Fermilab | U.S. DEPARTMENT OF ENERGY | Office of Science

QSC PI's group photo, Fall 2022

Fermilab Research in the Quantum Science Center

Aaron S. Chou

January 18, 2023

QUANTUM SCIENCE CENTER

Quantum Science Center

QSC overarching goal:
Overcoming key roadblocks in quantum state resilience, controllability, and ultimately scalability of quantum technologies

- Address the fragility of quantum states through the design of new topological materials for QIS
- Develop algorithms and software for computation and sensing with current/future QIS hardware
- Design new **quantum devices and sensors to detect dark matter** and topological quasiparticles

QSC comprises ~100 researchers across 16 institutions.

Fermilab headcount:
9 scientists (~2.5 FTE), 3 PD,
5 engineers

Last week's QSC site visit:
New cryogenic test stand in SiDet Lab G

QSC Organization

Department of Energy
Office of Science
Claire Cramer (PM)

Fermilab Emerging Technologies Directorate
Panagiotis Spentzouris

Fermi Quantum Institute
Joe Lykken

Director
Travis Humble (ORNL)

Deputy Director
Vivien Zapf (LANL)

Chief Scientist
Joel Moore (UCB)

Admin
Teresa Hurt

Science Advisory Council
Chair, Allan MacDonald (UT-Austin)

Industry Advisory Council
Chair, Bo Begole (AMD)

Governance Advisory Board
Chair, Doug Kothe (ORNL)

Integrated Co-design Leads

- **Topologically Protected Quantum Information**
  Filip Ronning (LANL)
- **Quantum Simulations for Scientific Applications**
  David Weld (UCSB)
- **Quantum Sensing for Real-World Applications**
  Daniel Bowring (FNAL)

BES

- **T1: Quantum Materials Discovery and Design**
  Michael McGuire (ORNL)
- **SA1: Topological Electronic Materials**
  Roman Lutchyn (Microsoft)
- **SA2: Quantum Spin Systems**
  Alan Tennant (LANL)
- **SA3: Quantum Probes**
  Amir Yacoby (Harvard)

ASCR

- **T2: Quantum Algorithms and Simulations**
  Andrew Sornborger (LANL)
- **SA1: Quantum Algorithms**
  Yigit Subasi (LANL)
- **SA2: Quantum Applications**
  Alexandra Boltasseva (Purdue)
- **SA3: Software**
  Karol Kowalski (PNNL)

HEP+QIST

- **T3: Quantum Devices and Sensing**
  Aaron Chou (FNAL)
- **SA1: Sensors for Quantum Materials**
  Vlad Shalaev (Purdue)
- **SA2: Devices for Quantum Simulation**
  TBD
- **SA3: Sensors for Dark Matter**
  Lauren Hsu (FNAL)

Chief Operations Officer
Joe Lake(ORNL)

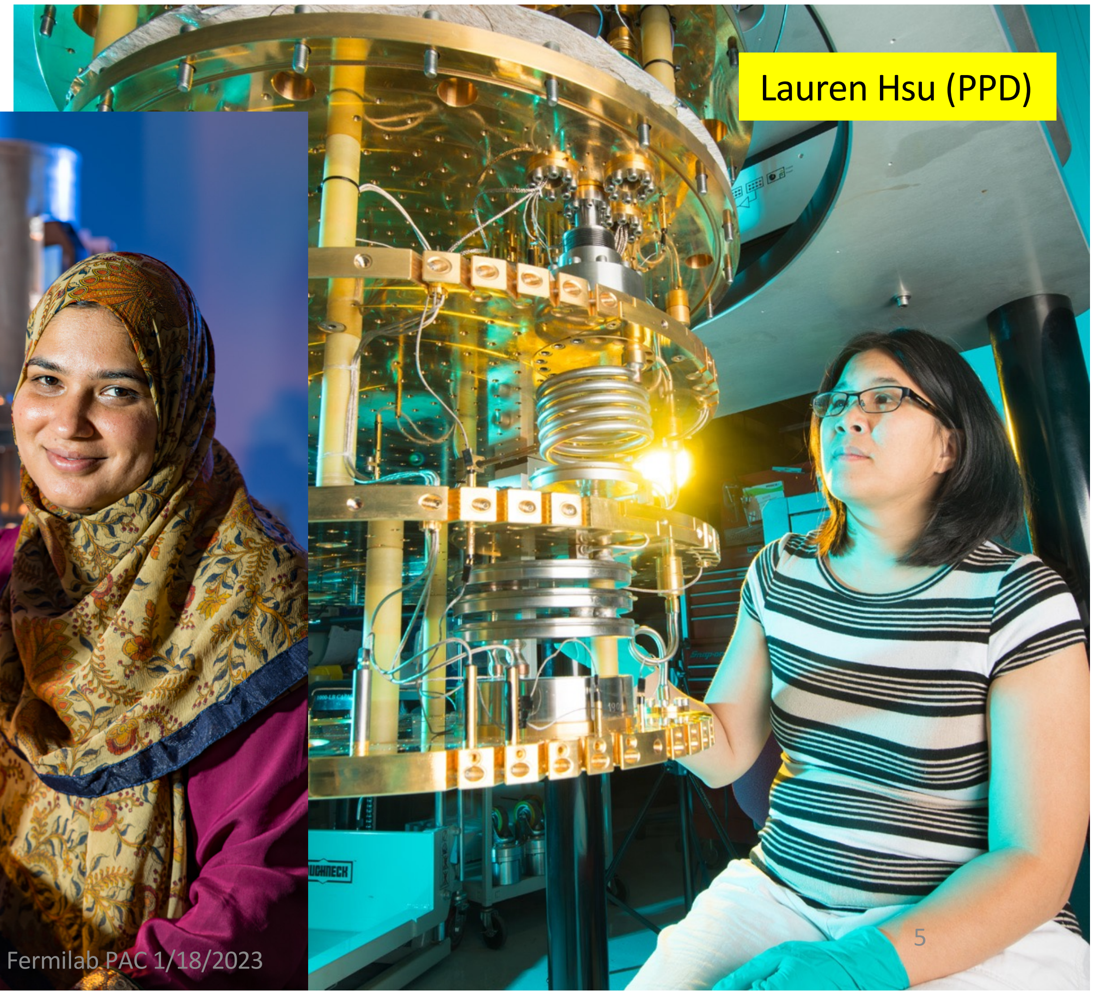
- **Communications**
  Elizabeth Rosenthal (ORNL)
- **Finance**
  Brad Dunsmore (ORNL)
- **Project Management**
  David Ellestad (ORNL)
- **ESH&Q and Infrastructure**
  Sam Mckenzie (ORNL)
- **Partnerships**
  Jeff Cornett (ORNL)

Workforce Development
Alexandra Boltasseva (Purdue)

Strategy: Leverage Fermilab/HEP instrumentation capabilities for QIST R&D

Facilitates development of new quantum materials, devices, and sensors;
Provides testbeds for quantum algorithms for sensing and simulation.

In return, new collaborations with BES/ASCR/QIST will enhance HEP science.



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Thrust 3: *Quantum Devices and Sensors for Discovery Science,* **Aaron Chou** (FNAL)

Specific Aim 3.1

Quantum Sensors for Materials

Vlad Shalaev (Purdue)

Project 1.3.1.1: *Hybrid Quantum Sensors*

Vlad Shalaev (PI, Purdue)

Alexandra Boltasseva, Yong Chen, Alex Lagoutchev, Pramey Upadhyaya (Purdue)

Prineha Narang (UCLA)

Amir Yacoby (Harvard)

Benjamin Lawrie (ORNL)

Han Htoon (LANL)

Aaron Chou (FNAL)

Project 1.3.1.2: *Superconducting CQED Sensors*

Alex Ma (PI, Purdue)

Yong Chen, Leonid Rokinson (Purdue)

Aaron Chou (FNAL)

Specific Aim 3.2

Quantum Devices for Robust Quantum Simulations

John Comish(ORNL)

Project 1.3.2.1: *Cryogenic Electronics for Ion Traps*

Farah Fahim (PI, FNAL)

Chris Seck (ORNL)

Specific Aim 3.3

Quantum Sensors for Dark Matter

Lauren Hsu (FNAL)

Project 1.3.3.1: *Low Background Sensors and Materials*

Dan Baxter (PI, FNAL)

Lauren Hsu, Pat Lukens, Tali Figueroa (FNAL)

Yong Chen, Alex Ma (Purdue)

Project 1.3.3.2: *High Throughput Cryogenic Sensor Arrays*

Rakshya Khatiwada (PI, FNAL)

Adam Anderson, Gustavo Cancelo

Project 1.3.3.3: *Squeezed Readout of Quantum Sensors*

Claire Marvinney (PI, ORNL)

Stephen Jesse, Benjamin Lawrie (ORNL)

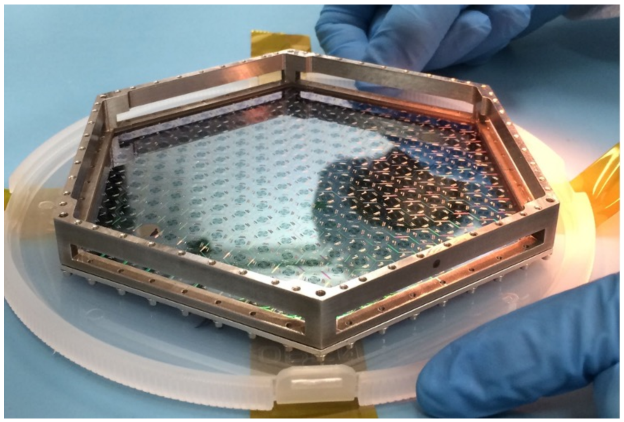
Sunil Bhave, Rafael Lang (Purdue)

Scott Crooker (LANL)

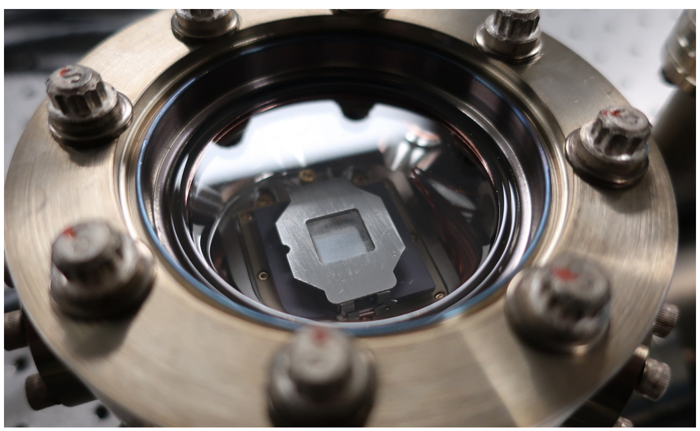
Gustavo Cancelo (FNAL)

+**Steve Mrenna** (Q simulations)
PDs: **Kelly Stifter, Dylan Temples, Ryan Linehan,**
6 graduate students

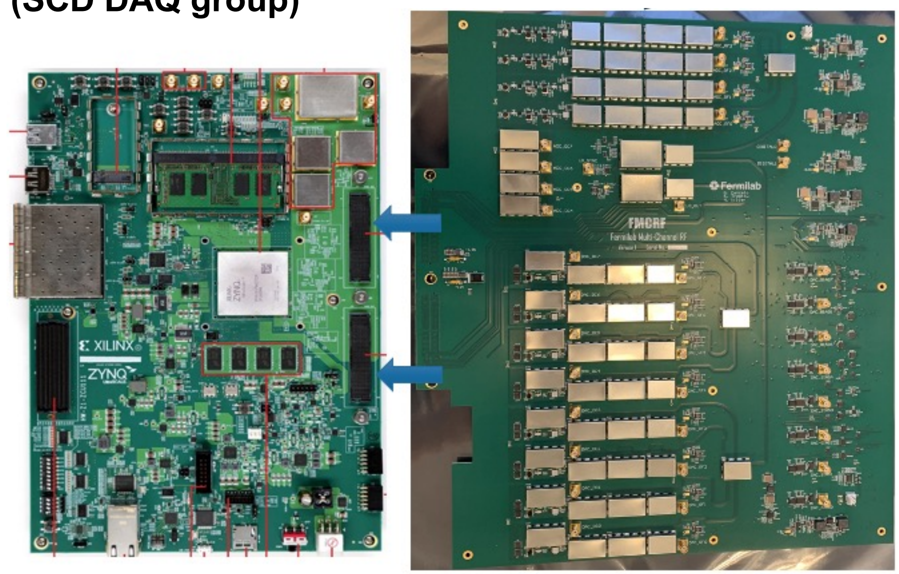
HEP custom instrumentation for high channel count sensor arrays



Frequency-domain multiplexing is used to read out cryogenic sensor arrays **(PPD CMB group)**



Flexible FPGA system for control, readout of qubits and sensors **(SCD DAQ group)**



ZCU111:
FPGA+ADC+DAC+
memory+interfaces

Custom DC + RF board:
RF inputs, outputs, LO, fast flux
control, high precision bias

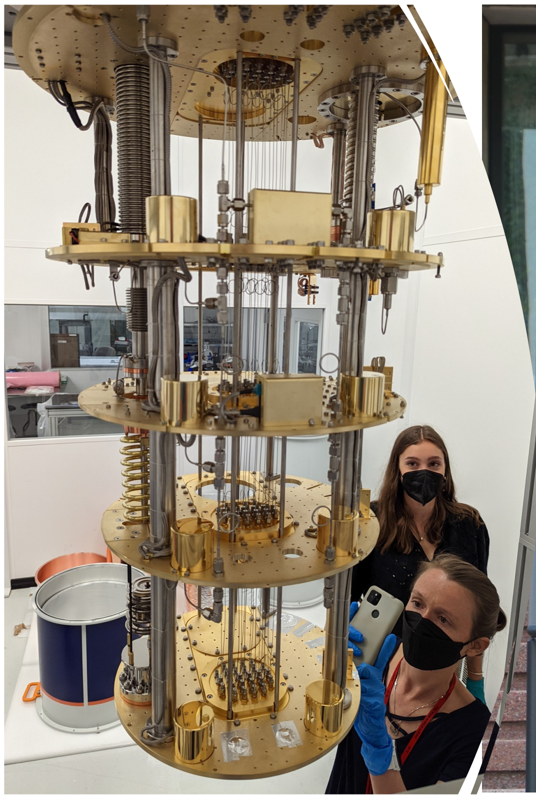
Cryogenic electronics for low noise control of ion trap quantum simulator **(ETD Microelectronics Division)**

Applications: Qubit control, Quantum materials/devices, Dark matter

QSC cryogenic test stands to develop quantum sensor arrays:

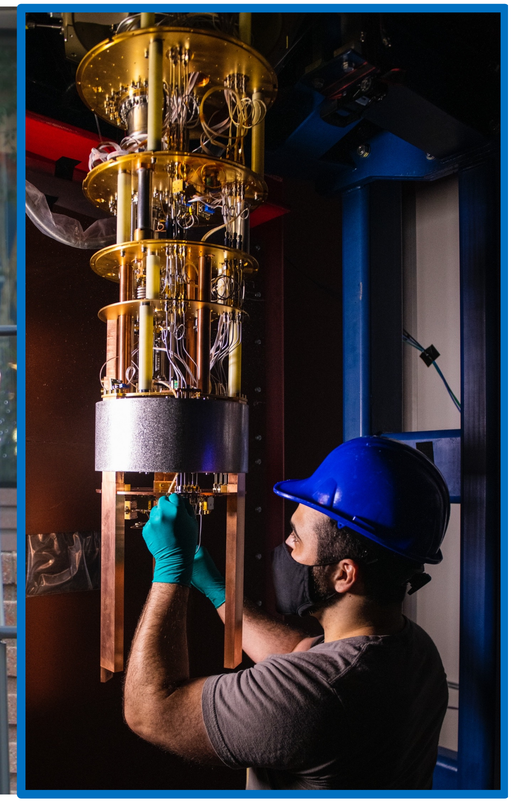
Study detector and materials response to ionizing radiation and dark matter

SiDet Lab G



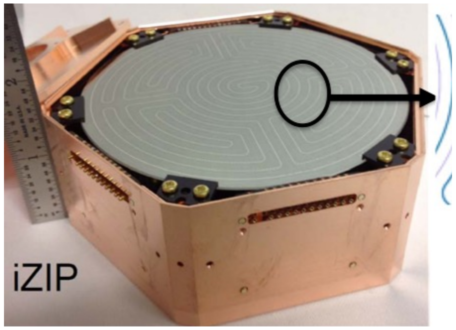
Fermilab QSC dark matter group

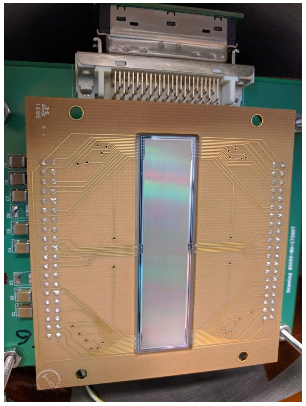
NuMI underground



Qubit-based sensing could reduce dark matter thresholds by factor 10^4

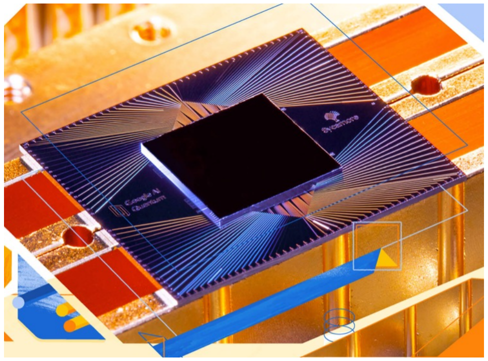
HEP silicon detector (SuperCDMS, SENSEI)





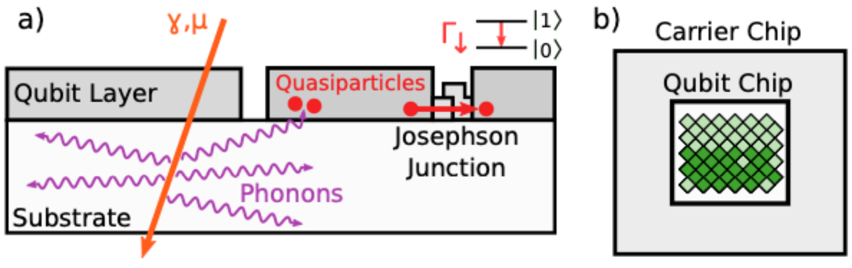
Semiconductors:
1 eV threshold to create electron/hole pair in silicon or germanium, detect with single electronics

Google Sycamore chip



Superconductors: 10^{-4} eV threshold to break Cooper pair
All qubits on chip wiped out by single cosmic ray, 100 keV energy deposit

M. McEwen, et al., Nature Physics 18 (2022)



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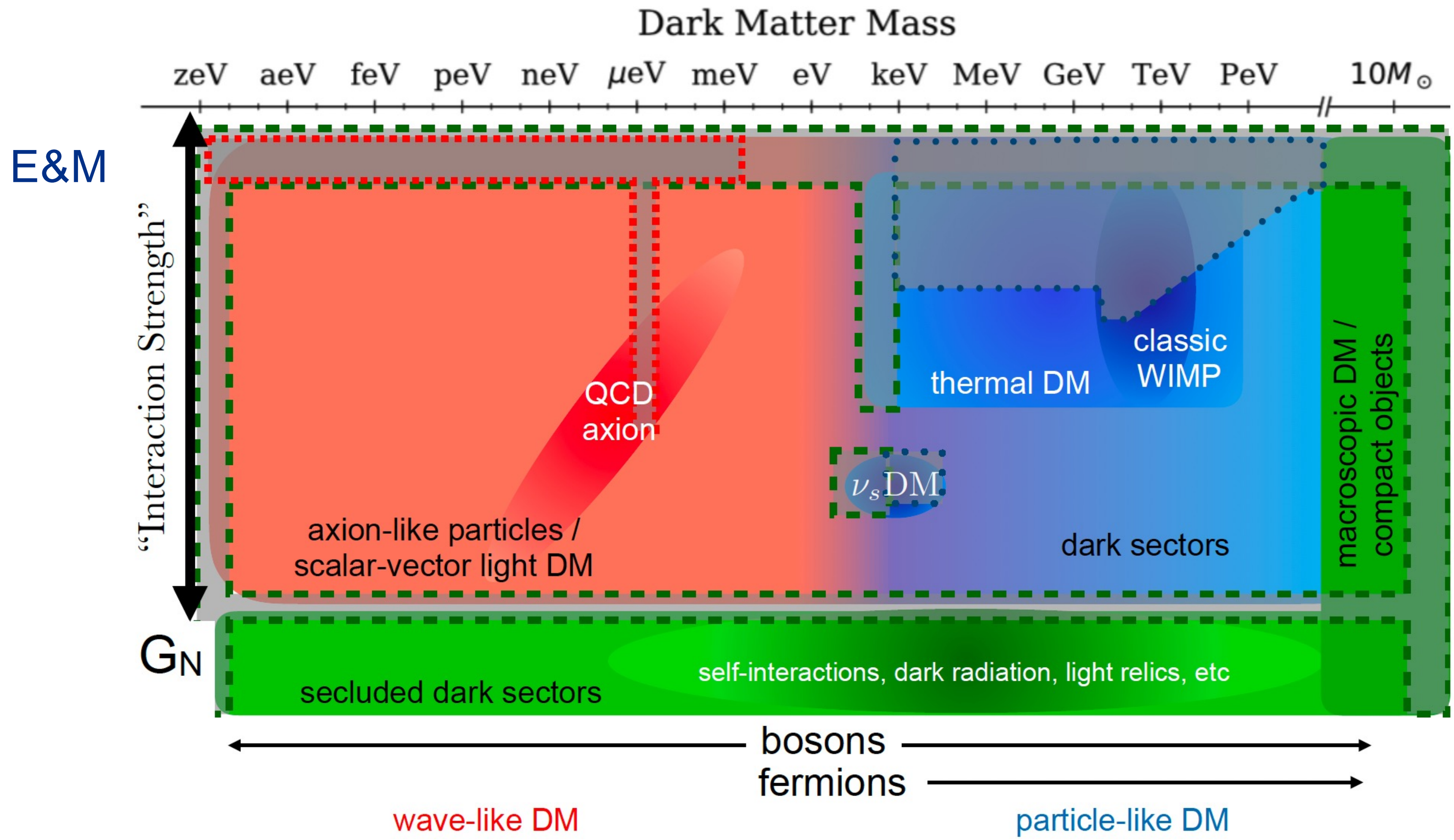
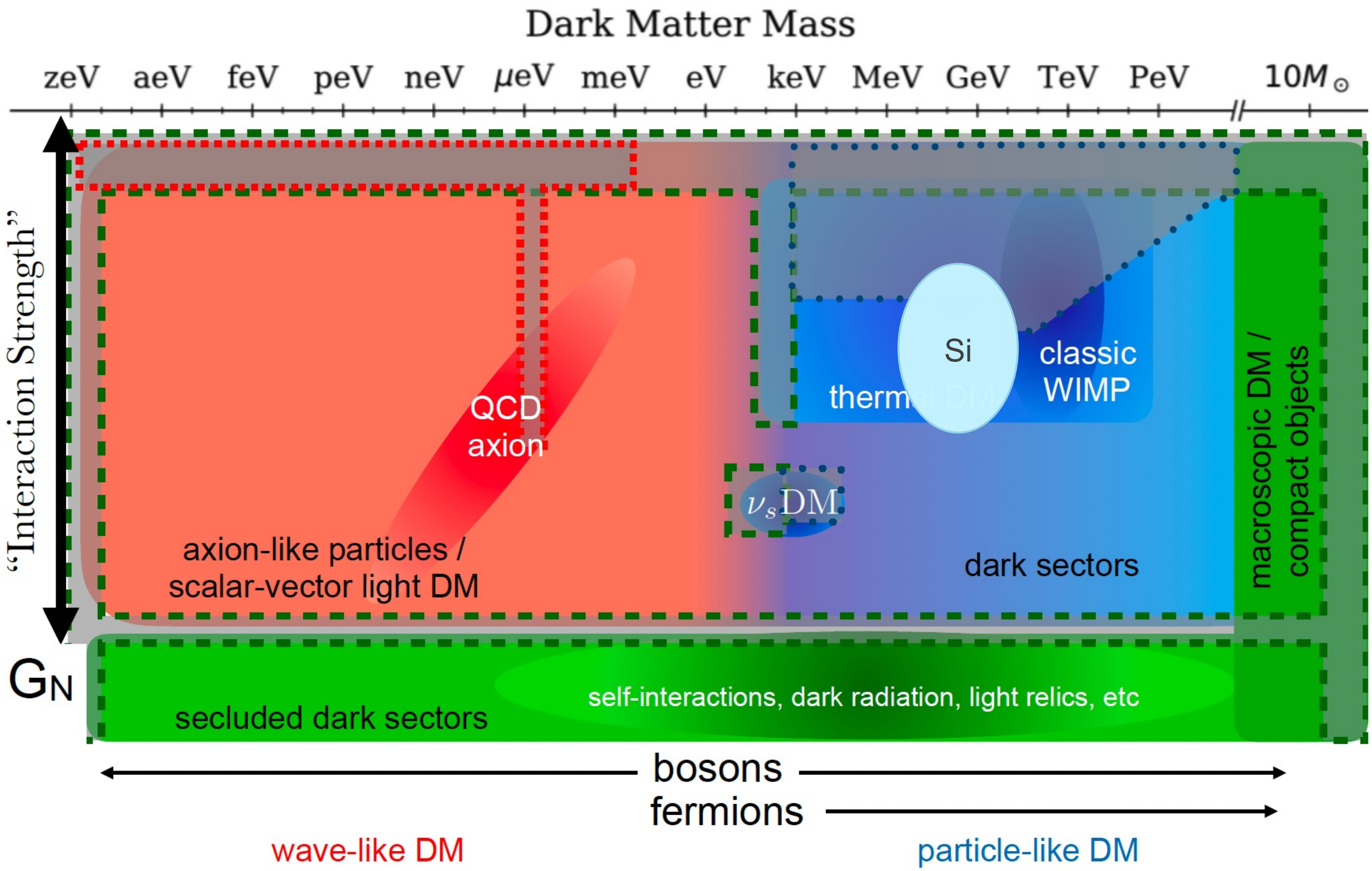
Snowmass Dark Matter Strategy: Delve Deep, Search Wide



Cartoon from Snowmass

Semiconductor detectors target sub-GeV mass dark matter

E&M

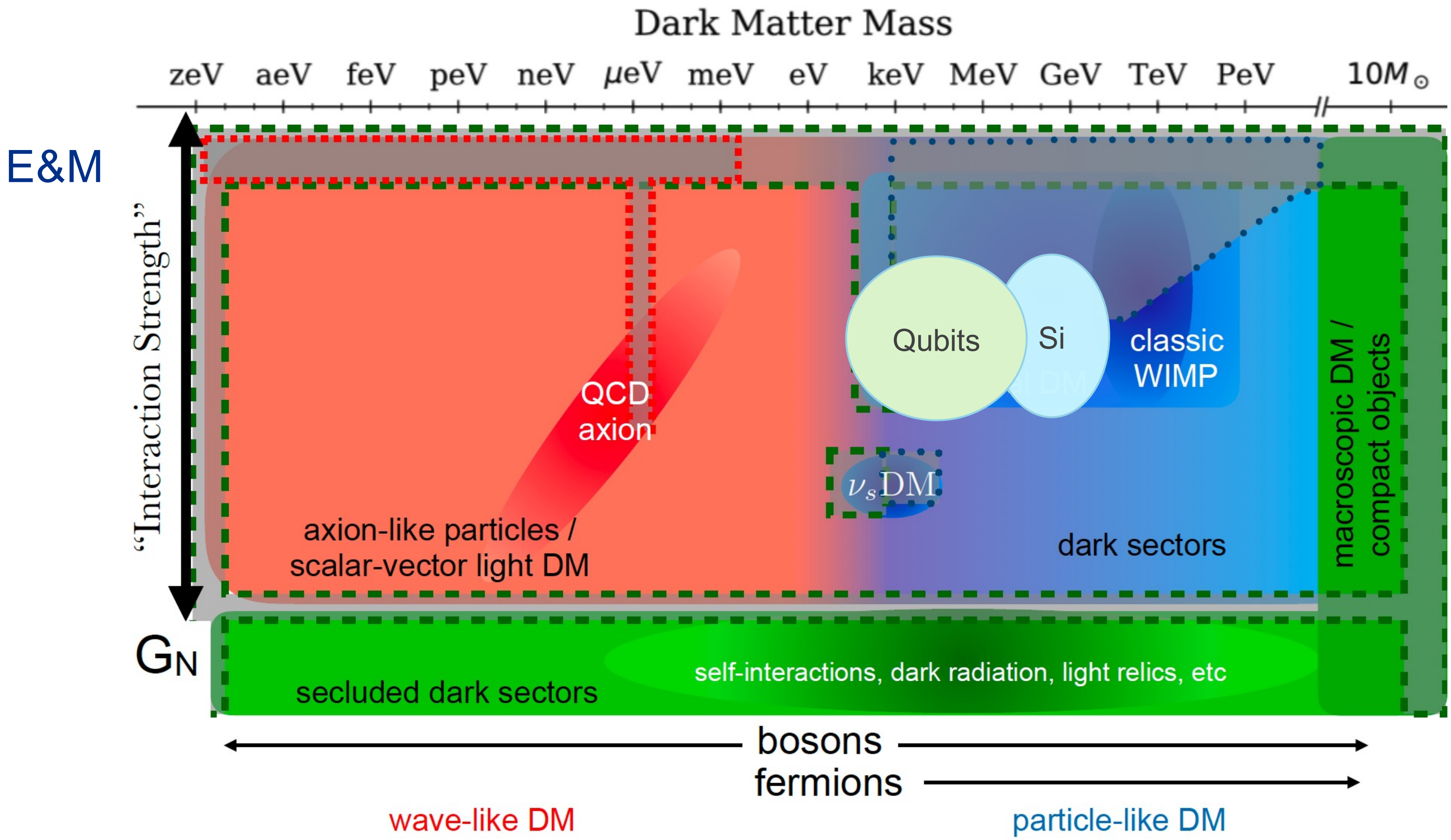


G_N

Cartoon from Snowmass

Fermilab

QSC's quantum sensors target sub-MeV mass dark matter



Cartoon from Snowmass

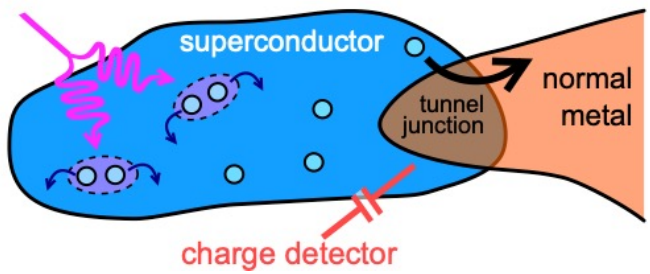
Low energy backgrounds are largely unknown:

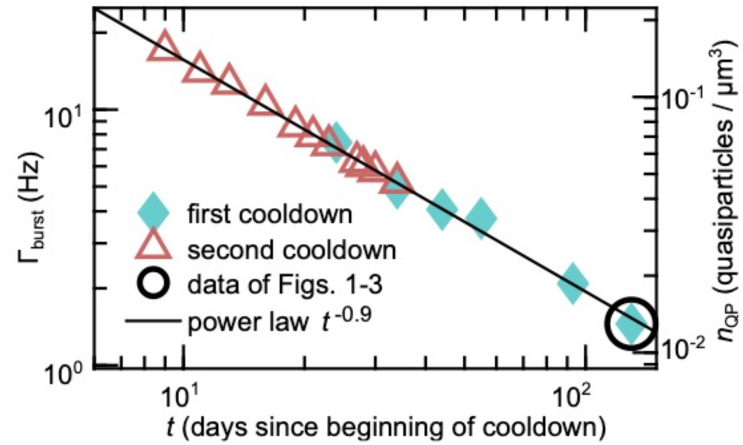
Superconducting devices have mysterious non-equilibrium quasiparticle population:

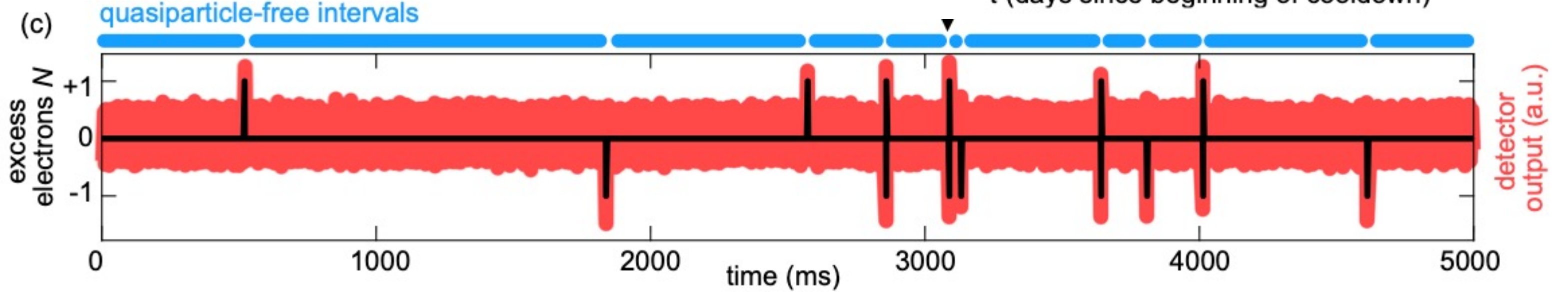
n >> Boltzmann suppressed $n = e^{-1.2K/0.01K} = 10^{-52}$

These now appear to be created in discrete, time-resolved events with much higher rate than cosmic rays.

E.T. Mannila, et al., Nature Physics 18 (2022)



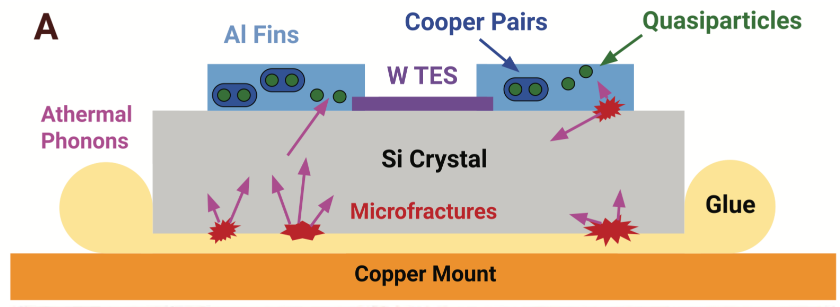




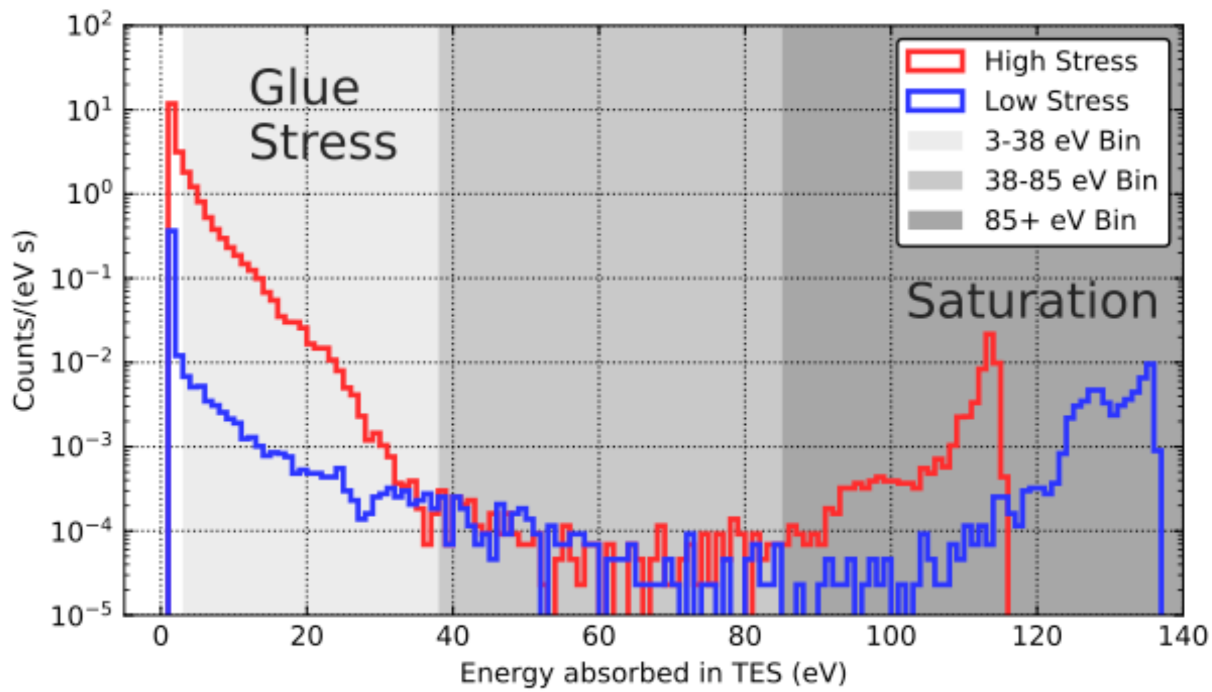
Have they discovered milli-charged dark matter?

Large noise backgrounds are now believed to be phonons caused by substrate microfracture events

R. Anthony-Petersen… M. Pyle, et al., arxiv:2208.02790



Measure spectrum using tiny, cold, low heat capacity TES sensors developed for CDMS dark matter search.



So non-equilibrium particles are **probably** not due to dark matter.

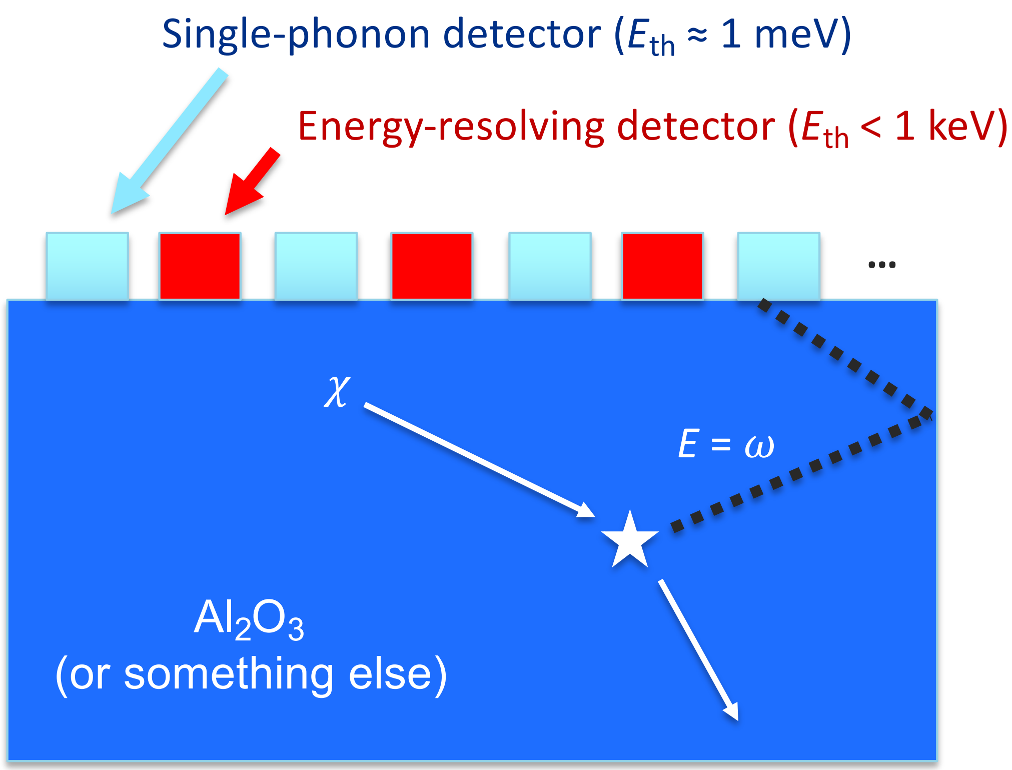
QSC will develop next-generation qubit-based microcalorimeters to reduce thresholds to milli-eV.

- Provide first look at sub-eV spectrum
- Test ideas to mitigate backgrounds

Designing an Experiment

QUANTUM SCIENCE CENTER

Proposing a novel, multiplexed quantum device for particle physics detection



- A low-mass DM recoil will deposit order meV-keV of energy ω in the substrate at location $\boldsymbol{r}$, producing phonons
- These will break Cooper-pairs in single-phonon detectors (qubits) with some efficiency $\varepsilon(\omega, \boldsymbol{r})$
- The energy-resolving detectors (veto), which have much higher thresholds, should see no simultaneous hits, since the energy deposition is below detector threshold

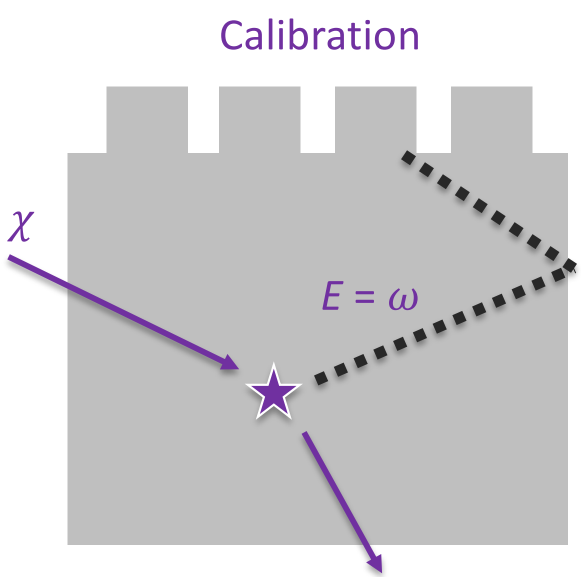
Slide from Dan Baxter

Fermilab

Designing an Experiment

FNAL group has progress on many fronts towards this goal!

MEMS = "Micro-Electro-Mechanical System"



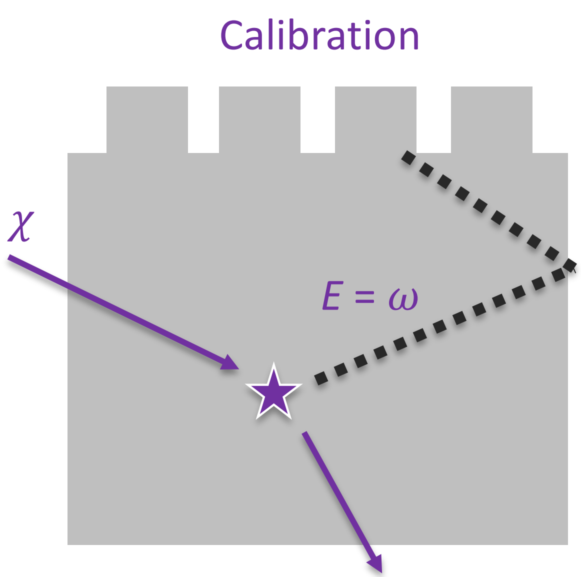
Work by Kelly Stifter & Hannah Magoon

- Laser Calibration – scan over device w/ UV-optical-IR photons to determine phonon response as a function of ***position***
- MEMS Mirror – outputs up to mW at full scanning speed and range, "none" while stationary
- **Initial cold tests w/ KIDs are successful!**

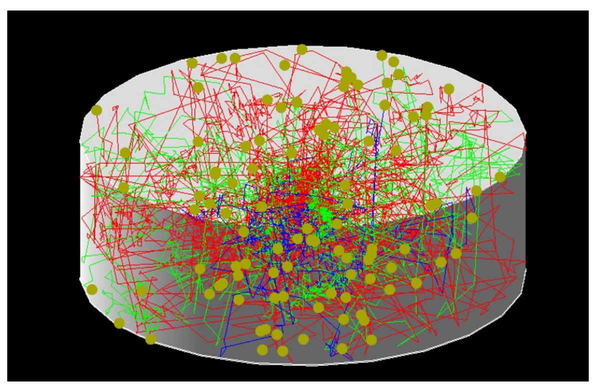
Slide from Dan Baxter

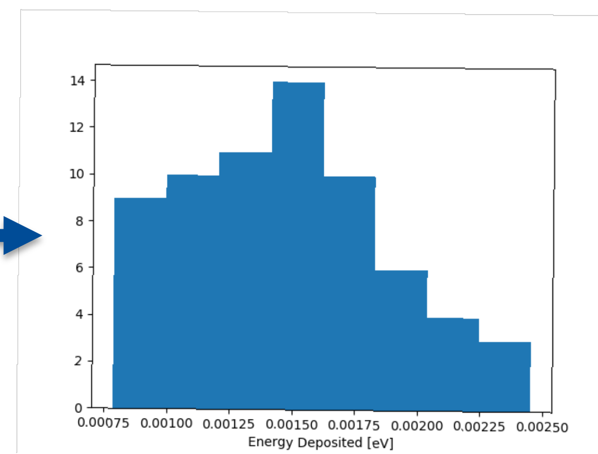
Designing an Experiment

FNAL group has progress on many fronts towards this goal!



- G4CMP – build on efforts within SuperCDMS to simulate phonon propagation/kinematics in devices and compare with laser calibration scan
- Seek better understanding on the impact of radiation on qubits and the propagation of incident energy that results in the broken Cooper pairs in aluminum





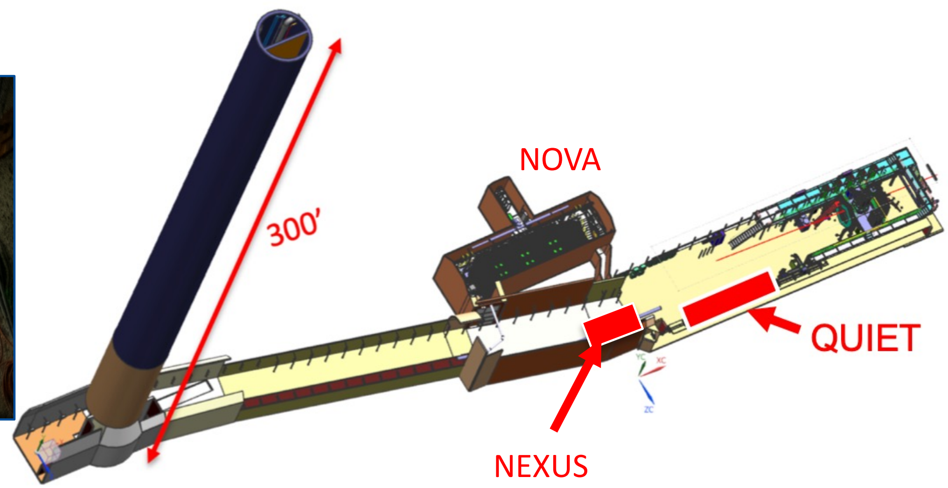
Work by Israel Hernandez & Ryan Linehan

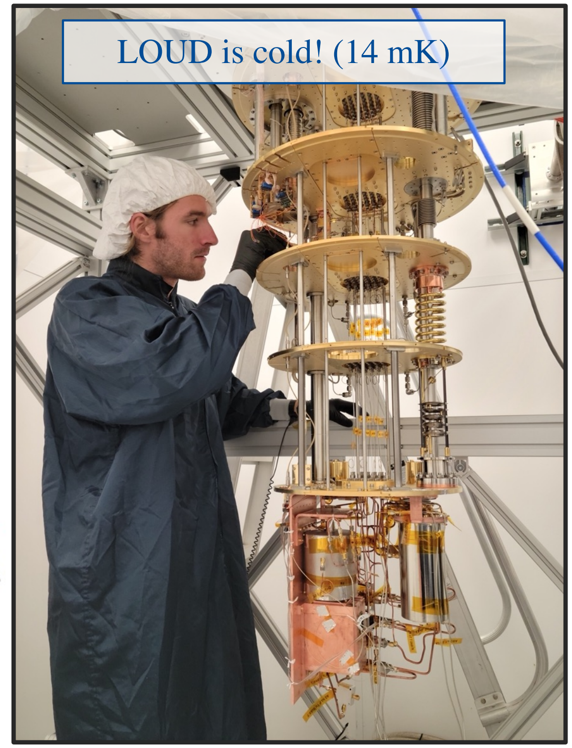
Slide from Dan Baxter

Designing an Experiment

FNAL group has progress on many fronts towards this goal!

- **Two identical new facilities being constructed at FNAL over the next year!**
- LOUD – high-throughput surface facility to advance qubit-based technology necessary to develop DM & radiation detectors
- QUIET – underground clean facility (next to NEXUS; 225 mwe) to operate characterized devices in low-background (target 100 dru) environment (x10^3 reduction)





LOUD Run Coordinator: Ryan Linehan

Slide from Dan Baxter

QSC provides QIST training for the Fermilab user community

QSC cryogenic engineering and quantum sensing training 2022

Sep 15, 2022, 12:15 AM → Sep 16, 2022, 6:30 PM US/Central

Fermilab

Rakshya Khatiwada (IIT/ Fermilab)

Description The goal of this training is to prepare the local FNAL/IIT/NW QSC workforce in quantum sensing research with a special focus on immediate needs of QSC projects 1.3.3.1 and 1.3.3.2. The training will be conducted for two days with general overview talks on the first day (in person +virtual) in topics which fall broadly under cryogenic engineering and quantum sensing that are essential in building quantum experiments. Second day activities will be in person demo, overviews and short training relevant to cryogenic engineering and qubit control and readout electronics and spectroscopy. The hope is that by the end of this training students and postdocs will have the tools and direction they need in order to jump start their experiments in the two new QSC dilution refrigerators.

Organizers: Kelly Stifter, Israel Hernandez, Lauren Hsu, Matthew Hollister, Dylan Temples, Hannah Magoon, Rakshya Khatiwada

REGISTRATION CLOSED Thank you!

ZOOM link will be sent in email to the registered participants.

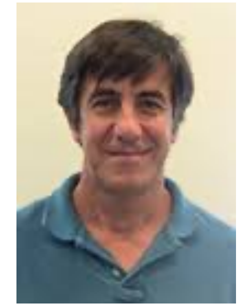
Day1_audio.m4a | Day1_chat.txt | Day1_video.mp4 | QSC training flyer 2...

Assistant Professor/Scientist rkhatiw@fnal.gov 5154419091

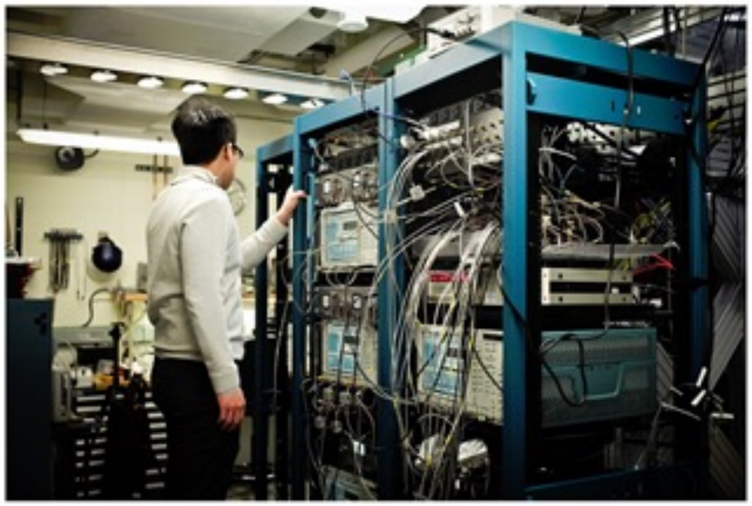
https://indico.fnal.gov/event/56046/

45 participants (in-person + virtual)

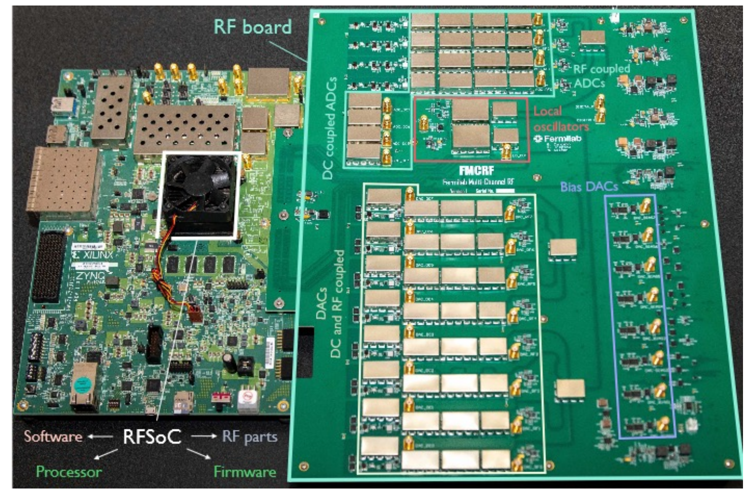
Quantum Intrumentation Control Kit (QICK), Gustavo Cancelo et al.



- **New HEP multiplexed control/readout electronics now being deployed in major quantum computing labs and industries across the country.**
- **Goal: Control 100-1000 qubits per board in quantum computers and quantum sensor arrays. Reduce cost per channel from $100k to < $1. Enable million qubit machine!**



QICK



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

"The development of the Quantum Instrumentation Control Kit is an excellent example of U.S. investment in joint quantum technology research with partnerships between industry, academia and government to accelerate pre-competitive quantum research and development technologies," said the U.S. Department of Energy's Harriet Kung.

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

QICK Workshop at Fermilab, January 12, 2023

- **Brought together leaders in QIST from academia, labs, industry to explore use cases and standardization of quantum controls**

Quantum Control QICK workshop

January 12, 2023
America/Chicago timezone

Enter you

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- Participant List
- Hotel Recommendations

For more info

cancelo@fnal.gov
8762

The QICK workshop will bring experts in QIS (Quantum Information science), in computing, quantum networking and quantum sensing to Fermilab to outline a and determine requirements for an open Control and Readout system based or platform. https://arxiv.org/abs/2110.00557

https://aip.scitation.org/doi/full/10.1063/5.0076249

There will be presentations from key speakers from academia, DOE labs and sc enough room for discussions and new ideas.

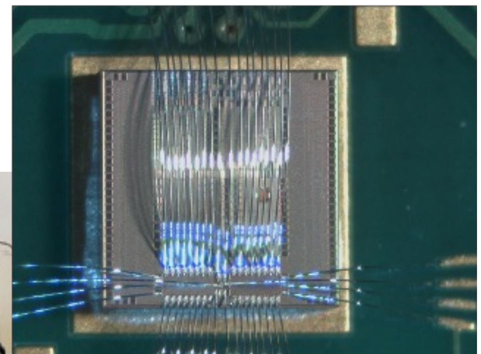
	qolab and U. Santa Barbara	*Dr John Martinis*	14:10 - 14:25
	QICK workshop session: Coffe break		14:25 - 14:40
	Rigetti talk	*Dr Glenn Jones*	14:40 - 14:55
15:00	**AWS talk**	*Dr Jeff Heckey*	14:55 - 15:10
	IBM Controls	*Dr Thomas Alexander*	15:10 - 15:25
	AMD-Xilinx talk	*Dr Patrick Lysaght*	15:25 - 15:40
	ColdQuanta talk	*Dr Ryan Jones*	15:40 - 15:55
16:00	**QICK workshop session: Meeting with DOE centers and University PIs and companies**	*Dr David Schuster*	
	o and technical Q&A	*Martin Di Federico, Sho*	

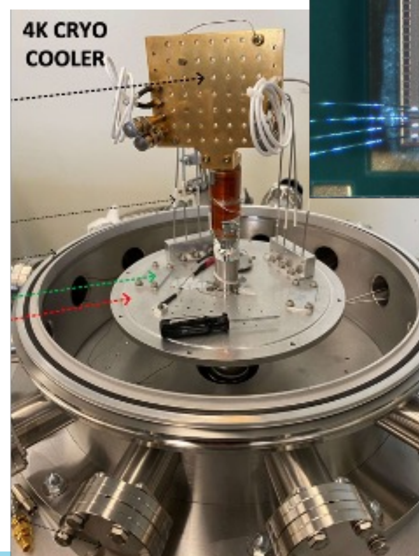
140 participants (in-person + virtual)

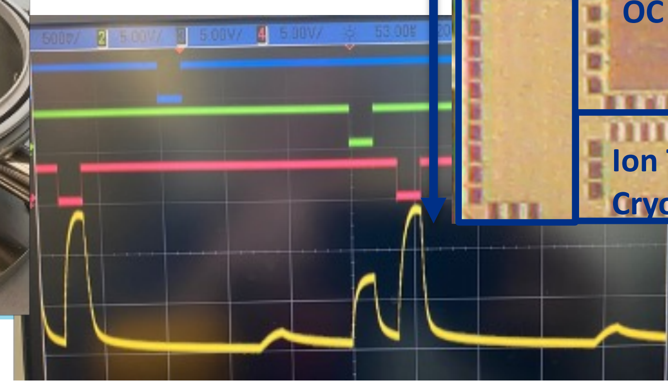
Fermilab Cryogenic ASICs for low noise control of trapped ion quantum simulator (Farah Fahim, Shaorui Li)

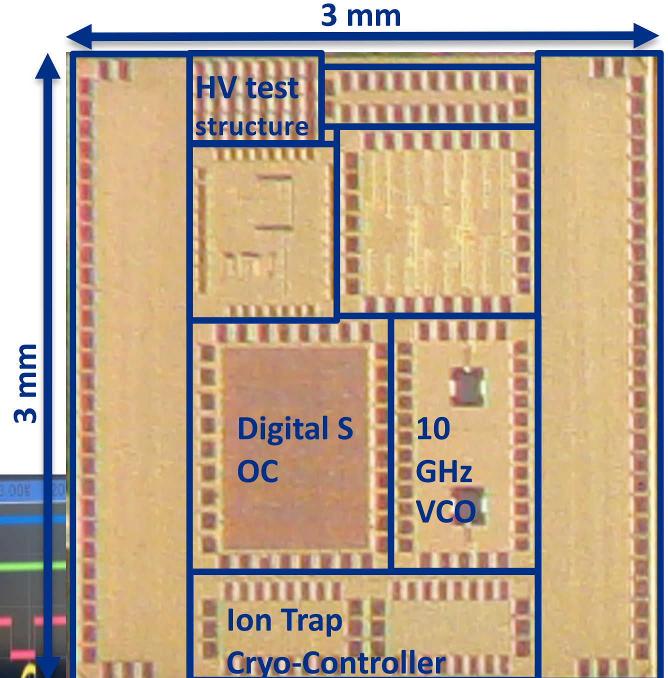
Deep cryogenic electronics on advanced technology nodes (Global Foundries 22 nm FDX) operating at 4K

- 2 channels of Cryo DAC: 100 MSPS, 10V O/P swing
- 10 GHz VCO for on-chip PLL
- High voltage test structure for debugging
- Digital SOC









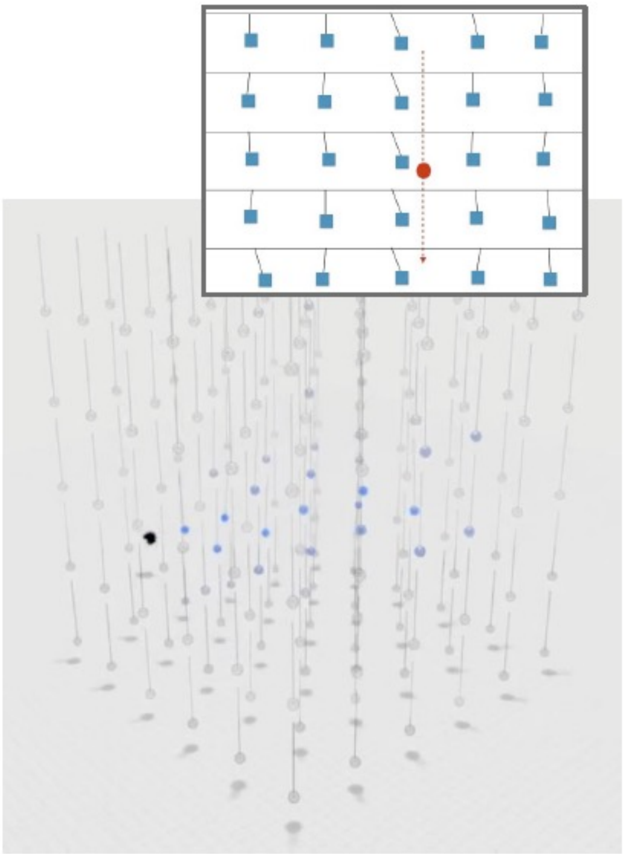
5 year goal: 16 to 128 DAC channels integrated with the ion-trap system operating at 4K with an extremely low power budget

Science target: simulation of quantum spin liquids

Windchime concept:

Larger mass accelerometers needed for detecting gravitational (spin-2) force from DM

Phys.Rev.D 102 (2020) 7, 072003



Cubic meter array of **10^9 accelerometers** with millimeter spacing to detect force from passing dark matter.

Probably gravitational force is too weak but can still focus on scalar or vector-mediated forces.

How to affordably read out sensor array and reconstruct track of 1000 excitations in real-time???

- Probably impossible with classical computers.
  - cf. LHC = 400M channels
  - Heat load = 5 dedicated nuclear power plants
- Diffraction of light? Quantum annealing?
- **If Dark matter detector = Quantum Computer**
  → Should provide in-situ processing of tracks

Summary

- **Use Fermilab/HEP technical capabilities to advance QIST**
  - Use low-background dark matter techniques to reduce backgrounds and improve qubit performance
  - Provide scalable control and readout electronics for quantum computers
    - **Already have made high impact contribution to US quantum ecosystem with QICK**

- **Engage neighboring fields BES/ASCR/QIST. Import/adapt new technologies to target HEP Science:**
  - Develop qubit-based microcalorimetry for dark matter
    - Investigate new target materials, new quantum sensing algorithms
  - Create scalable high channel count sensor arrays

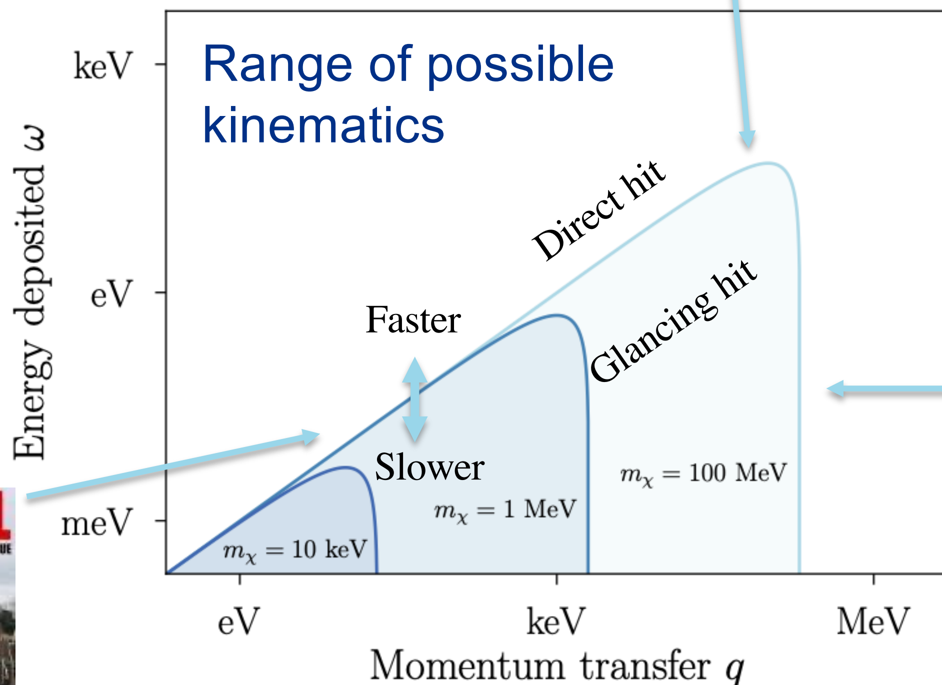
- **Future directions**
  - Quantum field theory calculations on quantum simulation hardware
  - HEP instrumentation to discover new quantum materials

BACKUP SLIDES

Dark matter scattering deposits energy to create quasiparticles in the scattering target

Pool ball stops when directly hitting an equal mass object. All kinetic energy is transferred.

For v = galactic escape velocity 10^{-3} c, total kinetic energy available is 10^{-6} M



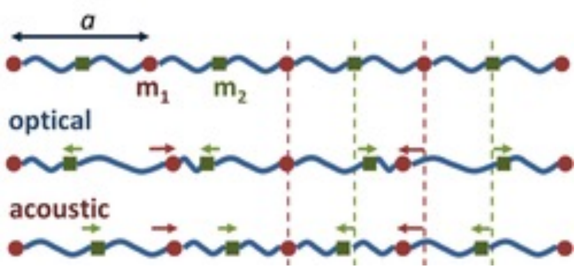
Train keeps moving forward when hitting a lighter obstacle

Ping pong ball just back scatters, does not transmit much energy to heavy wall.

Use optical phonon modes in bulk target for kinematic matching

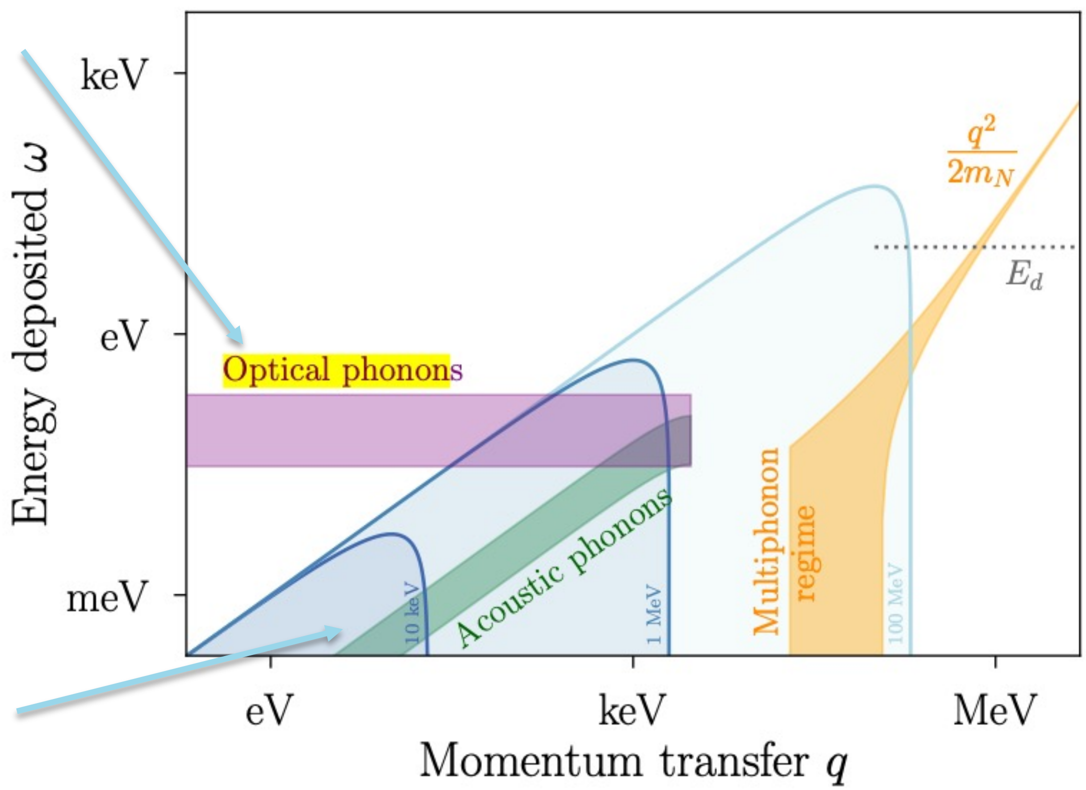
Y. Kahn and T. Lin, Rep. Prog. Phys. 85 (2022) 6, 066901

Optical phonons in polar materials with differently charged neighboring ions create electric dipole oscillations that couple well to photons (and dark photons).



Large phase velocity v = E/p ≈ Δ/p is better matched to the typical dark matter velocity v=10^{-3} c

Acoustic phonons have slow phase velocity given by the speed of sound v ≈ 10^{-5} c and can only couple well to the slowest dark matter in the galaxy



Higher mass DM can scatter on individual nuclei