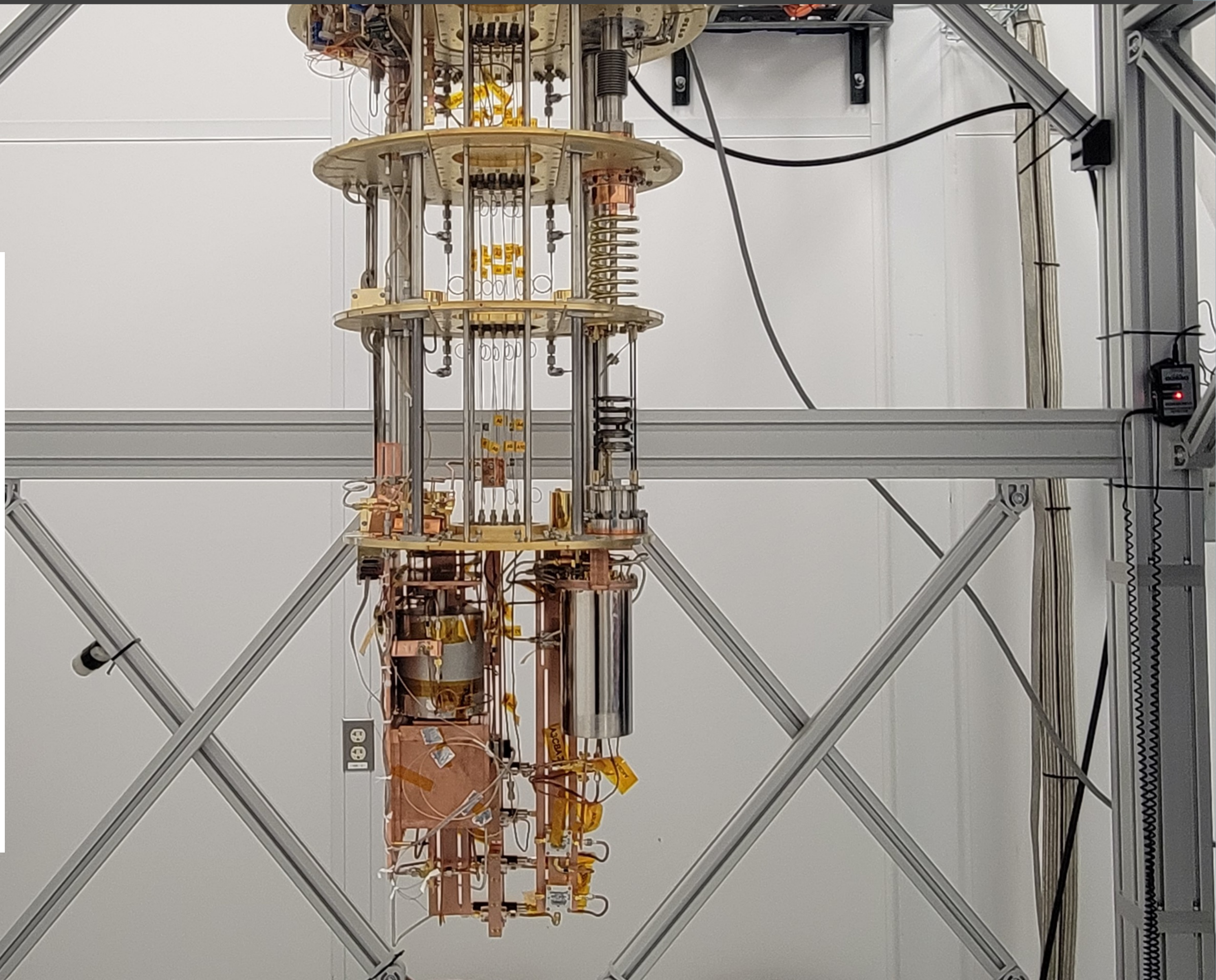
QUANTUM INFORMATION SCIENCE AT FERMILAB



Rakshya Khatiwada

Illinois Institute of technology

&

Fermilab

06/29/2023

OUTLINE

- **Quantum Science Program at Fermilab**

  → DOE Quantum Science Enabled Discovery (QuantiSED)

  → Quantum Science Center (QSC)

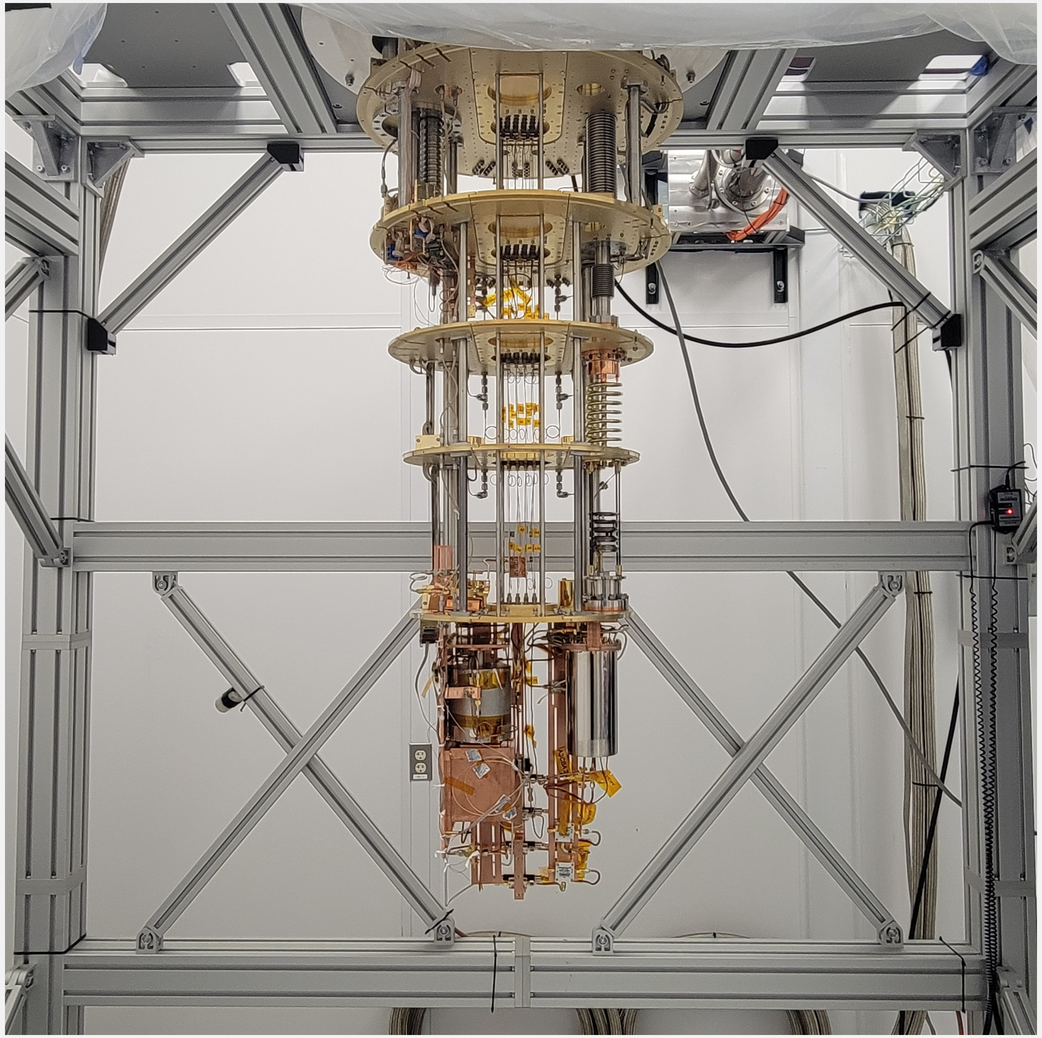
one of the five DOE Quantum Science Centers funded under National Quantum Initiative act passed by congress (2018). Led by Oak Ridge National Lab

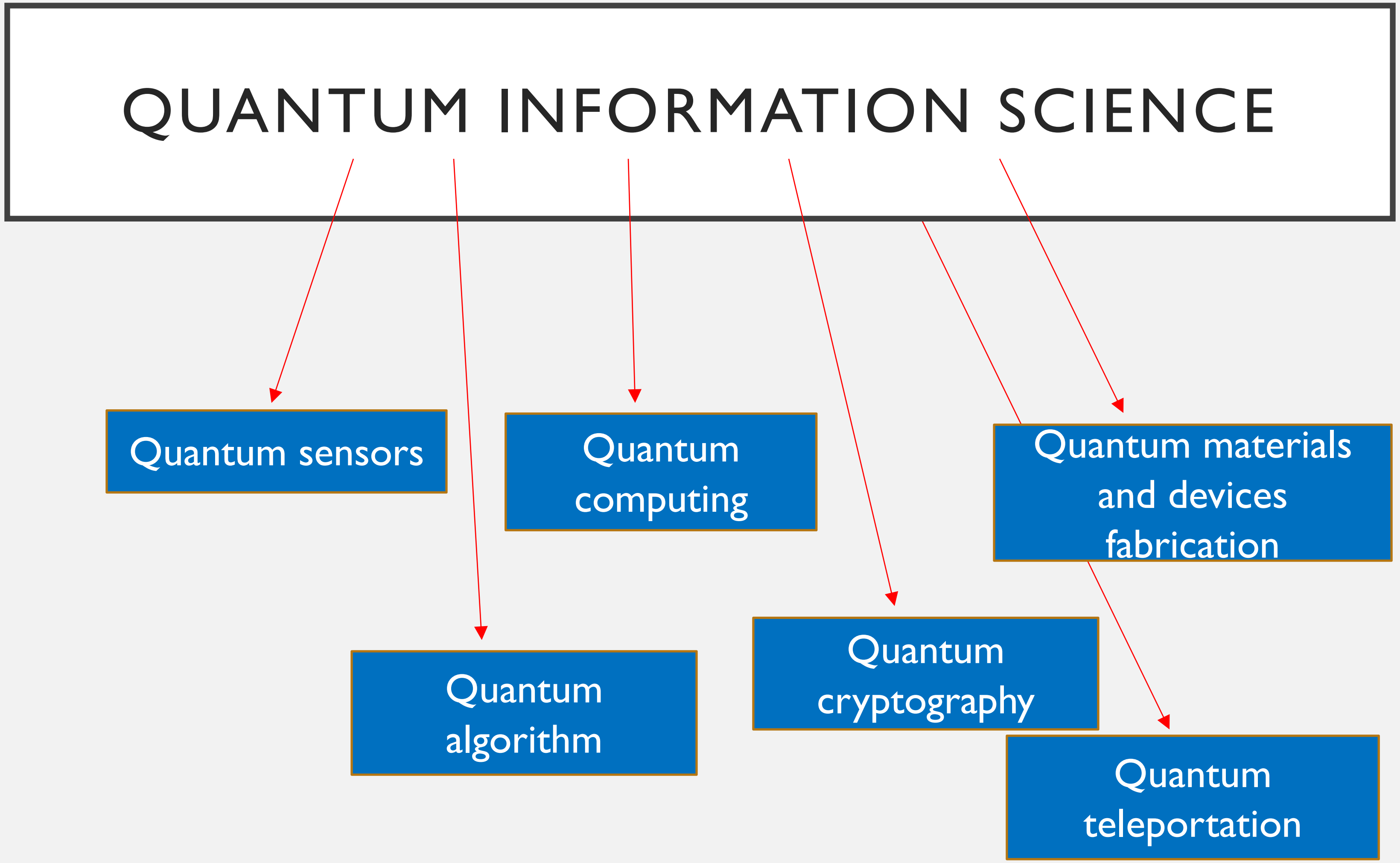
All of this is relatively new and very future focused!

"New Ideas for future projects at Fermilab"

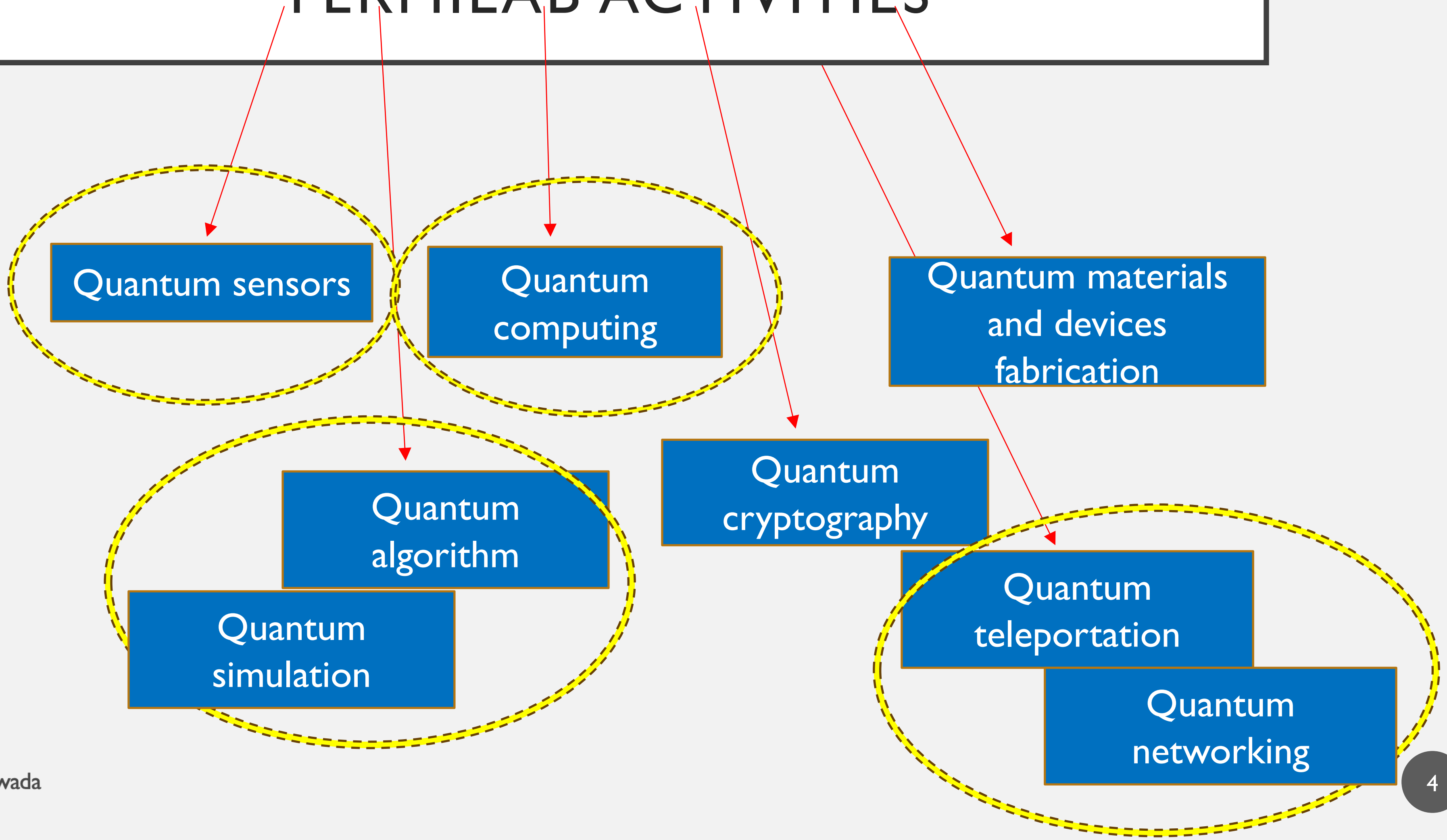
User's meeting 2023 theme

Rakshya Khatiwada




QUANTUM INFORMATION SCIENCE
Quantum sensors
Quantum computing
Quantum materials and devices fabrication
Quantum algorithm
Quantum cryptography
Quantum teleportation

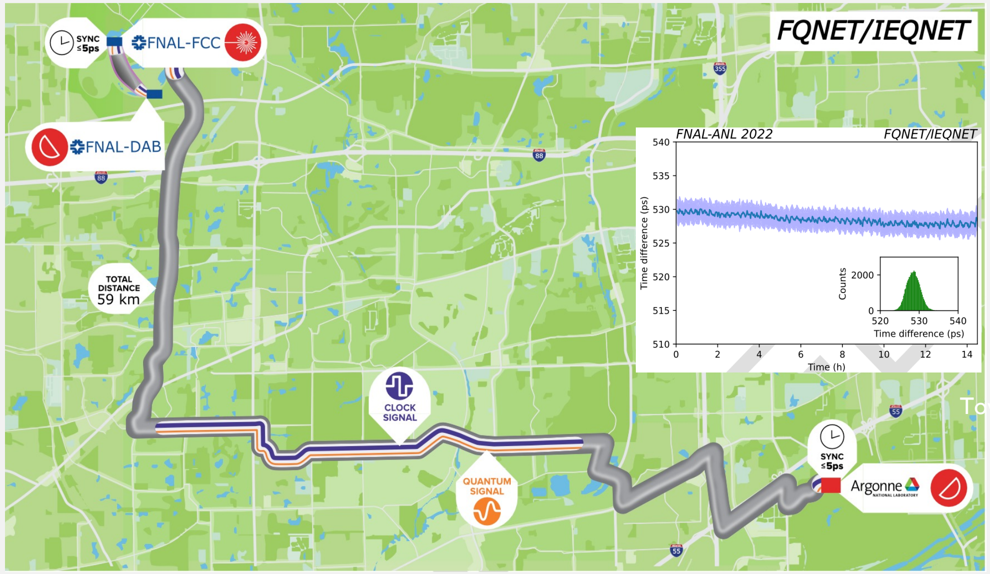
QUANTUM INFORMATION SCIENCE FERMILAB ACTIVITIES



FERMILAB QUANTUM NETWORK (FQNET)

QuantiSED

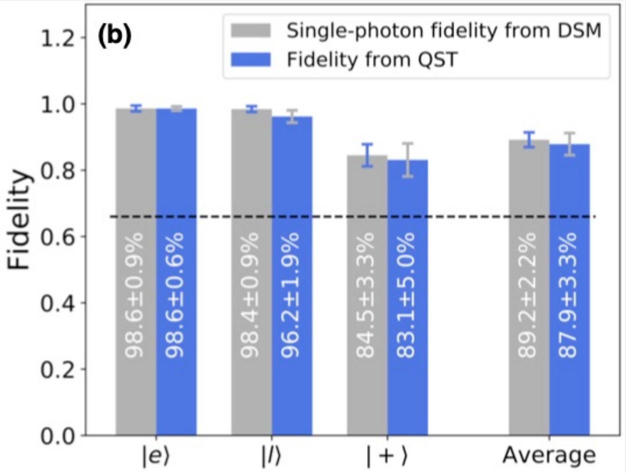
Picosecond level entanglement distribution and clock synchronization *EEE JQE 59*,1-7 (2023)
doi: 10.1109/JQE.2023.3240756



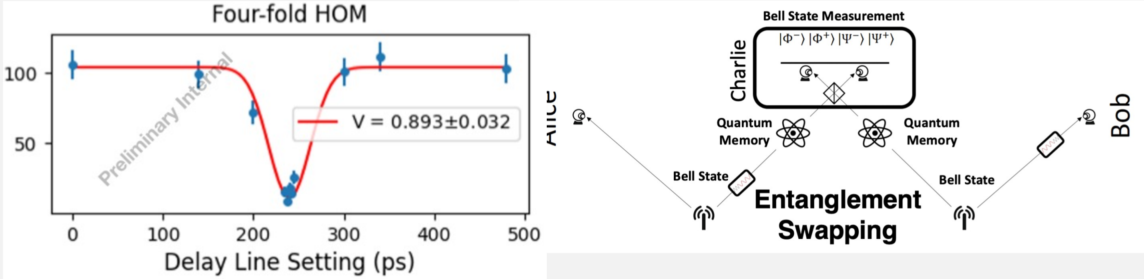
- → Collaboration: **FNAL, Argonne, Caltech, Northwestern University.**
- → Illinois Express Quantum Network (IEQNET)
- → Hosts **photonics and optical fiber based local quantum teleportation nodes**, between Chicagoland institutions
- → High fidelity **quantum teleportation was achieved between multiple nodes (50 km apart) at Argonne and Fermilab** (2022) using entangled photons
- → Picosecond level entanglement distribution and clock synchronization between two nodes.
- → **Step forward in building Quantum networking over metropolitan distances**

High-fidelity quantum teleportation
PRX QUANTUM ***1****, 020317 (2020)*

Quick-Quantum Network (QICK-QN): https://arxiv.org/abs/2304.01190



Teleportation of entanglement: entanglement swapping



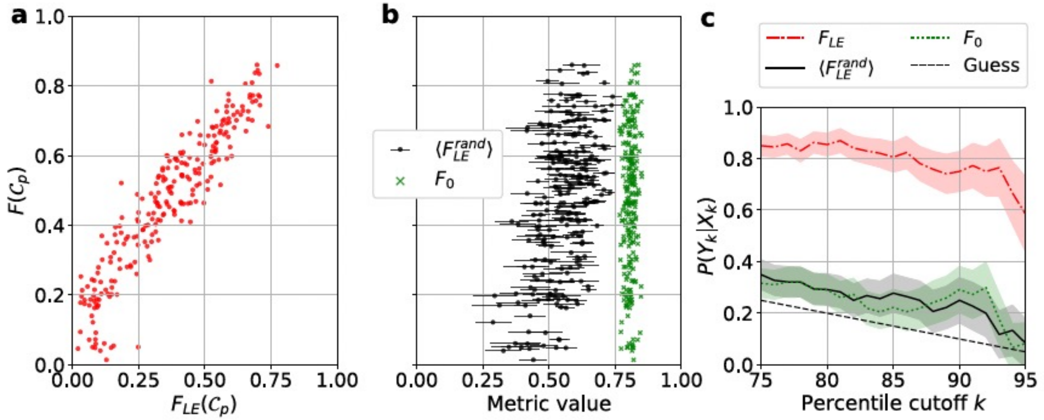
QUANTUM COMPUTING AND ALGORITHMS

https://doi.org/10.1103/PRXQuantum.3.040333

Qubit assignment using time reversal

Evan Peters,[1,2,3,*] Prasanth Shyamsundar,[1] Andy C. Y. Li,[1] and Gabriel Perdue[1,†]
[1] Fermi National Accelerator Laboratory, Batavia, IL 60510
[2] Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada
[3] Department of Physics, University of Waterloo, Waterloo, Ontario, N2L 3G1, Canada
(Dated: October 8, 2022)

- In order to run quantum circuits on hardware, we need to map logical qubits to the physical hardware (qubit assignment problem).
- For NISQ-era devices, we need to perform this task in a noise-aware manner.
- Sub-tasks:
  - Efficiently estimate the performance of different qubit choices (Loschmidt Echoes)
  - Efficiently search the space of possible qubit assignments (simulated annealing)

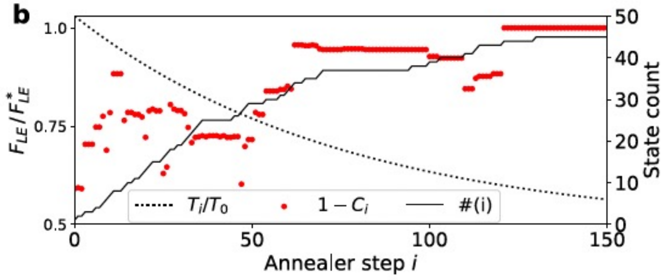


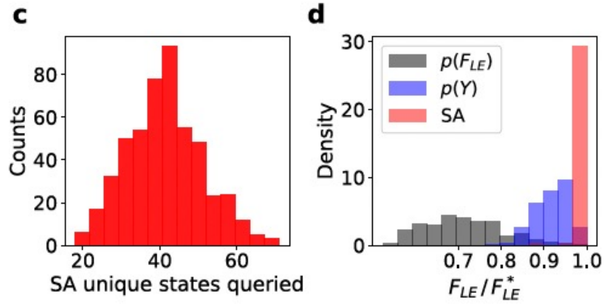
- 8 qubit GHZ circuit on Google Rainbow (23 qubits)
- Loschmidt Echo (red) fidelity estimator using the target circuit tracks more closely to true process fidelity for a given qubit assignment than a random circuit estimator (black) or historical calibration data (green).
- Far right plot shows the probability of an assignment truly being within the k[th] percentile of fidelities given a metic observation in the k[th] percentile.

Fermilab

DOE: Quantum Information Science Enabled Discovery (QuantISED)

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





- Simulated annealing is a good optimization strategy.
  - Top panel shows the performance progression one run of SA.
  - Bottom left shows the number of unique states queried in a 10,000 circuit simulation.
  - Bottom right shows the fidelities over all assignments (grey), random sampling (using SA query counts and keeping the best, blue) and simulated annealing (red)

QUANTUM SENSING

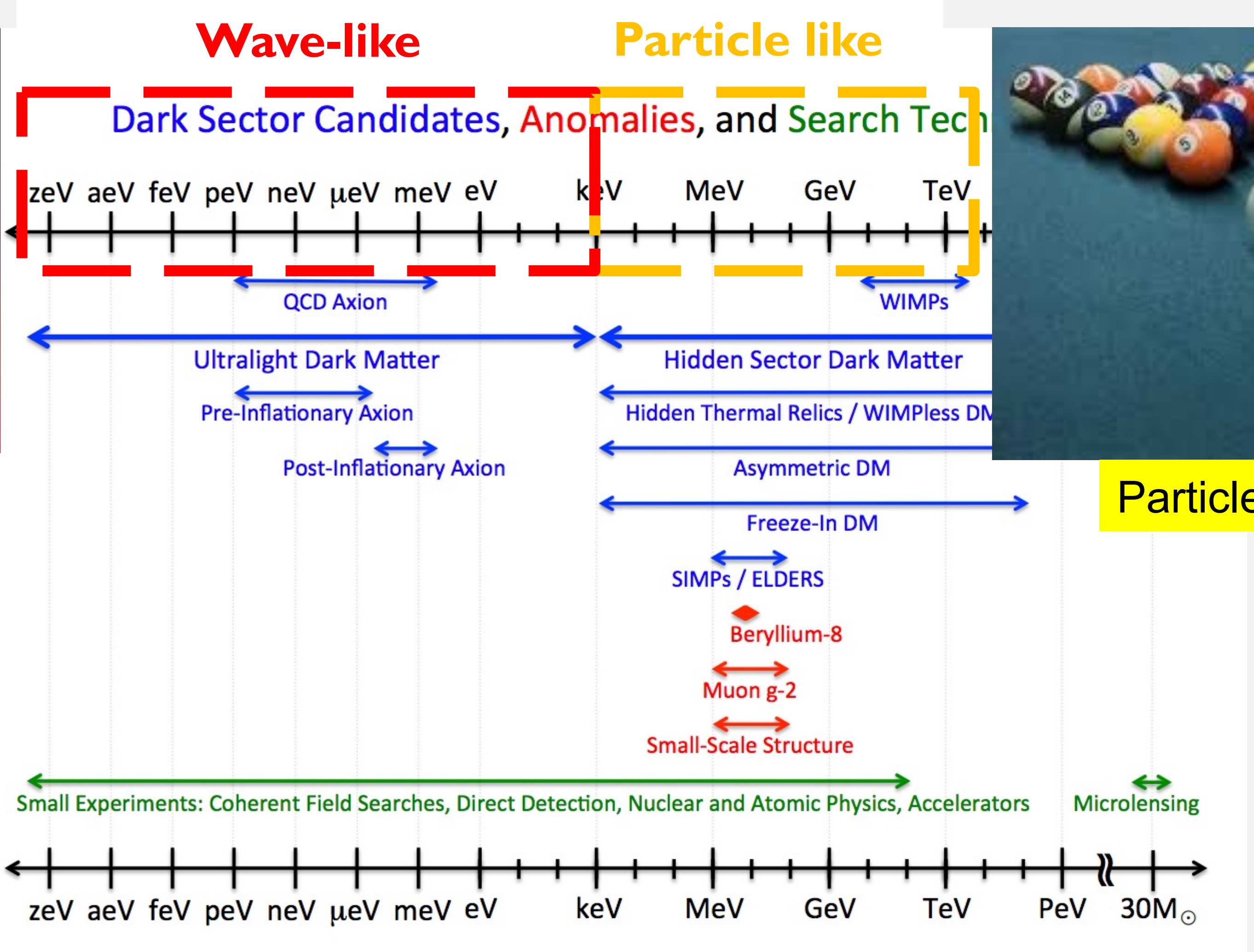
QUBIT BASED DETECTORS FOR ULTRALIGHT AND LIGHT DARK MATTER SEARCHES

ADVANTAGES OF QUBITS OVER CURRENT DARK MATTER SEARCH TECHNOLOGY

- ***Sensitivity to sub-eV energy threshold***
- Dark Matter can be coupled to ***phonons*** (lattice vibrations of the substrate) or ***as photon absorption*** in the superconducting part of qubit
- ***Broken cooper pairs generated in the qubit when $E > 2\Delta$*** (superconducting bandgap energy) → ***can be used as Dark Matter signal***
- ***Easy signal readout*** with a qubit readout protocol (T_1, T_2, charge parity measurements)
- Qubit superconducting systems in ***mK cryostat***, ideal for ***thermal noise reduction*** for Dark Matter searches.

DARK MATTER CANDIDATES

Wave like DM



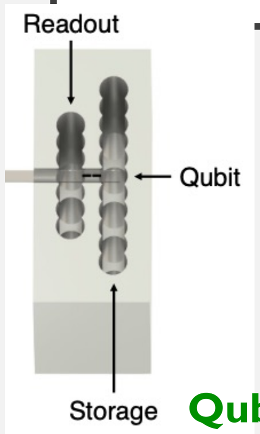
Particle like DM

WHAT HAS BEEN DEMONSTRATED WITH QUBIT BASED DARK MATTER DETECTORS?

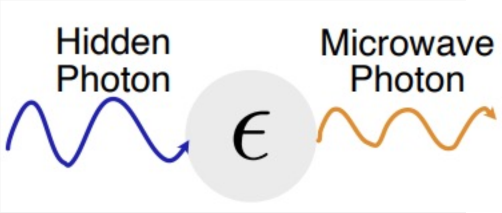
HIDDEN PHOTON DARK MATTER SEARCH WITH QUBITS
PROTOTYPE DEMONSTRATION

QuantiSED

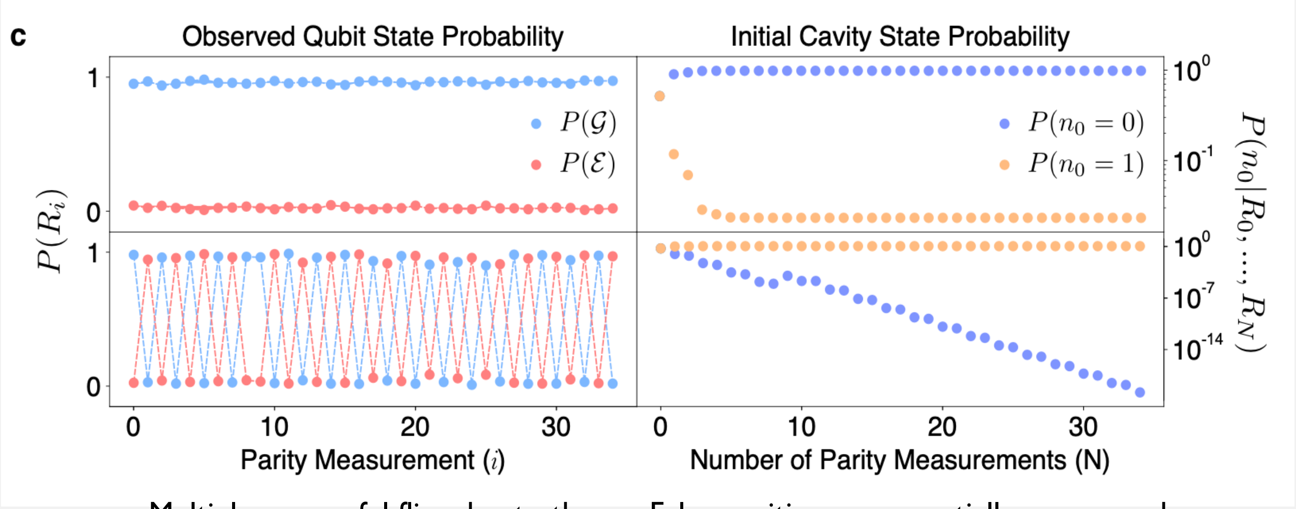
U Chicago/FNAL



Aluminum cavity
Q~10^7
ω_r~ 8 GHz
ω_s~ 6 GHz
ω_q ~ 4.5 GHz



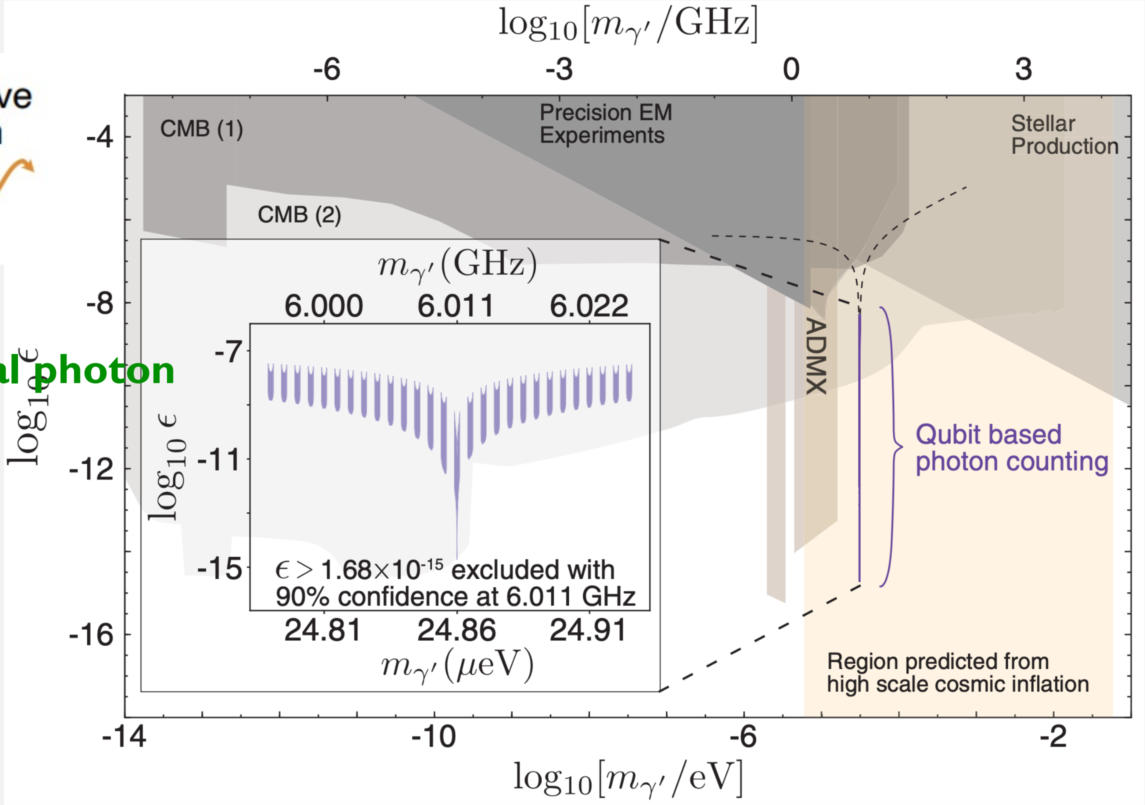
Qubit + 3D cavity – qubit excited state probability due to presence of a DM signal photon



Multiple successful flips due to the presence of a photon

False positives exponentially suppressed due to repeated measurements

Rakshya Khatiwada



Hidden photon world limits set by qubits in 8 s integration time

Phys. Rev. Lett. **126**, 141302

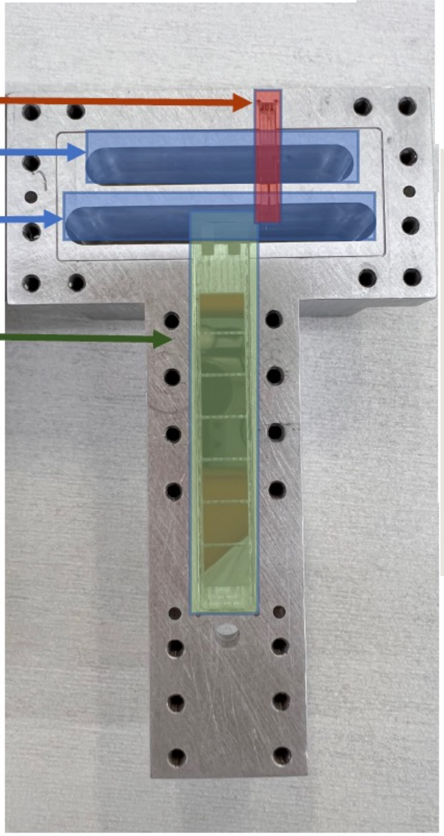
HEISING-SIMONS FOUNDATION

NOVEL TECHNOLOGY DEVELOPMENT UTILIZING QUANTUM TOOLS

QuantiSED

Dark Matter:
Hidden Photons
Axions

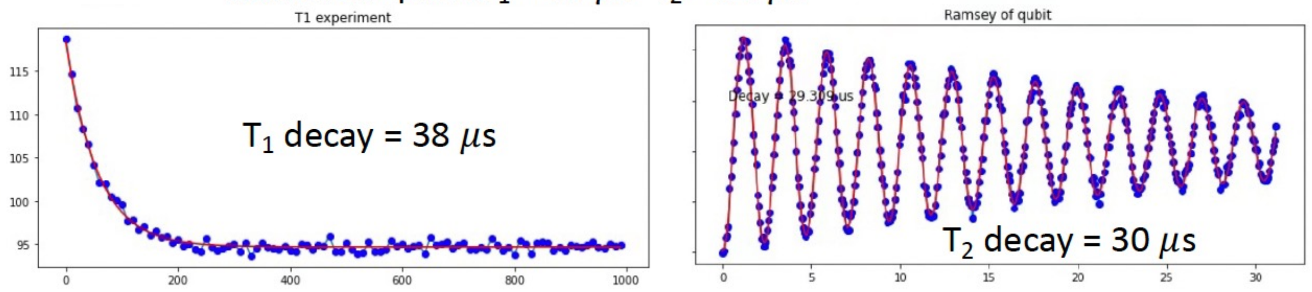
Superconducting Quantum Interference Device (SQUID) tunable cavity



How to tune the cavity frequency to match the Dark Matter mass?

Flux biased SQUID
→ coupled to cavity
→ tunes the frequency

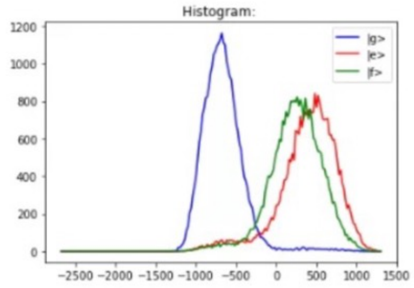
Transmon qubit: T_1 = 38 μs T_2 = 30 μs

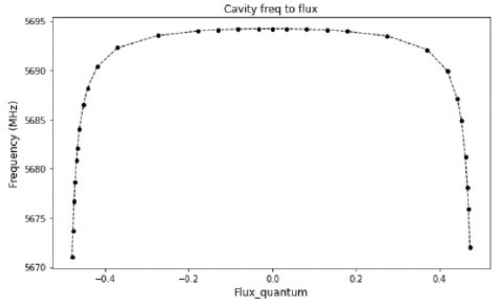


Hidden photon Dark Matter Search prototype demonstrated using qubits (2021)
→ making the cavity tunable now

Searching for Dark Matter with a Superconducting Qubit

Akash V. Dixit, Srivatsan Chakram, Kevin He, Ankur Agrawal, Ravi K. Naik, David I. Schuster, and Aaron Chou
Phys. Rev. Lett. **126**, 141302 – Published 8 April 2021



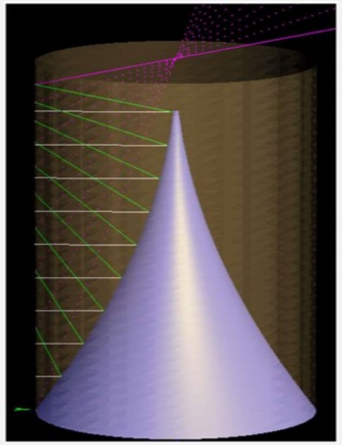


DARK MATTER DETECTOR R&D

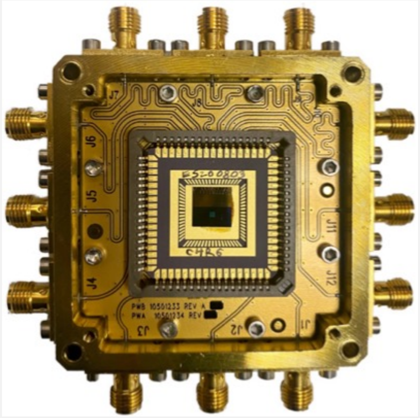
QuantiSED

Broadband Axion Antenna (BREAD) and **Superconducting Nanowire Single Photon Detector** for Dark Matter

SNSPD R&D for axion detection experiments *Appl. Phys. Lett.* 122, 243506 (2023)



BREAD concept

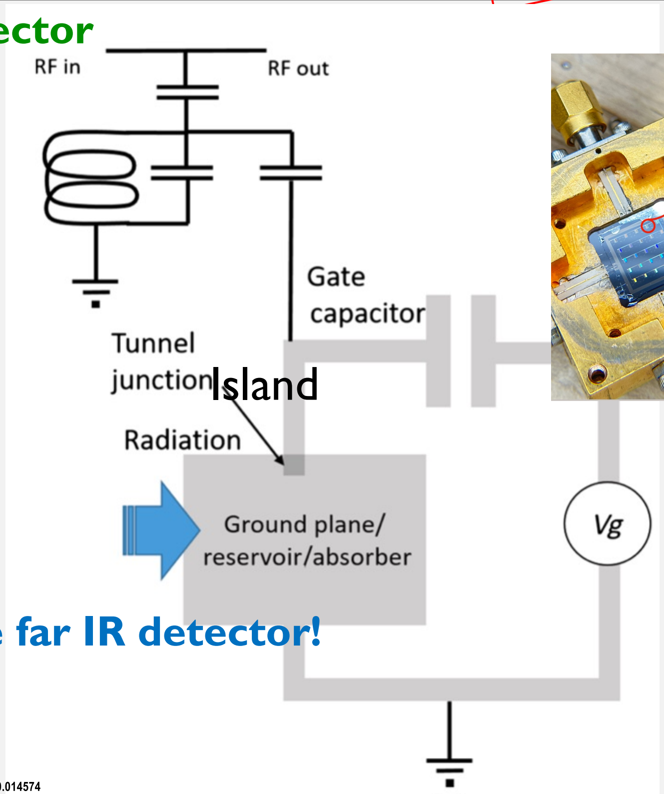


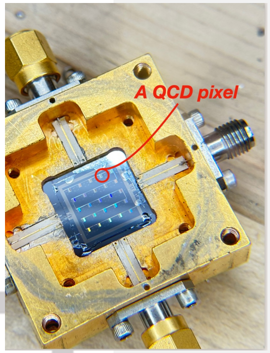
SNSPD

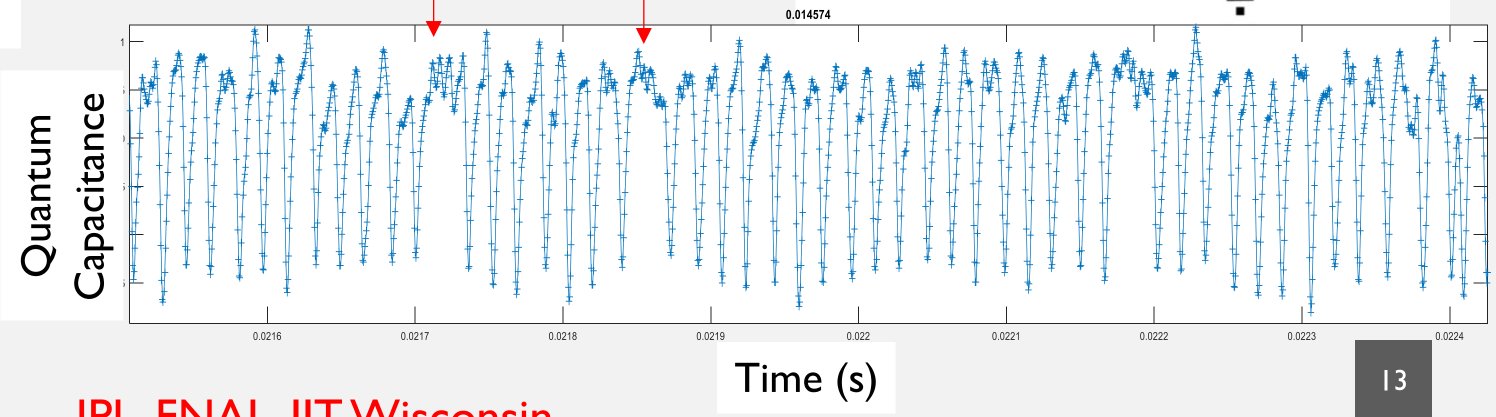
Caltech, JPL, FNAL etc.

Quantum Capacitance Detector (QCD)

- 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!**







JPL, FNAL, IIT, Wisconsin

QUANTUM SCIENCE CENTER (QSC)

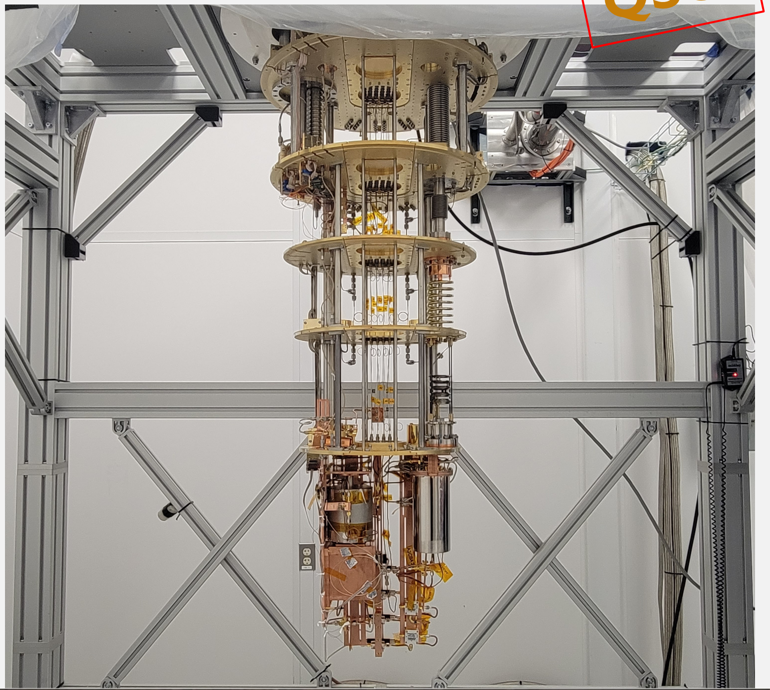
→***High throughput cryogenic facility*** for development and readout of ***large arrays of quantum sensors*** (Commissioned Fall 2022)

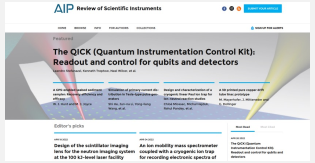
→***Dark Matter and radiation sensing with sub-eV single photon/phonon resolution*** qubit-based sensors

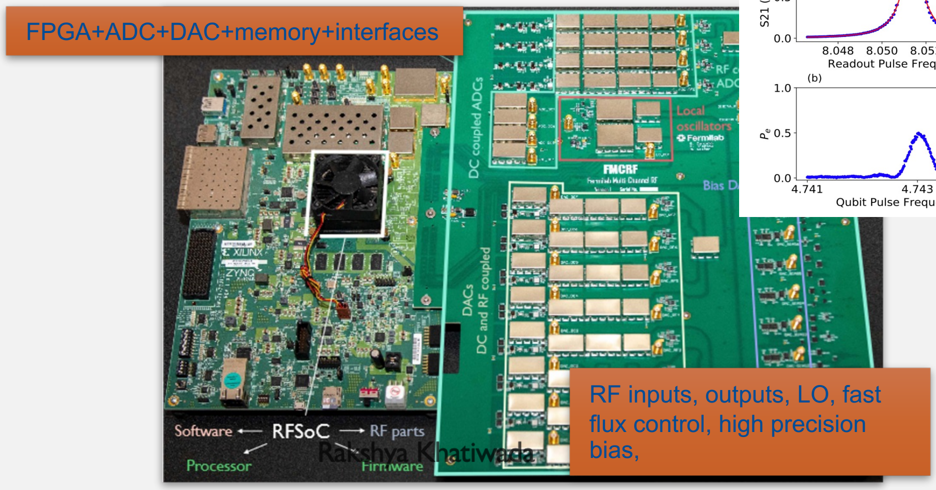
→multiplexed readout of array of quantum sensors using FNAL developed ***Quantum Instrumentation Control Kit (QICK)*** based on Radio Frequency on Chip (RFSoC) fpga technology.

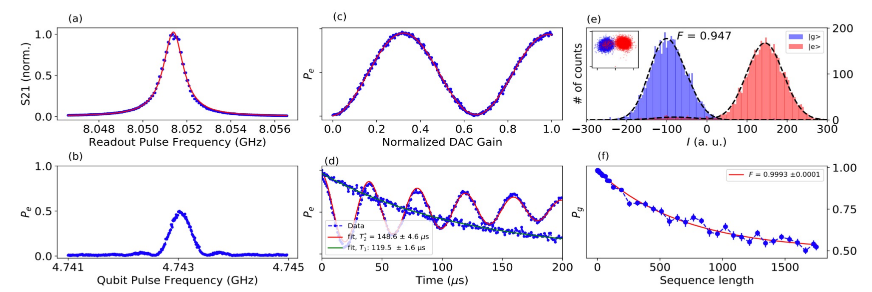
- **>30 labs in the US and abroad**
- **20 science talks in APS March meeting!**

SiDet Lab G







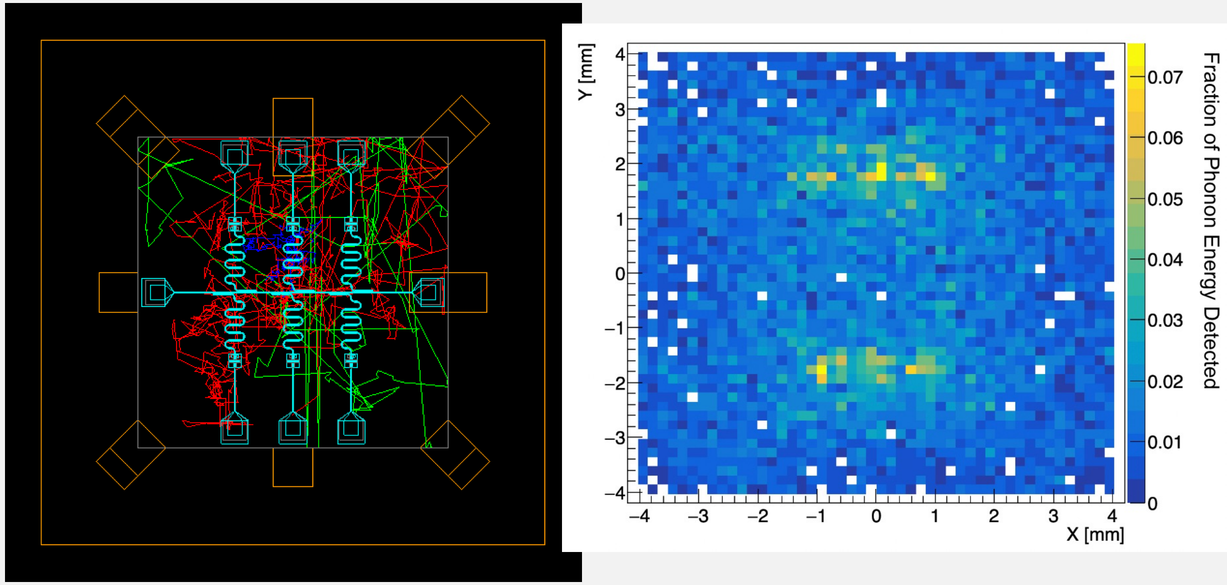


Qubit readout using QICK

Open source: including hardware schematics/layout firmware, software. See https://github.com/openquantumhardware

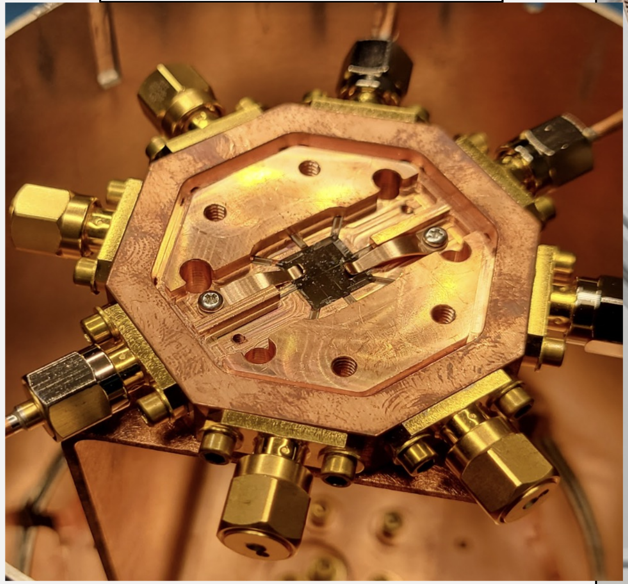
UNDERSTANDING ENERGY DISSIPATION IN QUBITS

- Investigate **~ eV energy dissipation through e + h and phonon production**
- Simulation effort on **charge transport and phonon kinematics in Si**.
- Application of particle physics **simulation tools like G4CMP to understand qubits** (various substrates and geometry)
- Cryogenic photon source development (**0.62 – 6.9 eV**)

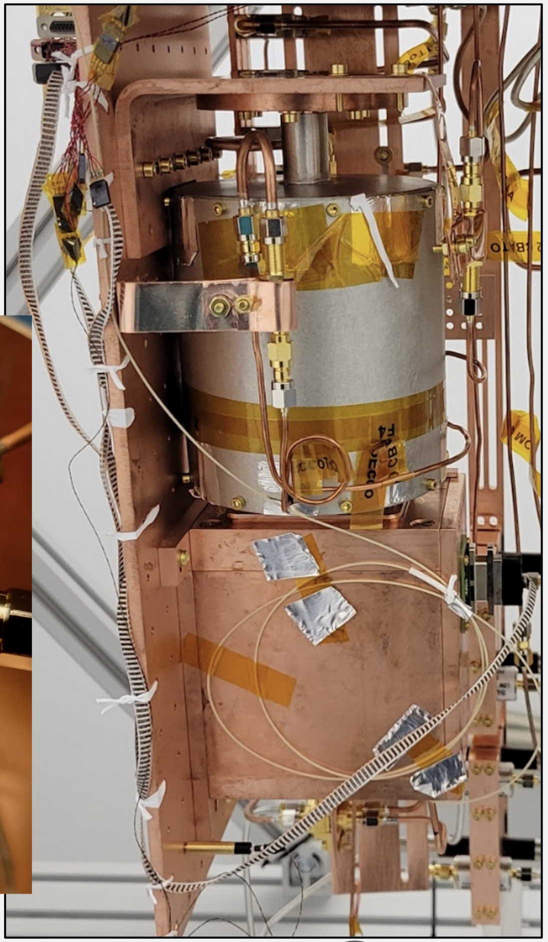


phonon simulation in a 6-qubit silicon chip using G4CMP

6 qubit chip (Si)



MEMS cryogenic photon source

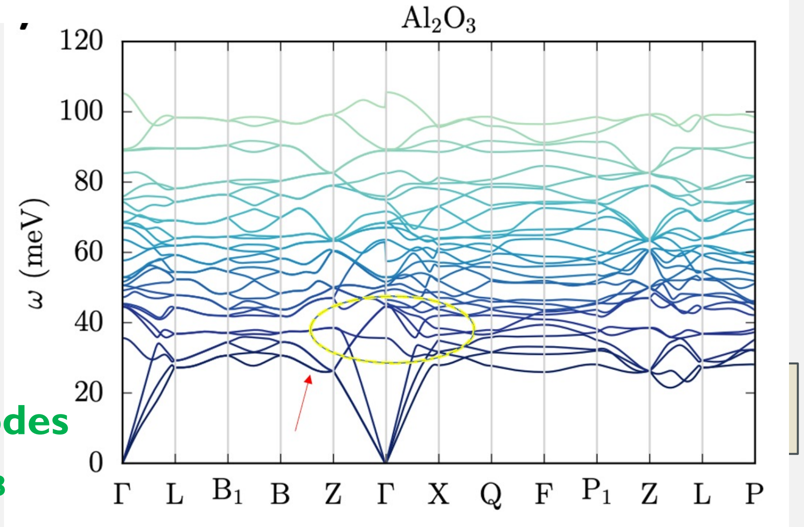


(1.3.3.02)

QUBITS FOR LOW ENERGY THRESHOLD DARK MATTER DETECTION

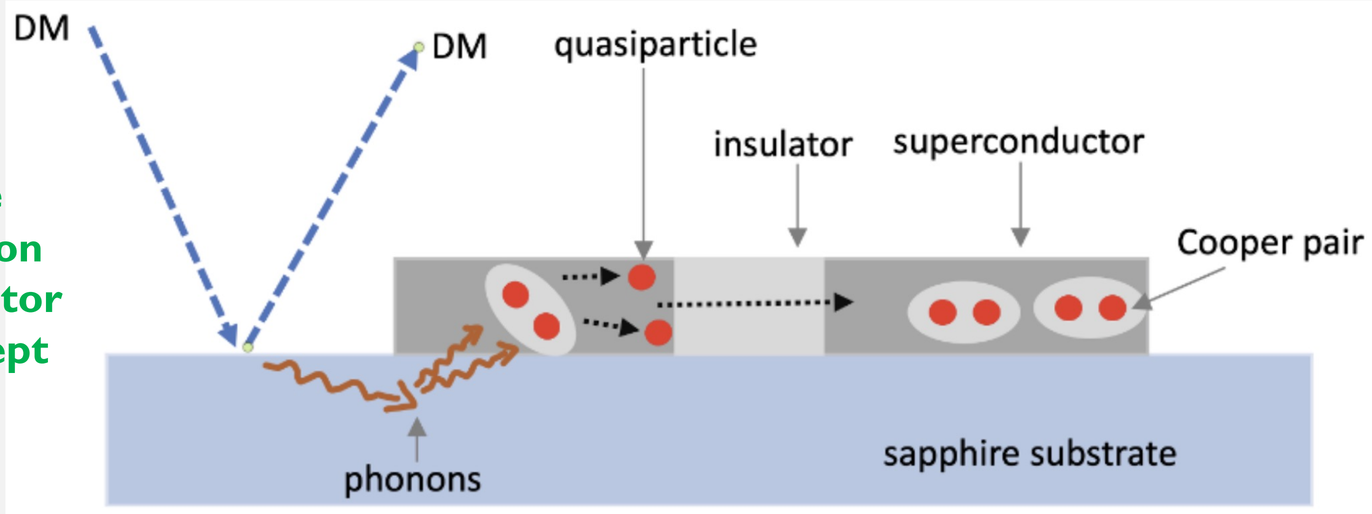
- **Single phonon detectors for Dark Matter** using Al_2O_3 qubits
- **Sub-eV sensitivity** (100 - 40 meV optical phonons)
- Dark Matter → optical phonons in Al_2O_3 → phonon down-conversion → phonon propagation to Al → broken Cooper pairs in Al → qubit readout protocol → Dark Matter signal
- 4 qubit chip from Purdue University
- QICK + RFSoC + RF boards readout in progress (done by end of this year)
- Early Career effort of Khatiwada supported by QSC

Phonon modes In Al_2O_3

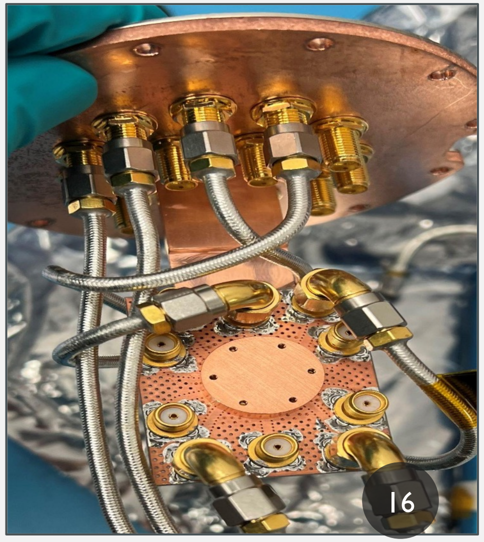


Brillouin zones

single Phonon detector concept



4 qubit chip array In LOUD



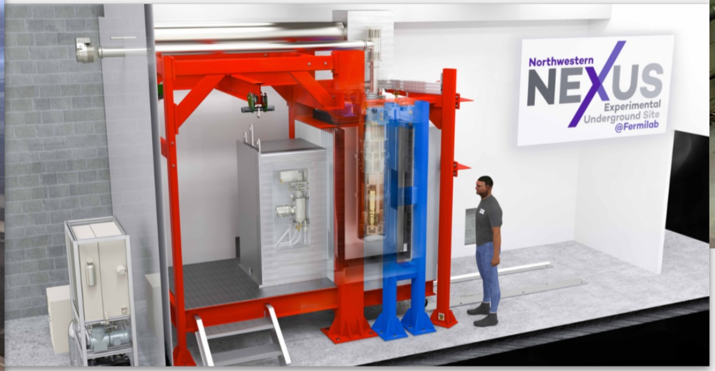
(1.3.3.02)

UNDERGROUND, LOW BACKGROUND FACILITY AT FERMILAB FOR FUNDAMENTAL SCIENCE

UNDERGROUND FACILITY AT FERMILAB

Neutrino tunnel at Fermilab: perfect place to study radiation effects on qubits

NEXUS facility for SuperCDMS



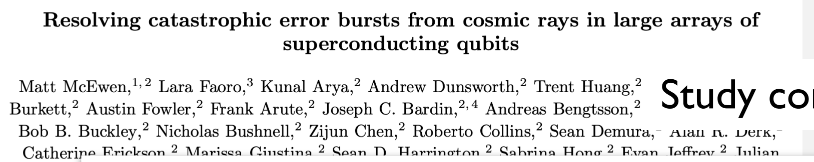
QUIET low background facility by Quantum Science Center (QSC)

Dark Matter

Impact of radiation in superconducting detectors

IMPACT OF COSMIC AND TERRESTRIAL RADIATION ON QUANTUM COMPUTERS

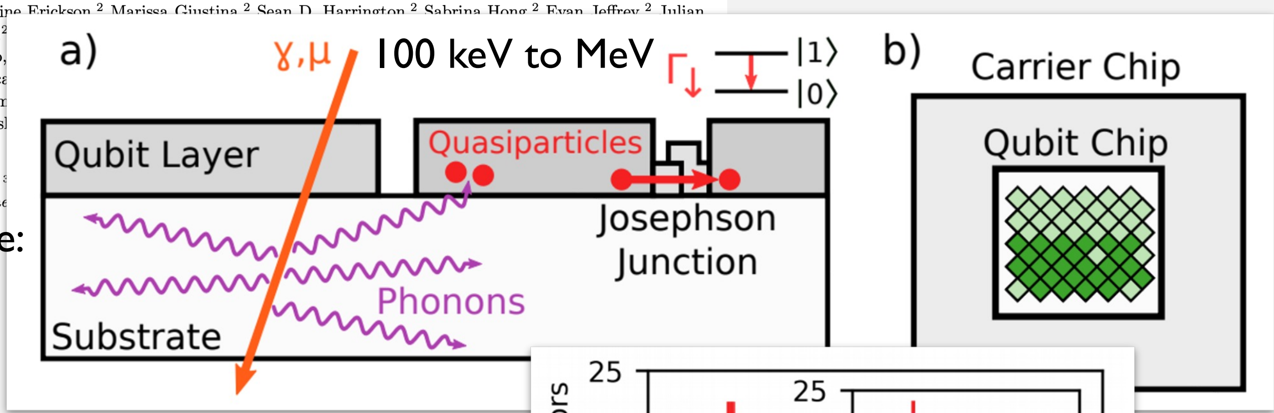
High energy radiation: source of quasiparticle in qubits



Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits

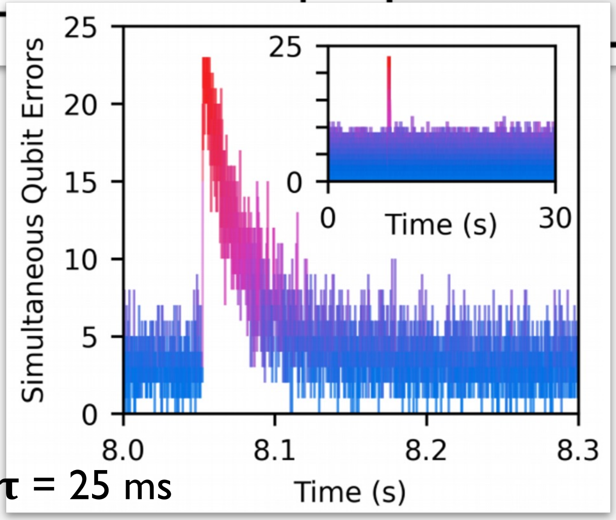
Matt McEwen,[1,2] Lara Faoro,[3] Kunal Arya,[2] Andrew Dunsworth,[2] Trent Huang,[2] Burkett,[2] Austin Fowler,[2] Frank Arute,[2] Joseph C. Bardin,[2,4] Andreas Bengtsson,[2] Bob B. Buckley,[2] Nicholas Bushnell,[2] Zijun Chen,[2] Roberto Collins,[2] Sean Demura,

Study context: Quantum Error Correction



event rate: 1/7.6 s & 1/38 s

muon or **γ** absorption
↓
phonon reservoir Si substrate
↓
Phonons break cooper pair
↓
quasiparticle tunnel to the junctions
↓
qubit decoherence



τ = 25 ms

https://arxiv.org/abs/2104.05219

Why should we care?

- Building superconducting devices (qubit) based experiment for DM
- Need to decrease dark rate of available SPD
- Hasn't been studied in detail before

- Direct measurement on google processor
- Non localized impact of radiation in qubit (quasiparticle absorb qubit energy and cause excited state to decay)
- Suppressed T_1 throughout the device
- **Mitigation:** shielding, underground operation quasiparticle and phonon traps being studied

SUMMARY

- Various activities under Quantum Information Science at FNAL

  → **FNAL at the forefront of novel Quantum Science based research**

- **Aboveground and Underground cryogenic facilities at Fermilab** great platforms for studies of impact of radiation in superconducting devices and quantum sensing for Fundamental science
- **Dark Matter community developed resources and expertise** being utilized for Quantum Science research
- These **activities expected to expand further** in the coming years

ACKNOWLEDGEMENT

DOE-OHEP-QuantiSED

QUANTUM SCIENCE CENTER

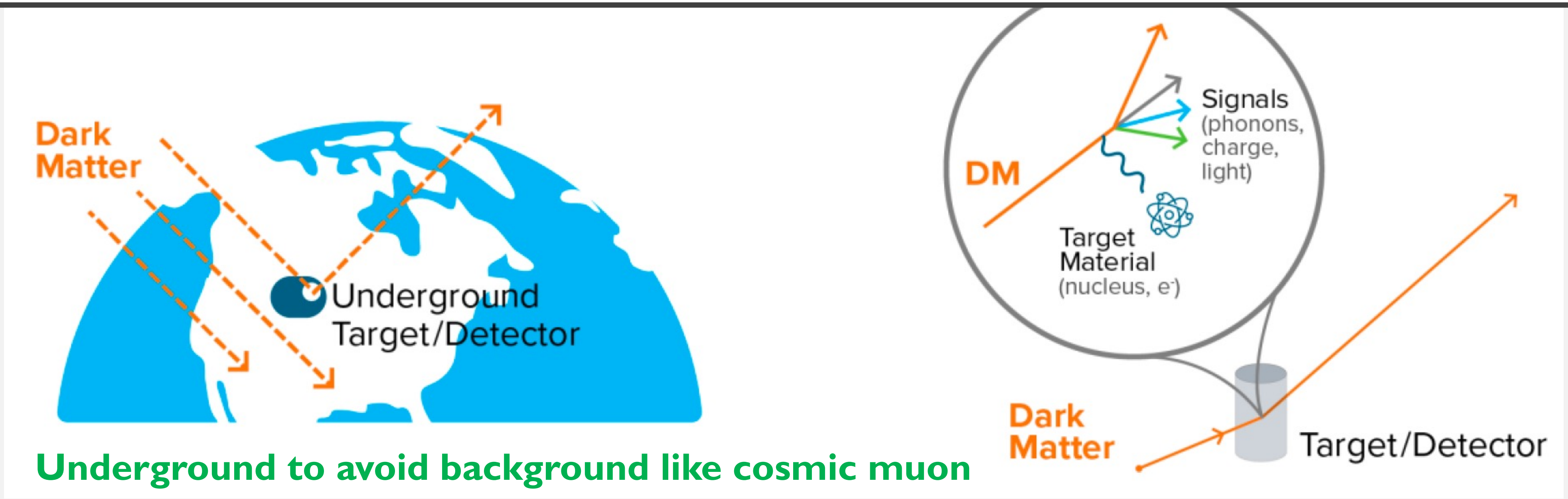
U.S. DEPARTMENT OF ENERGY | Office of Science

This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Quantum Science Center.

Fermilab

- This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

PARTICLE LIKE DARK MATTER SEARCH OVERVIEW



Processes:

--*DM Scattering off of nuclei*

--*DM Scattering off of electrons*

*Fraction of DM Energy transferred to the target material (nuclear, electron recoil)

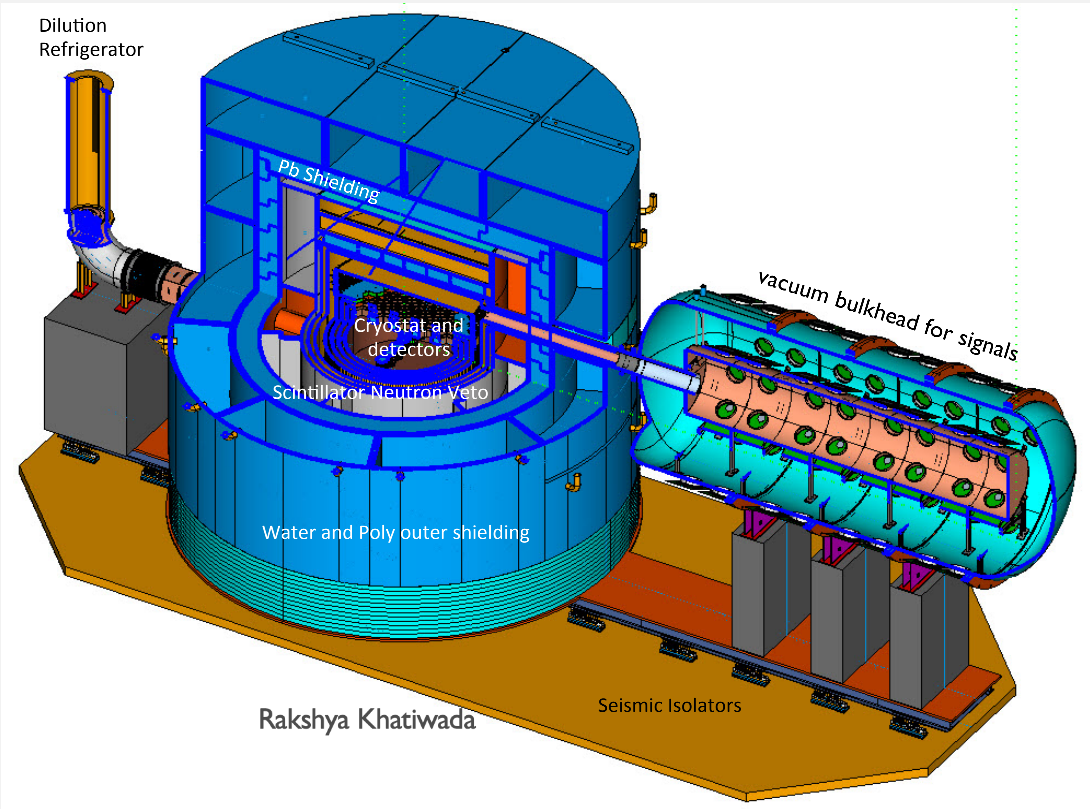
--*Absorption of DM*

DM Energy absorbed by the target material

SOME EXPERIMENTS

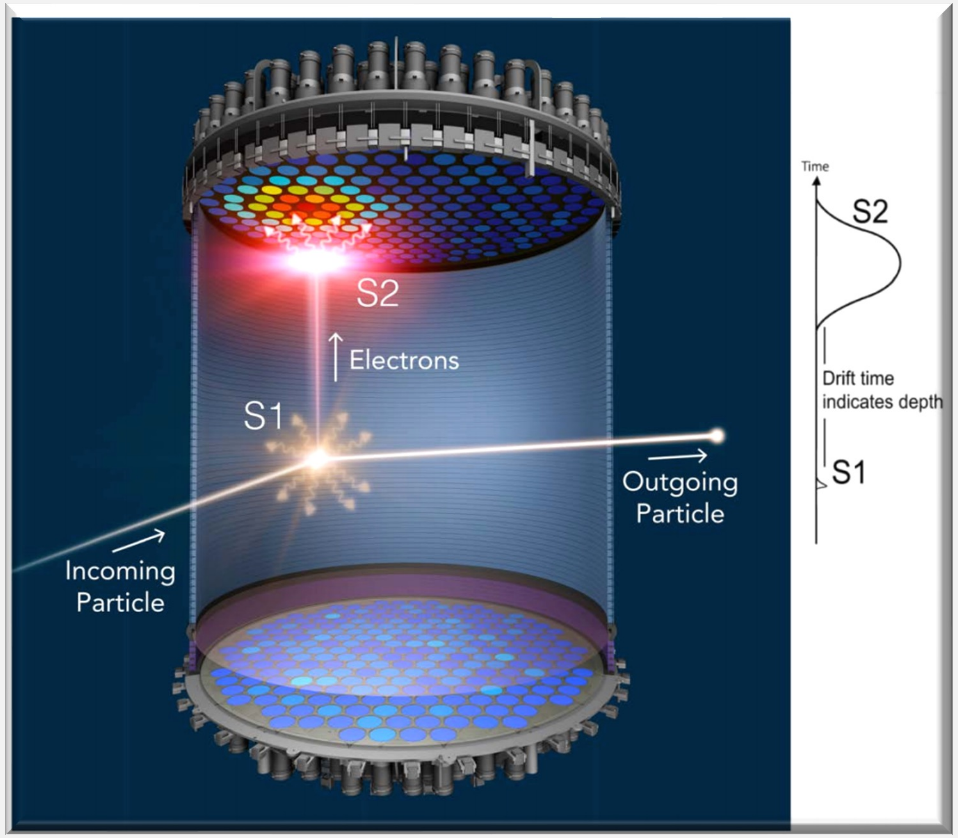
Super-CDMS-SNOLAB

-- DM-nuclei scattering (signal nuclear recoil) produces phonons (Ge/Si crystal lattice vibrations) and electrons through ionization (charge)



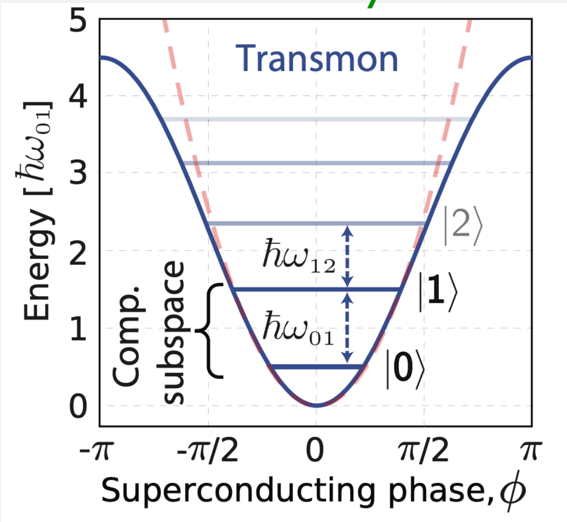
LZ (LUX-ZEPLIN)

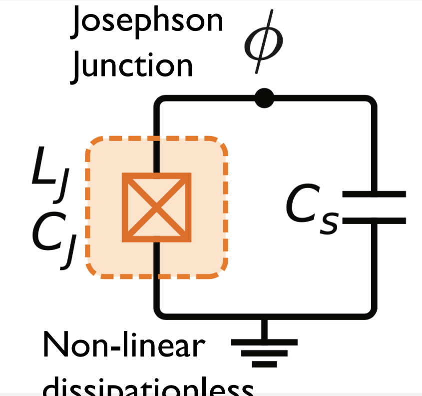
-- DM-Xe nuclei interaction produces electrons through ionization and photons that drift to the top causing flash of light (PMT)



WHAT IS A QUBIT?

two level system



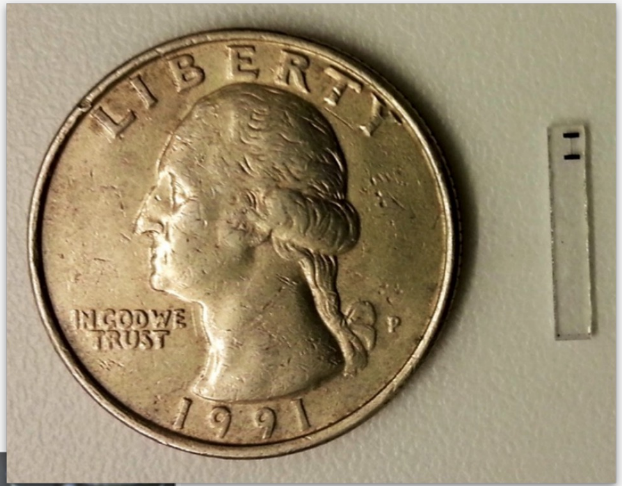


$E_J \gg E_C$

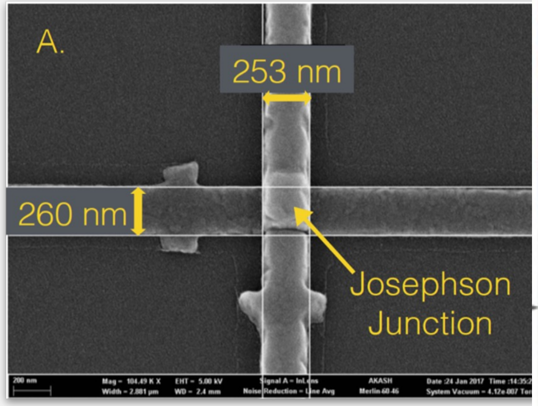
$E_c = e^2/2C$ charging energy

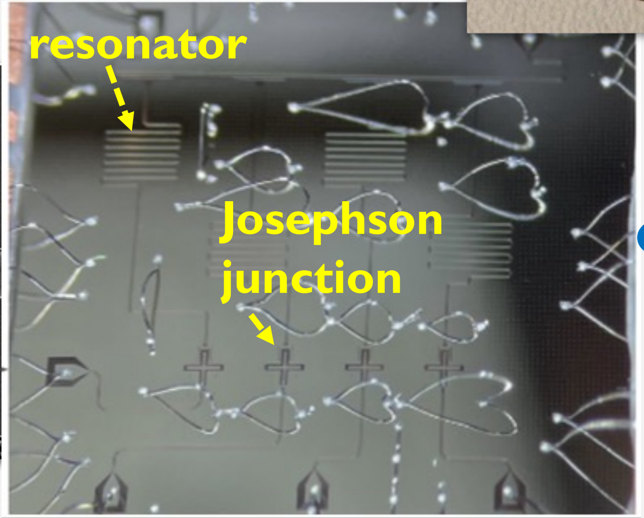
$E_J = I_c\Phi_0/2\pi$ Josephson energy

where Φ_0 = h/2e magnetic flux quantum



Quadratic energy potential of QHO reshaped by Josephson Inductance to sinusoidal potential



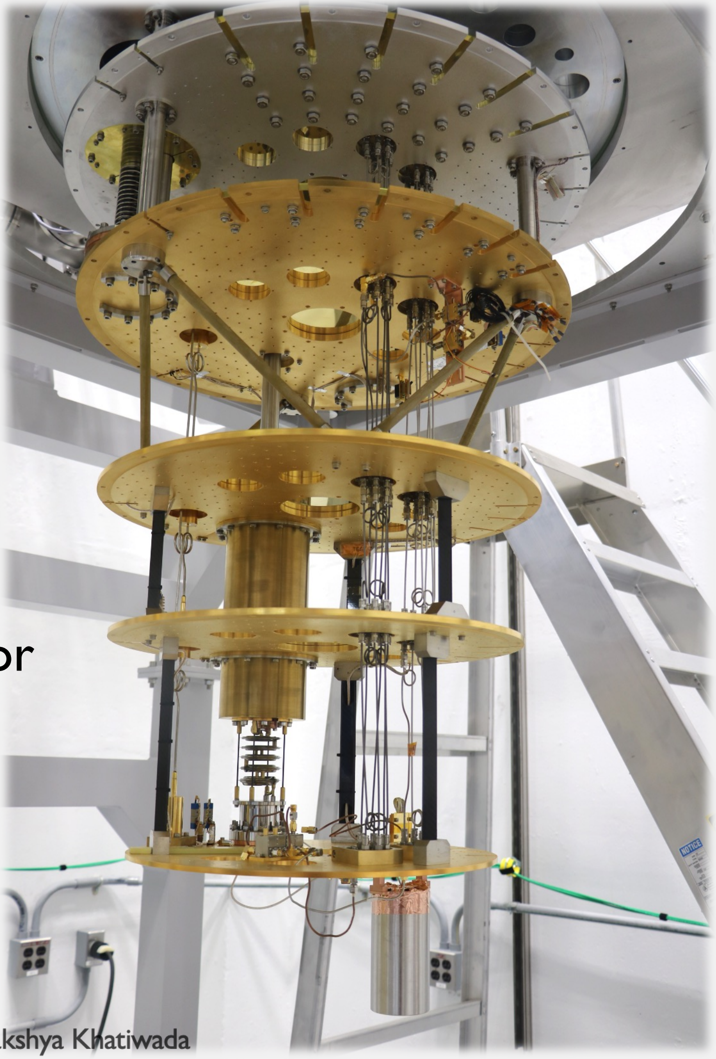


Qubit and resonator circuit on a Si substrate

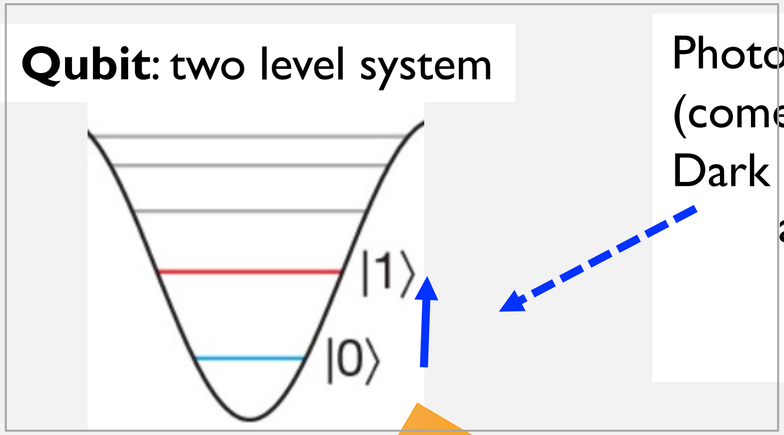
--Superconducting Transmon and its variants ***can be utilized for Dark Matter detection through several mechanisms of coupling***

App. Phys. Rev., **6**, 2, 10.1063 (2019).

DETECTING DARK MATTER WITH QUBITS

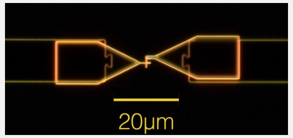


Dilution Refrigerator based at Fermilab



Photon (comes from Dark matter axion)

Readout using a coupled cavity



Superconducting Josephson junction

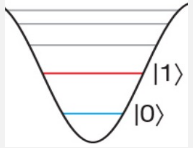
copper cavity

QUBIT BASED WAVE-LIKE DARK MATTER SEARCH

$$H = \omega_c a^\dagger a + \omega_q \sigma_z + 2\frac{g^2}{\Delta} a^\dagger a \sigma_z$$

Cavity
Harmonic
Oscillator

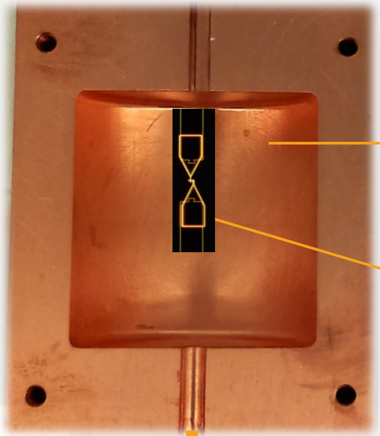
qubit
two level system



mixed state
g ~ **d.E**:
Δ: ω_q-ω_c
g^2/Δ: Stark shift

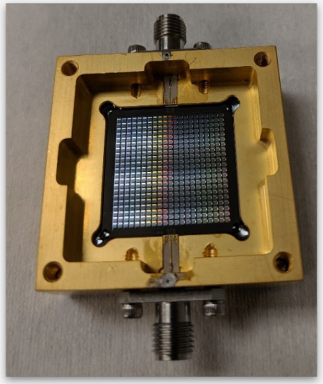
Qubit detector

excellent photon detector

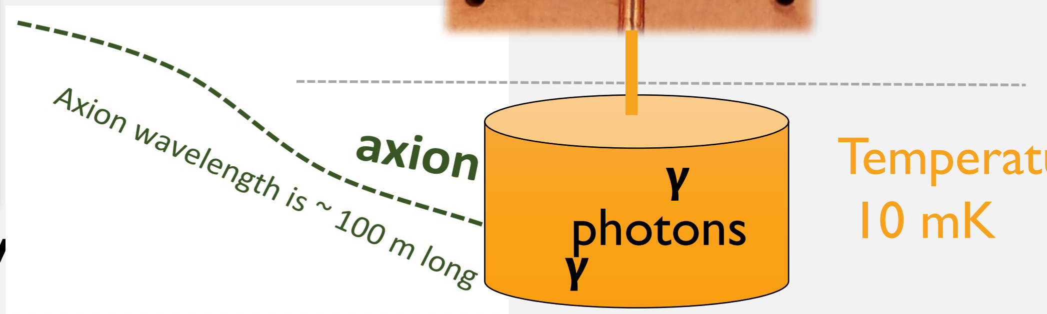


readout cavity

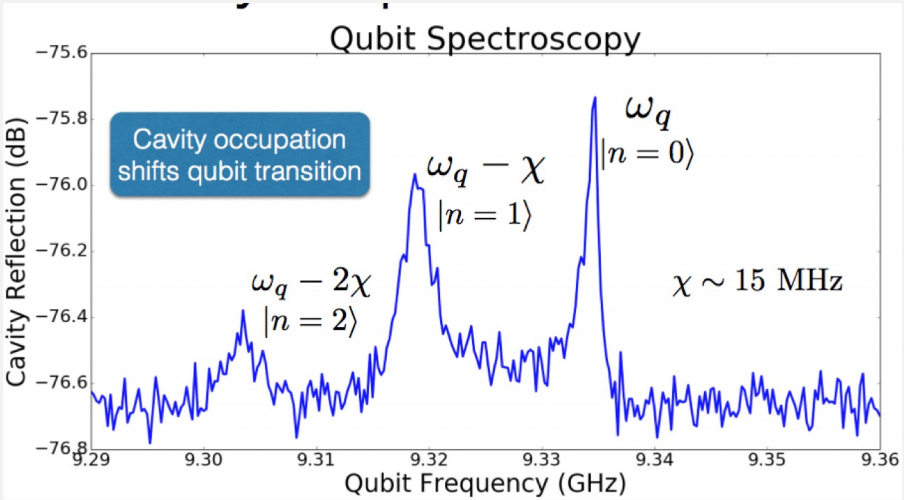
qubit



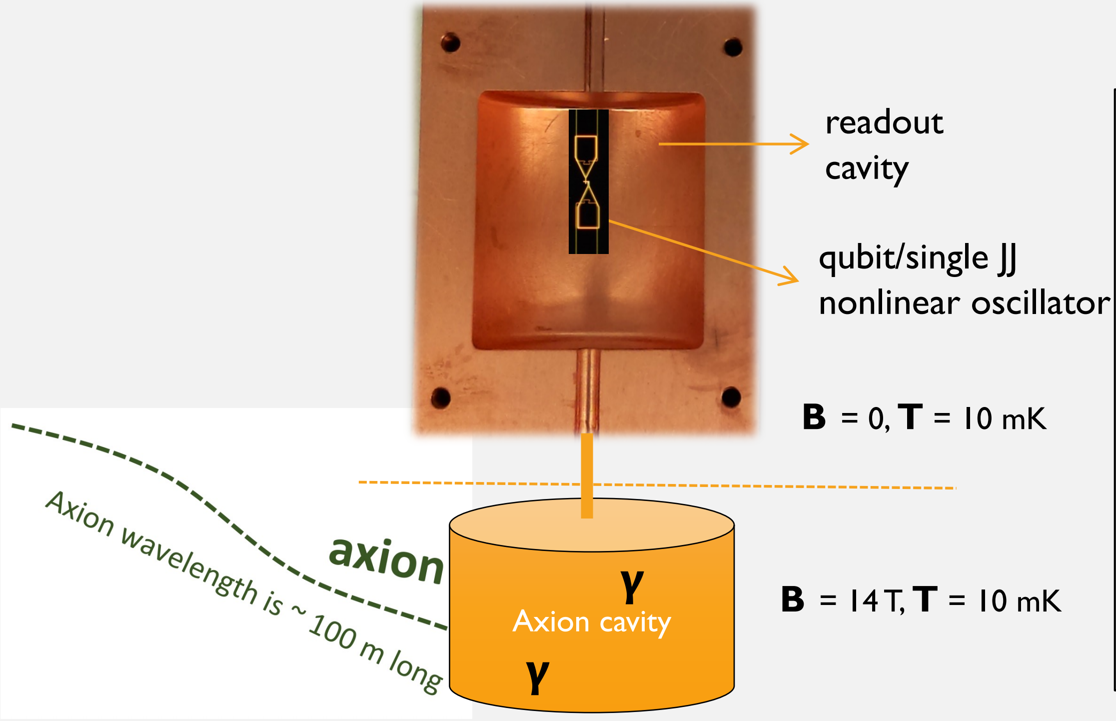
Qubit array



Temperature
10 mK



QUBIT BASED AXION DETECTOR



Ways of enhancing the signal:

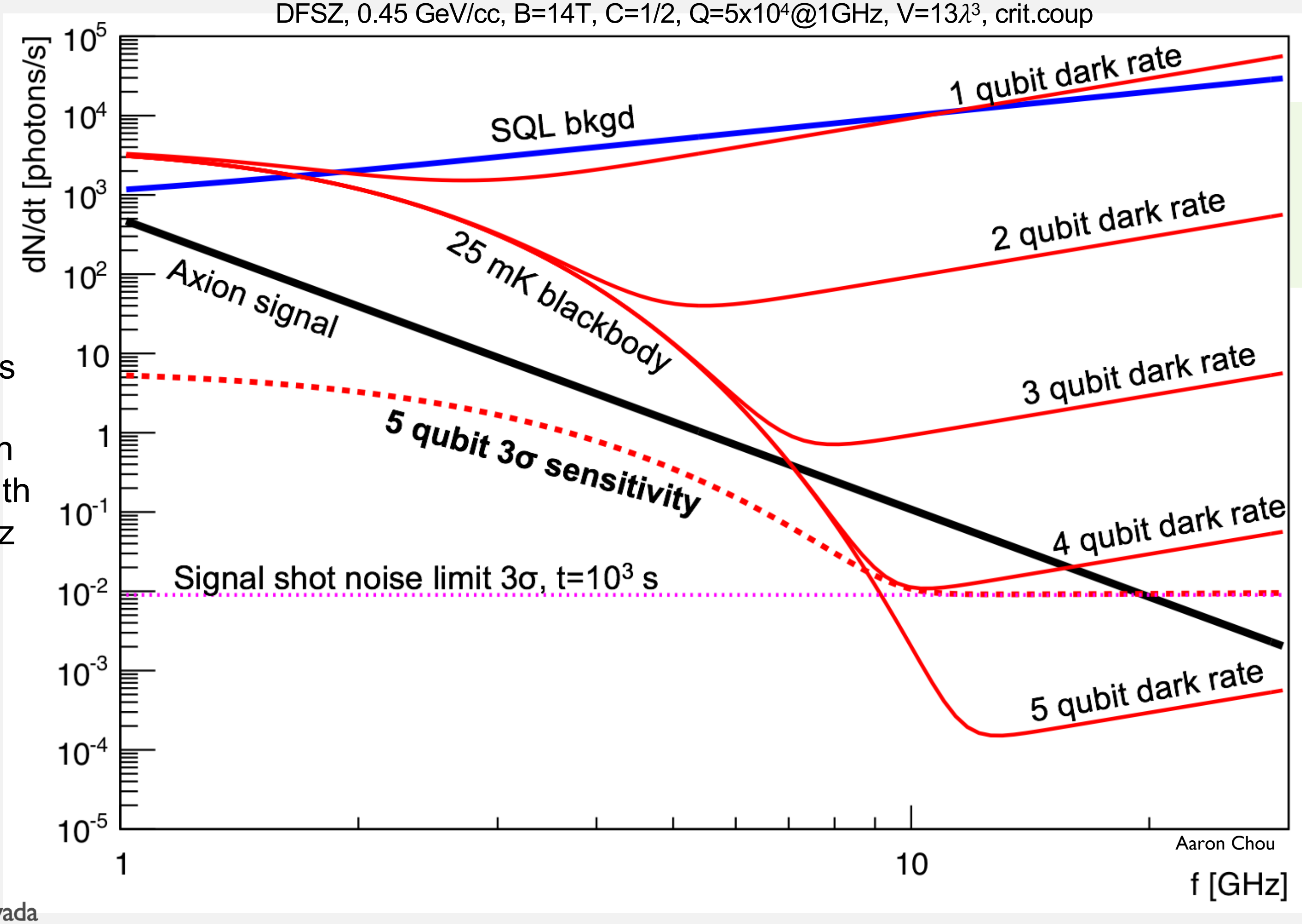
→ Multiple measurements:
Mulitple qubits:

$$p_{err} \to (0.01)^N$$

→ Stimulated emission (N+1 enhancement)

Photon # counting evades the quantum noise limit

SIGNAL AND NOISE RATE



Assumes axion detection bandwidth $\Delta f \sim$ MHz

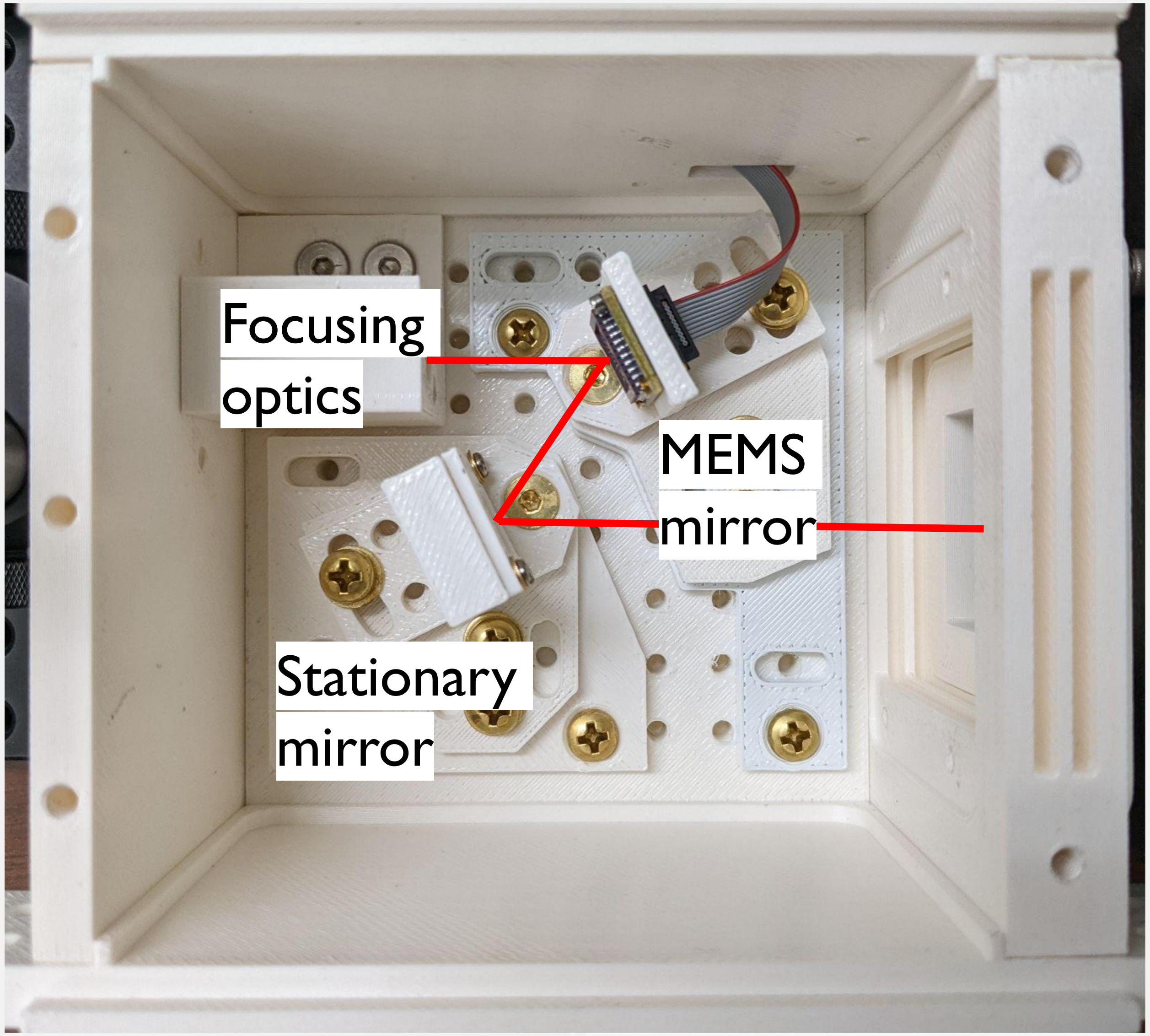
N QND measurements
dark rate = $(10^{-2})^N \Delta f$

Sensitivity limited only by signal photon shot noise.

NQI Program Component Areas

- **Quantum Sensing and Metrology (QSENS)** refers to the use of quantum mechanics to enhance sensors and measurement science. This can include uses of superposition and entanglement, non-classical states of light, new metrology regimes or modalities, and advances in accuracy and precision enabled by quantum control, for example with atomic clocks.
- **Quantum Computing (QCOMP)** activities include the development of quantum bits (qubits) and entangling gates, quantum algorithms and software, digital and analog quantum simulators using programmable quantum devices, quantum computers and prototypes, and hybrid digital plus analog, as well as quantum plus classical computing systems.
- **Quantum Networking (QNET)** includes efforts to create and use entangled quantum states, distributed over distances and shared by multiple parties, for new information technology applications and fundamental science; for example, networking of intermediate scale quantum computers (modules) for enhanced beyond-classical computing capabilities.
- **QIS for Advancing Fundamental Science (QADV)** includes foundational efforts to invoke quantum devices and QIS theory to expand fundamental knowledge in other disciplines; for example, to improve understanding of biology, chemistry, computation, cosmology, energy science, engineering, materials, nuclear matter, and other aspects of fundamental science.
- **Quantum Technology (QT)** catalogues several topics: work with end-users to deploy quantum technologies in the field and develop use cases; basic R&D on supporting technology for quantum information science and engineering, e.g., infrastructure and manufacturing techniques for electronics, photonics, and cryogenics; and efforts to understand and mitigate risks raised by quantum technologies, e.g., post-quantum cryptography (see Box 4.1).

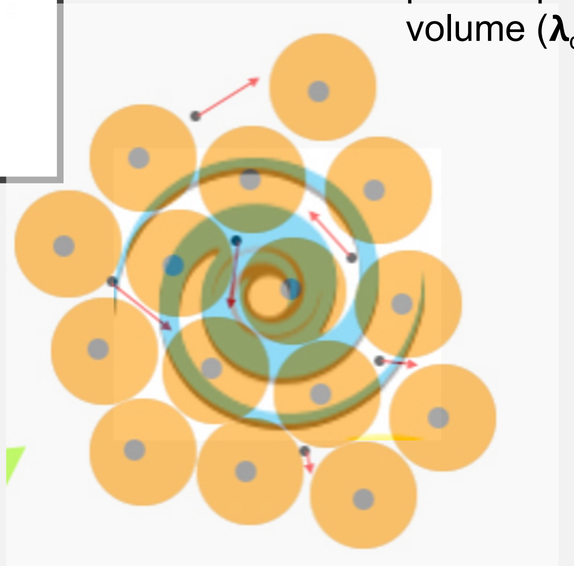
MEMS mirror allows for desired operating specifications:



- ~1.5” x 1.5” scanning area
- <100μm spot size
- ~10μm position resolution
- O(100)Hz scanning speed
- O(μs) pulse width
- >10mK operating temperature

NATURE OF DARK MATTER

Fermions: 1 DM particle per mode volume $(\lambda_{deBroglie})^3$



For **mass < 70 eV**, Pauli exclusion principle causes dark matter clumps to swell up to be larger than the size of the smallest dwarf galaxies. (Randall, Scholtz, Unwin 2017)

Wave like DM

Particle like DM

AXION PRODUCTION

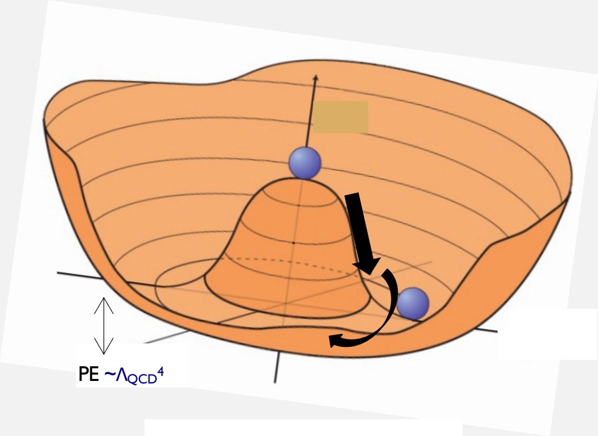
- Global symmetry broken at scale f_a
  -- axion produced through misalignment mechanism
  -- during QCD phase transition, trough tilted by Λ_{QCD}^4
- PE $\sim\Lambda_{QCD}^4$ released, makes up dark matter

-- oscillation of the QCD θ angle about its minimum--vacuum energy to axions

- QCD axion mass $m_a \sim \Lambda_{QCD}^2/f_a$
  $\sim (200\ \text{MeV})^2/f_a$

--- f_a unknown

⇒**GHz frequencies at $f_a \sim 10^{13}$ GeV scale**



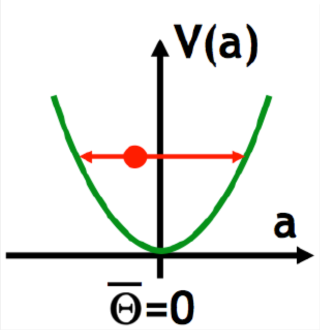
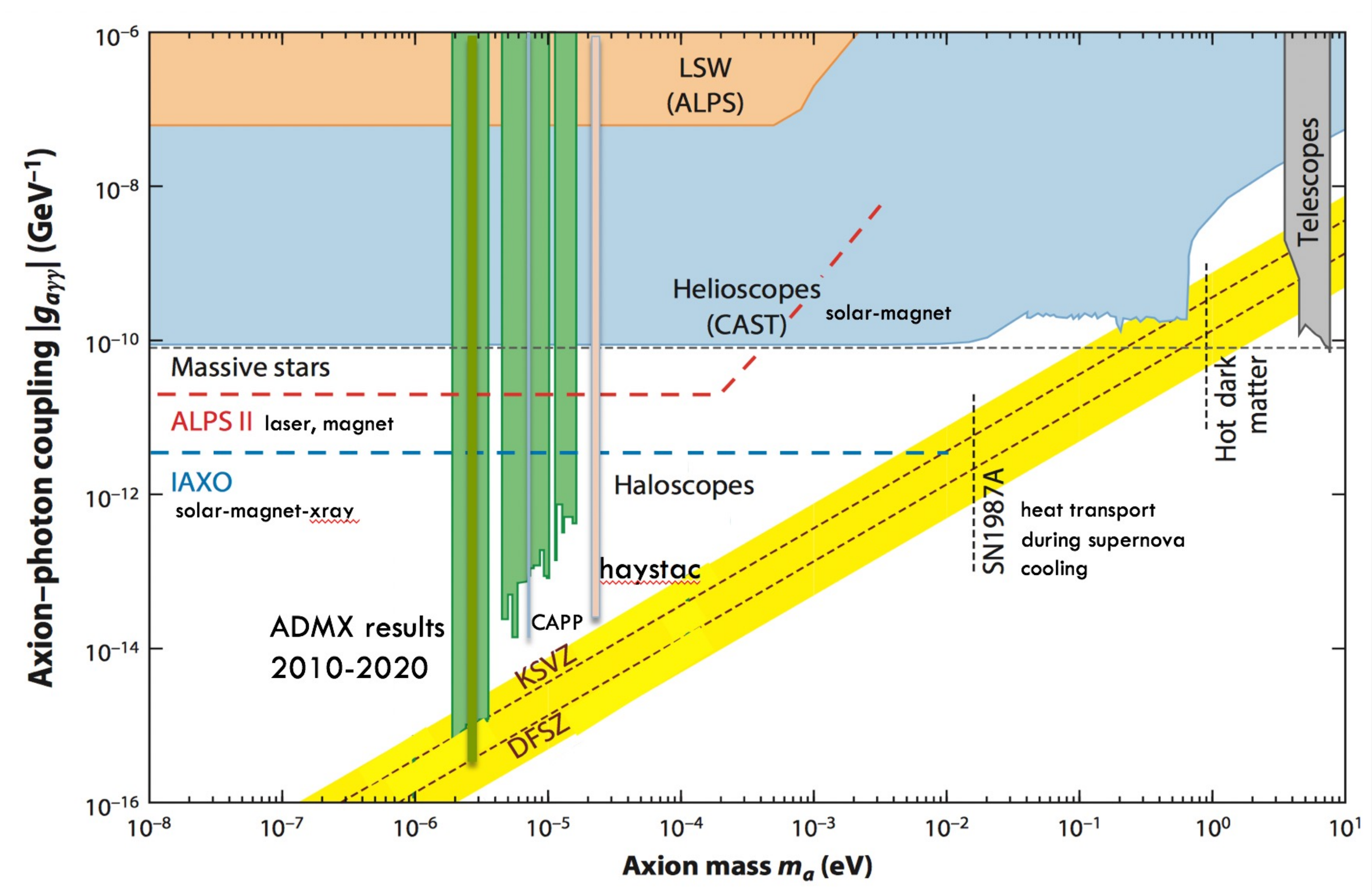


Fig 1:J. Ellis et al; arxiv:1201.6045v1

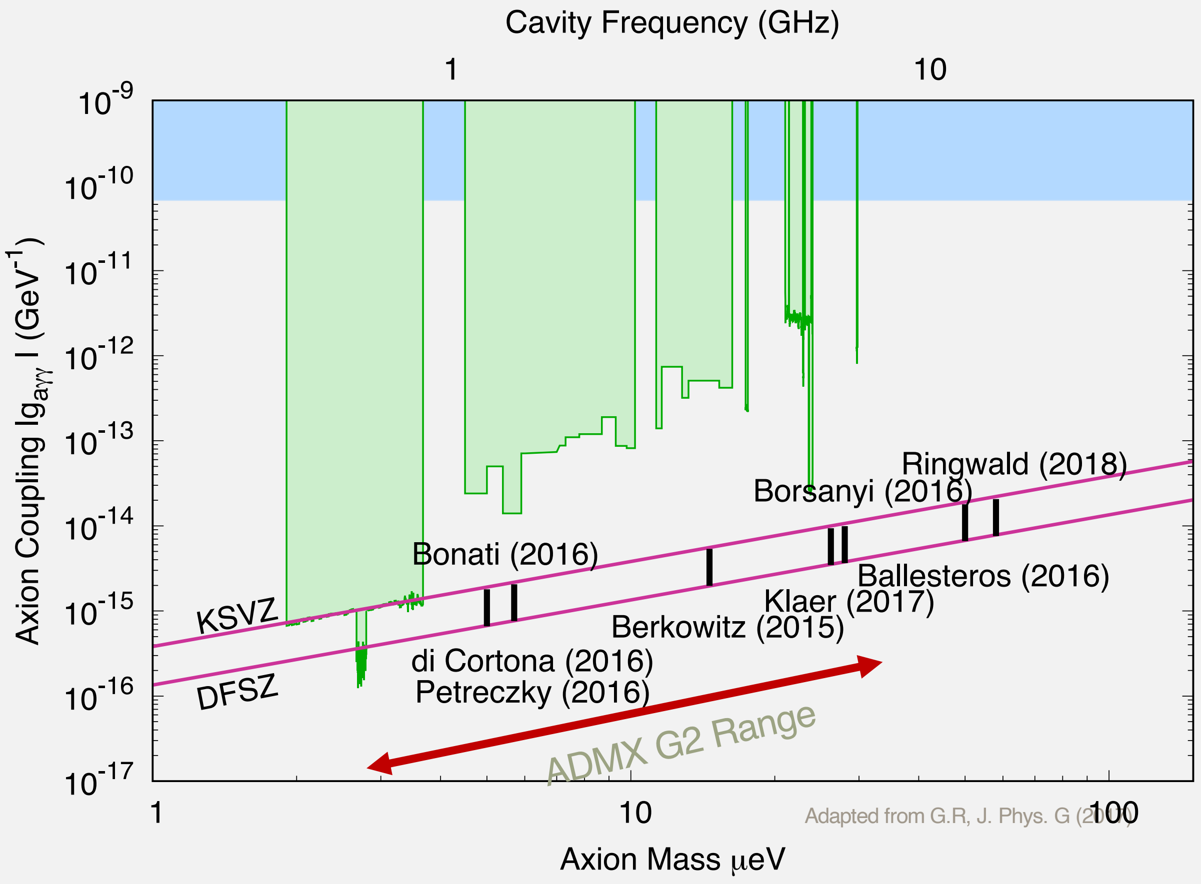
AXION SEARCHES OVERVIEW



Graham, et. al (2016)

AXION SEARCHES OVERVIEW CONTD.

Analytic and lattice predictions of the axion mass, given it makes 100% Dark matter



Adapted from G.R, J. Phys. G (2017)

QUANTUM AMPLIFIERS

Why quantum amps.?

Intrinsically low noise (superconducting technology)

⇒ low resistance elements

⇒ low thermal dissipation

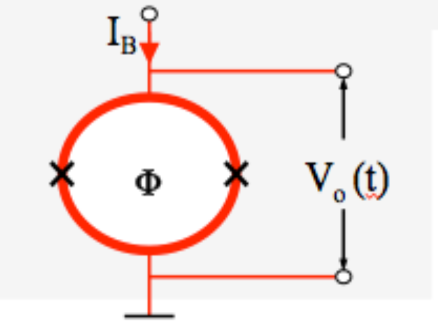
⇒ Add very low added noise during amplification

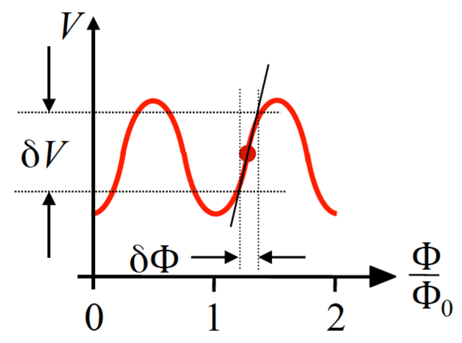
=> Tunable in frequency

Josephson Parametric Amplifier

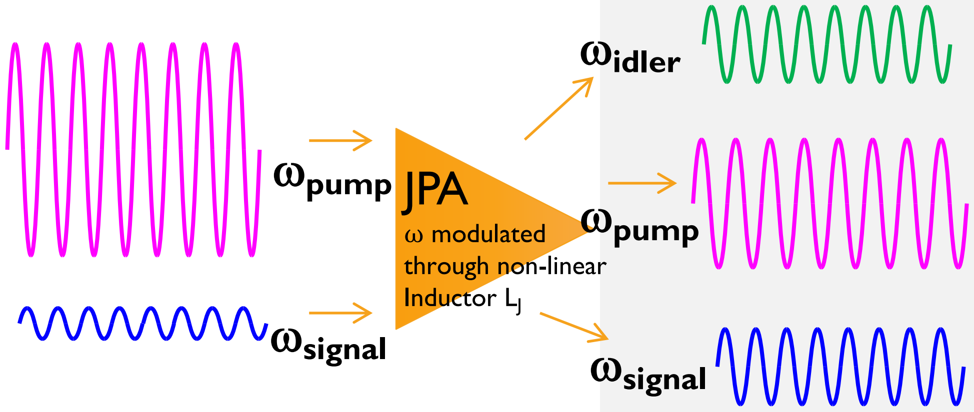
JPA

dc SQUID





- Energy transfer from pump to two normal modes of swing



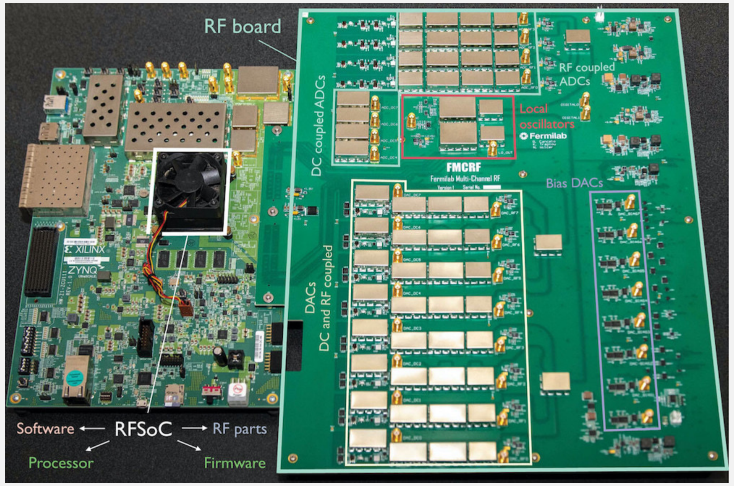
Only limited by Quantum Noise

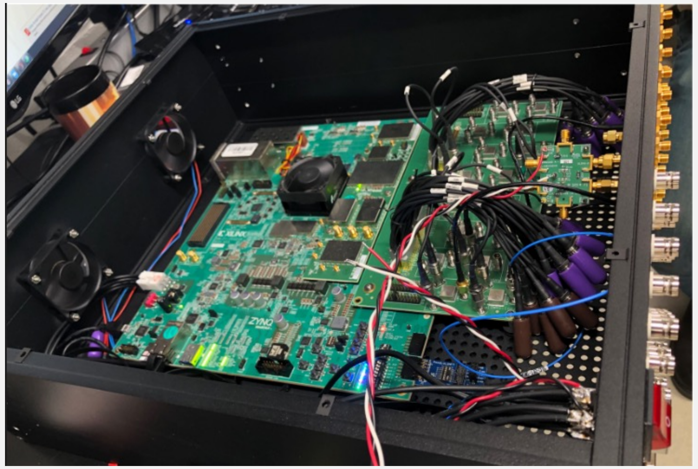
QUANTUM INSTRUMENTATION CONTROL KIT (QICK)

- **Primary support through QSC**
- **Broadly used: >30 labs in the US and abroad**
- **> 20 science talks in APS March meeting!**

- 16 DAC outputs from DC to 10GHz all digital mixers.
  - This is critical need for quantum. => Better experiments.
  - Minimizes calibrations.
- 16 ADC inputs from DC to near 10GHz without analog mixers.
  - Input noise 120K (i.e. 1.2dB)
- 8 x 20-bit DAC outputs for bias (BW of 10 or 100Hz) ultra low noise, ±10V outputs.
- <200ns latency for error correction (fastest in the market).
- Optimal filtering, no dead-time 3ns pulses.
- 100 pico-second pulses for QN.
- Accurate timing readout 2ps resolution.
- RF multiplexing of 10K detectors per board.

AMD-RFSoC ZCU111 +QICK custom RF/DC amplifiers, bias

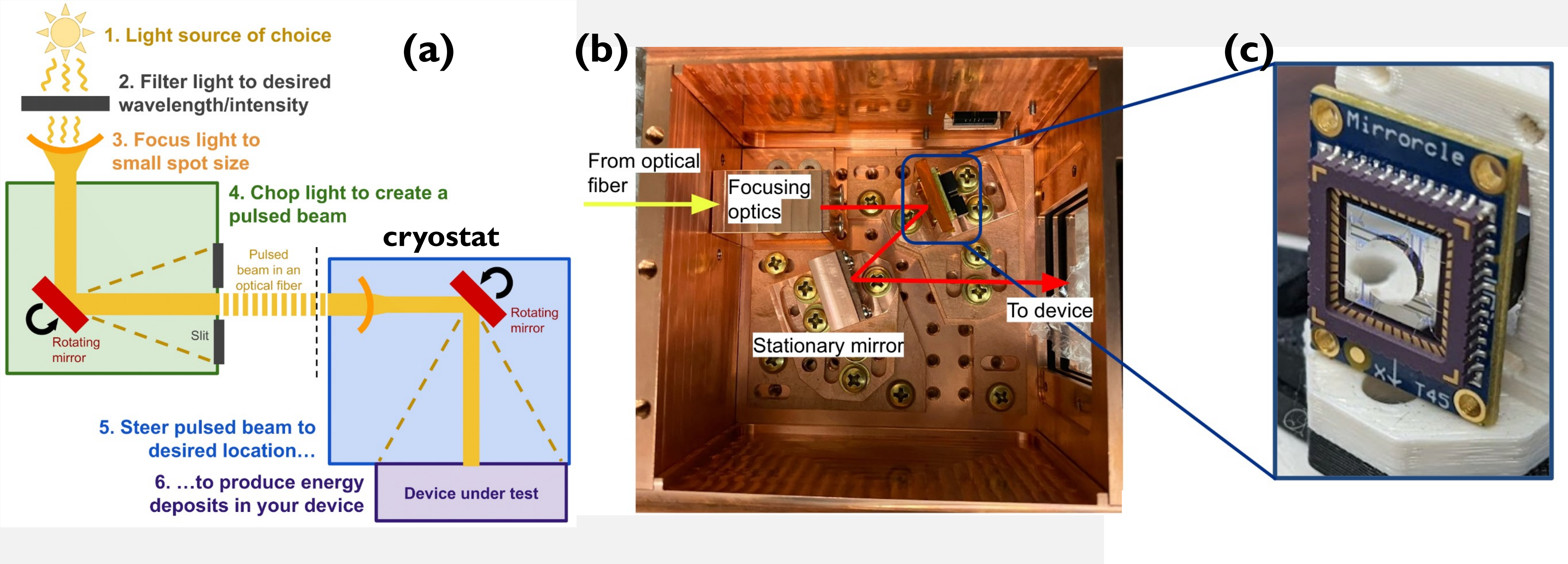




AMD-RFSoC ZCU216 QICK custom RF/DC amplifiers, bias under design

(1.3.3.02)

Cryogenic photon source for Detector Characterization



WHAT'S CAUSING THESE DARK COUNTS?

A superconductor free of quasiparticles for seconds

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V. Vesterinen,[3] L. Grönberg,[3] J. Hassel,[3] V. F. Maisi,[2] and J. P. Pekola[1]

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(Dated: February 2, 2021)

Microfractures due to GE Varnish and mounting glue on Si substrate causing phonon bursts breaking cooper pair -> qp poisioning

Eliminated cosmic muon and radioactive background from suspects since qp poisoning suppressed over longer ~ a week cooldown period

Used similar device to charge parity device like QCD

A Stress Induced Source of Phonon Bursts and Quasiparticle Poisoning

R. Anthony-Petersen,[1] A. Biekert,[1,2] R. Bunker,[3] C.L. Chang,[4,5,6] Y.-Y. Chang,[1] L. Chaplinsky,[7] E. Fascione,[8,9] C.W. Fink,[1] M. Garcia-Sciveres,[2] R. Germond,[8,9] W. Guo,[10,11] S.A. Hertel,[7] Z. Hong,[12] N.A. Kurinsky,[13] X. Li,[2] J. Lin,[1,2] M. Lisovenko,[4] R. Mahapatra,[14] A.J. Mayer,[9] D.N. McKinsey,[1,2] S. Mehrotra,[1] N. Mirabolfathi,[14] B. Neblosky,[15] W.A. Page,[1,*] P.K. Patel,[7] B. Penning,[16] H.D. Pinckney,[7] M. Platt,[14] M. Pyle,[1] M. Reed,[1] R.K. Romani,[1,*] H. Santana Queiroz,[1] B. Sadoulet,[1] B. Serfass,[1] R. Smith,[1,2] P. Sorensen,[2] B. Suerfu,[1,2] A. Suzuki,[2] R. Underwood,[8] V. Velan,[1,2] G. Wang,[4] Y. Wang,[1,2] S.L. Watkins,[1] M.R. Williams,[16] V. Yefremenko,[4] and J. Zhang[4]

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4 Aug 2022