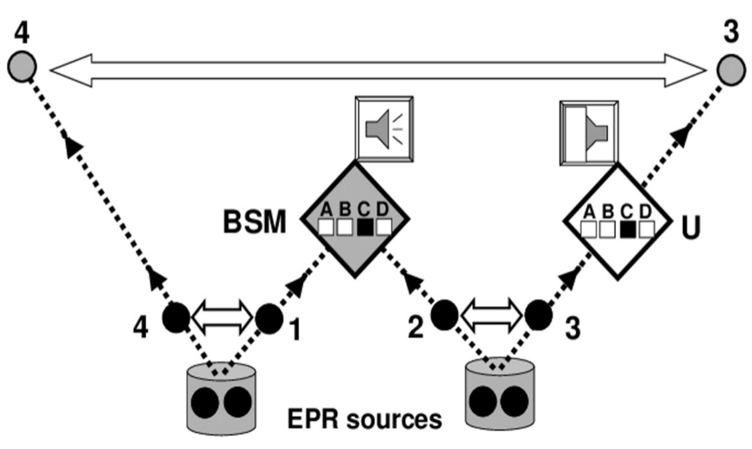


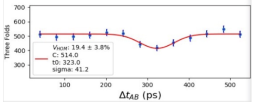
ADC reads out detector signals

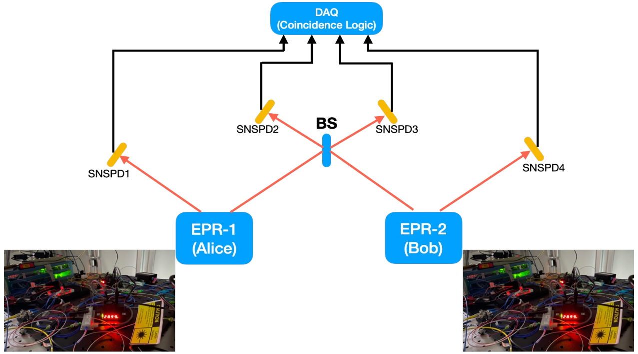
DAC generates pulses

Next step: entanglement swapping

Underpins long-distance quantum communication





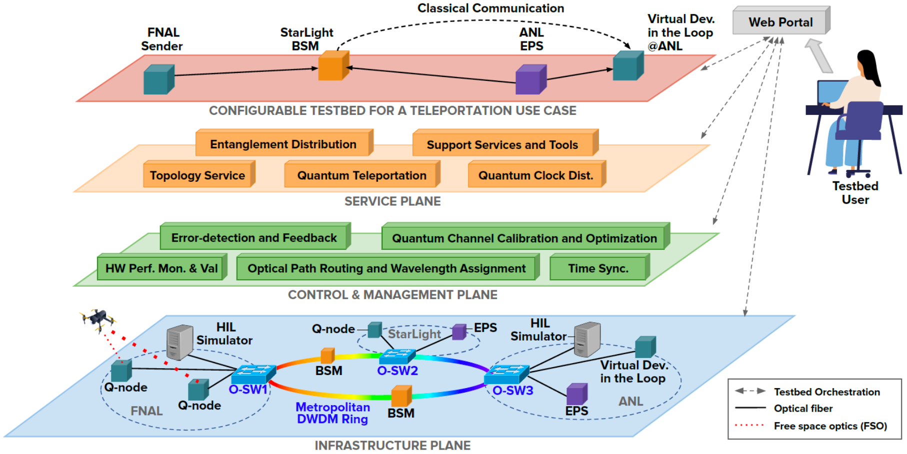


Underway at FQNET@FCC lab, objective is demonstration between the 2 FQNET labs in FY23; ASCR funded, 1 year project to bridge gap to anticipated CHIPS act call.

Quantum Networks: towards a Quantum Internet

Vision is to create a **Midwest quantum network backbone**, to connect quantum devices at the sites; a testbed for cutting edge systems under development at SQMS@Fermilab and Q-NEXT@Argonne. Compete for CHIPS act funding (UIUC joined the collaboration in FY22).

Ongoing work to characterize fiber connections between UIUC and upstream stations and Argonne and Starlight



Summary

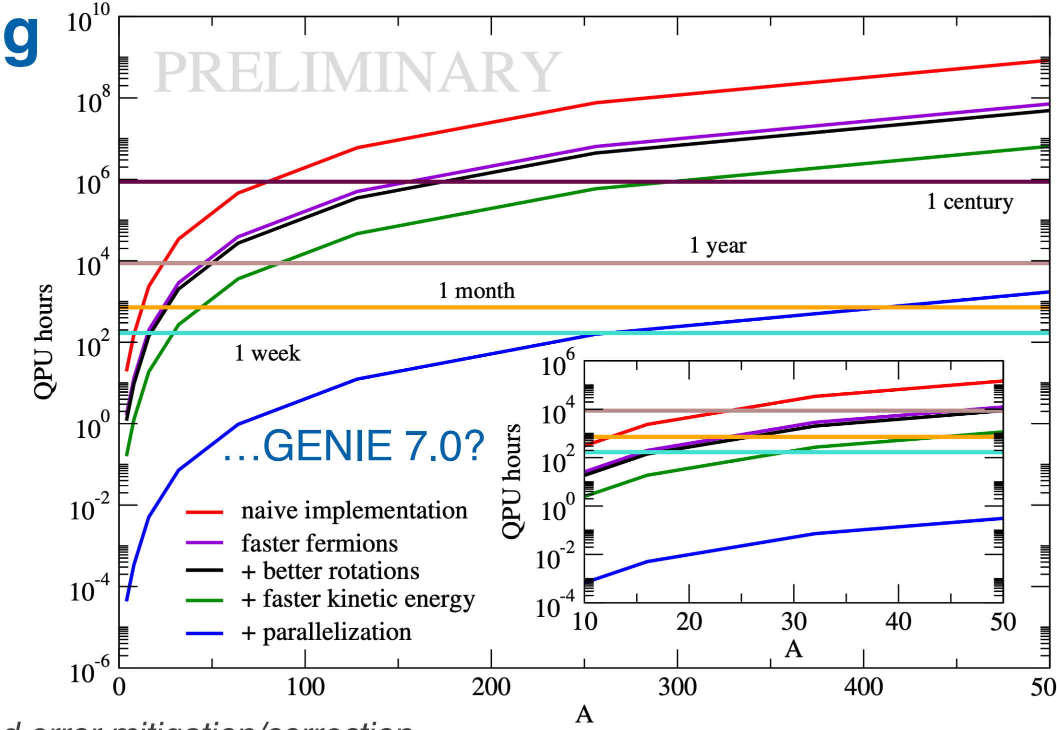
- The FQI approach of leveraging lab competencies and infrastructure, and building partnerships with QIS&T experts to develop capabilities for advancing HEP science is delivering
  - Demonstrated by QuantISED and other R&D project success (quantified by high impact published results)
  - In addition to supporting HEP science applications, the technology and techniques we have developed are attracting interest from other SC programs
- Continuing our focus on delivering on our ongoing activities
  - but a lot of our current projects will end in the beginning of FY24
- Preparing for the next phase of our program utilizing expertise acquired and lessons learned from our early program activities
  - targeting most appropriate R&D for supporting HEP science and leverage opportunities through broader DOE/SC new initiatives

Backup

Neutrino-nucleus scattering

- Algorithm design and resource estimation studied for fault tolerant hardware, with NISQ transition studies included.

- Full algorithm is impossible on NISQ hardware, but we performed resource estimates, studying varying approaches and options.



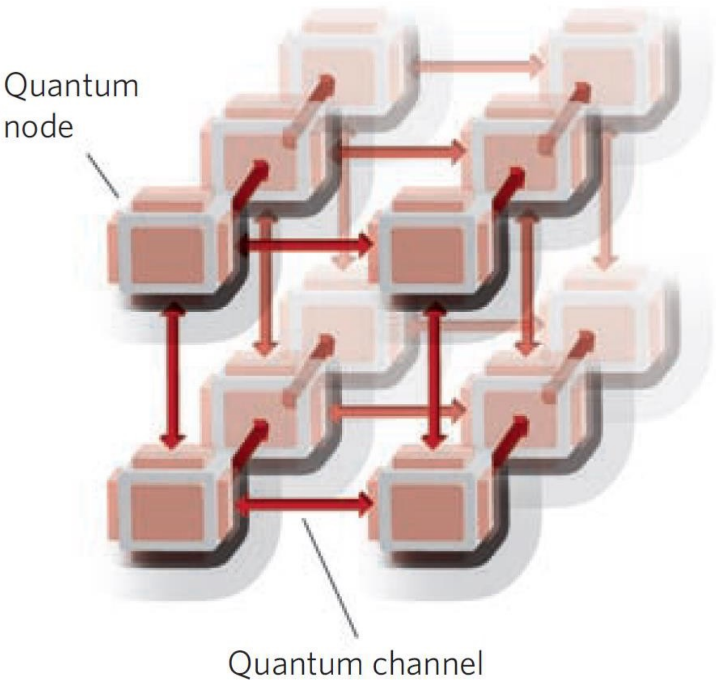
…GENIE 7.0?

Figure by A. Roggero (U. Trento)

- Algorithm efficiency is critical! - *need to understand error mitigation/correction.*
- Based on QC roadmaps, hardware is 10-15 years away (Google, IBM roadmap ~2030 for ~1000 logical qubits)
- ***Algorithm and theory innovation essential;*** Also testing & benchmarking**.** (Analog: HPC best algorithms need provable performance guarantees.)

A. Roggero et al, https://link.aps.org/doi/10.1103/PhysRevD.101.074038

The concept of a quantum network



H. J. Kimble, *Nature* 453, 1023 (2008)

- Quantum nodes: quantum information is stored and processed
  - *“atoms”*
    - *stationary qubits*
- Quantum channels: quantum information is transported
  - *photons*
    - *flying qubits*
- The original picture is missing the classical channels necessary for a functional quantum network
  - *photons*

The actual picture is more challenging

Like classical networks, we need to establish architecture for reliable, ordered, and error-checked delivery of qubits between quantum end-node applications

- Appropriately layered and platform independent, to inter-connect heterogeneous technologies

Unlike classical networks, no-cloning theorem prevents us from using established techniques for handling information loss

- e.g., packet switching

Although quantum-net architecture is not fully developed, it is broadly accepted that **quantum teleportation and entanglement distribution** are **major building blocks**

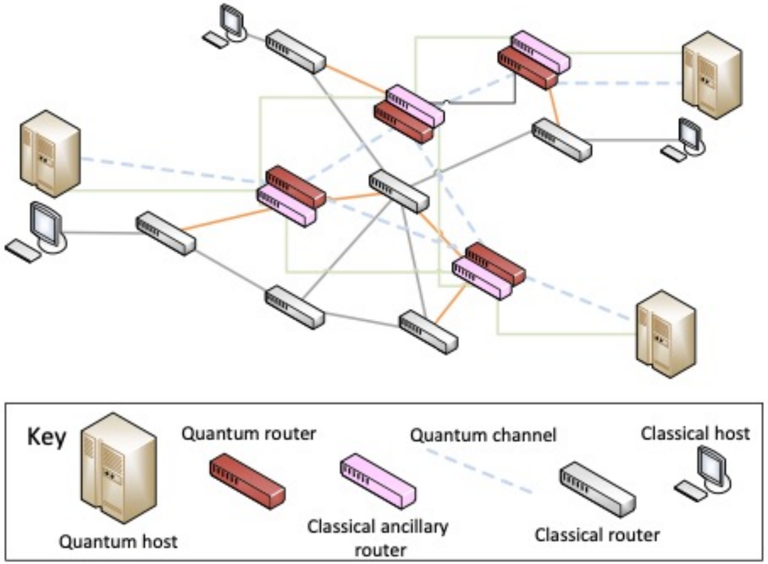
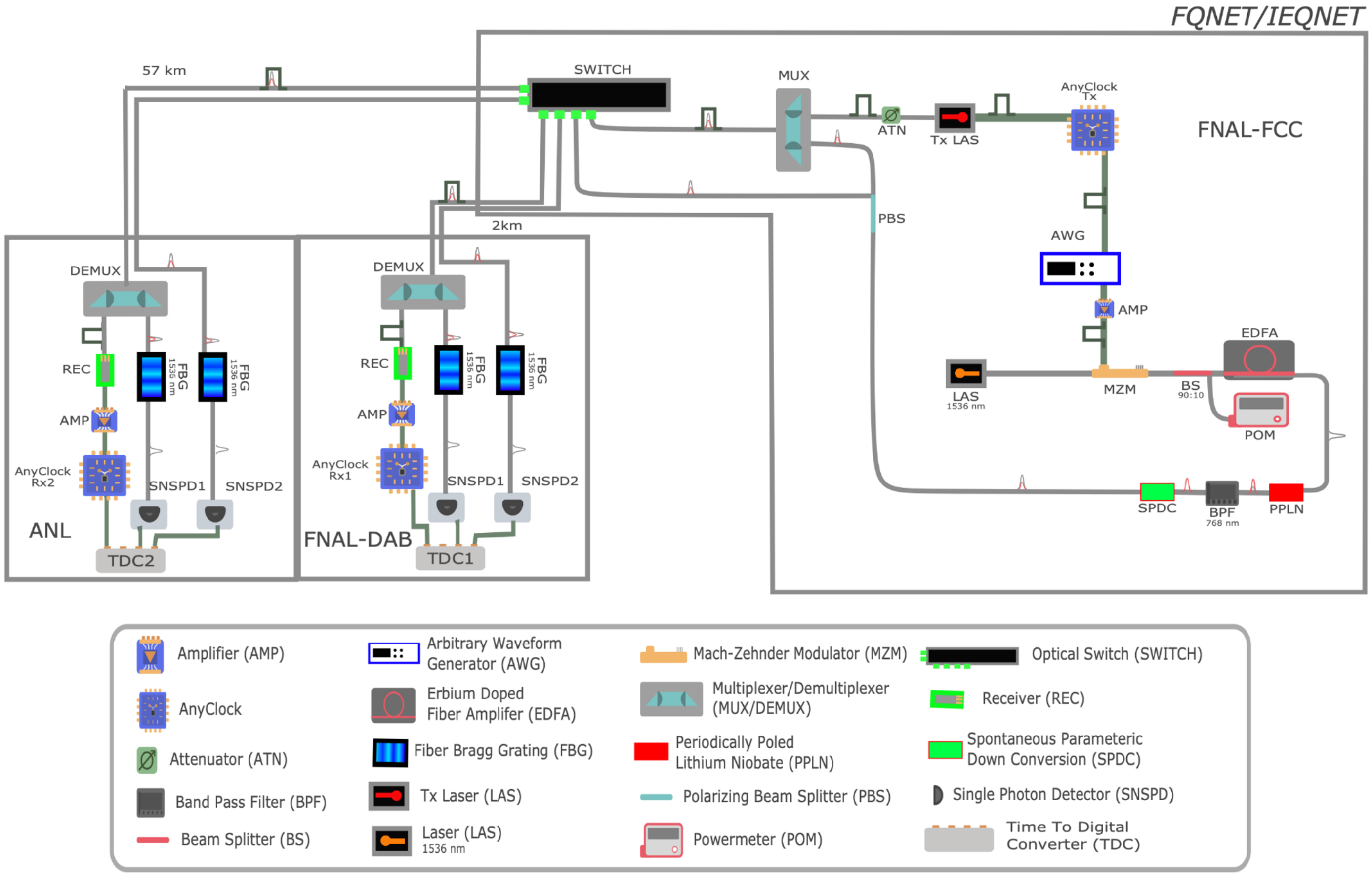


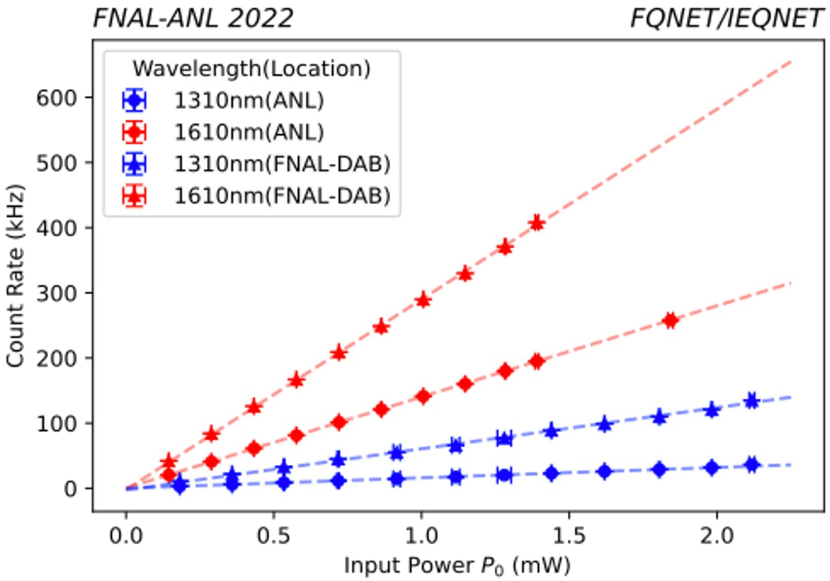
Image from Yu, et al, arXiv:1903.10685 [quant-ph]

Schematic diagram of the experiment

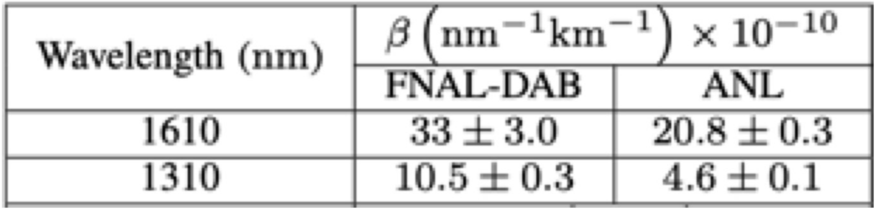


Raman Scattering background characterized

- Completed systematic study of Raman-scattered background to quantum channel on the FNAL-ANL link



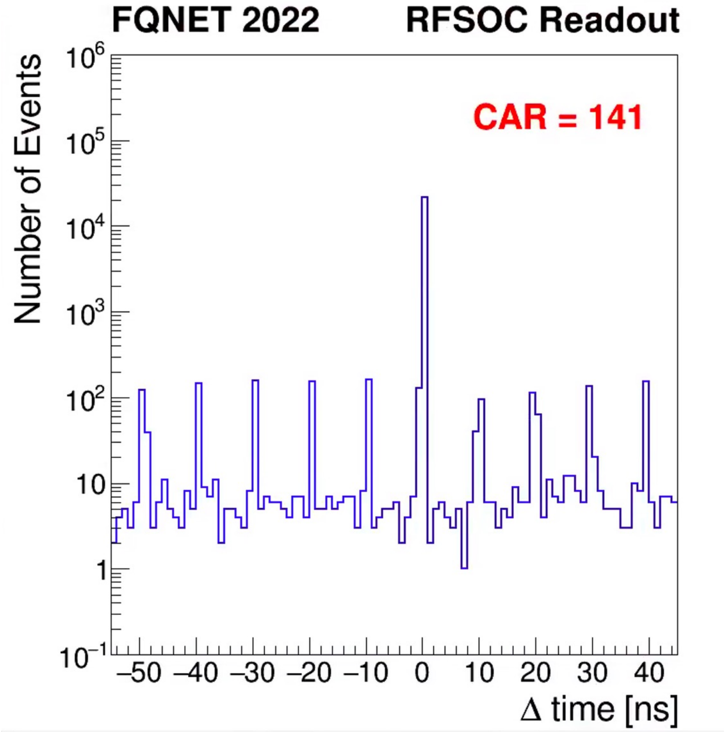
Raman scattering coefficients



Wavelength (nm)	$\beta\left(\mathrm{nm}^{-1}\mathrm{km}^{-1}\right) \times 10^{-10}$	
	FNAL-DAB	ANL
1610	33 ± 3.0	20.8 ± 0.3
1310	10.5 ± 0.3	4.6 ± 0.1

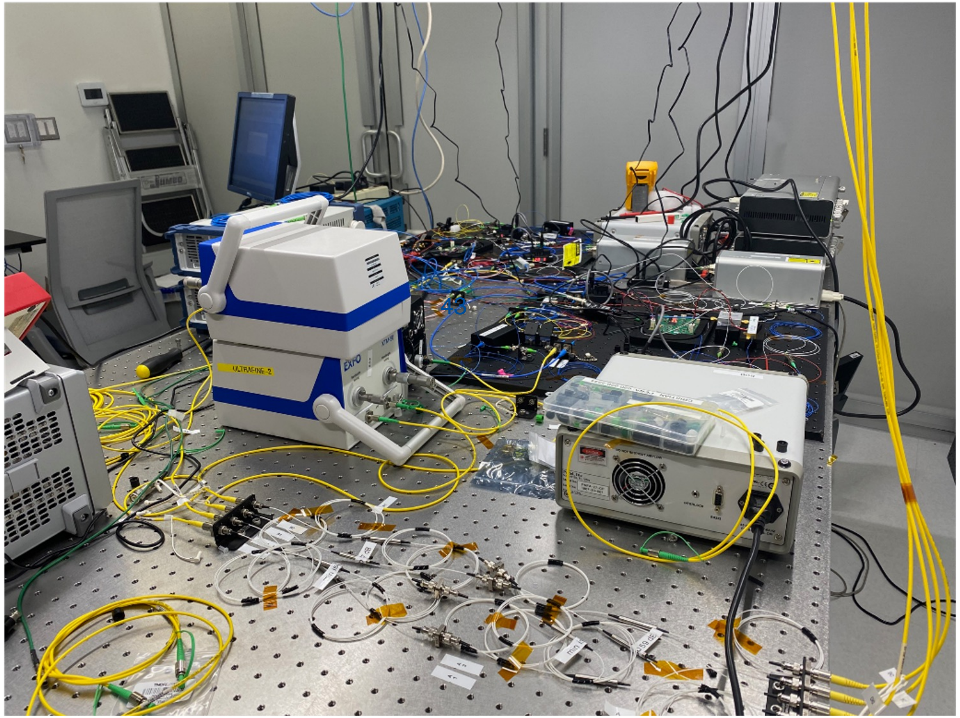
Characterization of Pair-Source driven by FPGA

- Measure CAR (coincidence-to-accidental ratio) of 141, consistent with pair-source driven by conventional AWG, and read out by QuTag

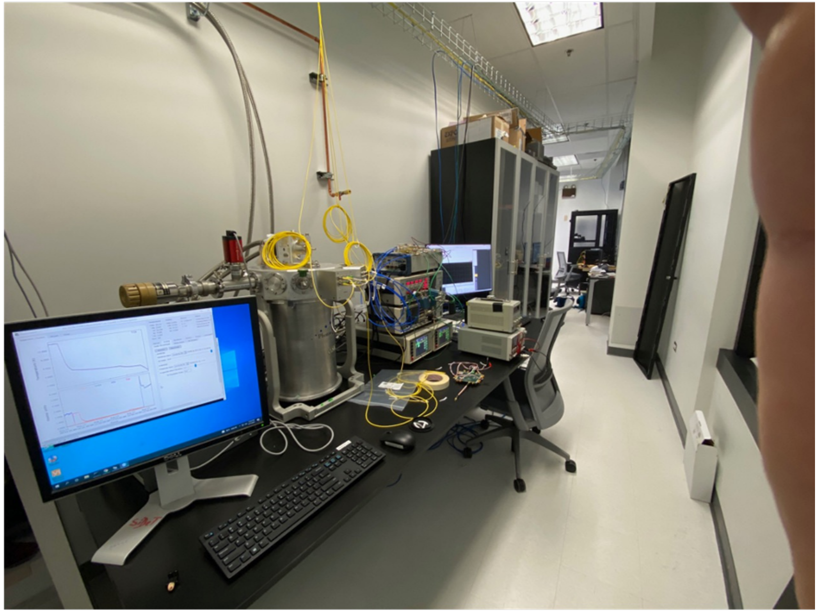


- Paper in preparation, to be submitted end of Jan 2023

FCC Quantum Node Commissioning Towards Entanglement Swapping



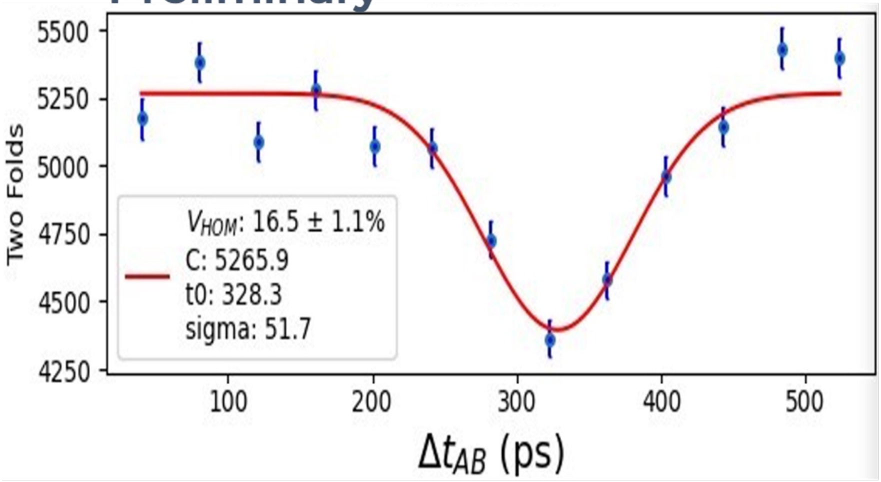
ONGOING!!

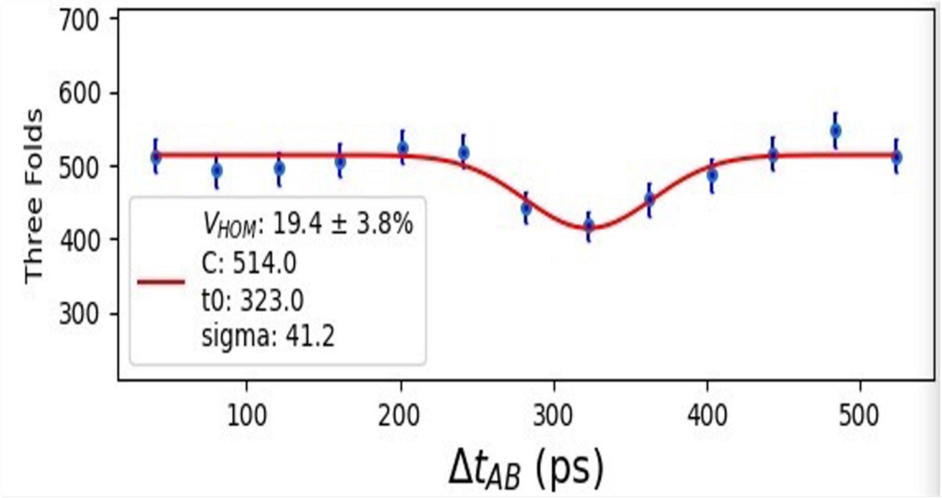


Entanglement Swapping: First Results

Observe clear two- and three-fold coincidence when interfering photons from two pair sources

Preliminary





- **Compatible time of the dip (t_0) in the two- and three-fold**
- **HOM visibility increases in three folds**