DARK MATTER DETECTION WITH QUBITS

Rakshya Khatiwada

Illinois Institute of technology

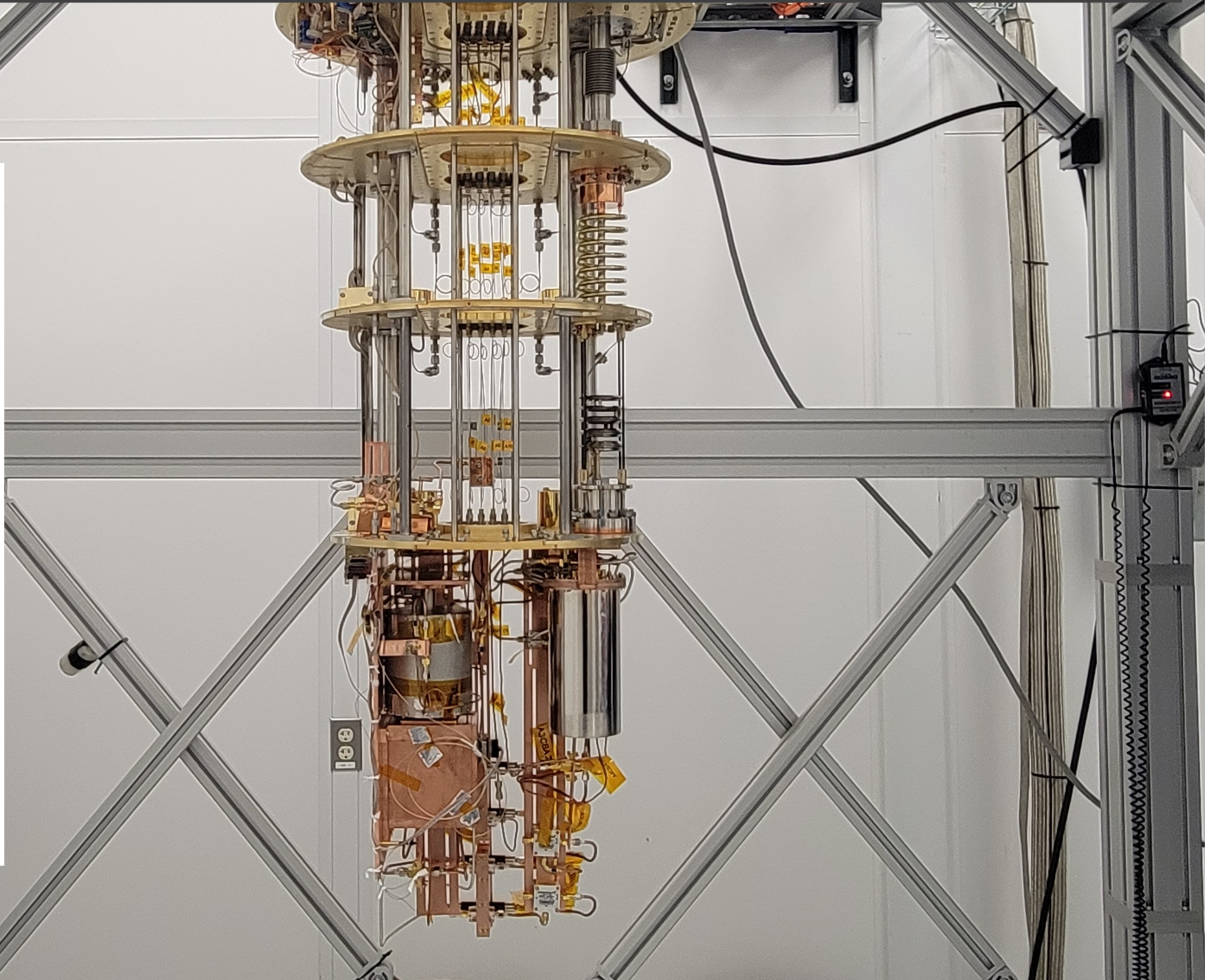
&

Fermilab

07/07/2023

18th Patras workshop

Rijeka, Croatia



OUTLINE

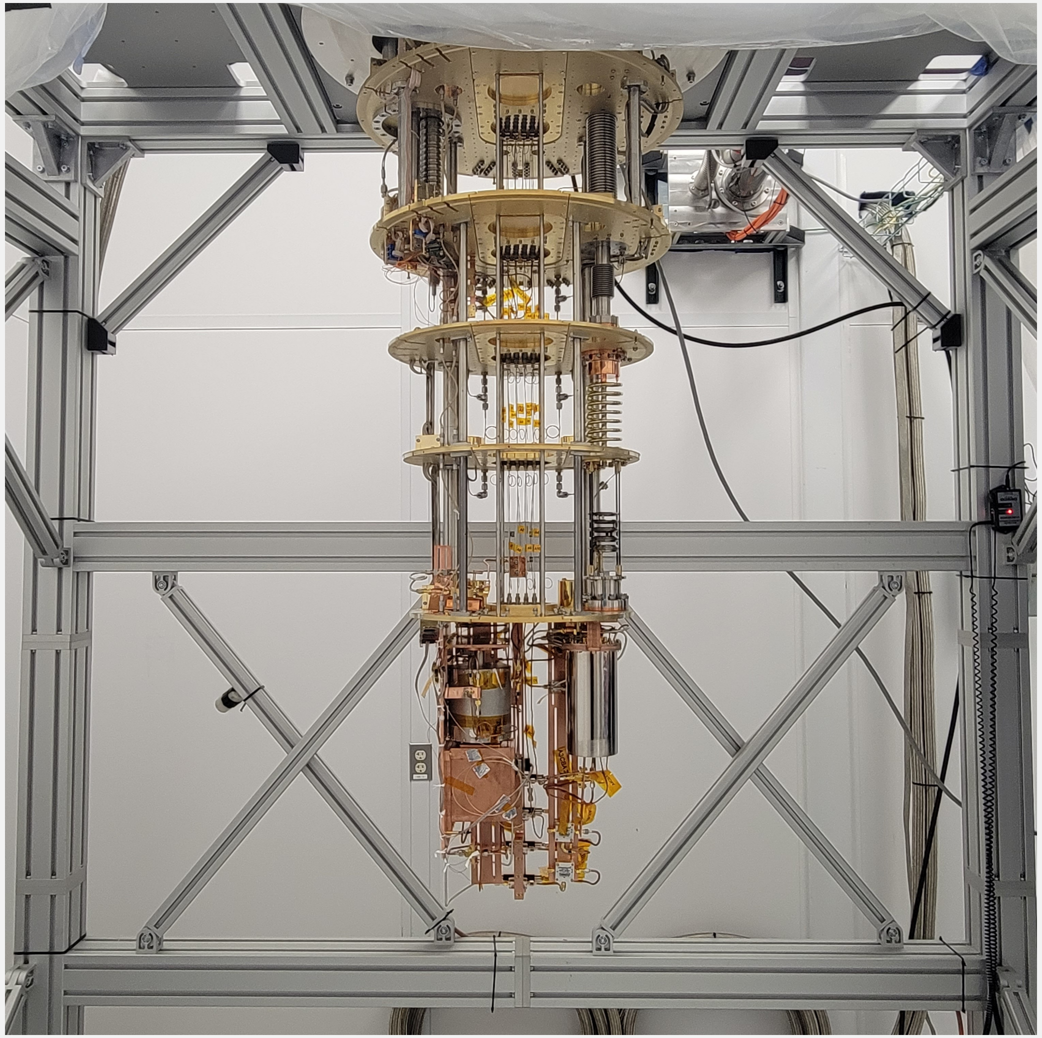
- **Quantum sensing for Dark Matter at Fermilab/IIT**

→ 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!



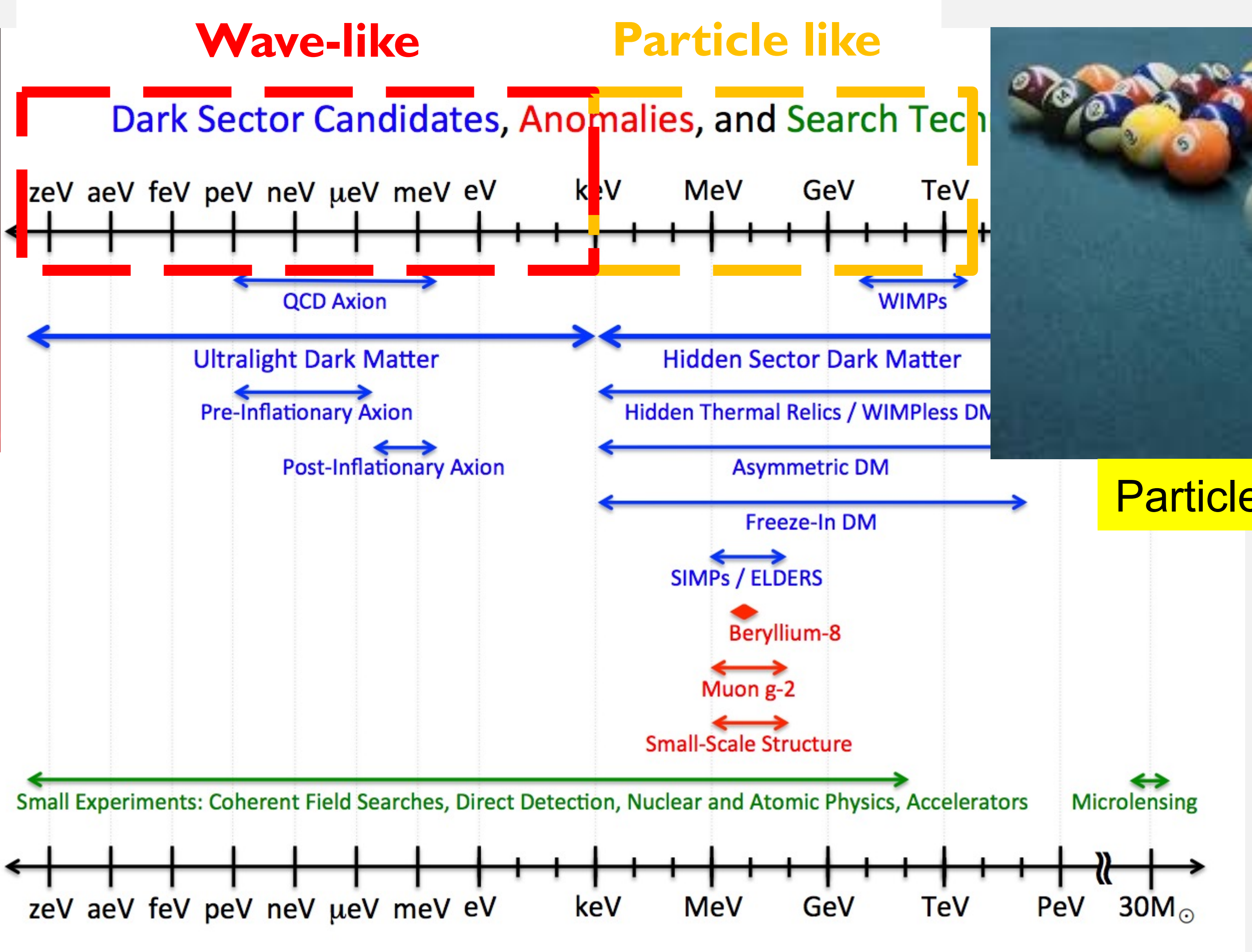
QUBIT BASED DETECTORS FOR ULTRALIGHT AND LIGHT DARK MATTER SEARCHES

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

NEAR AND LONG-TERM DARK MATTER SEARCH PLAN

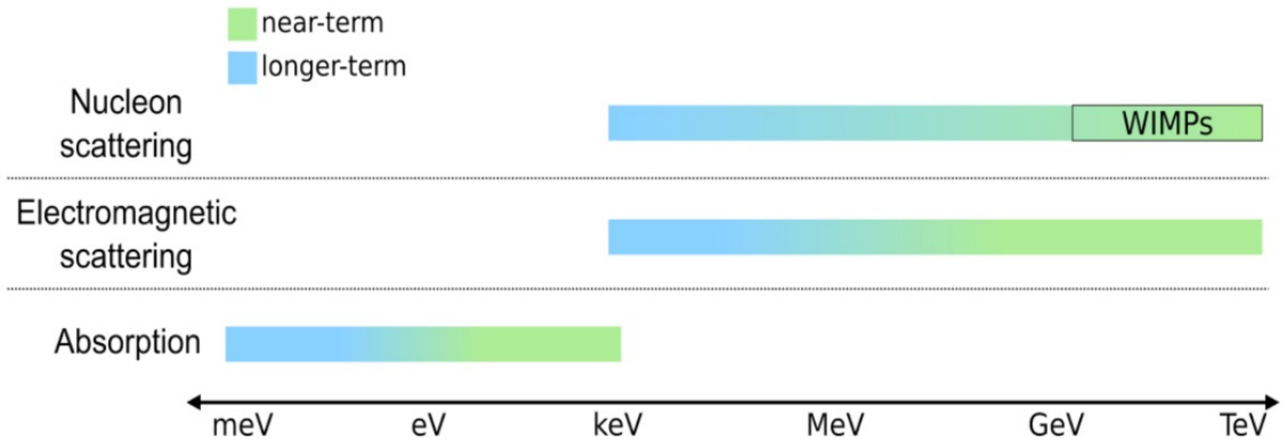


Figure 2-6: *Mass range probed for dark matter particles that scatter off nuclei, electrons, or collective excitations (1 keV to 1 GeV) and that are absorbed by nuclei, electrons, or collective excitations (1 meV to 1 keV). These masses are below those typically expected for WIMPs. Near-term experiments using existing advanced technologies can probe the mass range in green, while R&D on promising technologies can lead to experiments that can probe the extended mass range in blue.*

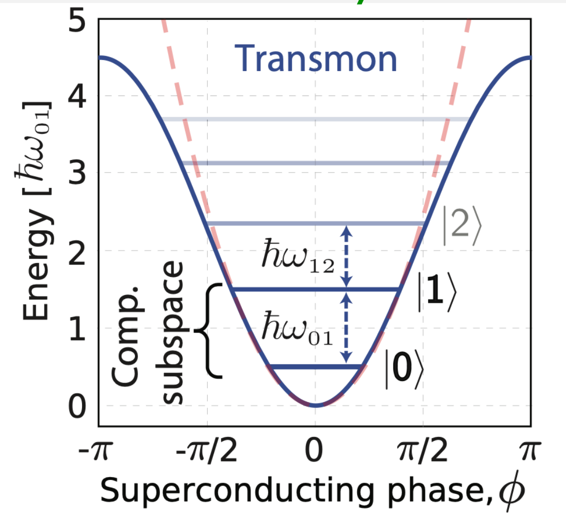
Need low energy threshold systems < 1 eV !

DM mass	DM energy or momentum	CM scale
50 MeV	$p_\chi \sim 50$ keV	zero-point ion momentum in lattice
20 MeV	$E_\chi \sim 10$ eV	atomic ionization energy
2 MeV	$E_\chi \sim 1$ eV	semiconductor band gap
100 keV	$E_\chi \sim 50$ meV	optical phonon energy

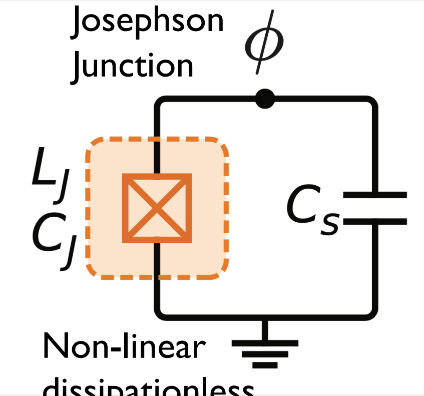
WHAT HAS BEEN DEMONSTRATED WITH QUBIT BASED DARK MATTER DETECTORS?

WHAT IS A QUBIT?

two level system



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



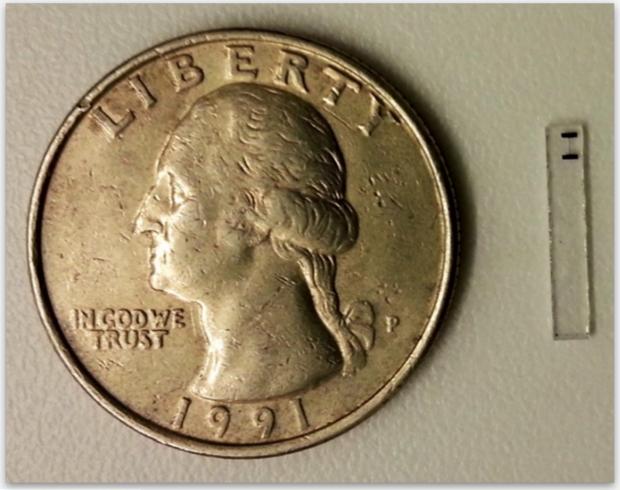
Non-linear dissipationless circuit element

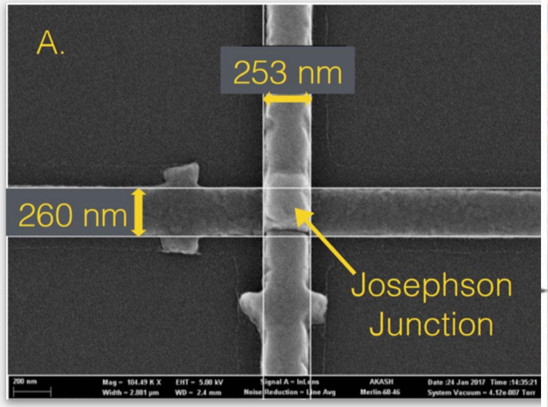
$E_J \gg E_C$

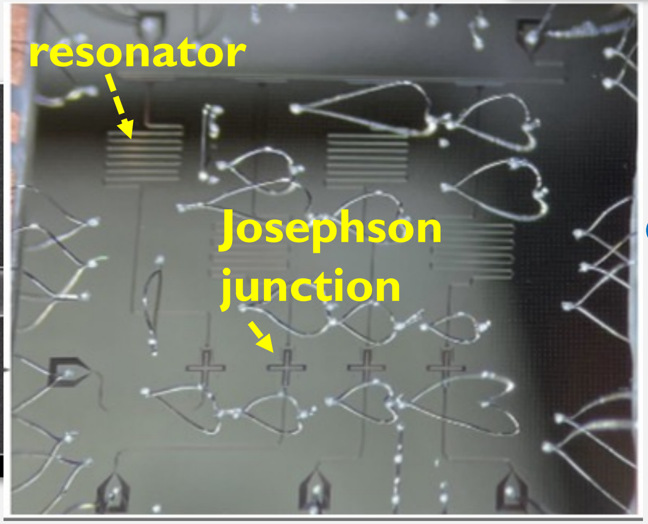
$E_c = e^2/2C$ charging energy

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

where $\Phi_0 = h/2e$ magnetic flux quantum







Qubit and resonator circuit on a Si substrate

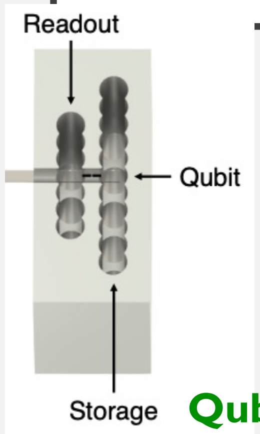
--Superconducting Transmon and its variants ***can be utilized for Dark Matter detection through several mechanisms of coupling***

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

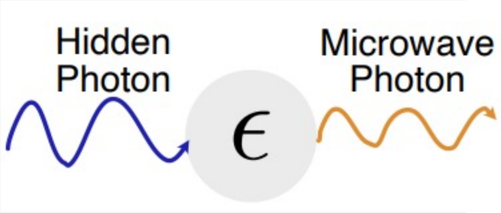
HIDDEN PHOTON DARK MATTER SEARCH WITH QUBITS
PROTOTYPE DEMONSTRATION

QuantiSED

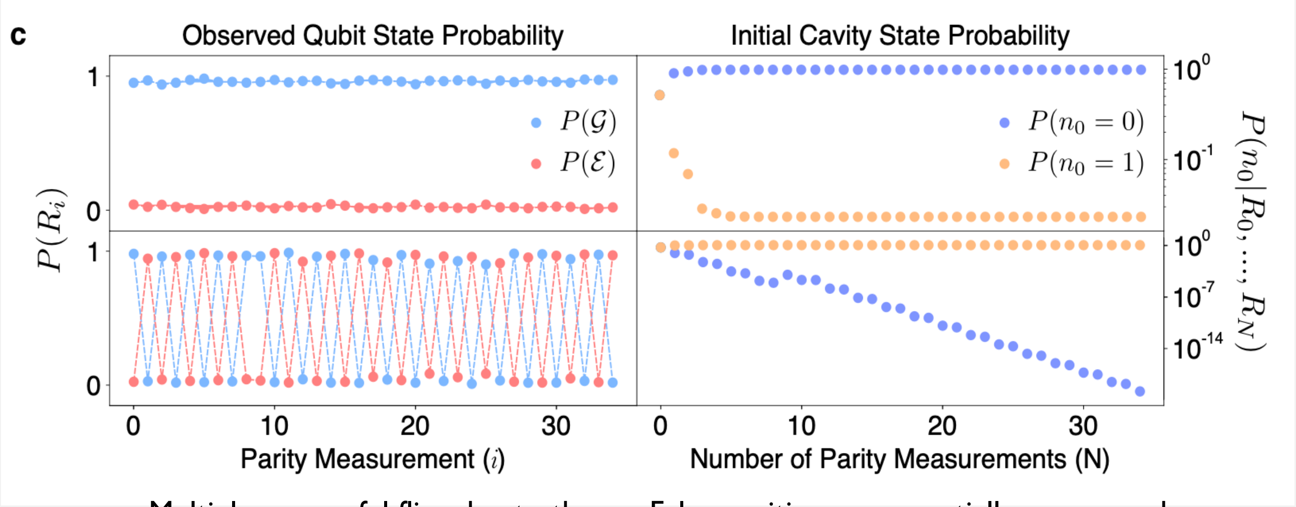
U Chicago/FNAL



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

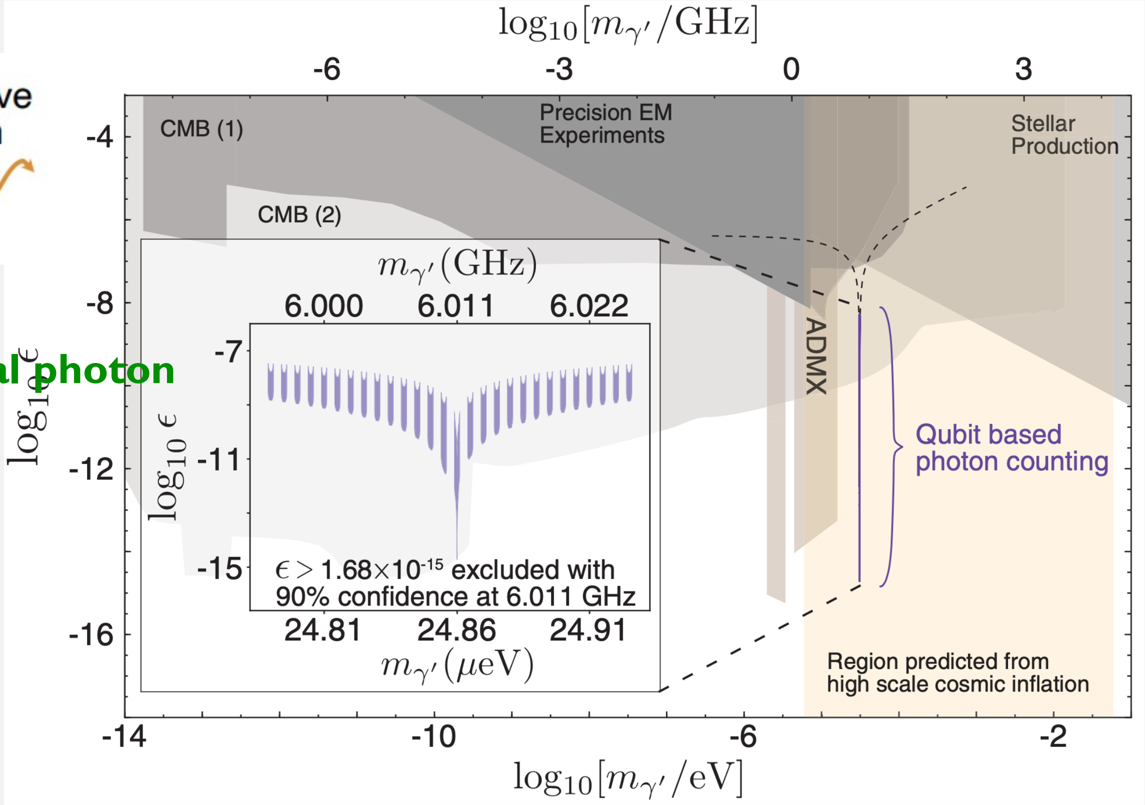


Qubit + 3D cavity – qubit excited state probability due to presence of a DM signal photon



Multiple successful flips due to the presence of a photon

False positives exponentially suppressed due to repeated measurements



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

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

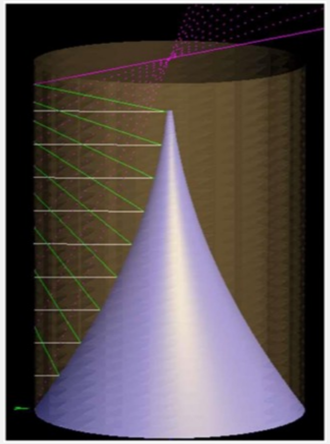
Rakshya Khatiwada

HEISING-SIMONS FOUNDATION

QUBIT BASED SINGLE PHOTON DETECTORS

QuantiSED

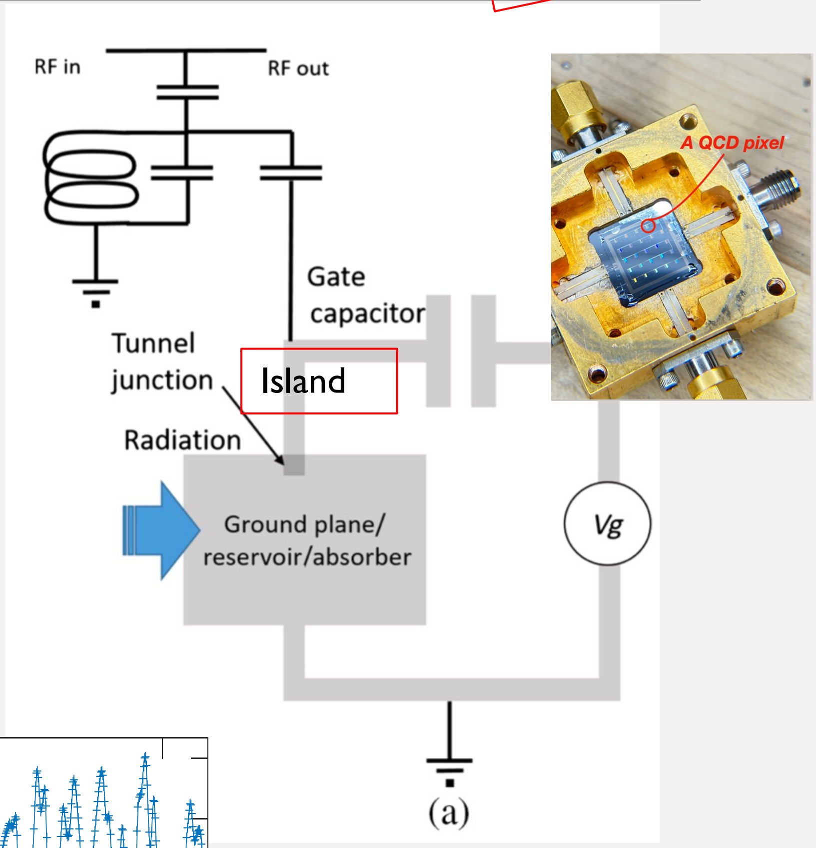
Broadband Axion Antenna (BREAD) for Dark Matter

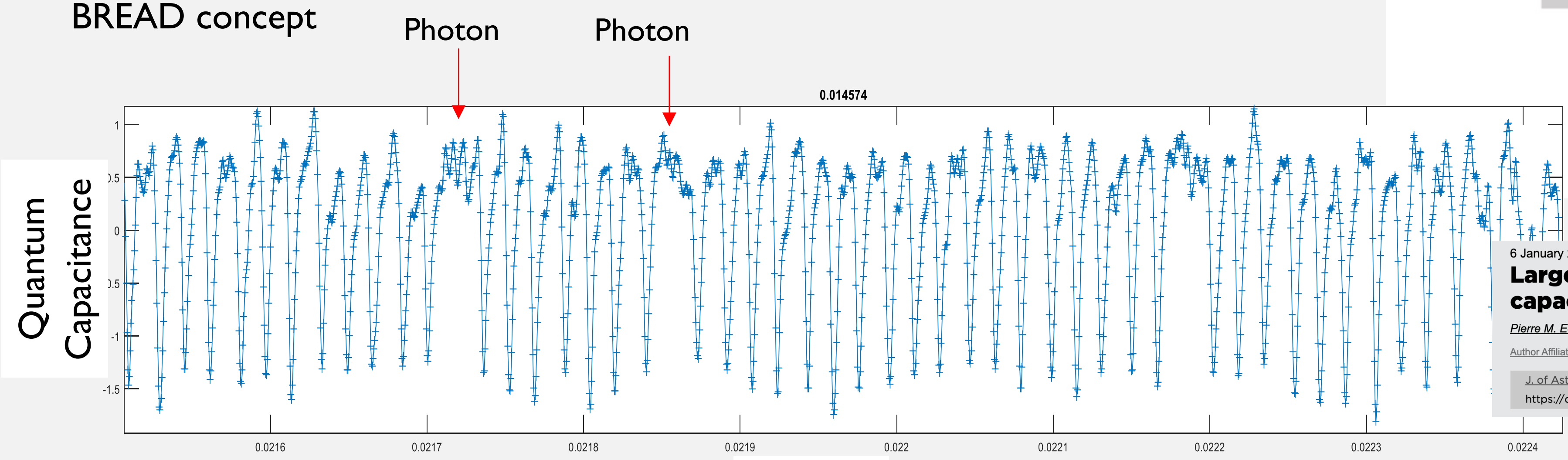


BREAD concept

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 => changes capacitance => frequency shift of the resonator
- **NEP < 10^{-20} W/√Hz at 1.5 THz**
  – most sensitive far IR detector!



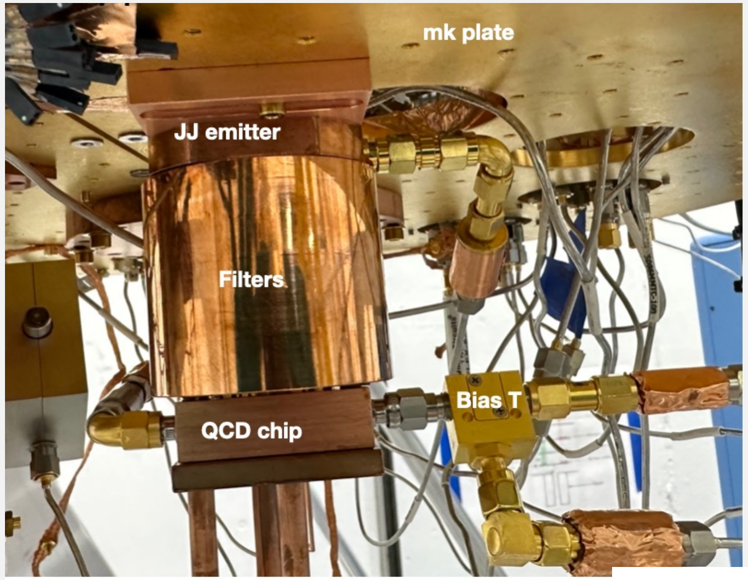


6 January 2021
Large array of low-frequency readout quantum capacitance detectors
Pierre M. Echternach, Andrew D. Beyer, Charles M. Bradford
Author Affiliations +
J. of Astronomical Telescopes, Instruments, and Systems, 7(1), 011003 (2021).
https://doi.org/10.1117/1.JATIS.7.1.011003

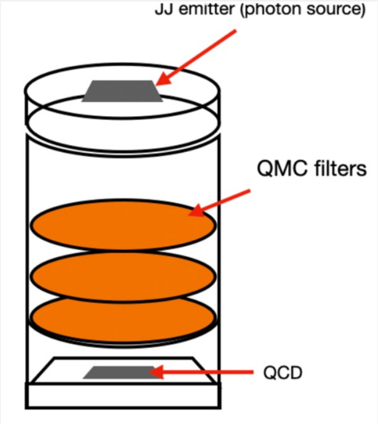
JPL, FNAL, IIT, Wisconsin

M. D. Shaw, J. Bueno, P. K. Day, C. M. Bradford, and P. M. Echternach, Phys. Rev. B 79, 144511 2009.

QUANTUM CAPACITANCE DETECTORS (QCDS)

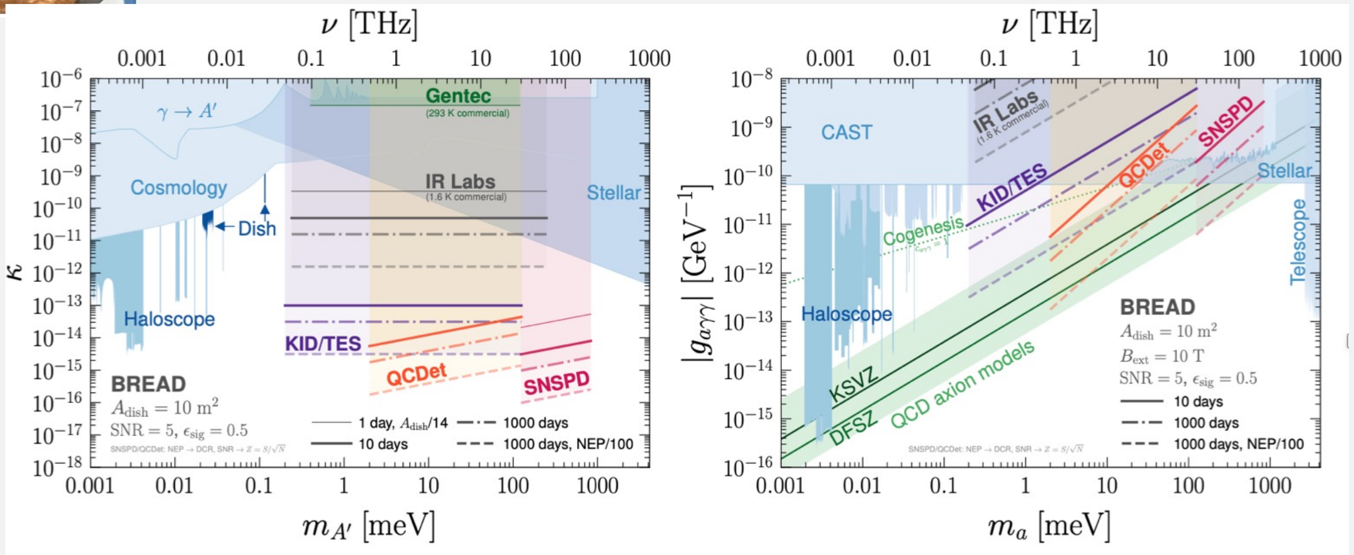


Fermilab setup of QCD + JJ photon source



- QCD + photon emitter source integration in progress at FNAL/IIT
- Josephson Junction based photon emitter source for fab. by Robert McDermott's group
- *JJ energy $E_j = 2eV_{DC}$ => **$f = 2eV_{DC}/h$ produces photons at this frequency***
- IIT Student Jilain Yu leading the work
- QCD multiple array readout and characterization in progress with RFSoC fpga boards

Projected sensitivity for BREAD experiment



IIT student Jialin Yu

(BREAD Collaboration) Phys. Rev. Lett. **128**, 131801 – Published 28 March 2022

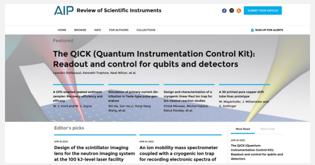
QUANTUM SCIENCE CENTER (QSC)

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

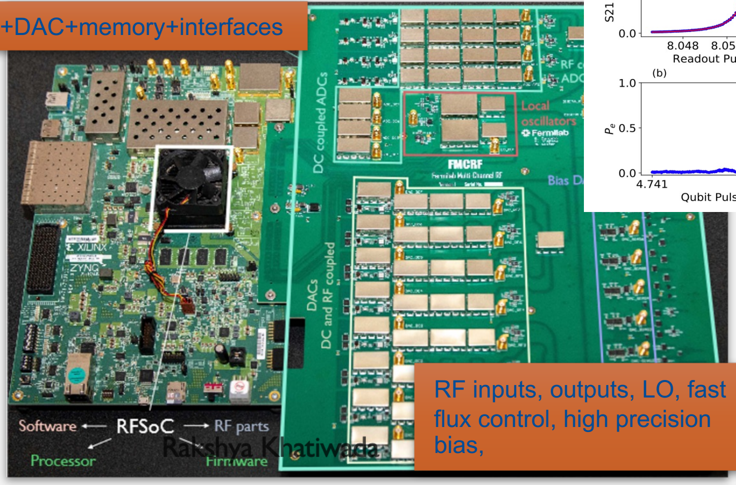
→***Dark Matter and radiation sensing with sub-eV single photon/phonon resolution*** qubit-based sensors

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

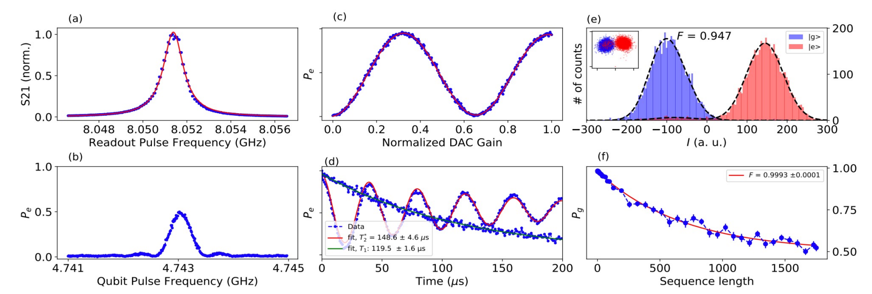
- **>30 labs in the US and abroad**
- **20 science talks in APS March meeting!**



FPGA+ADC+DAC+memory+interfaces



RF inputs, outputs, LO, fast flux control, high precision bias,

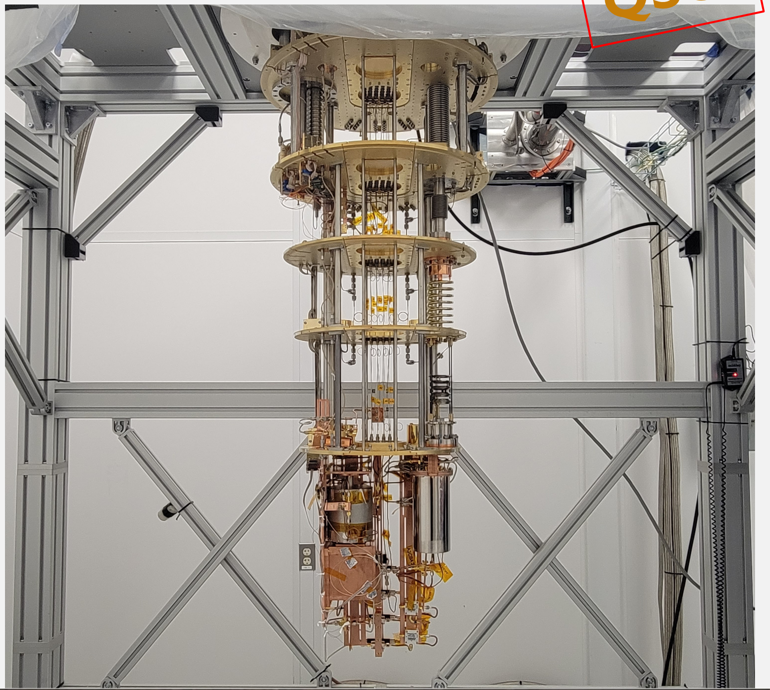


Qubit readout using QICK

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

SiDet Lab G

QSC

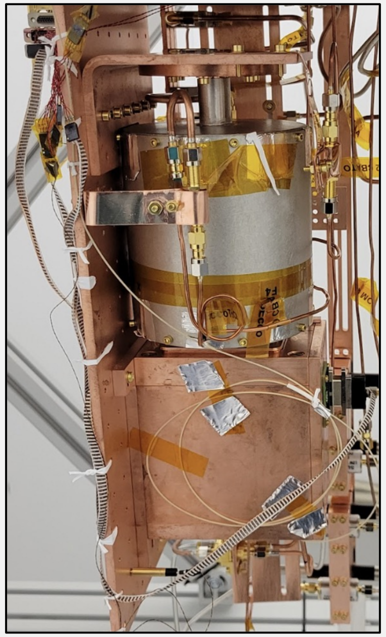


UNDERSTANDING ENERGY DISSIPATION IN QUBITS

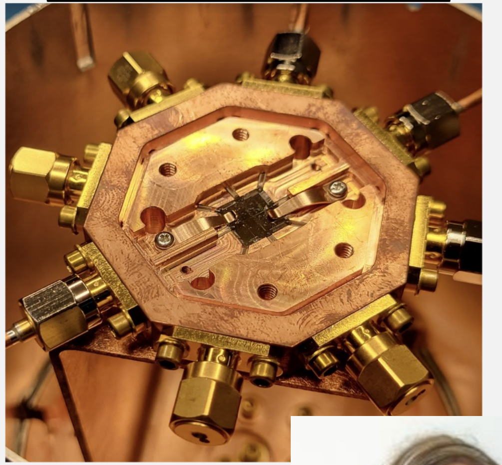
QSC

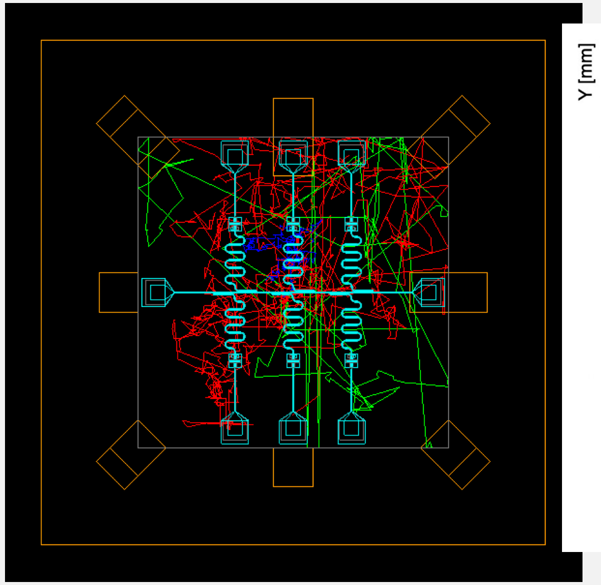
- Investigate **~ eV energy dissipation through e + h and phonon production**
- Simulation effort on **charge transport and phonon kinematics in Si**.
- Application of particle physics **simulation tools like G4CMP to understand qubits** (various substrates and geometry)
- Cryogenic photon source development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

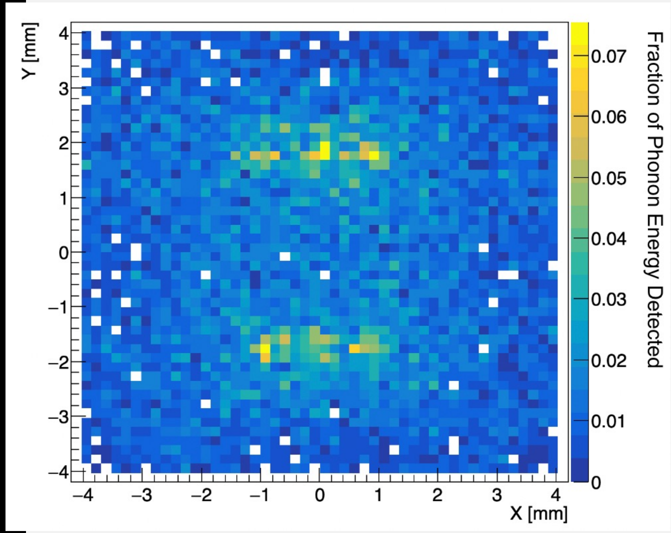
MEMS cryogenic photon source



6 qubit chip (Si)







phonon simulation in a 6-qubit silicon chip using G4CMP

Fermilab Postdoc
Ryan Linehan

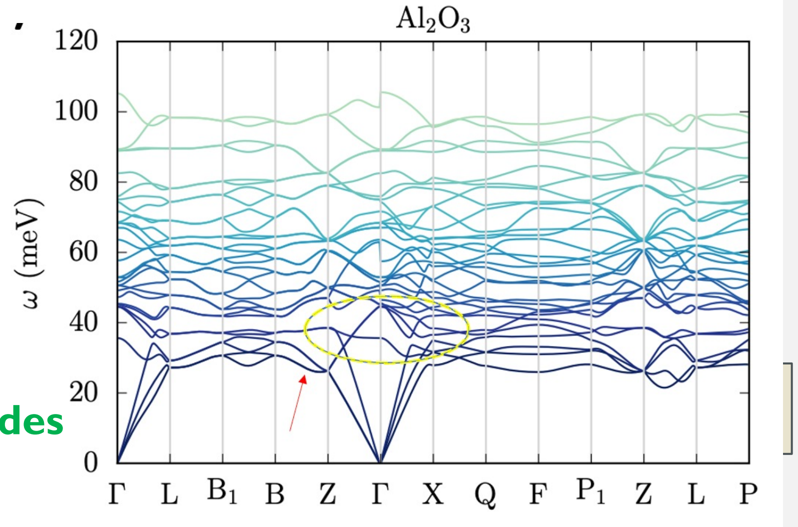
IIT student
Israel
Hernandez

(1.3.3.02)

QUBIT BASED SUB-EV SINGLE PHONON DETECTORS

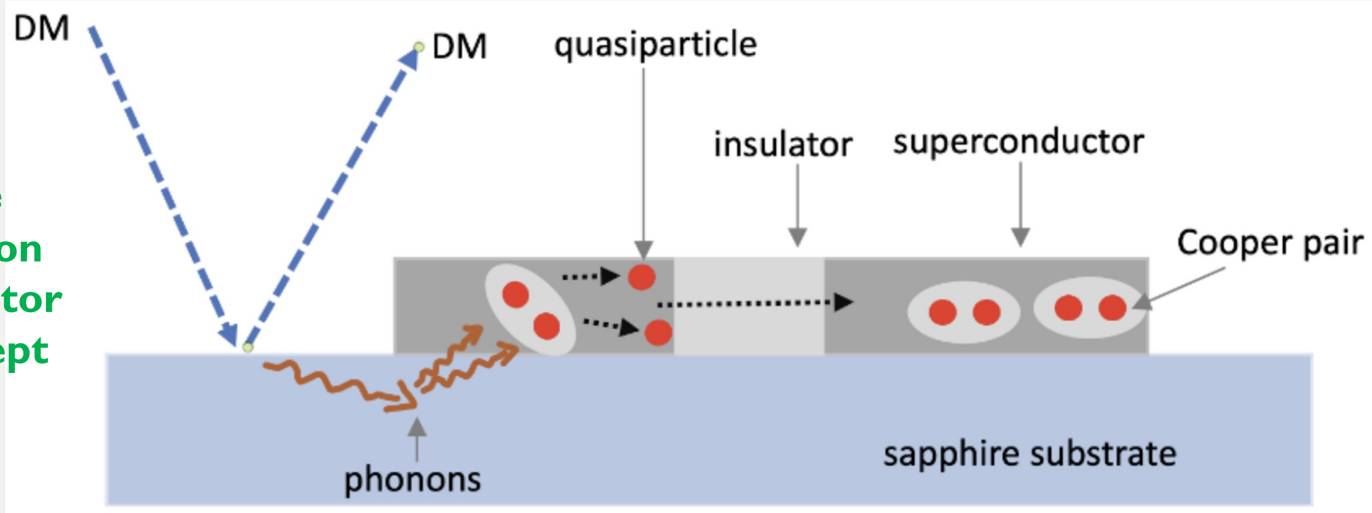
- **Single phonon detectors for Dark Matter** using Al_2O_3 qubits
- **Sub-eV sensitivity** (100 - 40 meV optical phonons)
- Dark Matter → optical phonons in Al_2O_3 → phonon down-conversion → phonon propagation to Al → broken Cooper pairs in Al → qubit readout protocol → Dark Matter signal
- 4 qubit 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

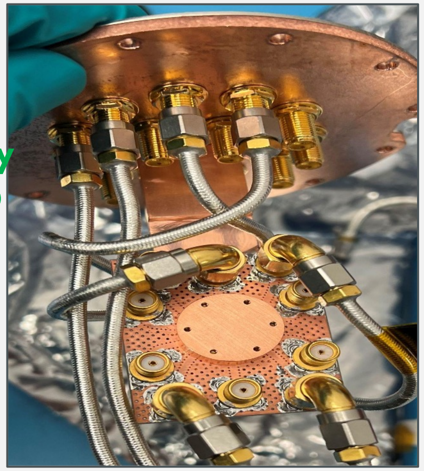


Brillouin zones

single Phonon detector concept



4 qubit chip array In LOUD



IIT student Kester Anyang

(1.3.3.02)

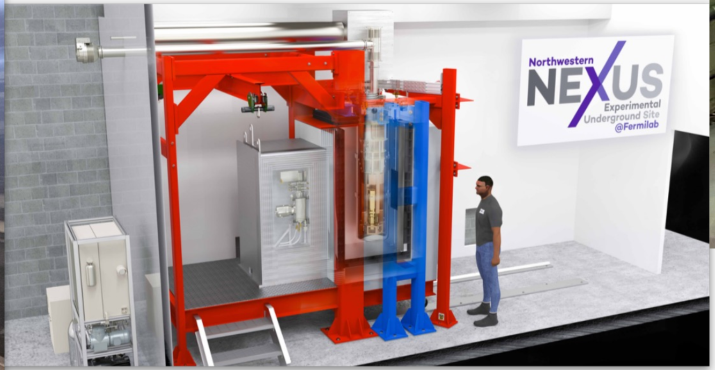
Trickle, T., Zhang, Z., Zurek, K.M. *et al.* Multi-channel direct detection of light dark matter: theoretical framework. *J. High Energ. Phys.* **2020**, 36 (2020).

UNDERGROUND, LOW BACKGROUND FACILITY AT FERMILAB FOR DARK MATTER SEARCHES

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 SUPERCONDUCTING DETECTORS

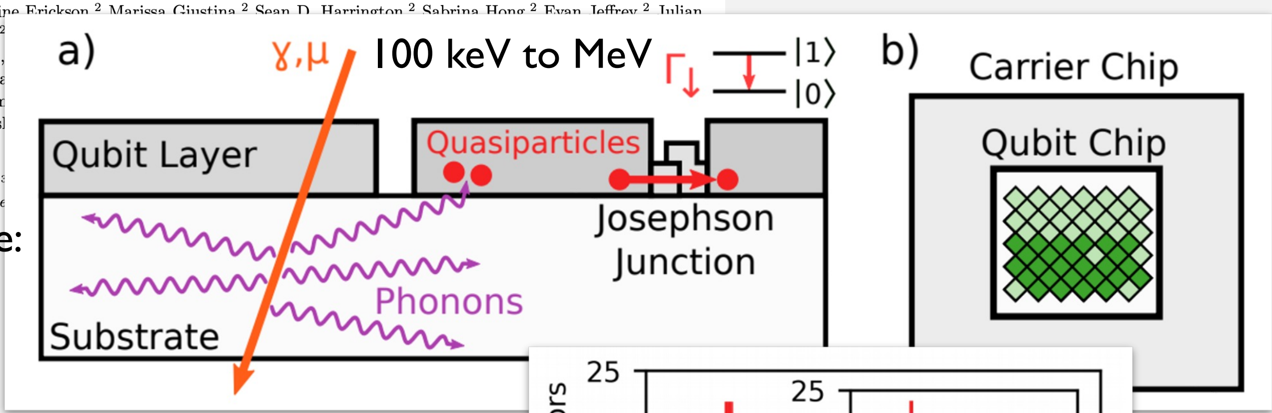
High energy radiation: source of quasiparticle in qubits

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, Catherine Erickson,[2] Marissa Giustina,[2] Sean D. Harrington,[2] Sabrina Hong,[2] Evan Jeffrey,[2] Julian Kelly, Miao, Opremca Vladim Smelyansk

Study context: Quantum Error Correction

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



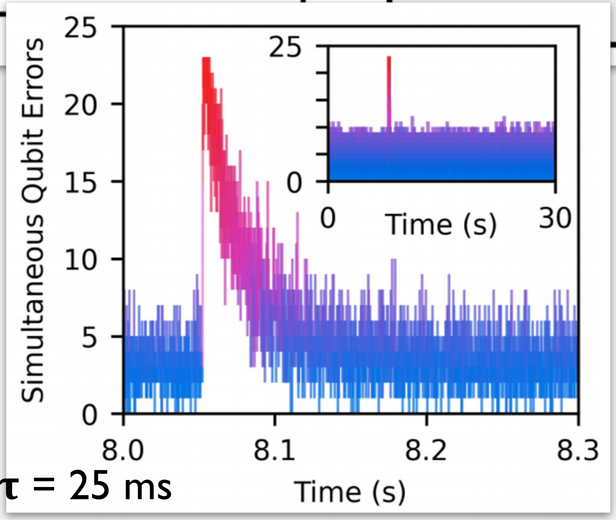
muon or γ absorption

phonon reservoir Si substrate

Phonons break cooper pair

quasiparticle tunnel to the junctions

qubit decoherence



τ = 25 ms

https://arxiv.org/abs/2104.05219

Rakshya Khatiwada

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

- **FNAL at the forefront of novel Quantum Science based research**
- Particular focus on **sub-eV threshold Light and Ultralight Dark Matter** searches
- **Brand new 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
- Parallel **technology development to bridge the gap** between Dark Matter detector development and necessary tools
- These **activities expected to expand further** in the coming years

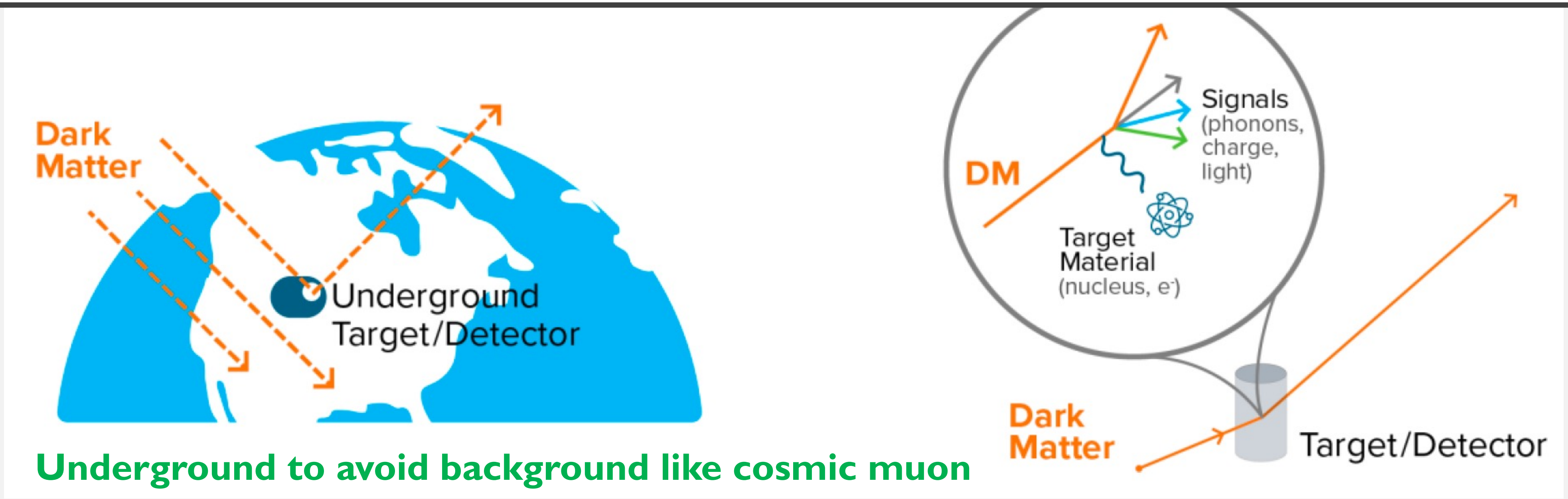
ACKNOWLEDGEMENT

DOE-OHEP-QuantiSED

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.

- 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)

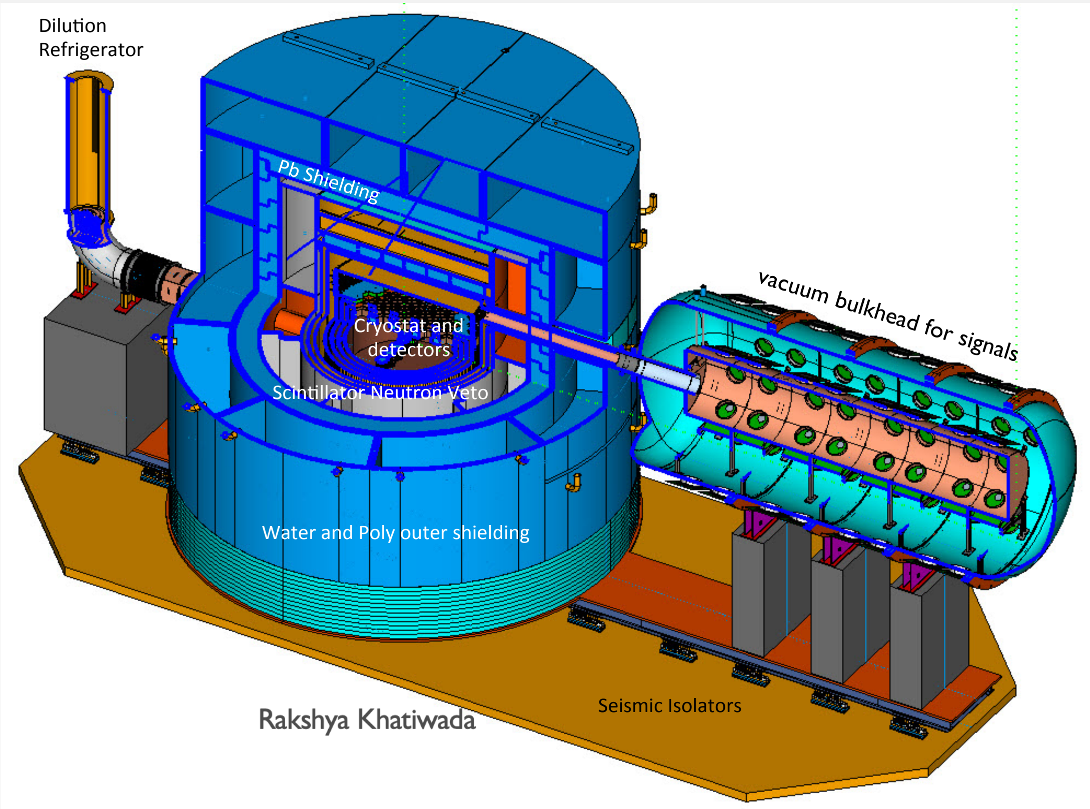
--*Absorption of DM*

DM Energy absorbed by the target material

SOME EXPERIMENTS

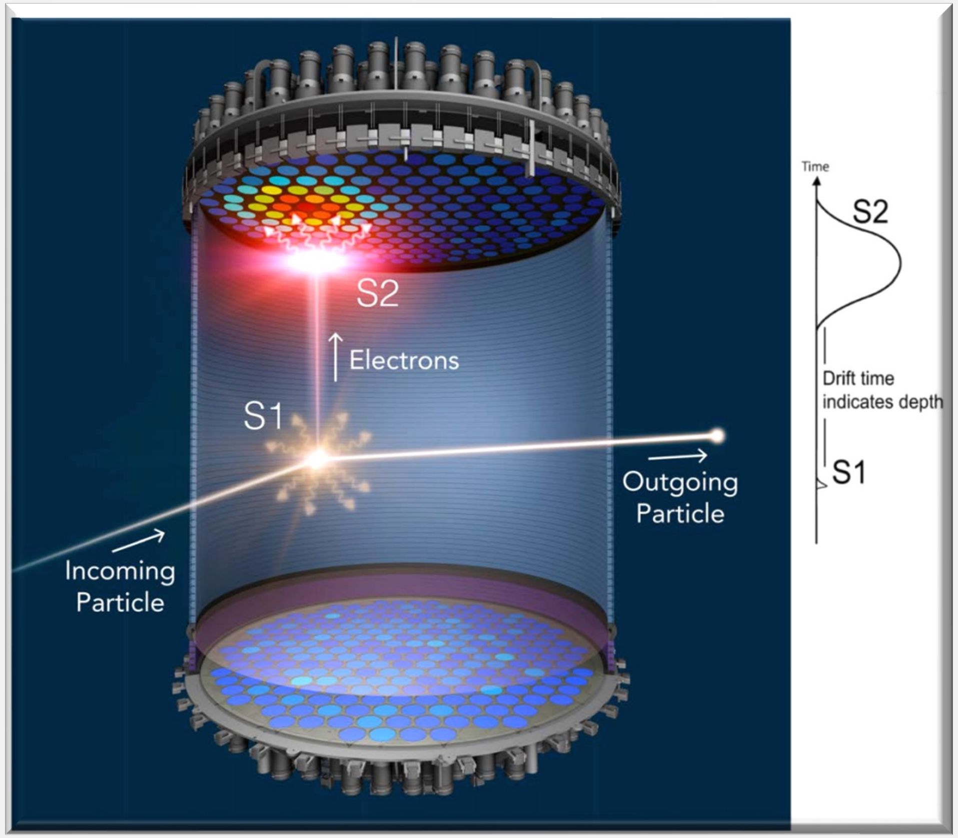
Super-CDMS-SNOLAB

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



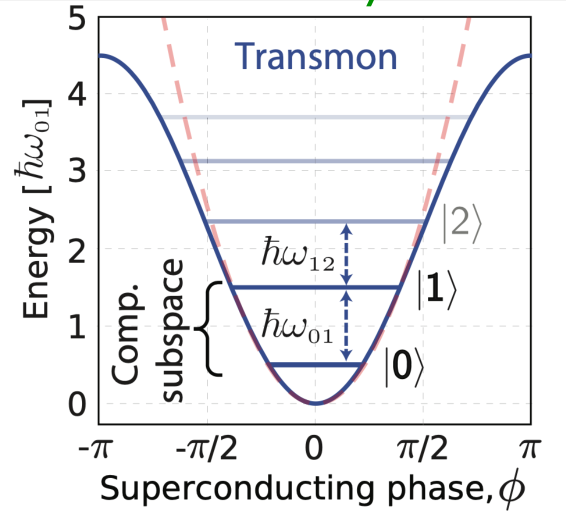
LZ (LUX-ZEPLIN)

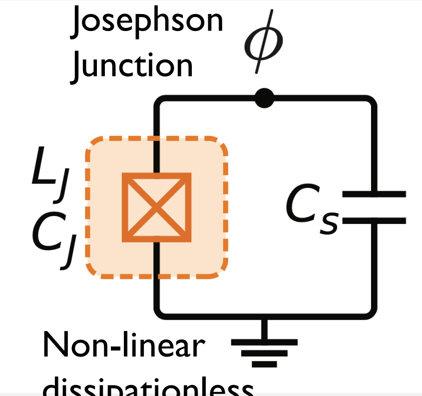
-- DM-Xe nuclei interaction produces electrons through ionization and photons that drift to the top causing flash of light (PMT)



WHAT IS A QUBIT?

two level system





Non-linear dissipationless circuit element

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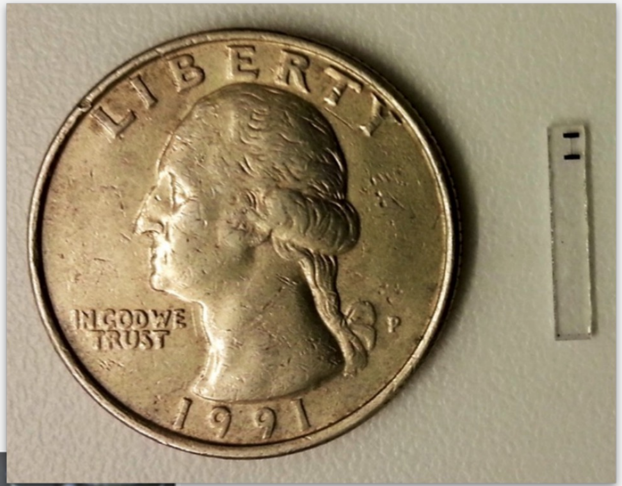

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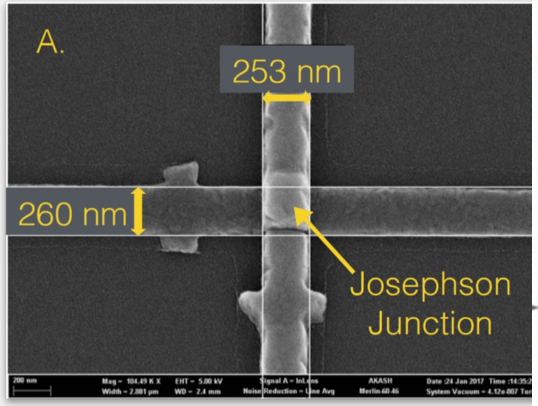

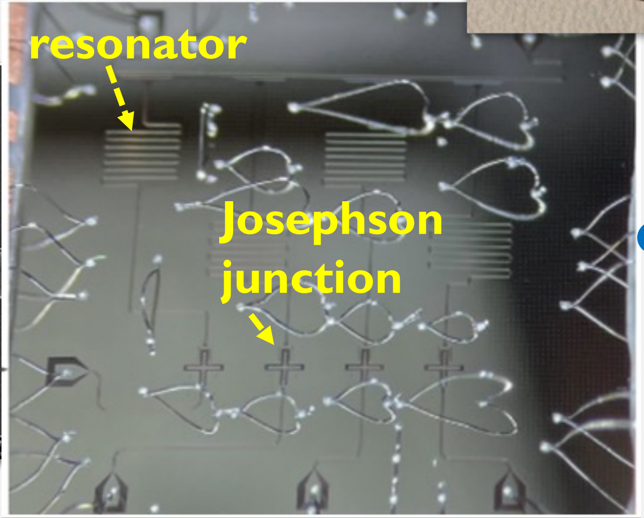

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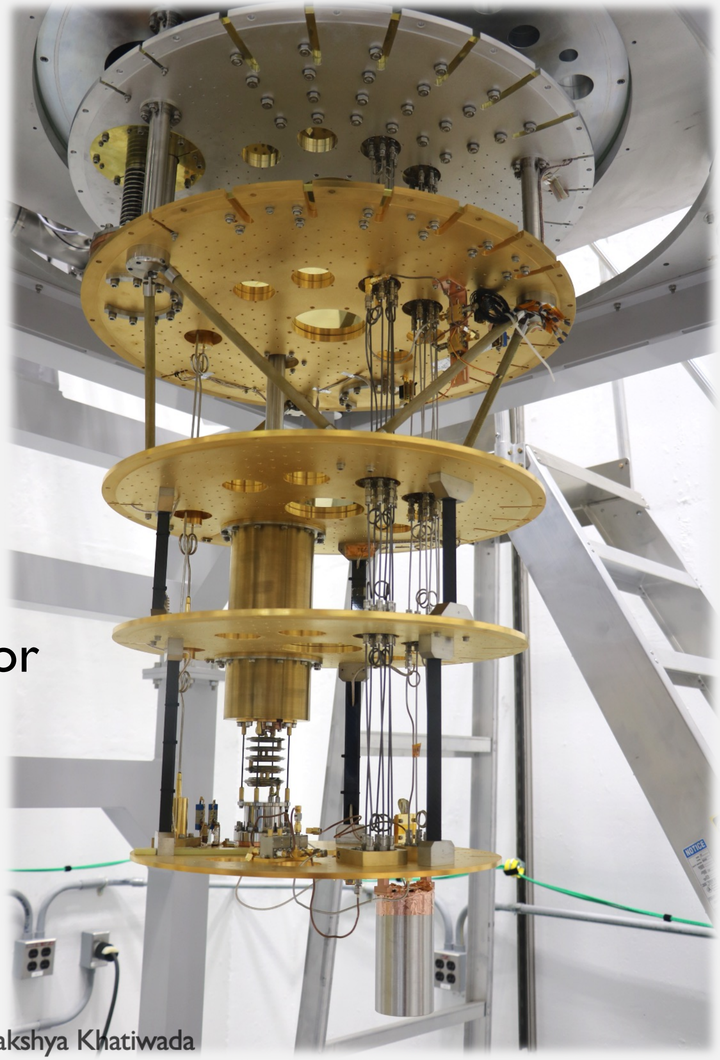
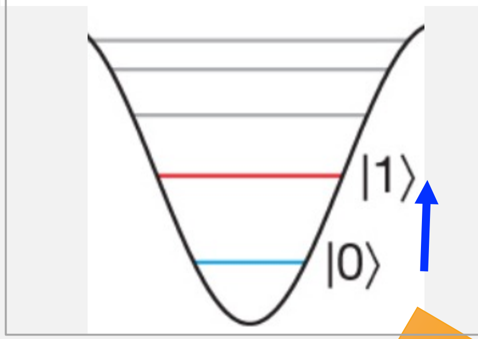
DETECTING DARK MATTER WITH QUBITS



Rakshya Khatiwada

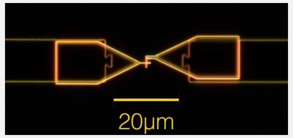
Dilution Refrigerator based at Fermilab

Qubit: two level system



Photon (comes from Dark matter axion)

Readout using a coupled cavity



Superconducting Josephson junction

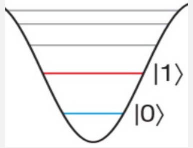
copper cavity

QUBIT BASED WAVE-LIKE DARK MATTER SEARCH

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

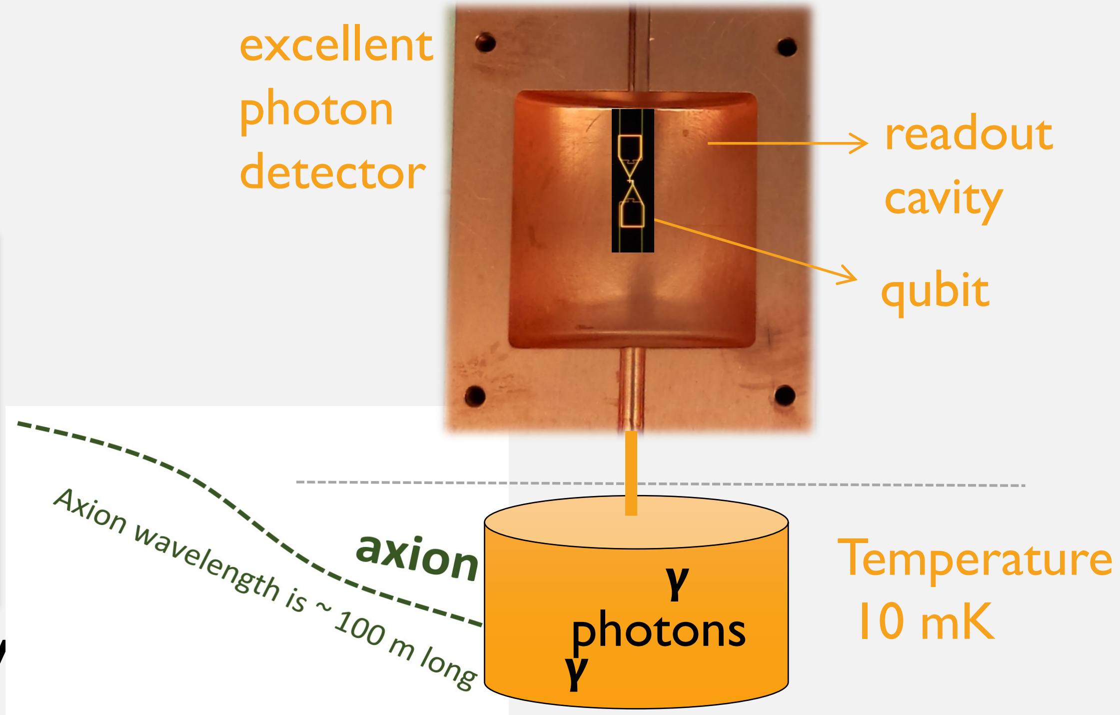
Cavity
Harmonic Oscillator

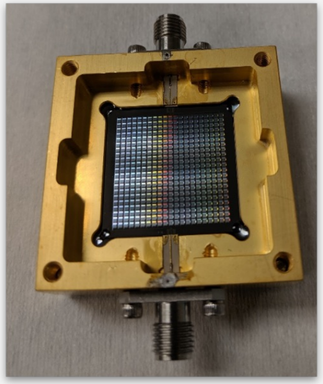
qubit
two level system



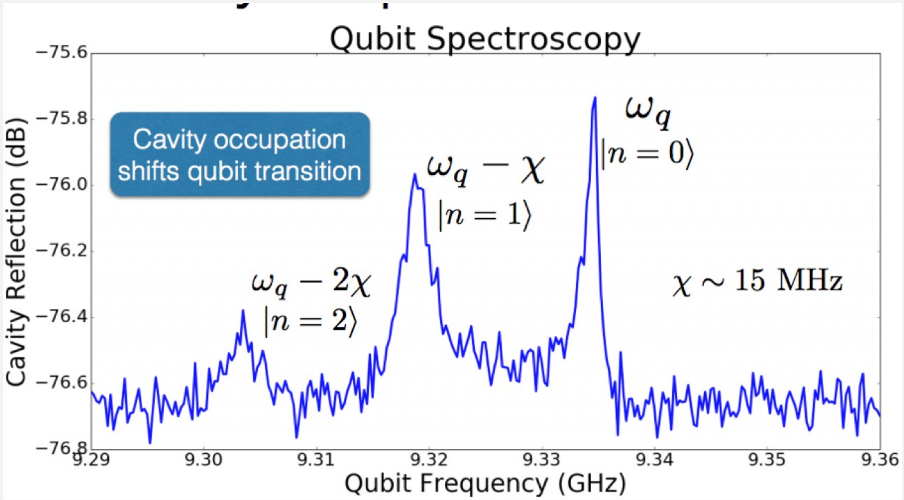
mixed state
g ~ **d.E**:
Δ: ω_q-ω_c
g^2/Δ: Stark shift

Qubit detector

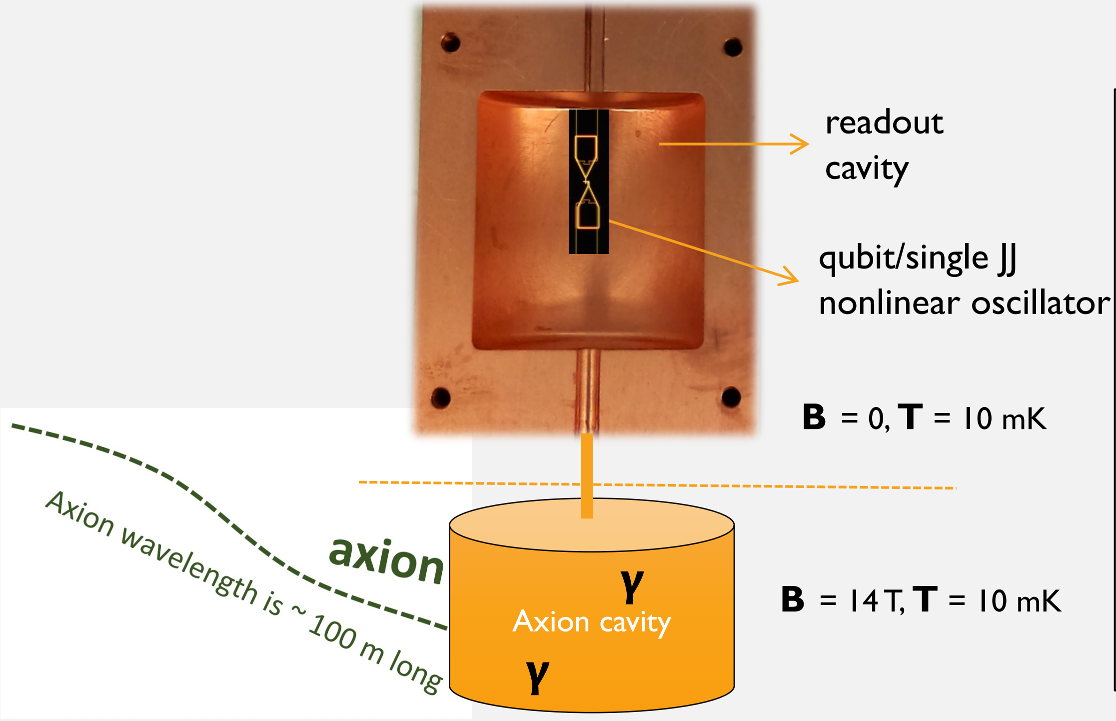




Qubit array



QUBIT BASED AXION DETECTOR



Ways of enhancing the signal:

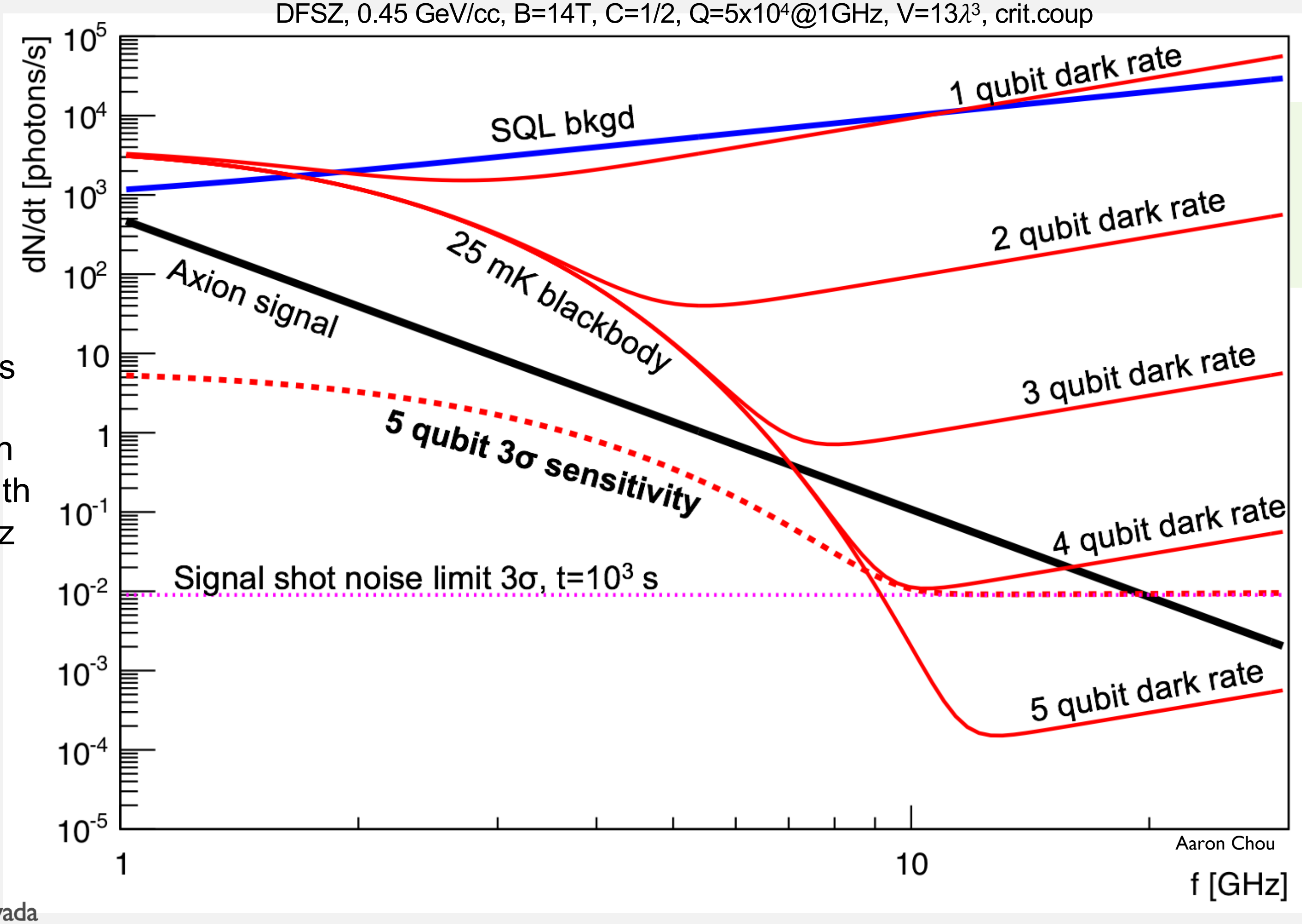
→ Multiple measurements:
Mulitple qubits:

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

→ 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.

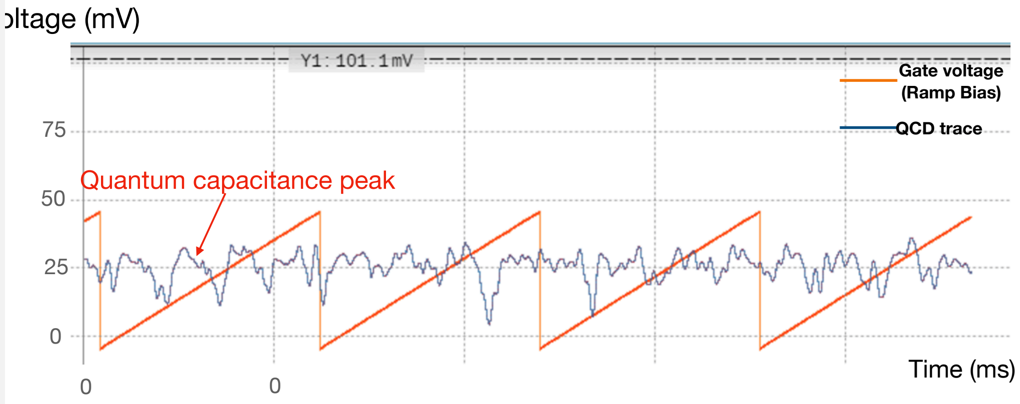
NQI Program Component Areas

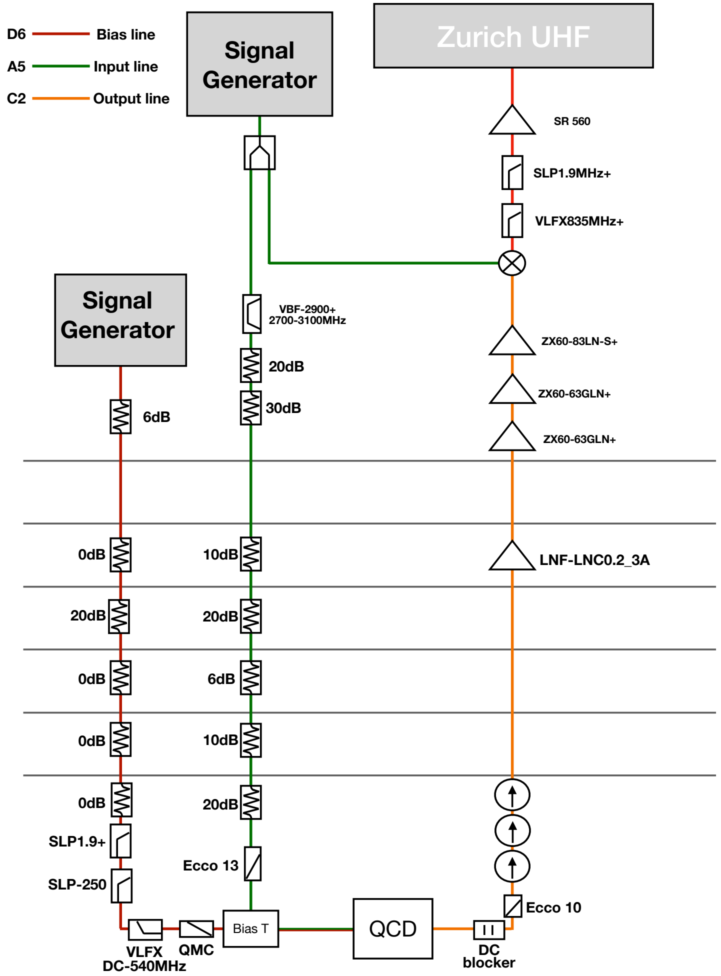
- **Quantum Sensing and Metrology (QSENS)** refers to the use of quantum mechanics to enhance sensors and measurement science. This can include uses of superposition and entanglement, non-classical states of light, new metrology regimes or modalities, and advances in accuracy and precision enabled by 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).

QCD READOUT

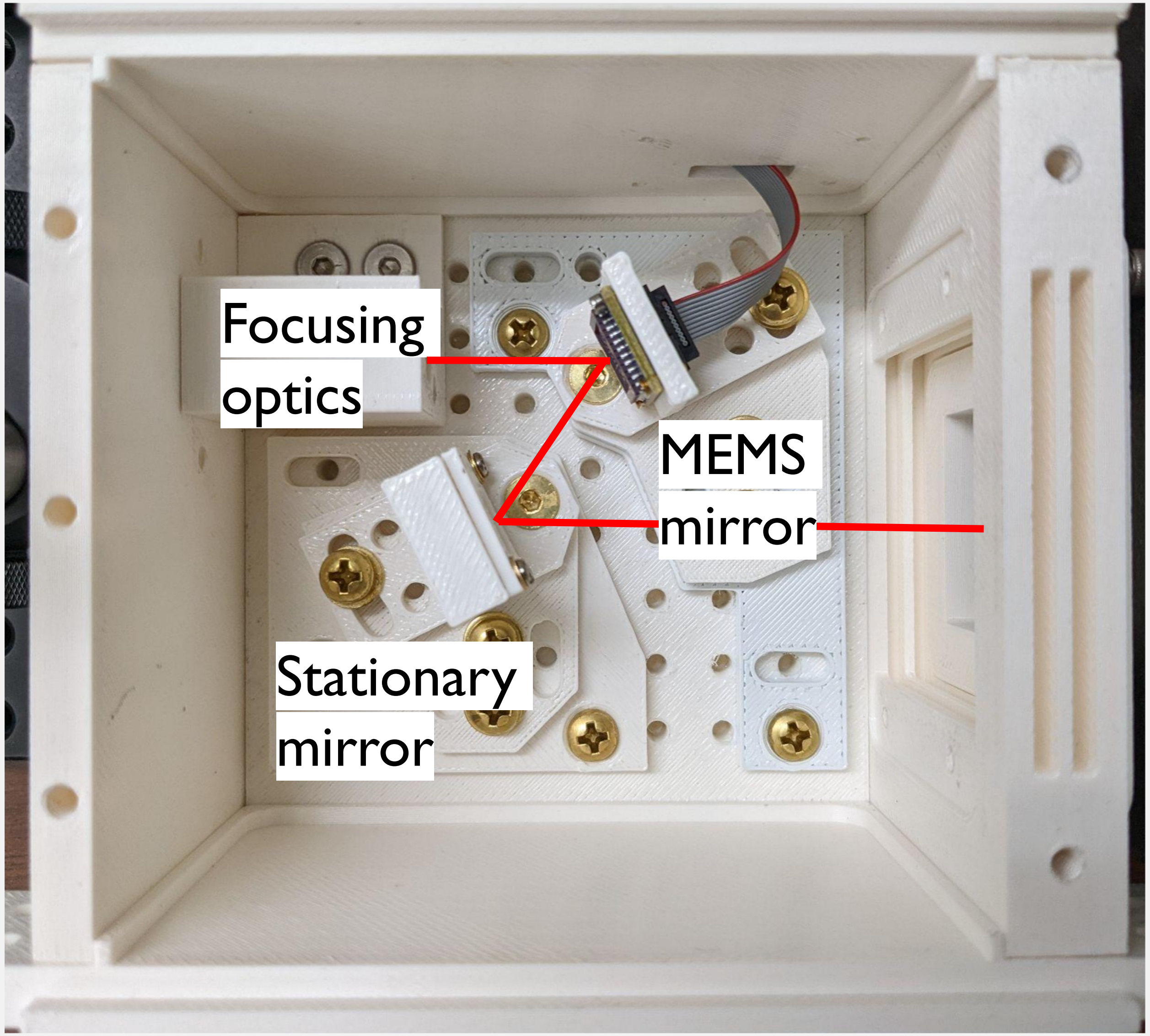
QCD Readout

- Sweep the gate voltage that spans a few quantum capacitance peaks.
- Counting the missing peaks (tunneling event)
- Missing peak rate shows that the dark count rate is high at this point





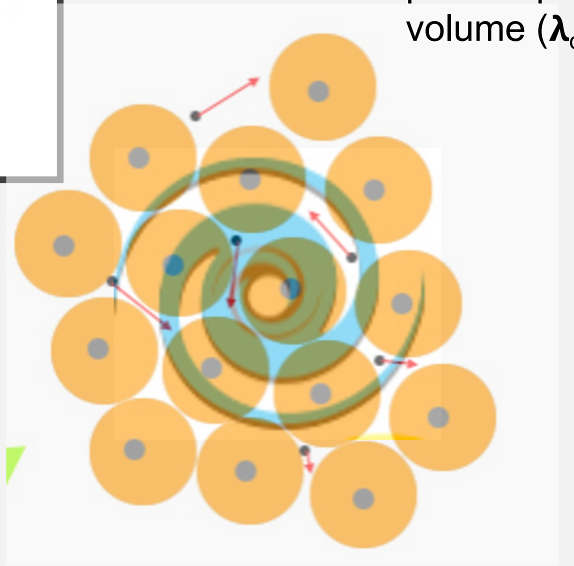
MEMS mirror allows for desired operating specifications:



- ~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 $(\boldsymbol{\lambda}_{deBroglie})^3$



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

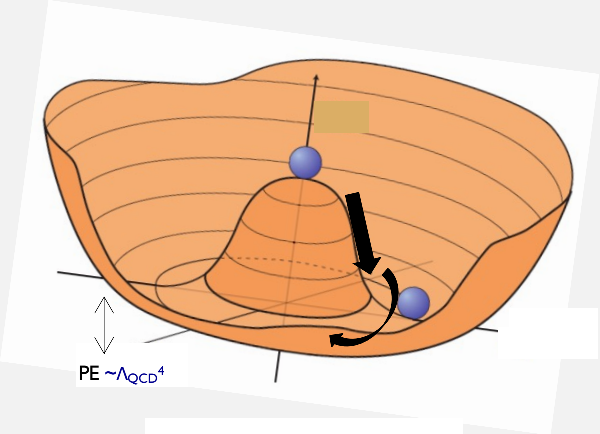
- Global symmetry broken at scale f_a
  -- axion produced through misalignment mechanism
  -- during QCD phase transition, trough tilted by Λ_{QCD}^4
- PE ~Λ_{QCD}^4 released, makes up dark matter

  -- 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**



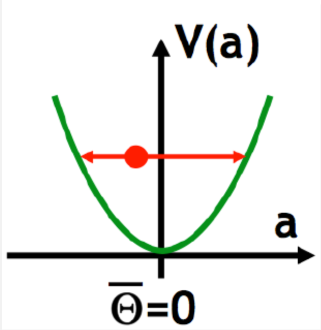
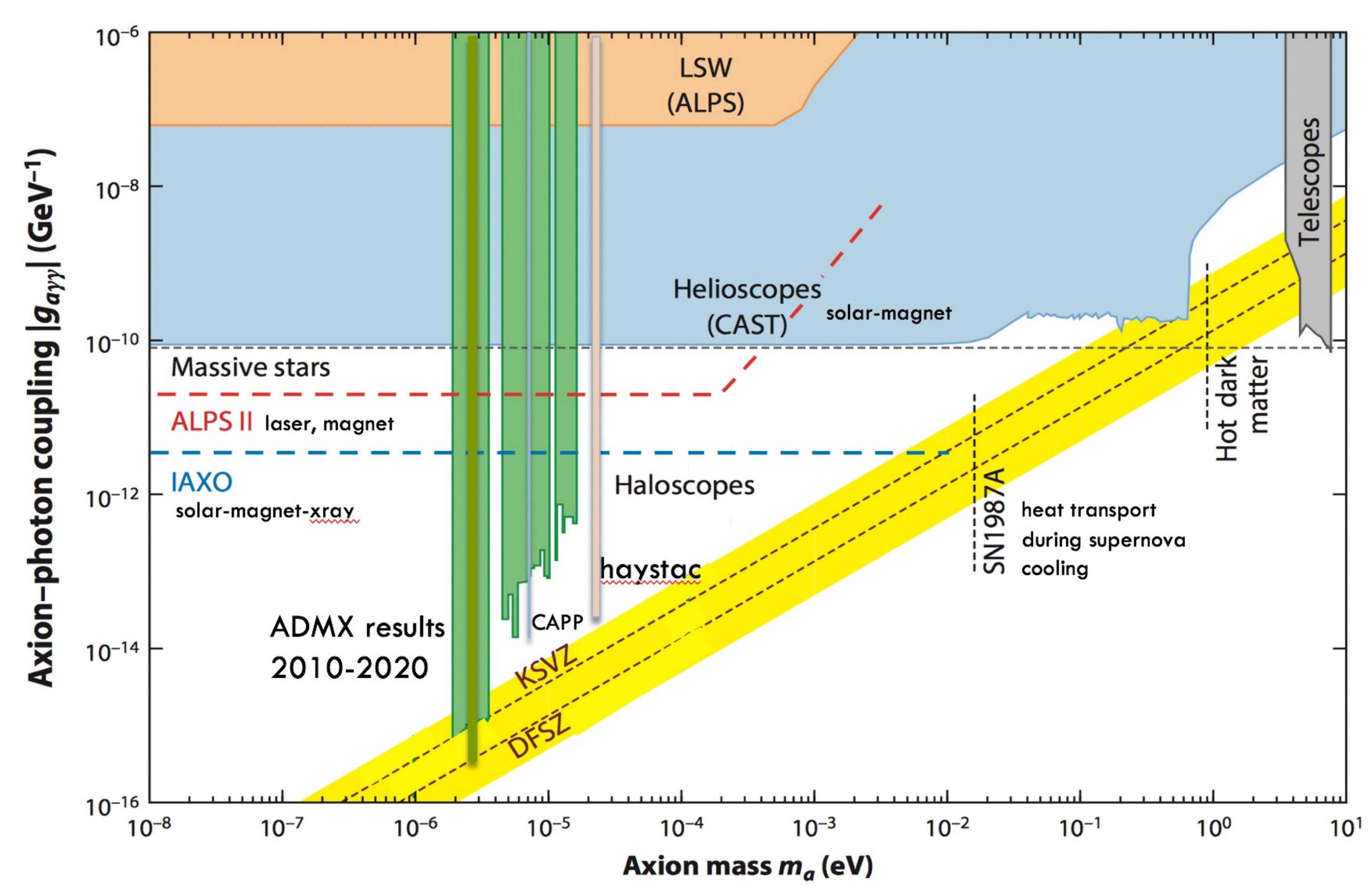


Fig 1:J. Ellis et al; arxiv:1201.6045v1

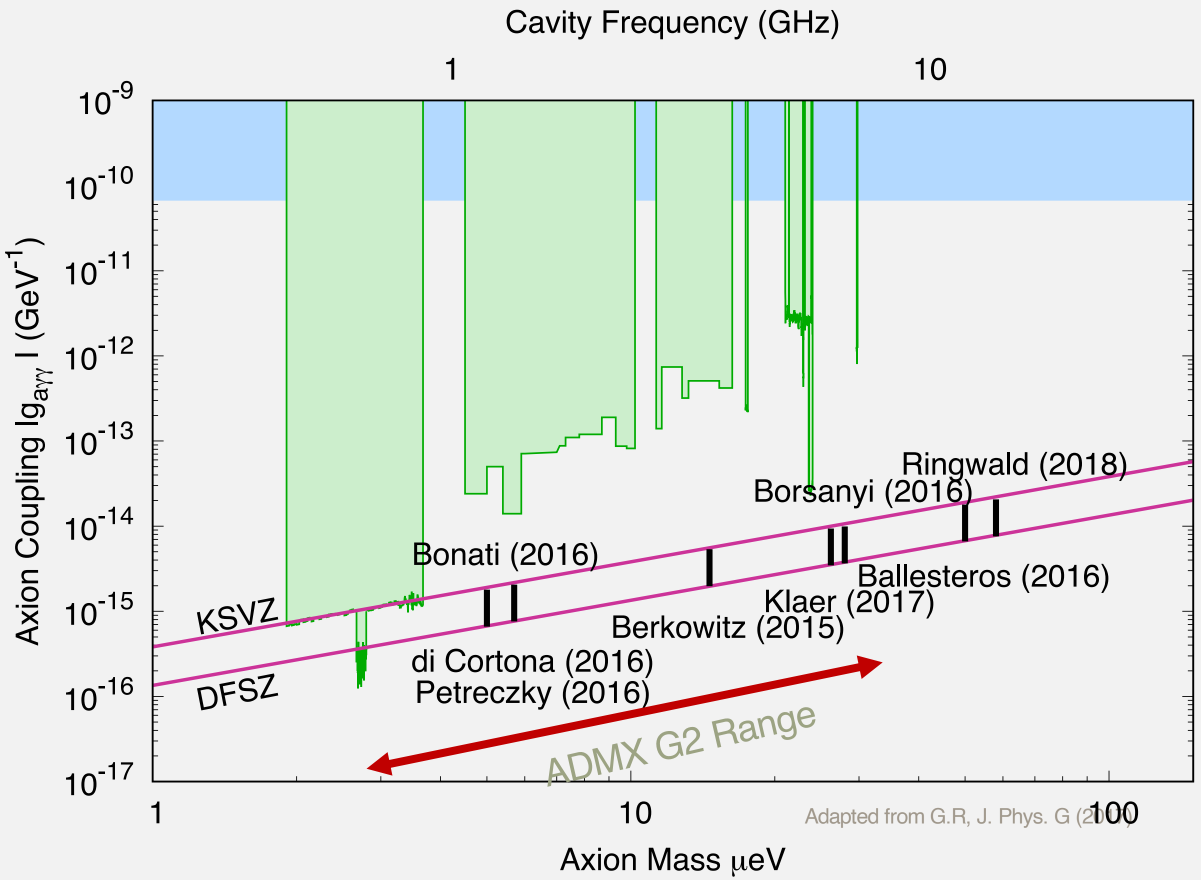
AXION SEARCHES OVERVIEW



Graham, et. al (2016)

AXION SEARCHES OVERVIEW CONTD.

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



QUANTUM AMPLIFIERS

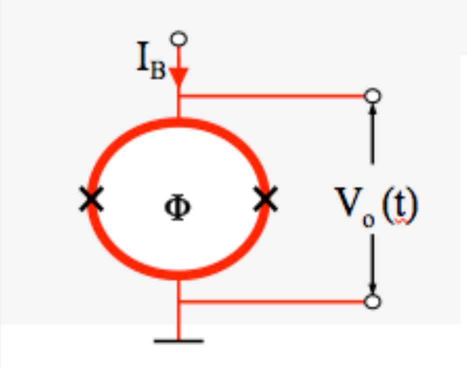
Why quantum amps.?

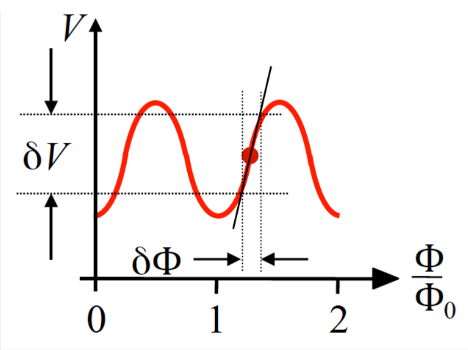
Intrinsically low noise (superconducting technology)
⇒ low resistance elements
⇒ low thermal dissipation
⇒ Add very low added noise during amplification
=> Tunable in frequency

Josephson Parametric Amplifier

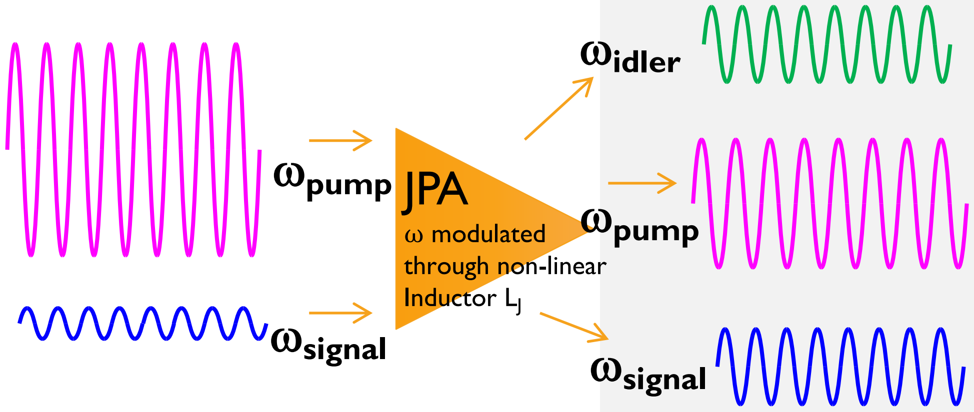
JPA

dc SQUID





- Energy transfer from pump to two normal modes of swing



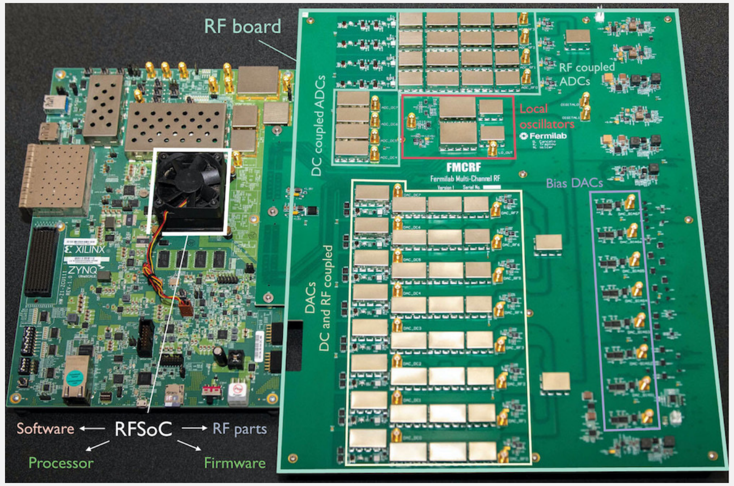
Only limited by Quantum Noise

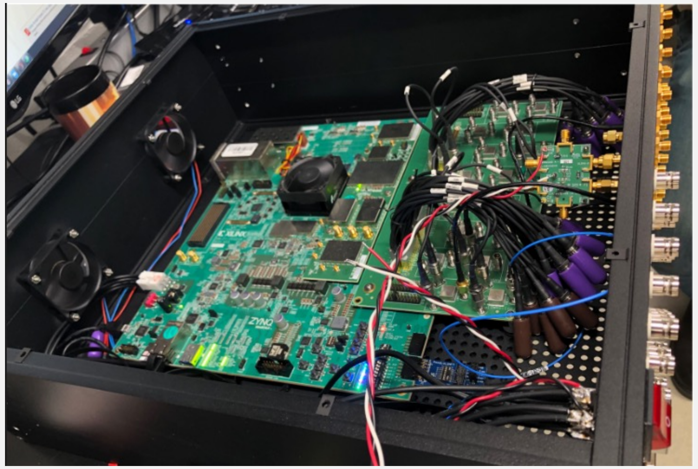
QUANTUM INSTRUMENTATION CONTROL KIT (QICK)

- **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

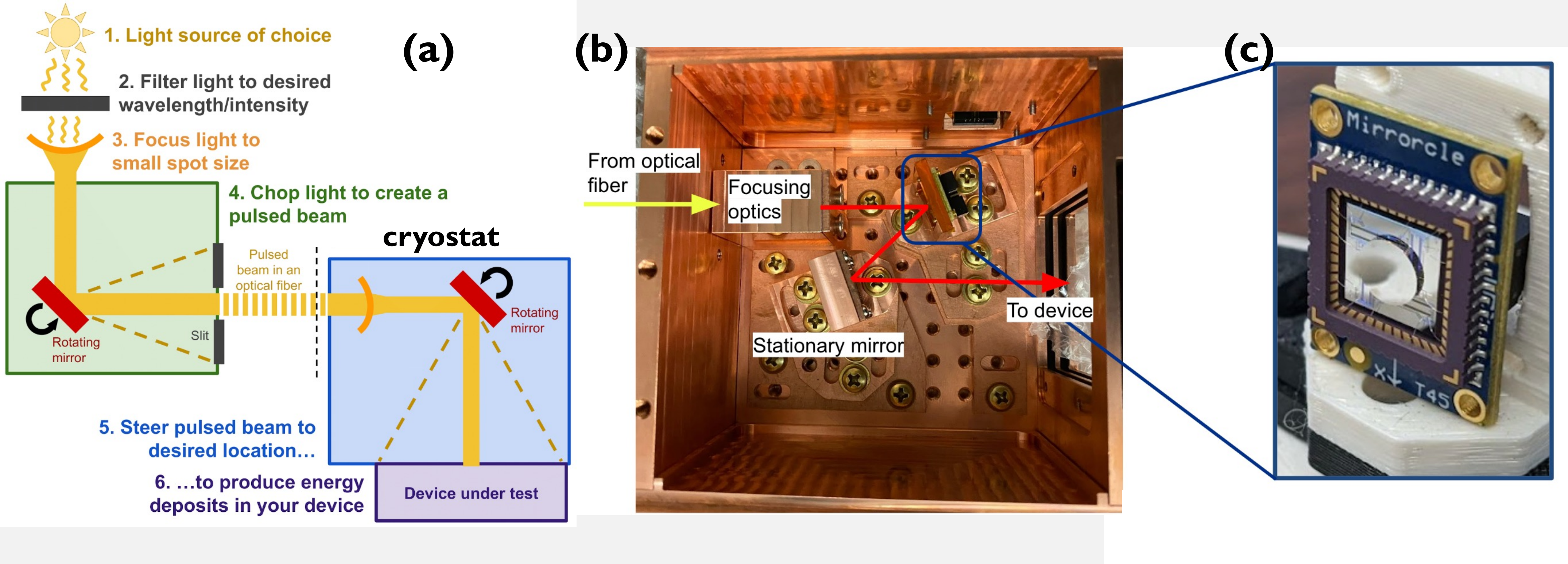




AMD-RFSoC ZCU216
QICK custom RF/DC amplifiers, bias under design

(1.3.3.02)

Cryogenic photon source for Detector Characterization



WHAT'S CAUSING THESE DARK COUNTS?

A superconductor free of quasiparticles for seconds

E. T. Mannila,[1,*] P. Samuelsson,[2] S. Simbierowicz,[3,†] J. T. Peltonen,[1]
V. Vesterinen,[3] L. Grönberg,[3] J. Hassel,[3] V. F. Maisi,[2] and J. P. Pekola[1]

[1] *QTF Centre of Excellence, Department of Applied Physics, Aalto University, FI-00076 Aalto, Finland*
[2] *Physics Department and NanoLund, Lund University, Box 118, 22100 Lund, Sweden*
[3] *VTT Technical Research Centre of Finland Ltd, QTF Centre of Excellence, P.O. Box 1000, FI-02044 VTT, Finland*

(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]

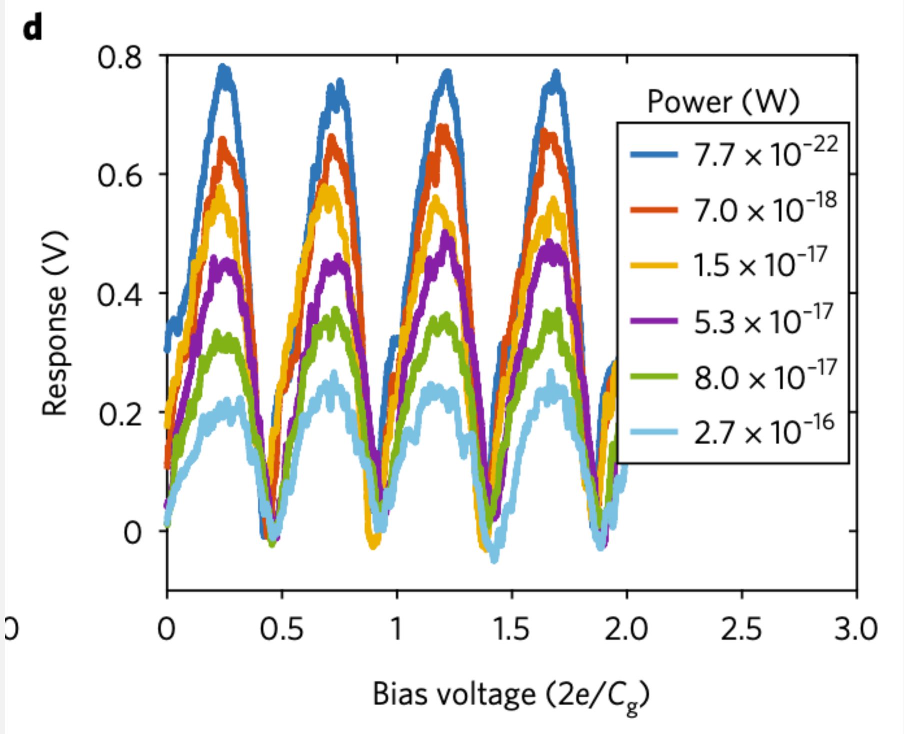
[1] *Department of Physics, University of California, Berkeley, CA 94720, USA*
[2] *Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[3] *Pacific Northwest National Laboratory, Richland, WA 99352, USA*
[4] *High Energy Physics Division, Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, Illinois 60439, USA*
[5] *Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, Illinois 60637, USA*
[6] *Kavli Institute for Cosmological Physics, University of Chicago, 5640 South Ellis Avenue, Chicago, Illinois 60637, USA*
[7] *Department of Physics, University of Massachusetts, Amherst, Massachusetts 01003, USA*

4 Aug 2022

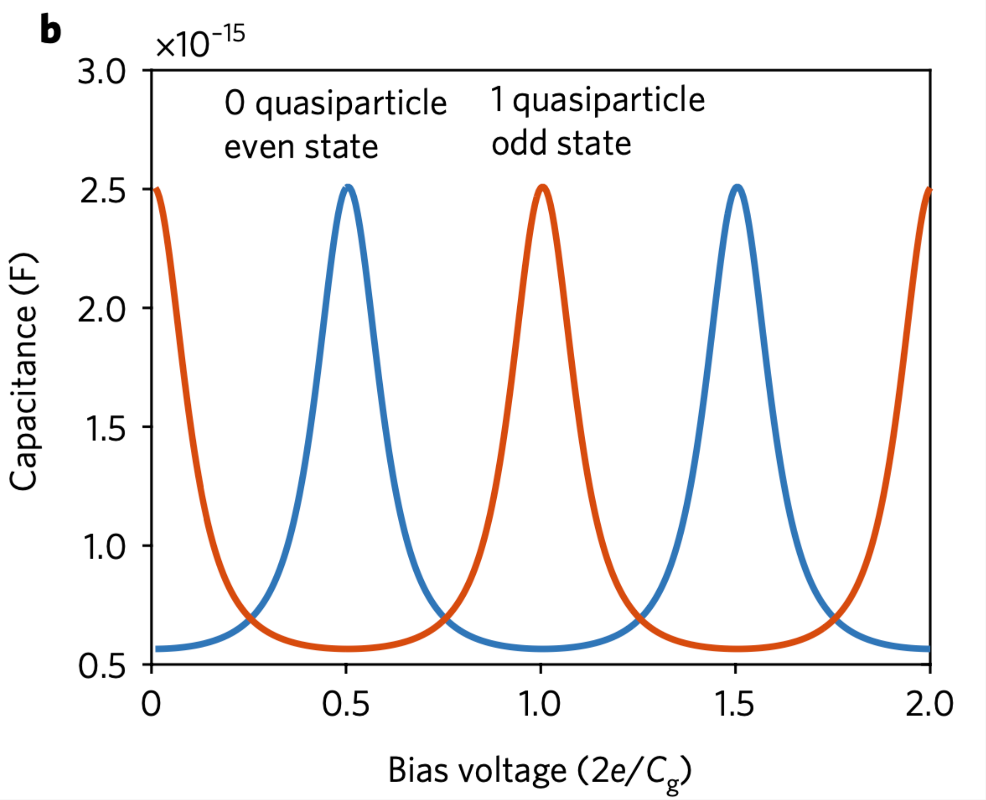
QCD READOUT

- Rate of qp $\text{Tunnel}_{in} \propto N_{qp}$
- Rate of qp Tunnel_{out} independent of N_{qp}
- Amplitude $\Delta C = T_{out} / (T_{in} + T_{out})\ (4\ E_C/E_J)(C_g^2/C_{tot})$
- Since $\Delta C \propto T_{in} \propto N_{qp}$ and $N_{qp} \propto$ signal photon power, measurement of ΔC gives signal photon power.

(amplitude of quantum capacitance)



Change in the charge changes the capacitance of the resonator which is quantized as a function of odd and even quasiparticle state in the island.



M. D. Shaw, J. Bueno, P. K. Day, C. M. Bradford, and P. M. Echternach, Phys. Rev. B 79, 144511 2009.

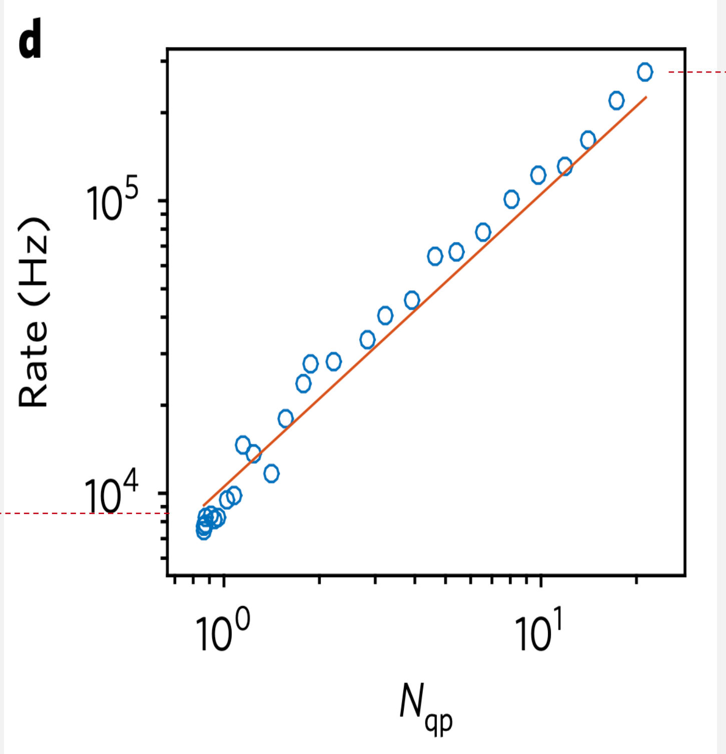
QCD PRODUCING QUASIPARTICLE

Despite having only 20 qp Produced, they keep on tunneling in and out of the island until thermalized so the tunneling rate is high

- Rate of quasiparticle tunneling vs. # of quasiparticles
- For a 1.5 THz photon: 210 kHz qp tunneling rate (instantaneous rate) for # qp 20 as opposed to 8 kHz residual qp rate (unknown background)

Instantaneous QP tunneling rate (Directly measured)

100 GHz incident photon



1.5 THz incident photon

10 THz photon ~ 133 qp
100 THz photon > 1000 qp

Note: N_{qp} inferred from QP tunneling rate fit.
N_{qp} not directly measured

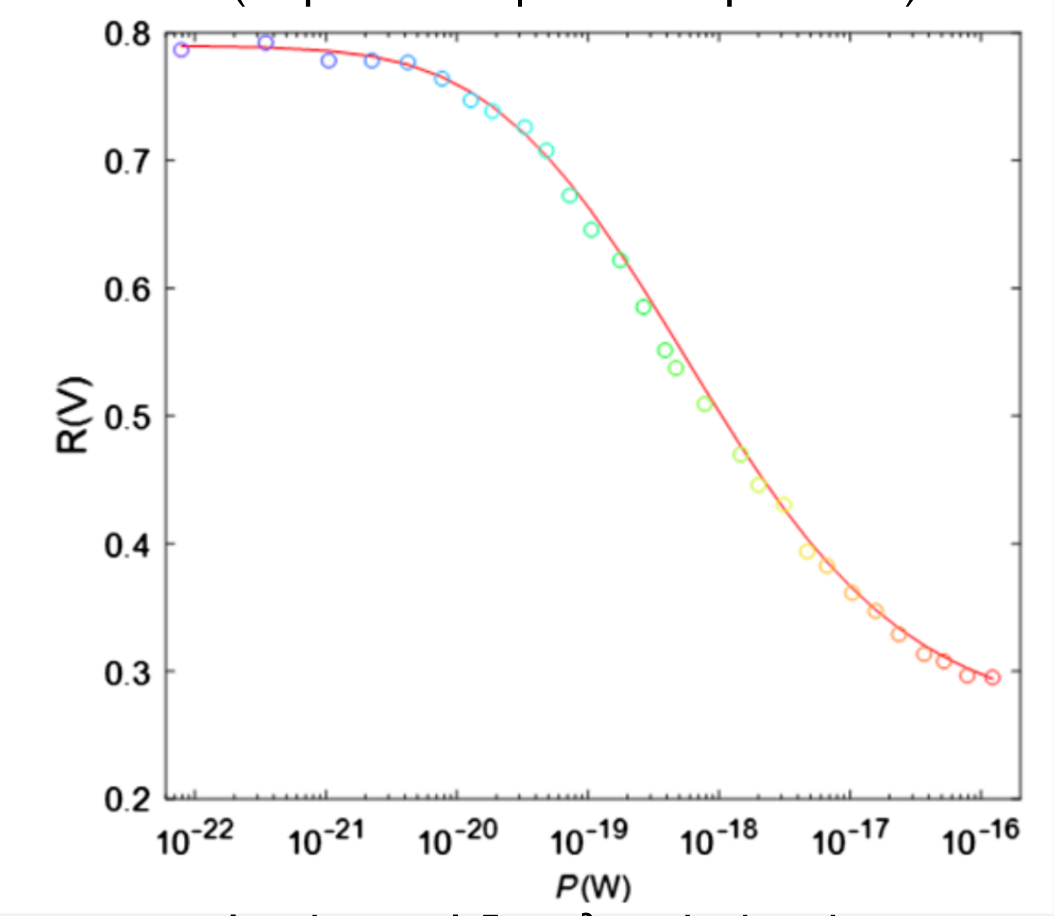
M. D. Shaw, J. Bueno, P. K. Day, C. M. Bradford, and P. M. Echternach, Phys. Rev. B 79, 144511 2009.

QCD RESPONSE AS A FUNCTION OF INCIDENT POWER (TRUE QCD OPERATION LIMIT)

Dynamic range for operation considerations:

- ***photon rate has to be < than Quasiparticle tunneling rate*** (otherwise device noise becomes higher than photon shot noise) (***No problem for DM***)
- Good operation regime between ***P = 10^{-20} to 10^{-17} W*** ***(shot noise dominated)***
- Noise source (Shot noise): big island and reservoir volume decreasing both tunneling in and tunneling out rates causes increased shot noise of electron tunneling.
- ***Can extend shot noise limited regime from P = 10^{-22} to 10^{-16} W*** with fabrication improvements including decrease in mesh and island size and increase in junction (decreases tunneling resistance increasing the tunneling rate) width etc.

R (amplitude of quantum capacitance)



Incident in 1.5 μm^3 mesh absorber