Quantum Sensors for Dark Matter searches

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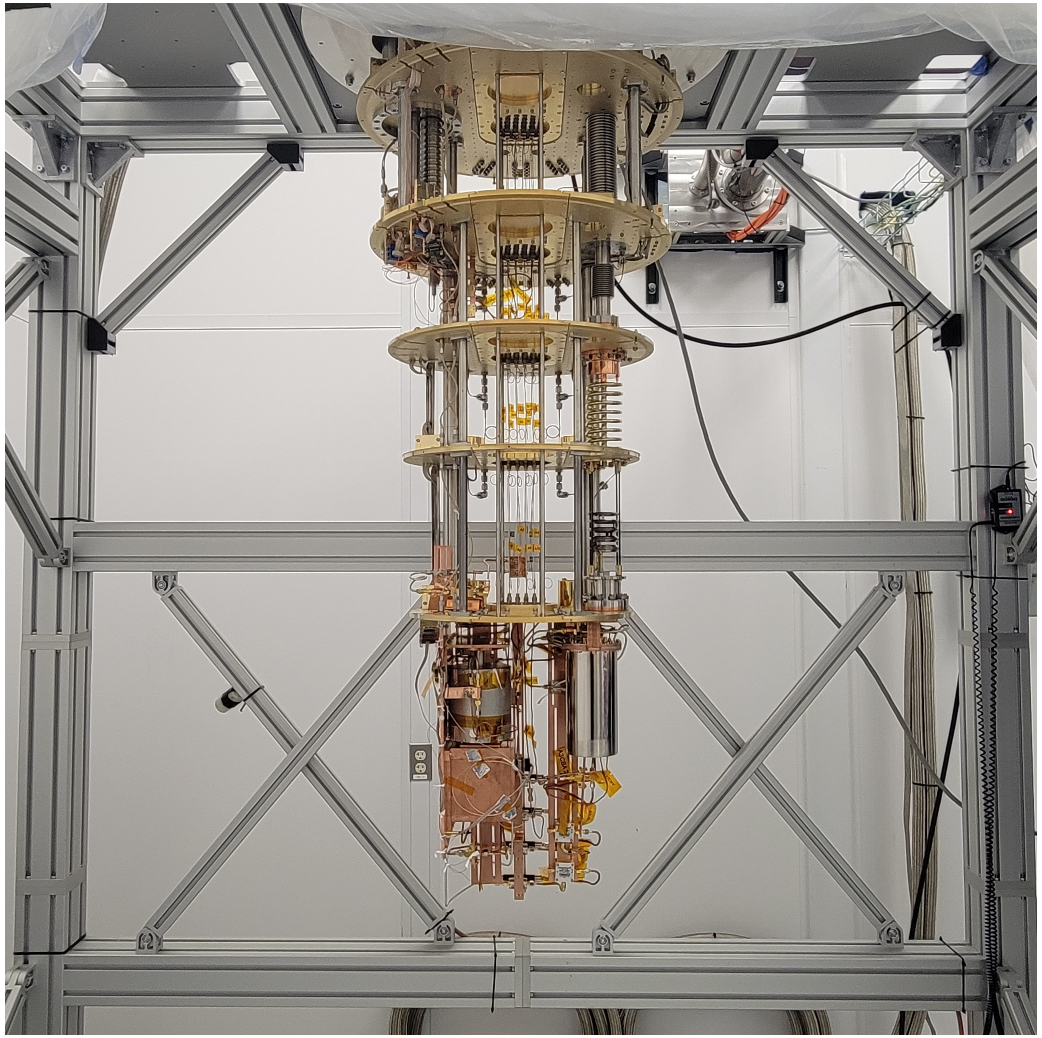
10/05/2023

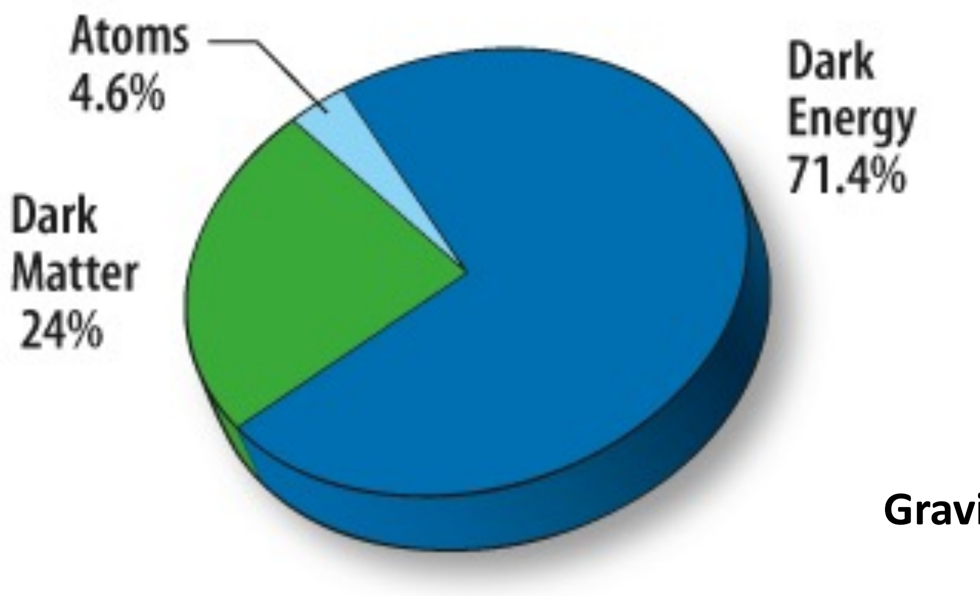
Outline

- Dark Matter search overview
- Why quantum sensors?
- Qubit based Dark Matter sensing
- Summary

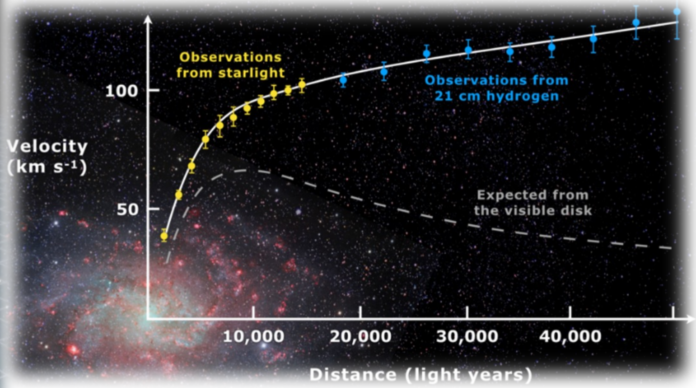
- Overview of Coordination Panel for Advanced Detectors (CPAD) activities
  → Coordination with ECFA DRDq

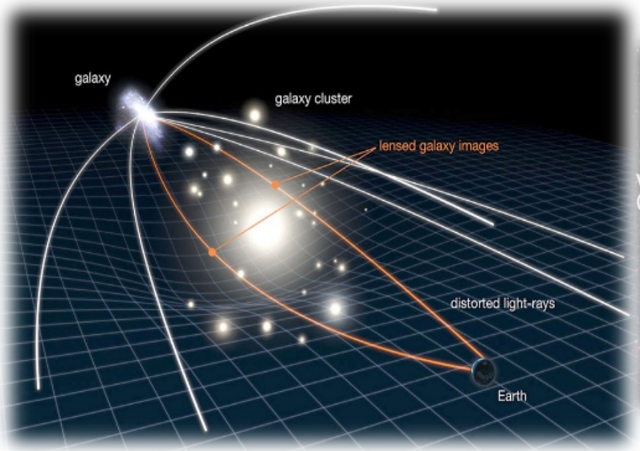


Dark Matter

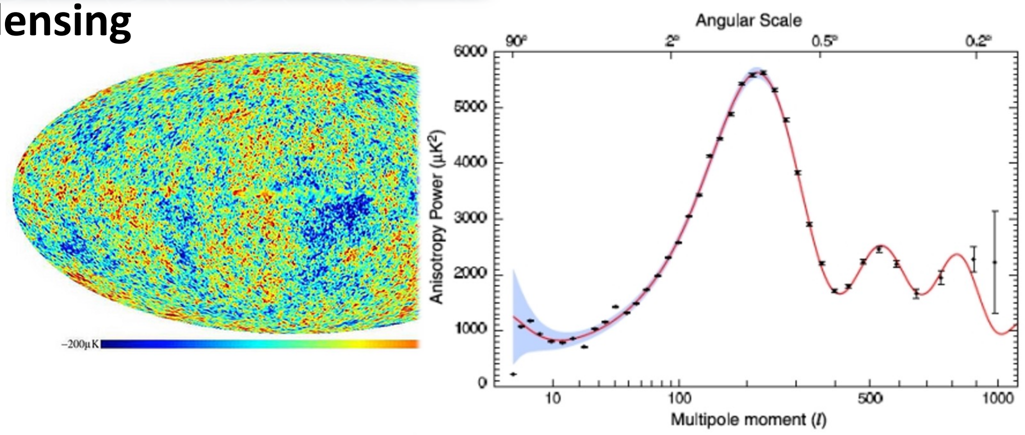


Galaxy rotation





Gravitational lensing



Cosmic Microwave background radiation

Properties:

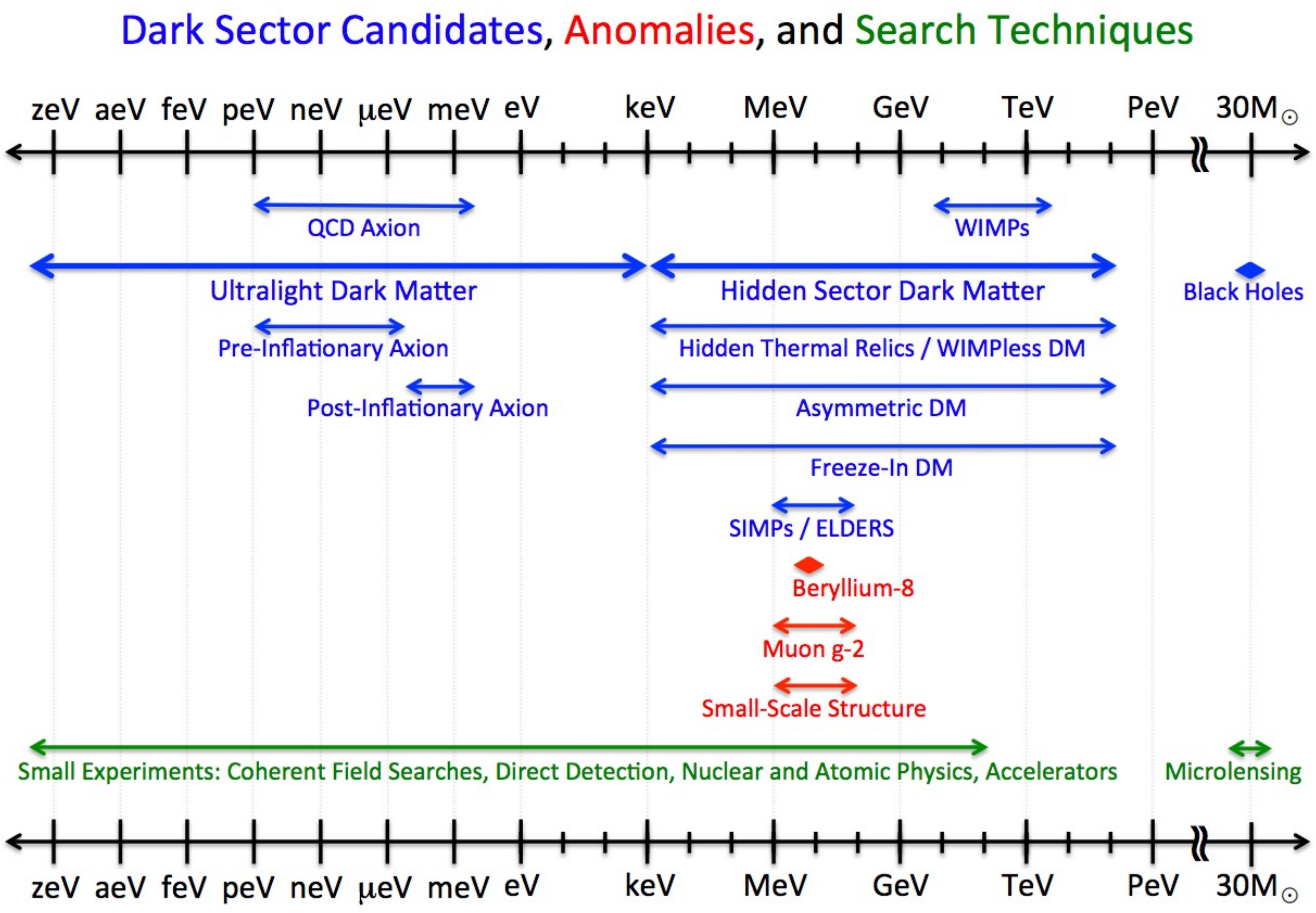
*Non-standard model particle

***Weakly interacting** – can't be detected with traditional observational astronomy

*Makes up large structures of the universe *forms clumps* – ***cold dark matter***

Dark matter candidates

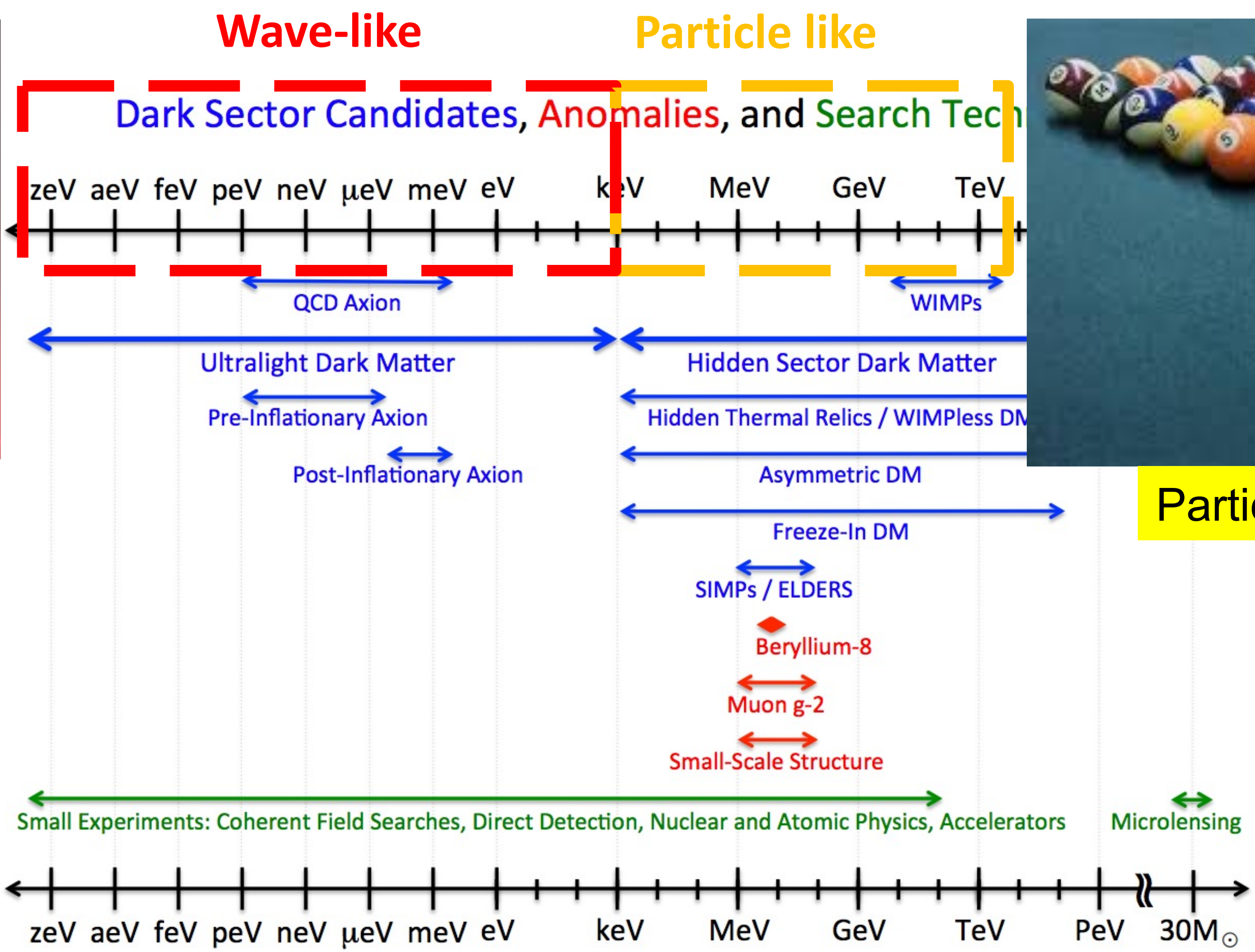
US Cosmic vision



For reference:
$m_e = 0.5\ MeV/c^2$
$m_p = 938.2\ MeV/c^2$

Dark matter candidates

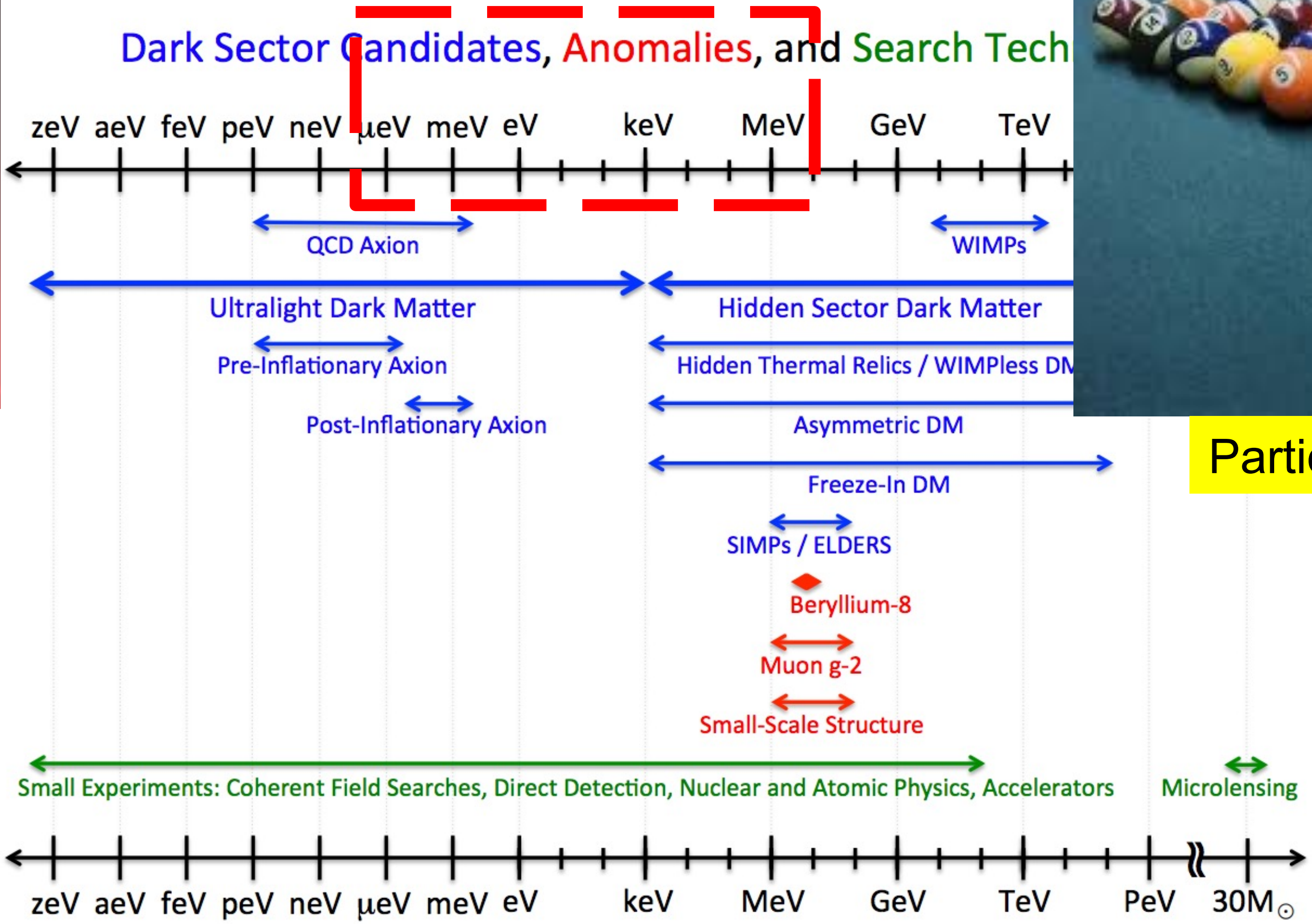
Wave like DM



Particle like DM

Dark matter candidates

Wave like DM

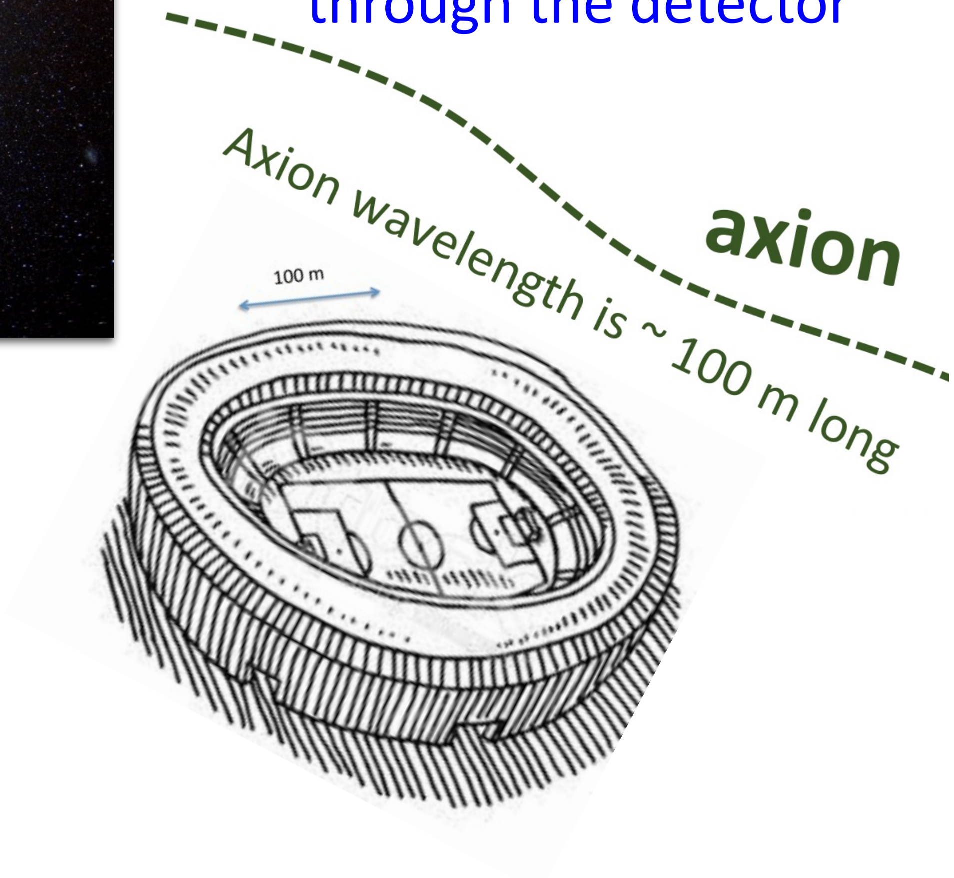


Particle like DM

Current detection mechanisms

Axions in the milky way halo

Football stadium sized clumps of axions drifting through the detector

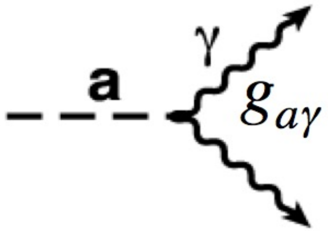


- *Big bang-> Milkyway halo-> gravitational potential-> Maxwell Boltzmann distribution of v (**mean 10^{-3}c ~ local virial velocity)***
- *# density local galactic halo ≈ 10^{14} cm^{-3}*

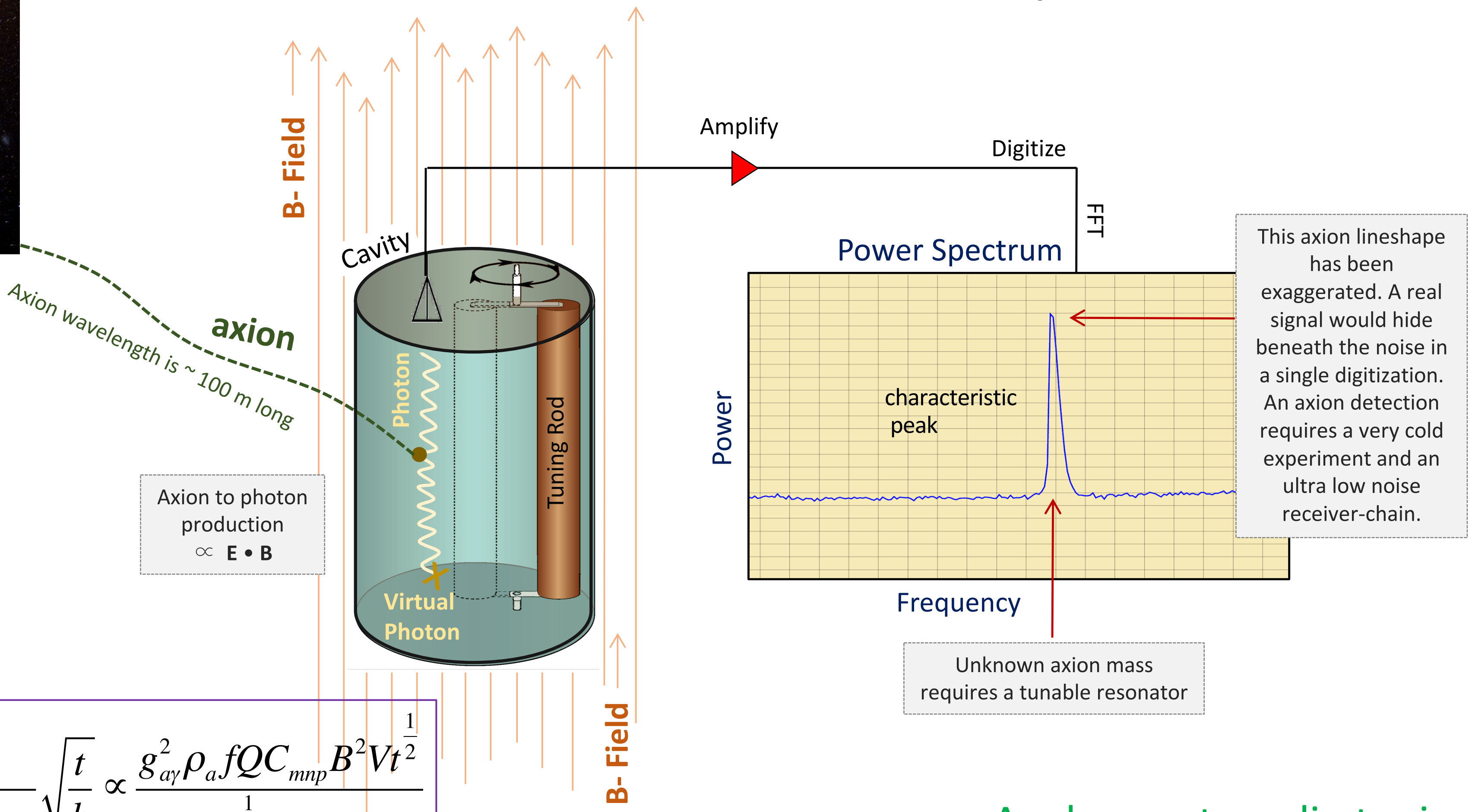
-- (ρ= 450 MeV/cm^3)

❑ *Lifetime 10^{42} years!*

The Axion Haloscope



$$\mathcal{L}_{a\gamma\gamma} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B},$$



$$SNR \propto \frac{P_{out}}{k_B T_{system}} \sqrt{\frac{t}{b}} \propto \frac{g_{a\gamma}^2 \rho_a f Q C_{mnp} B^2 V t^{\frac{1}{2}}}{b^{\frac{1}{2}} T_{system}}$$

Analogous to radio tuning

C. Boutan

Quantum noise

Δx: *position*
Δp: *momentum*

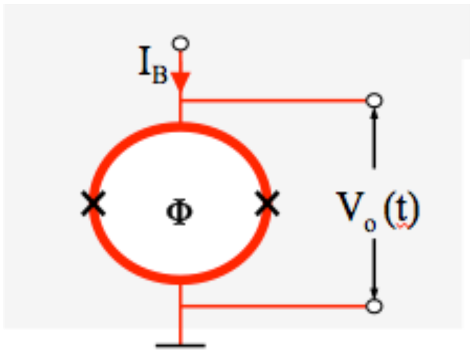
Similar to $\Delta x \Delta p \geq \hbar/2$

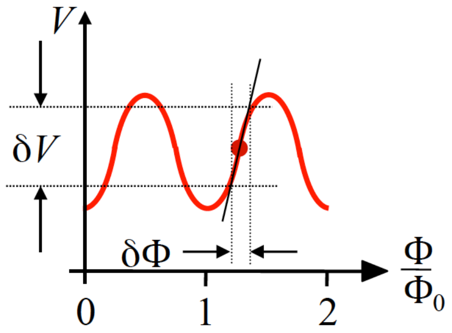
48 mK ($h\omega/k_B$ @1GHz)

Electromagnetic wave's phase and amplitude measurement uncertainty

Josephson Parametric Amplifier **(JPA)**

dc SQUID





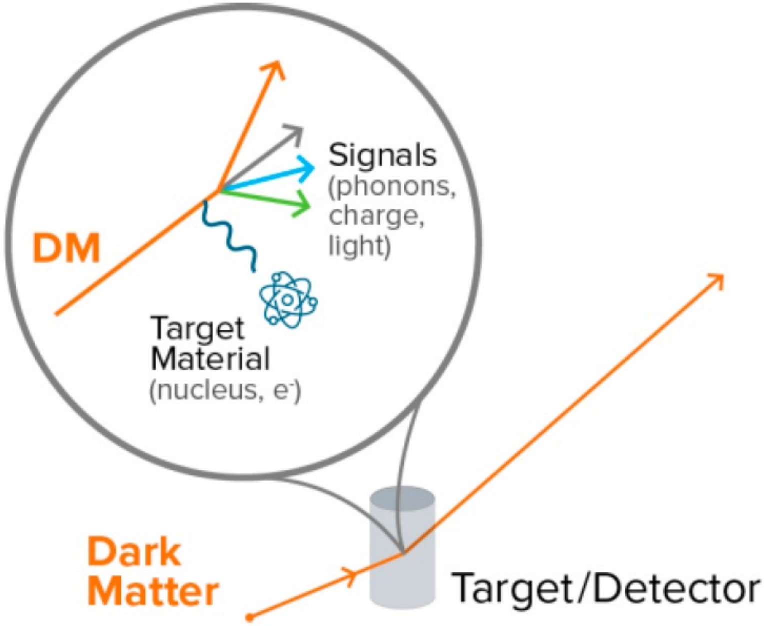
- Building blocks of quantum devices
- Flux to voltage transducer
- Magnetometers
- Quantum Amplifiers
- Signal readout from detectors

$$T_{system} = T_{amps.} + T_{physical}$$

$$SNR \propto \frac{P_{out}}{k_B T_{system}} \sqrt{\frac{t}{b}} \propto \frac{g_{a\gamma}^2 \rho_a f Q C_{mnp} B^2 V t^{\frac{1}{2}}}{b^{\frac{1}{2}} T_{system}}$$

Need lower noise than quantum noise
< 1/2 photons per quadrature !

Particle like Dark Matter Search overview



Underground to avoid background like cosmic muon

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*

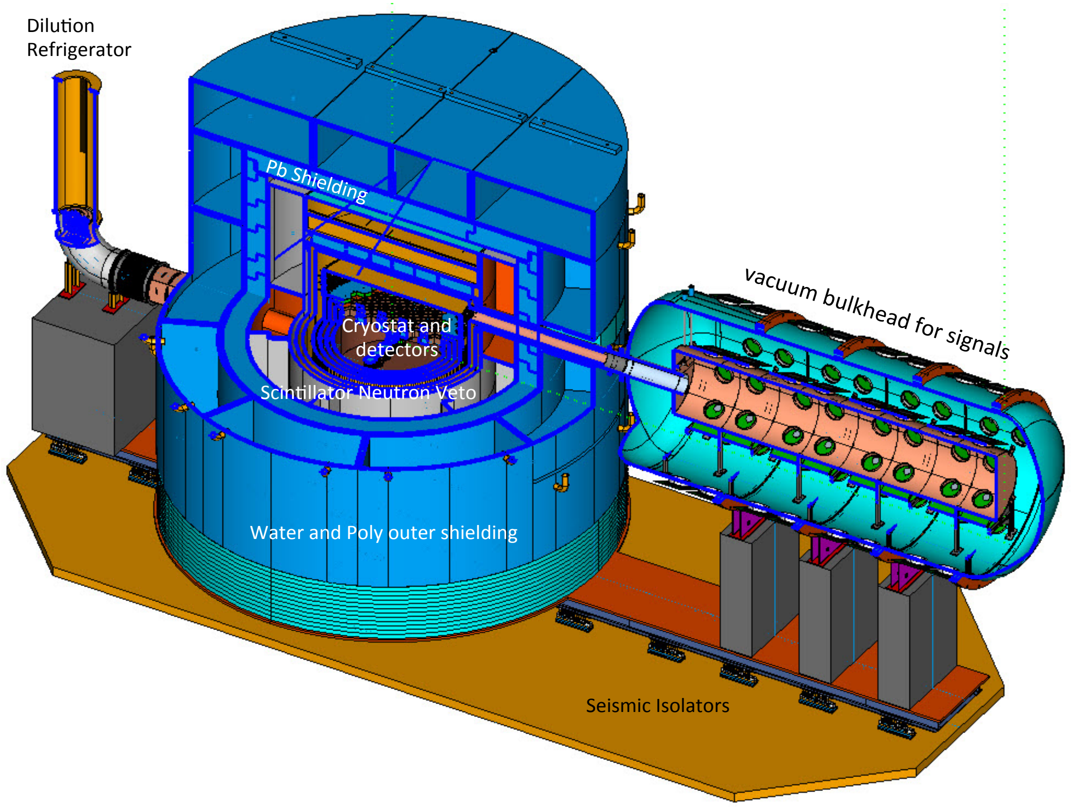
DM Energy absorbed by the target material

https://www.osti.gov/servlets/purl/1659757

Some Experiments

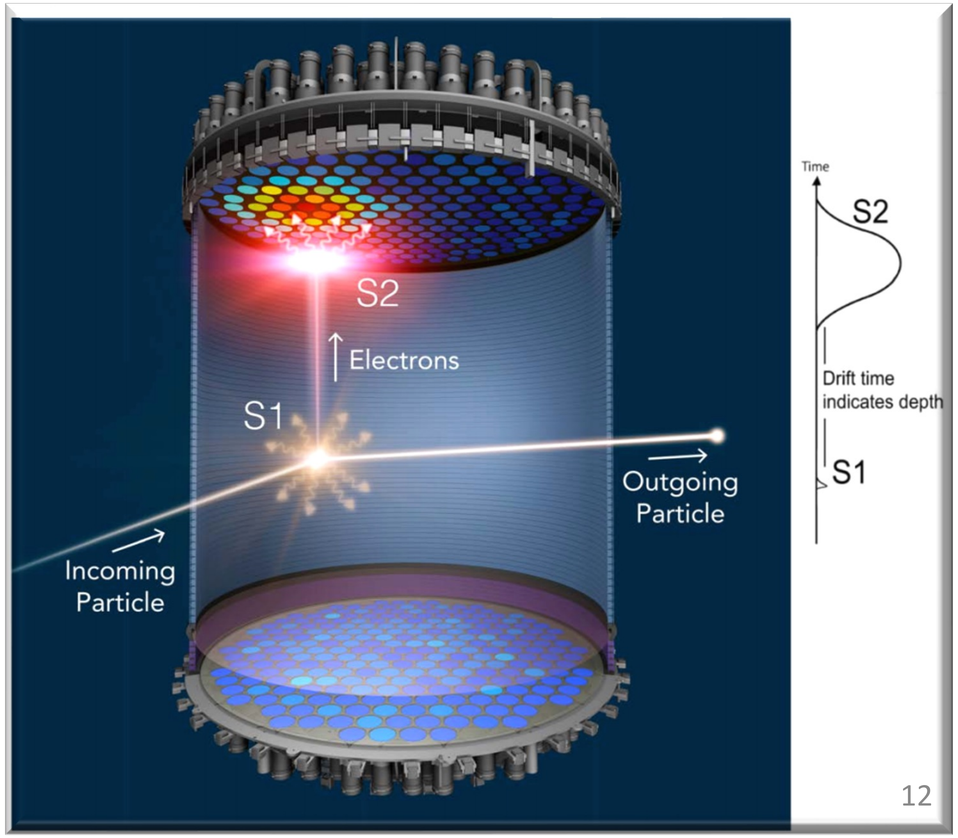
Super-CDMS-SNOLAB

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

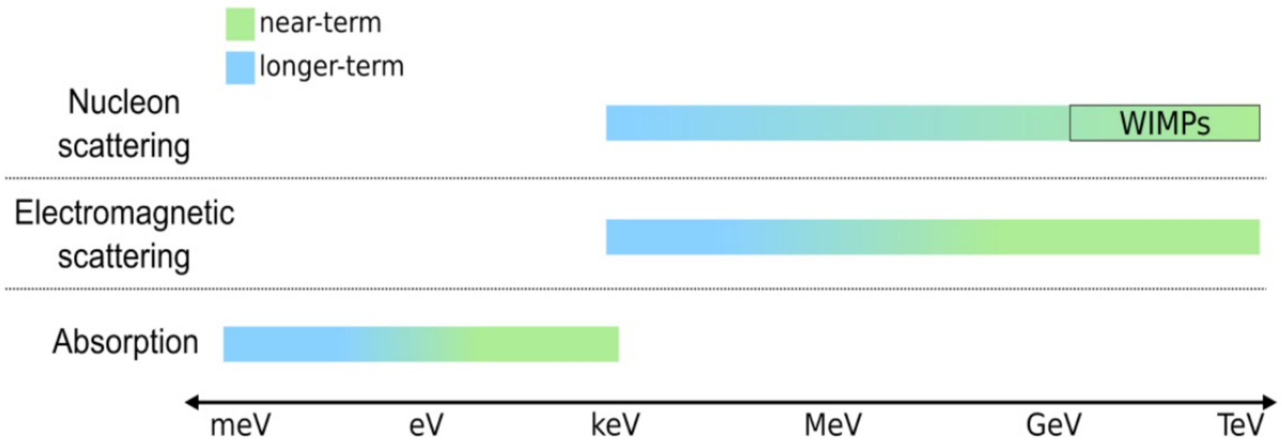


LZ (LUX-ZEPLIN)

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



Near and long-term Dark Matter search plan



Need low energy threshold systems < 1 eV !

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.*

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

Basic Research Needs (BRN)

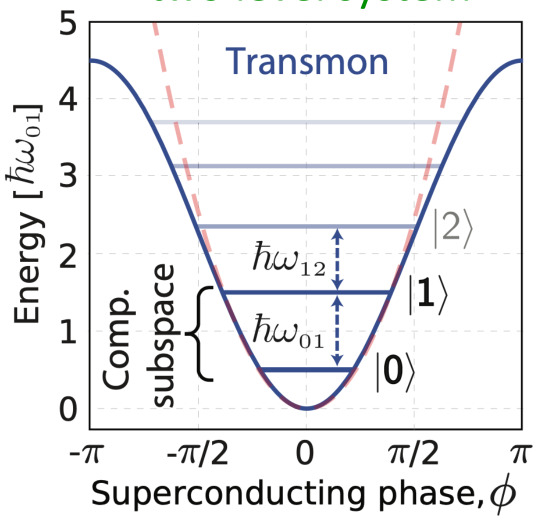
Qubit based Quantum detectors for Dark Matter searches

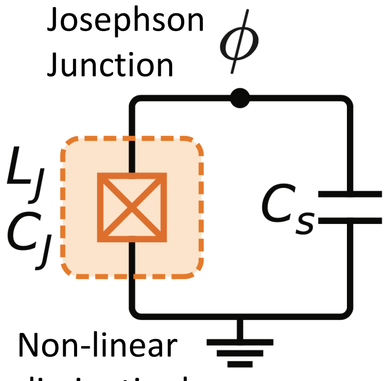
Advantages of qubits over current Dark Matter technology

- ***sensitivity to sub-eV energy*** from Dark Matter interaction
- energy can be coupled as ***single phonons (lattice vibrations)*** or ***single photons***
- Easy signal readout with a qubit readout protocol (T_1, T_2, charge parity measurements etc.)
- Qubit superconducting systems in mK cryostat, ideal for ***thermal noise reduction*** for Dark Matter searches.
- Superconducting technology; ***low noise***

What is a qubit?

two level system





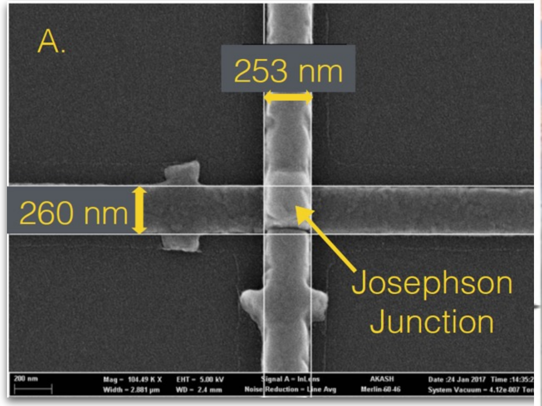
$E_J \gg E_C$

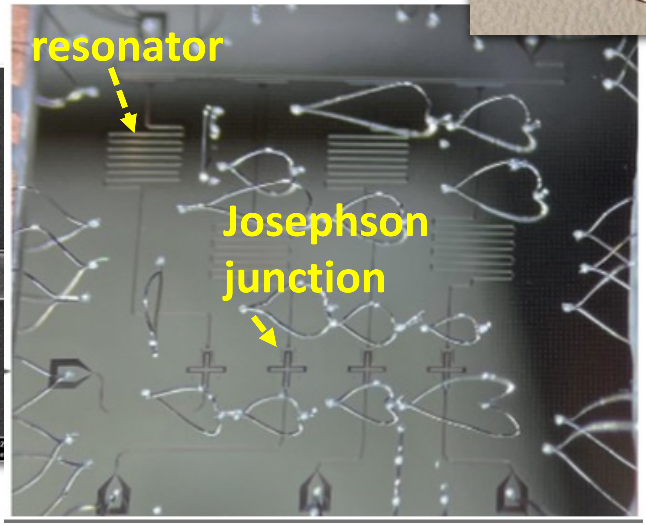
$E_c = e^2/2C$ charging energy

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

where $\Phi_0 = h/2e$ 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).

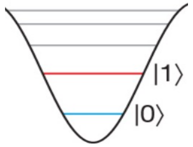
What has been demonstrated with qubit based Dark Matter detectors?

Qubit based wave-like Dark Matter search

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

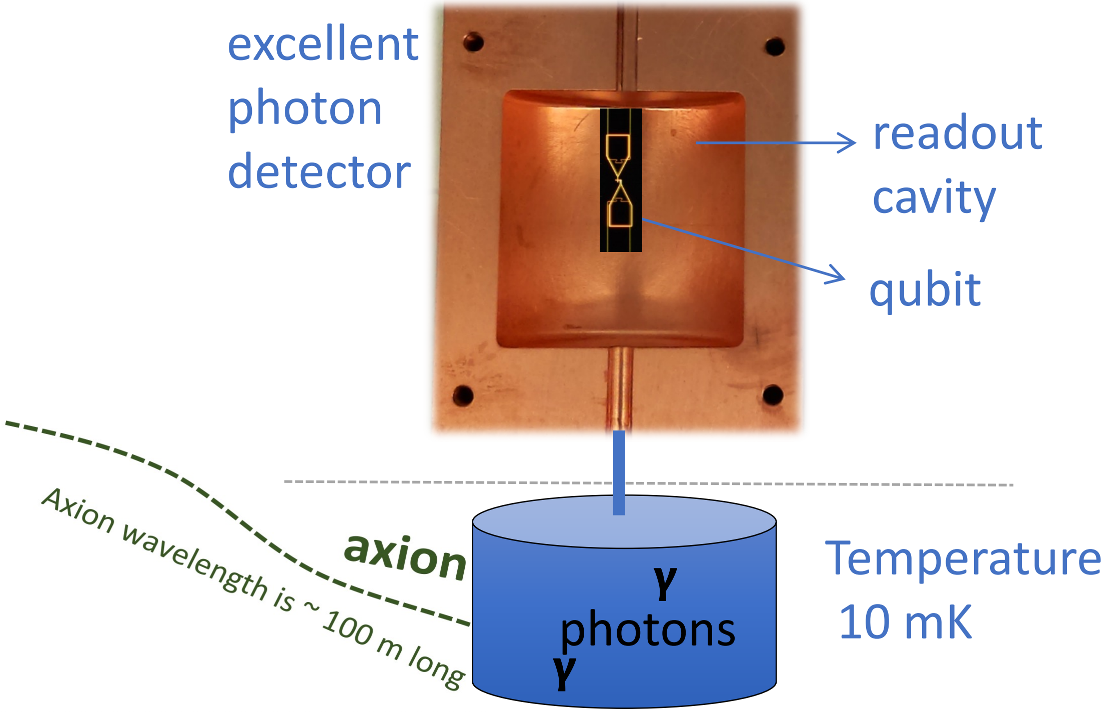
Cavity
Harmonic Oscillator

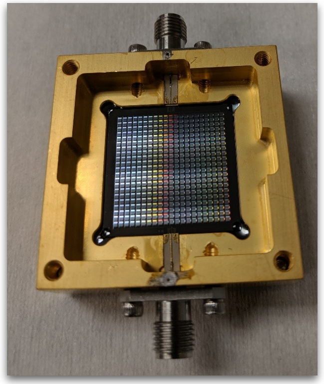
qubit
two level system



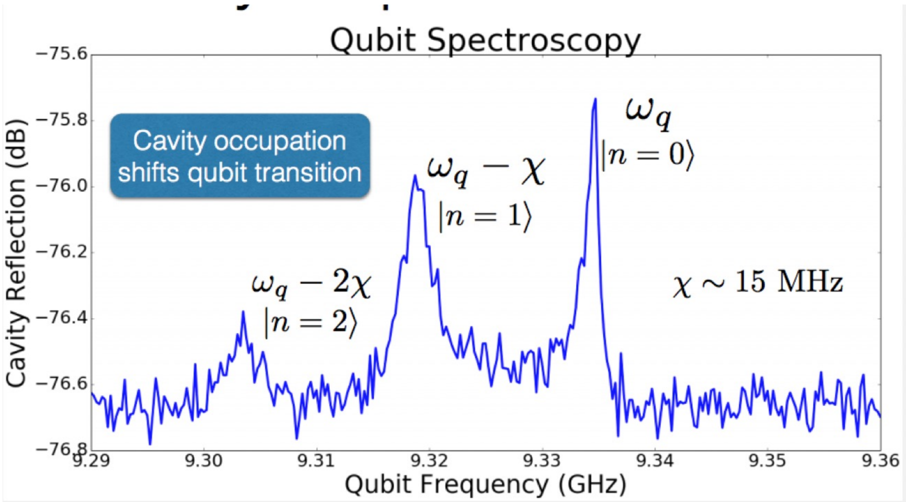
mixed state
g ~ **d.E**:
Δ: ω_q-ω_c
g^2/Δ: Stark shift

Qubit detector





Qubit array

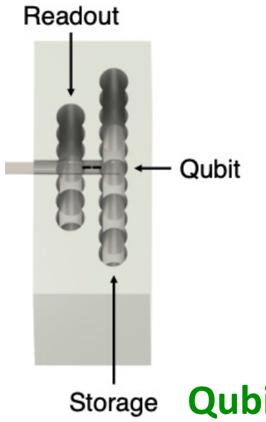


Hidden photon Dark Matter search with qubits

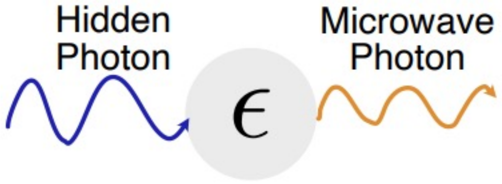
QuantiSED

prototype demonstration

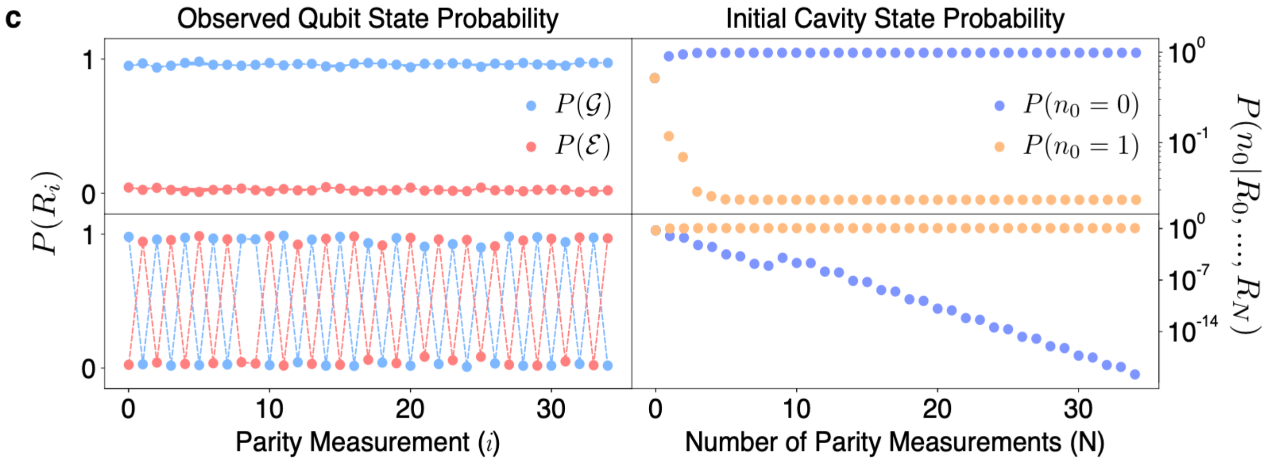
U Chicago/FNAL



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

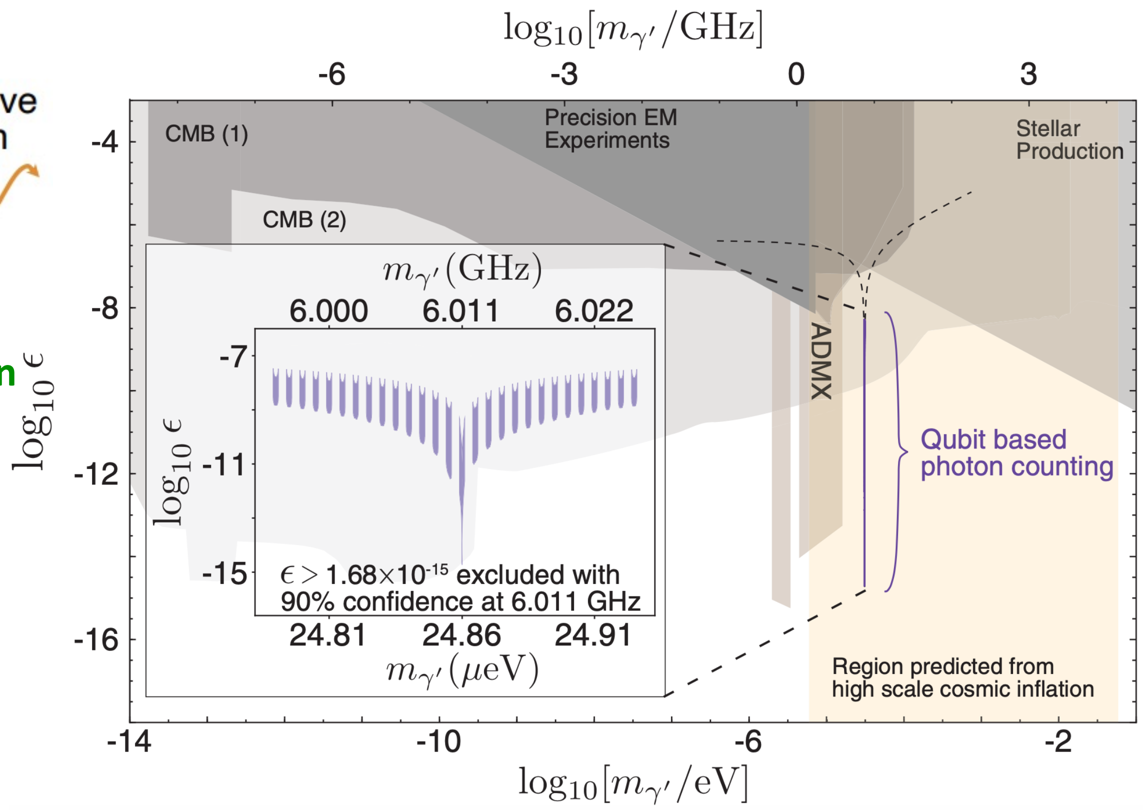


Qubit + 3D cavity – qubit excited state probability due to presence of a DM signal photon



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

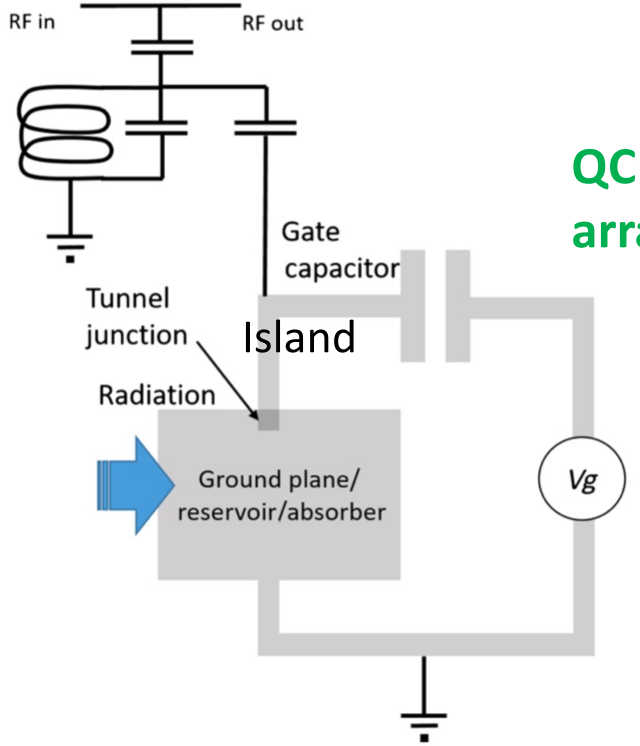
HEISING-SIMONS FOUNDATION

Some ongoing qubit-based projects at Fermilab/Illinois Institute of Technology

Quantum Capacitance Detector

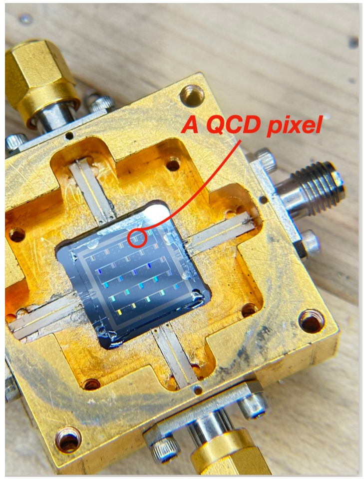
QuantiSED

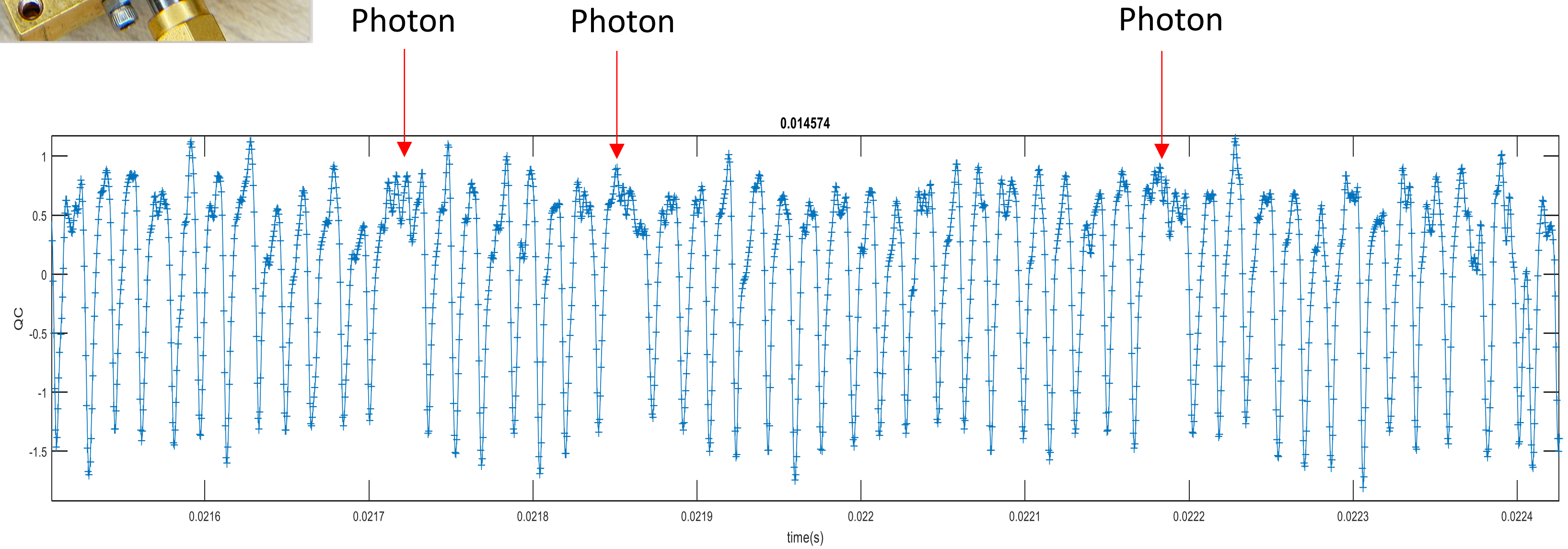
- far infrared spectroscopic missions (space telescope) Caltech/JPL
- Photon => superconducting absorber => broken cooper pairs => tunnel into a small capacitive island => causes non-equilibrium quasiparticle population to increase
- **NEP < 10^{-20} W/Sqrt Hz at 1.5 THz** – **most sensitive far IR detector!**
- Applications for **> 100 GHz wave like Dark Matter and possibly sub-MeV and eV Dark Matter as phonon**



(a)

QCD array

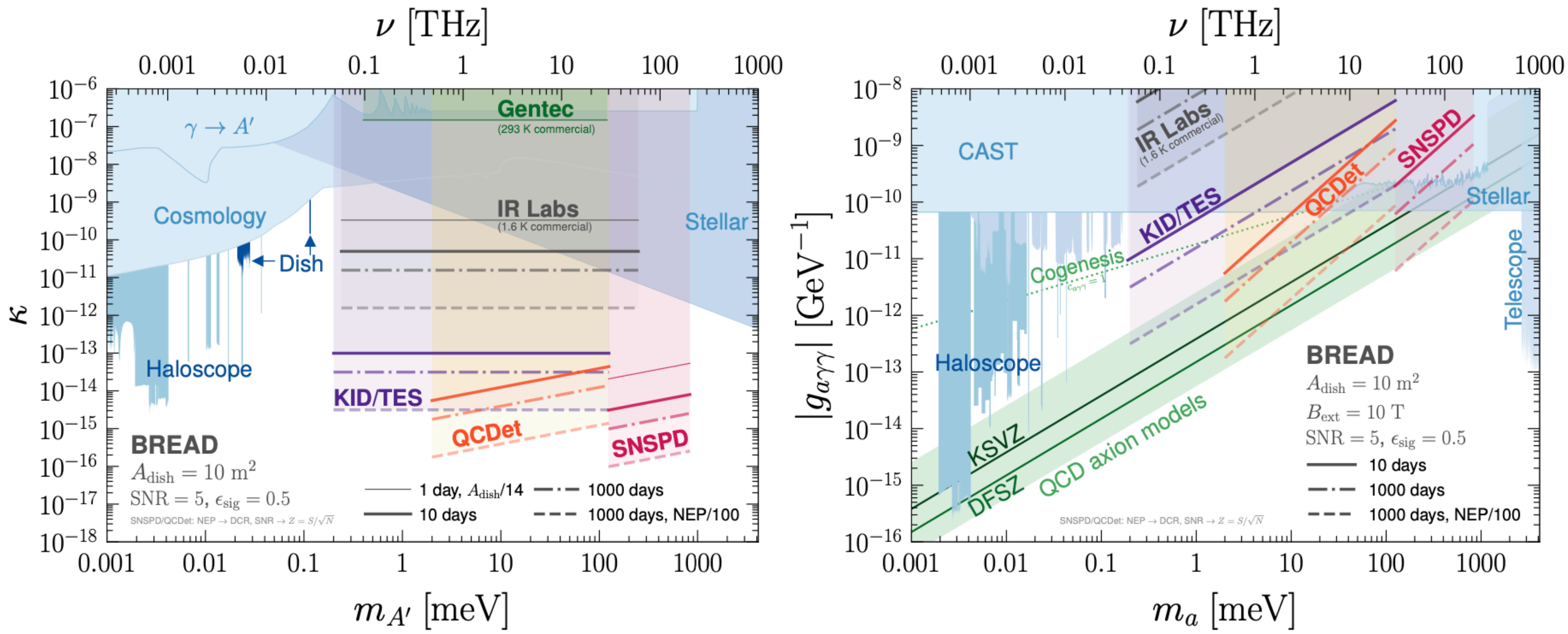




Collaboration: Fermilab Caltech/JPL, Wisconsin Madison

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

Projected sensitivity using QCD



Projected BREAD sensitivity by sensor technology in the dark photon A’(left) and axion a (right) coupling vs. mass plane

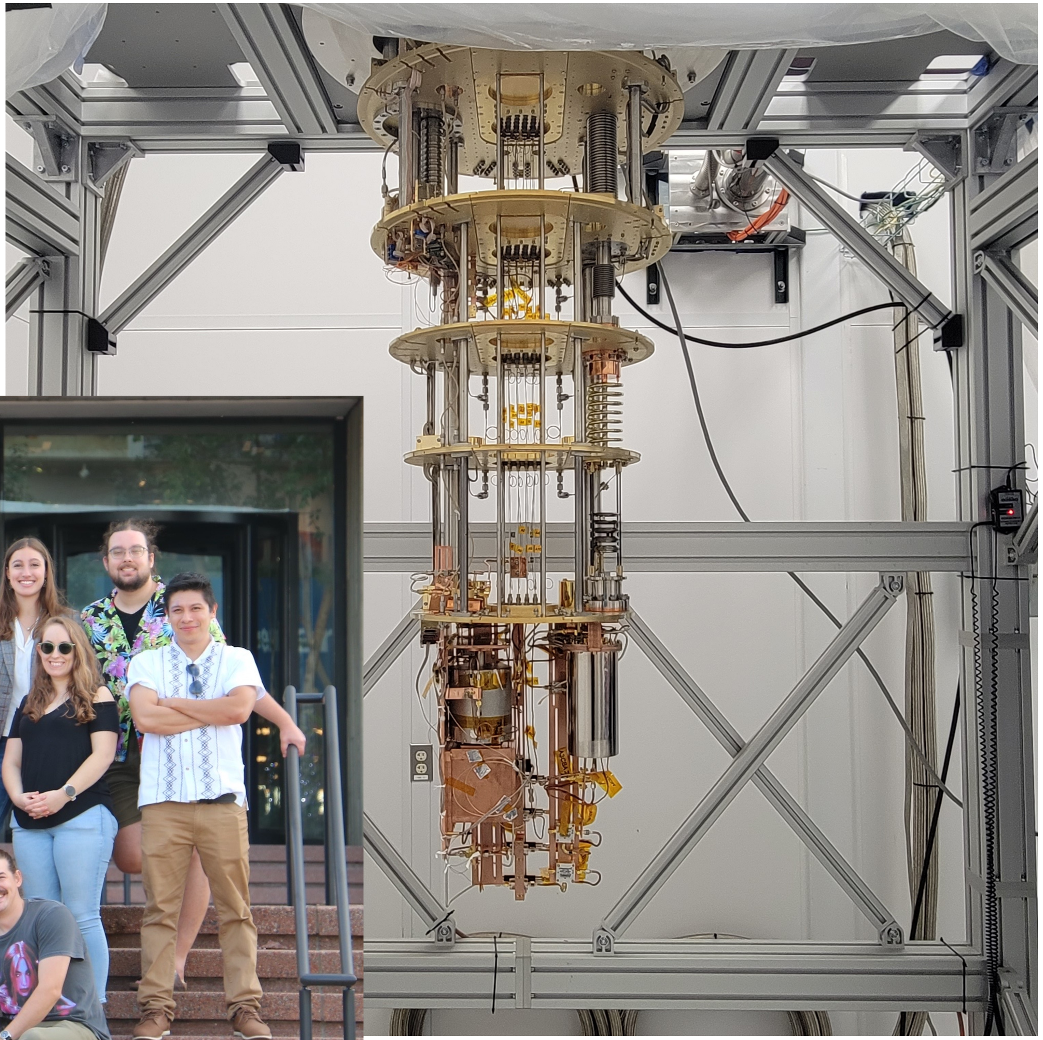
Using a Broadband Axion Antenna technology based on: https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.128.131801

x

QSC Dark Matter group

- Started new program in 2020.
- Two brand new dilution refrigerators installed and several new qubit-based experiments housed.
- IIT/Northwestern students and Fermilab postdocs at the forefront of this program.

QSC group FNAL/IIT/NW



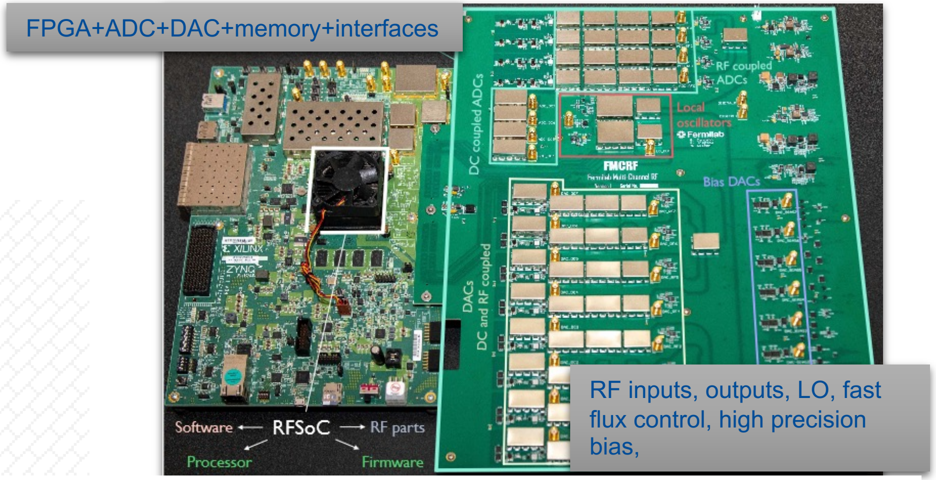
QSC dilution refrigerator FNAL

Quantum Instrumentation Control Kit (QICK)

The QICK (Quantum Instrumentation Control Kit): Readout and control for qubits and detectors

Leandro Stefanazzi, Kenneth Treptow, Neal Wilcer, Chris Stoughton, Collin Bradford, Sho Uemura, Silvia Zorzetti, and Gustavo Cancelo
Fermi National Accelerator Laboratory, Batavia IL, United States

Quantum Science Center QSC



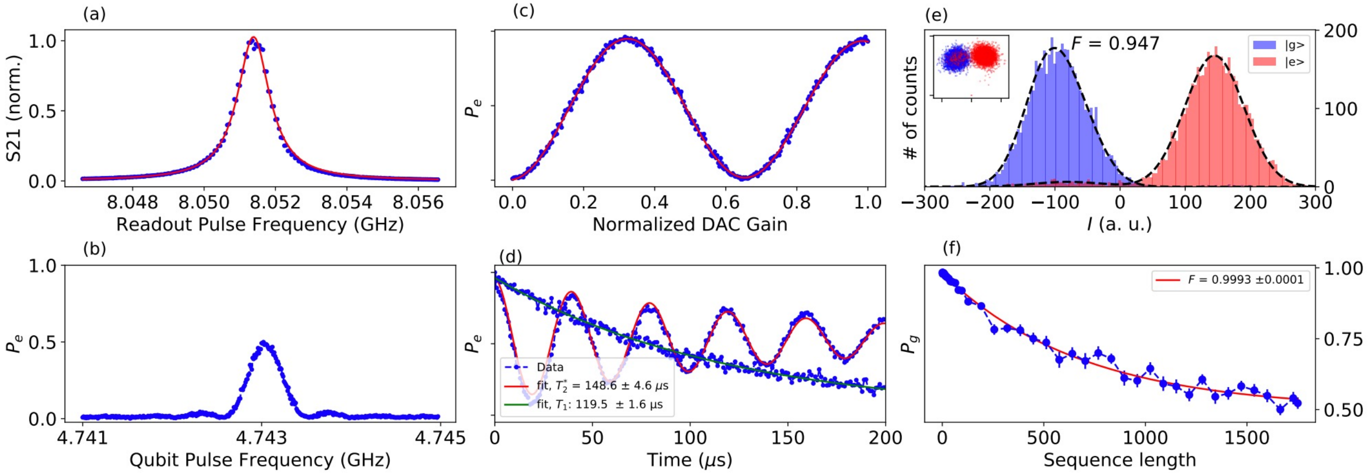
- *Software, firmware and hardware* to control and readout a large variety and array of qubits with *RFSoC (RF System-on-Chip) FPGA and RF electronics*
- ***Lowered the:***

  -- *cost of the control and readout electronics*

  -- *feedback control latency*

  -- *fridge real estate taken by qubit accessories*

Chances are, you will use this if you are working with multiple qubits at some point!



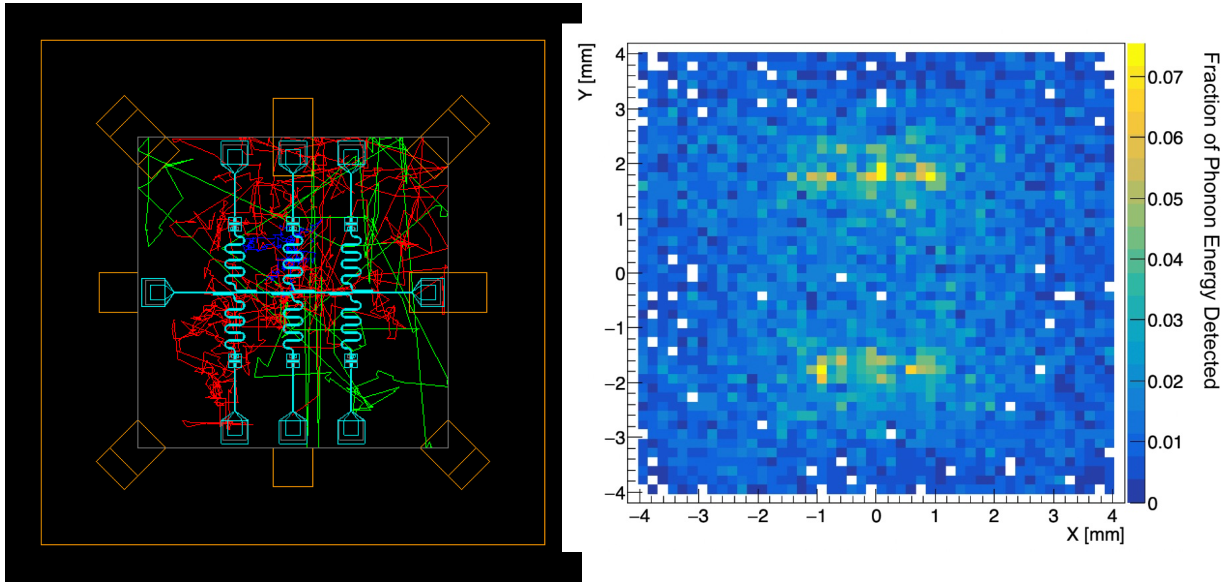
Qubit readout using QICK

arXiv:2110.00557

understanding energy dissipation in qubits

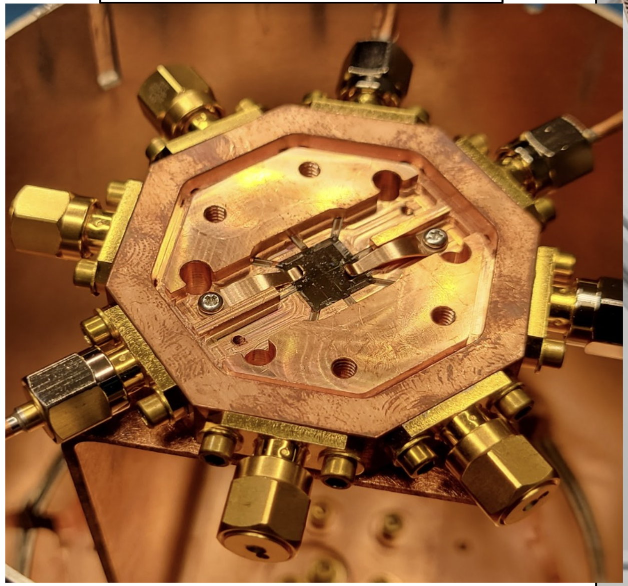
Quantum Science Center
QSC

- 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**)

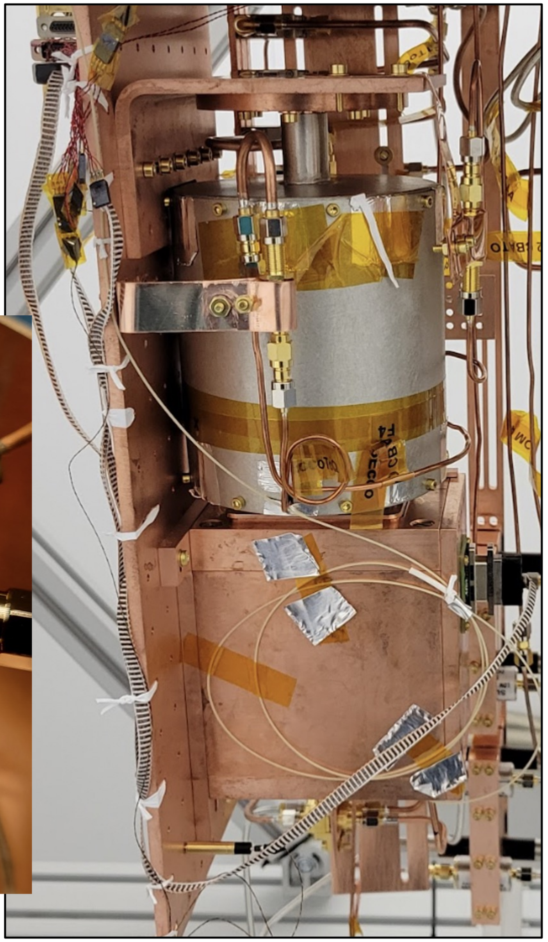


phonon simulation in a 6-qubit silicon chip using G4CMP

6 qubit chip (Si)



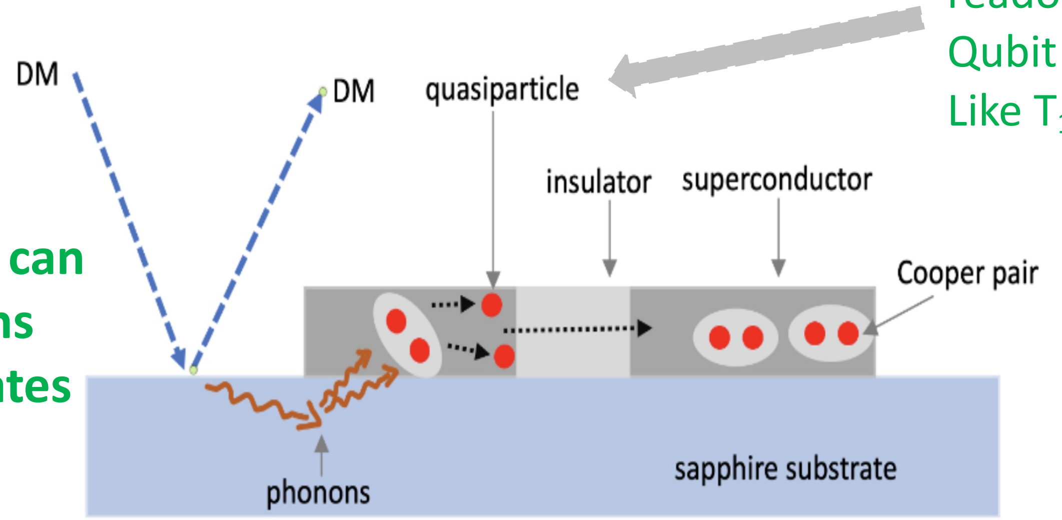
MEMS cryogenic photon source



Possible Qubit-based particle-like Dark Matter detector

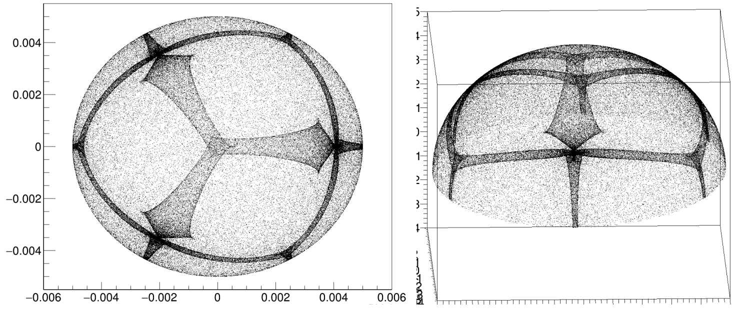
Excess quasiparticle readout using standard Qubit readout protocol Like T_1, T_2 etc.

Particle like DM can excite phonons in qubit substrates

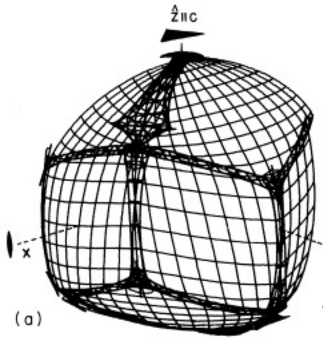


Phonon E ~ 10 to 100 meV

→ Phonon caustic and kinematics simulation in sapphire using G4CMP in progress



Simulated Phonon caustic IIT/Fermilab

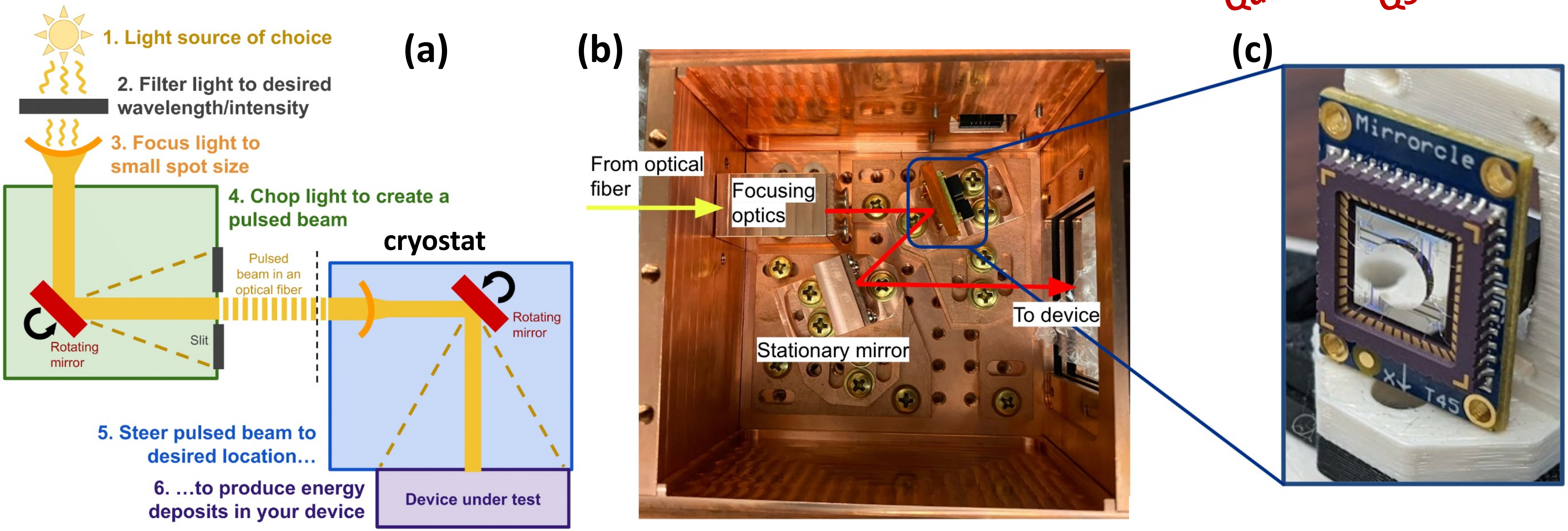


Literature Phonon caustic

https://journals.aps.org/prb/abstract/10.1103/PhysRevB.29.2190

Cryogenic photon source for Detector Characterization

Quantum Science Center
QSC

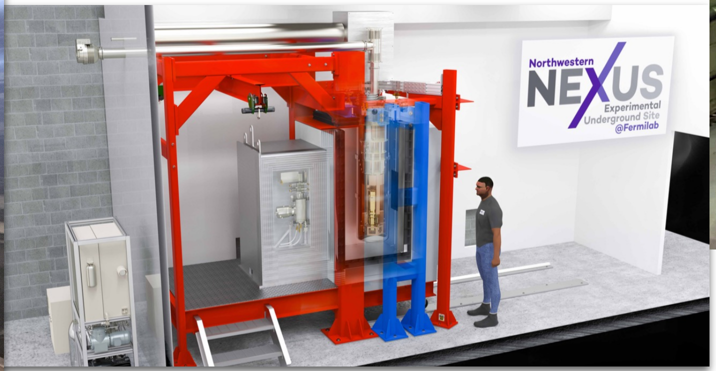


Underground, low background facility at Fermilab

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)

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

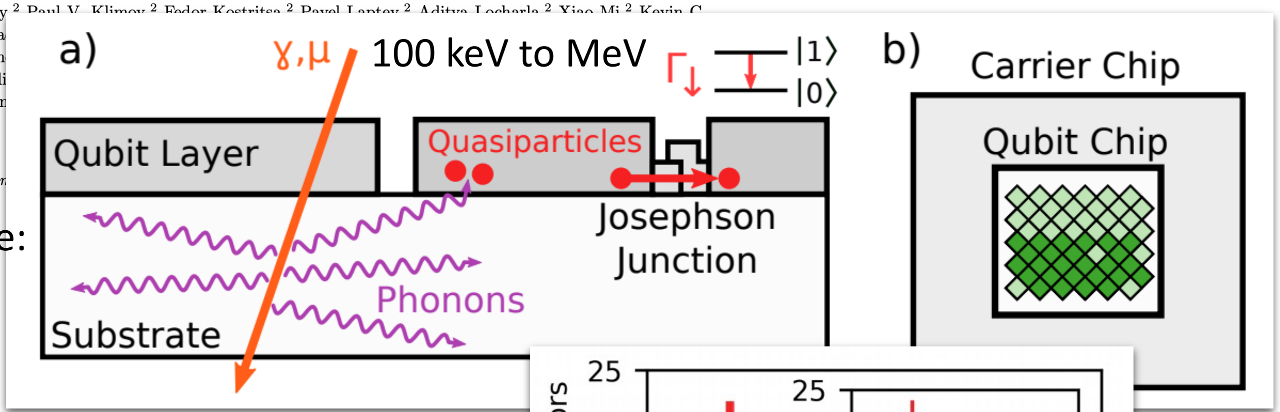
Matt McEwen,[1,2] Lara Faoro,[3] Kunal Arya,[2] Andrew Dunsworth,[2] Trent Huang
Burkett,[2] Austin Fowler,[2] Frank Arute,[2] Joseph C. Bardin,[2,4] Andreas Bengtsson
Bob B. Buckley,[2] Nicholas Bushnell,[2] Zijun Chen,[2] Roberto Collins,[2] Sean Demu
Catherine Erickson,[2] Marissa Giustina,[2] Sean D. Harrington,[2] Sabrina Hong,[2] Evan Jeffrey,[2] Julian
Kelly
Mia
Oprem
Vladi
Smelyan
[4] Departm

Study context: Quantum Error Correction

Why should we care?

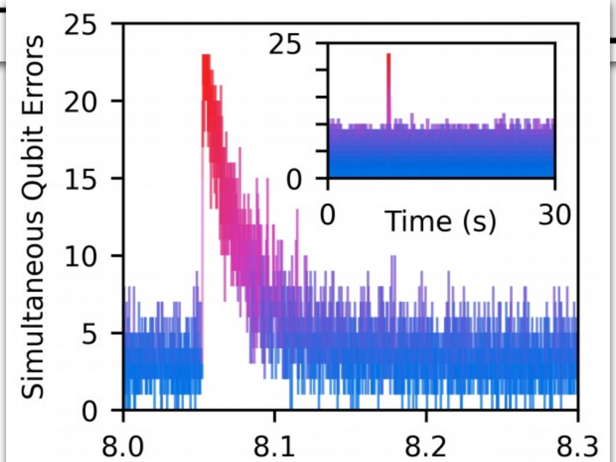
- Building superconducting devices (qubit) based experiment for DM
- Need to decrease dark rate of available SPD
- Hasn't been studied in detail before

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

https://arxiv.org/abs/2104.05219



τ = 25 ms

- 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

- Qubit **senses smallest quanta of energy**: photons and phonons
- Great for Dark Matter search
- Qubit can sense **different types of Dark Matter**
- Several qubit-based Dark Matter detector development efforts ongoing
- **Aboveground and Underground facilities at Fermilab** great platform for studies of impact of radiation in superconducting devices
- Dark Matter community developed resources: **particle simulation tools (G4CMP) to understand energy dissipation**

Community engagement and collaboration effort

Coordinating Panel for Advanced Detectors (CPAD)

US R&D COLLABORATIONS

⌂ > US R&D COLLABORATIONS

US R&D Collaborations

In a culmination of a decade of discussions within the US Detector Instrumentation community facilitated by CPAD, it has been decided at the last CPAD annual workshop to create a network of US Detector R&D Collaborations.

These Collaborations will be created covering major technology areas in line with the 2019

Navigation

US R&D Collaborations

11 RDCs focusing on different aspects of HEP Detector R&D

GOALS:

1. Two coordinators to work with the community & CPAD to define the R&D goals
2. The RDC will put together work packages which brings together a collaboration to tackle ideas and technologies
3. Turn work packages into proposals for funding

R&D Collaborations

RDC	Topic	Coordinators
1	Noble Element Detectors	Jonathan Asaadi, Carmen Carmona
2	Photodetectors	Shiva Abbaszadeh, Flavio Cavanna
3	Solid State Tracking	Sally Seidel, Tony Affolder
4	Readout and ASICs	Angelo Dragone, Mitch Newcomer
5	Trigger and DAQ	Jinlong Zhang, (TBN)
6	Gaseous Detectors	Prakhar Garg, Sven Vahsen
7	Low-Background Detectors (incl. CCDs)	Noah Kurinsky, Guillermo Fernandez-Moroni
8	Quantum and superconducting Detectors	Aritoki Suzuki, Rakshya Khatiwada
9	Calorimetry	Marina Artuso, Minfang Yeh
10	Detector Mechanics	Andy Jung, Eric Anderssen
11	Fast Timing	Gabriele Giacomini, Matt Wetstein

→ RDC8 is quantum and superconducting detectors

→ **Nov 7-11 annual CPAD workshop in SLAC, CA, USA**

Coordination effort with ECFA DRDq

- ➔ Met with Marcel Demarteau on how to better coordinate European and US effort
- ➔ Regular monthly meeting attendance
- ➔ CPAD presentation slot for ECFA DRDq
- ➔ Ensures better coordination between US and Europe

FERMILAB-SLIDES-23-323-ETD

Acknowledgement

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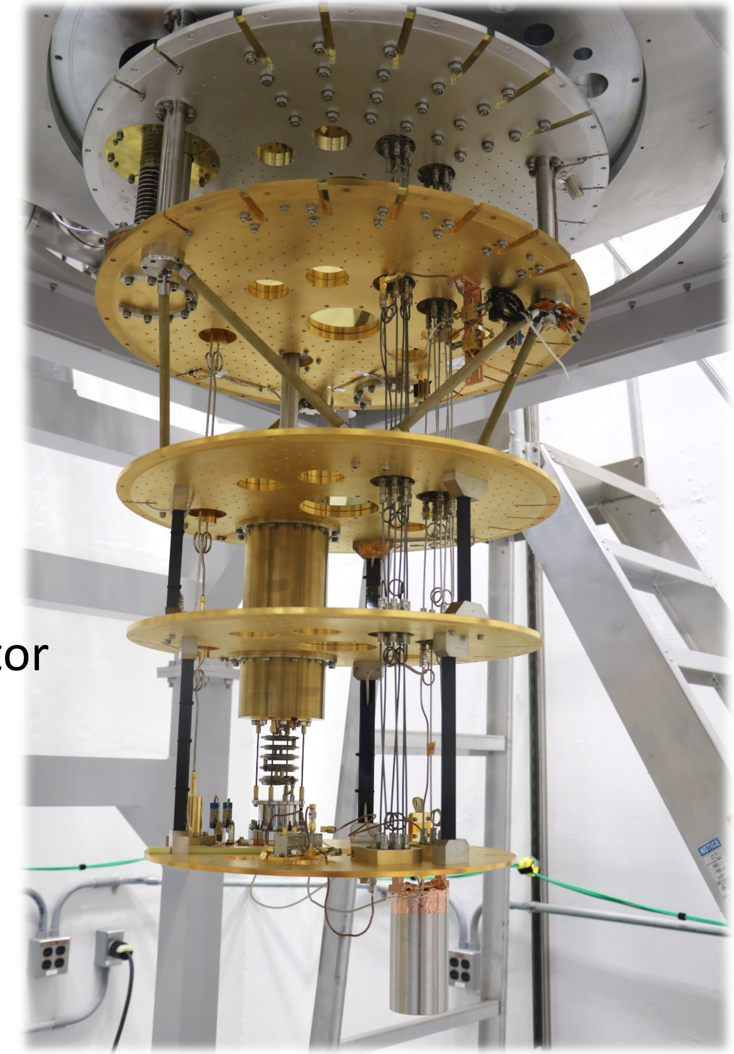
DOE-OHEP-QuantiSED

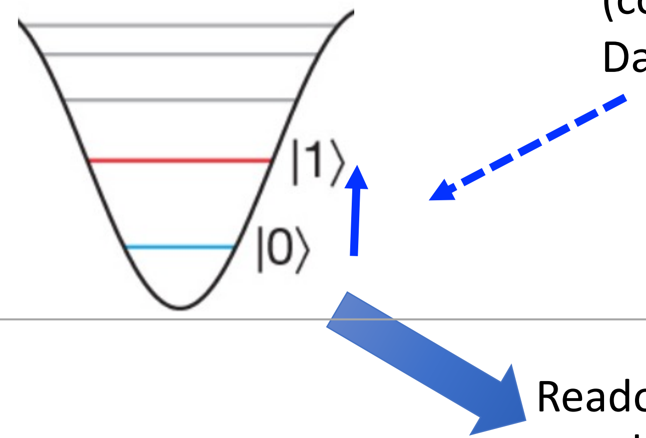
- This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Detecting dark matter with qubits



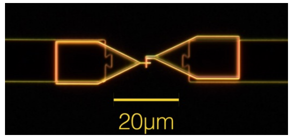
Dilution Refrigerator based at Fermilab

Qubit: two level system



Photon (comes from Dark matter axion)

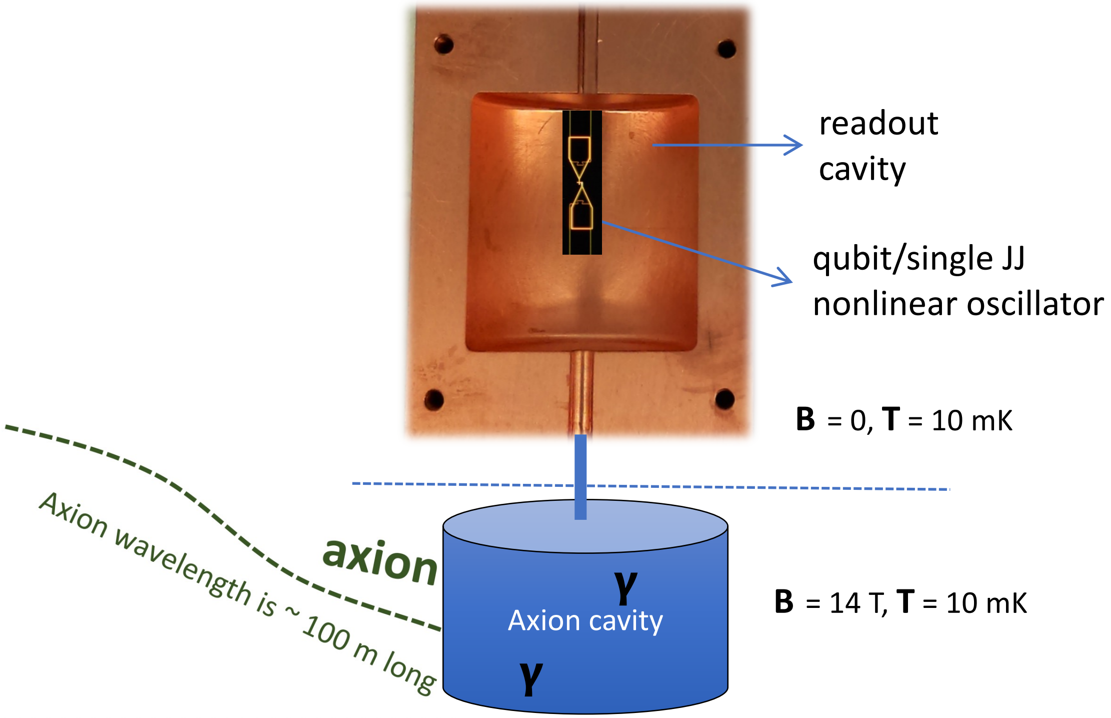
Readout using a coupled cavity



Superconducting Josephson junction

copper cavity

Qubit based dark matter detector

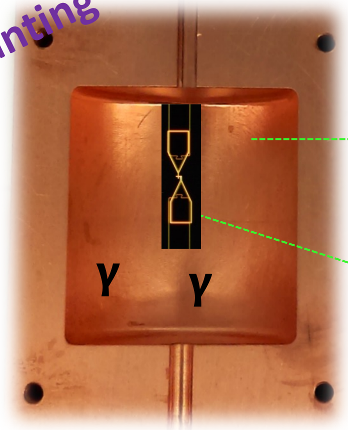


Photon # counting evades the quantum noise limit

Measure photon number
=> explore particle like
nature of light

Dark matter detector work in progress.

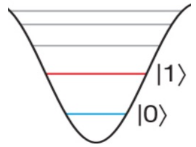
Qubit based photon counter



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

Cavity
Harmonic Oscillator

qubit
two level system



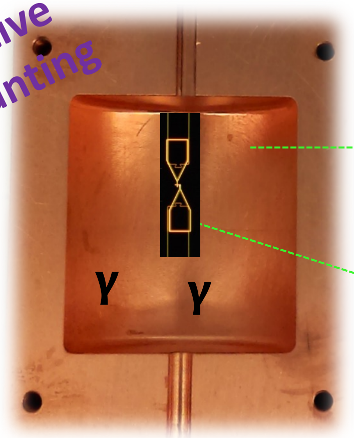
mixed state
g ~ **d.E**:
Δ: ω_q-ω_c
g^2/Δ: Stark shift

→ Repeated spectroscopic measurement of atomic transition frequencies
→ exact photon number of the cavity state
→ presence/absence of axion signal photon

* GHz qubits probe ~ 10^{-5} to 10^{-4} eV axions

Qubit based photon counter

Non absorptive photon counting



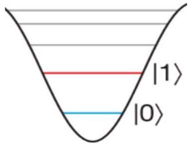
readout cavity

qubit nonlinear oscillator

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

Cavity

qubit
two level system



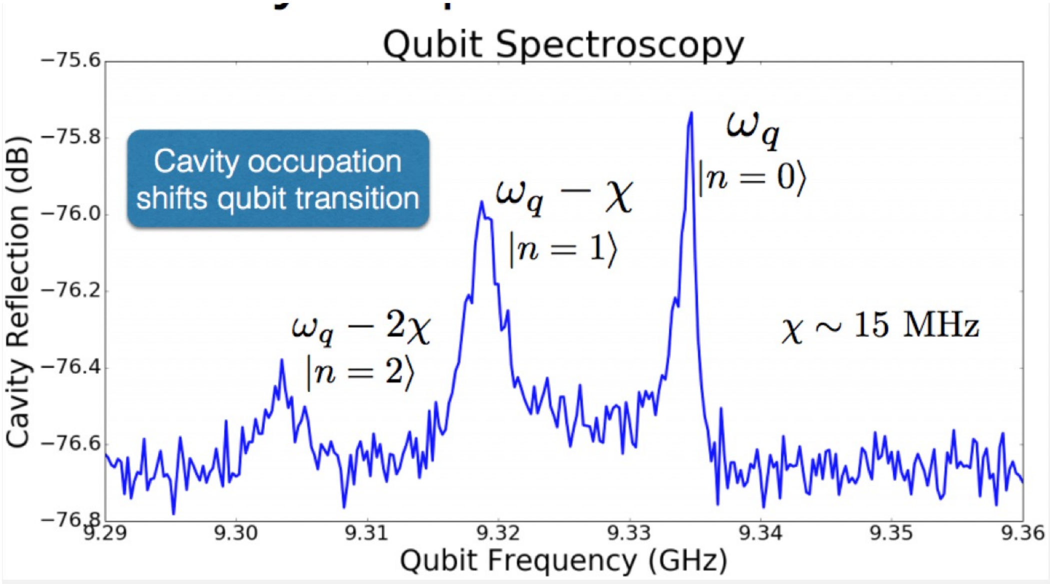
mixed state
g ~ **d.E**:
Δ: ω_q-ω_c
g^2/Δ: Stark shift

Photon shifts qubit transition

Excite qubit at shifted frequency

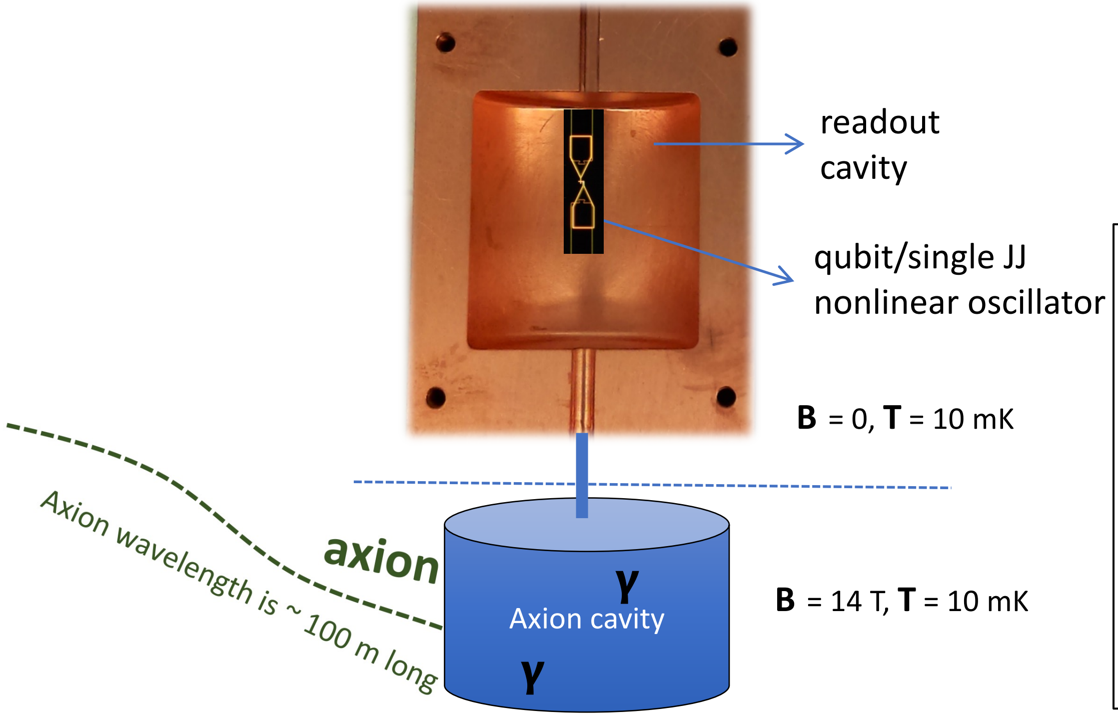
Measure flipped qubit by monitoring cavity line shift

counts photons!



Akash Dixit
U Chicago

Qubit based axion detector



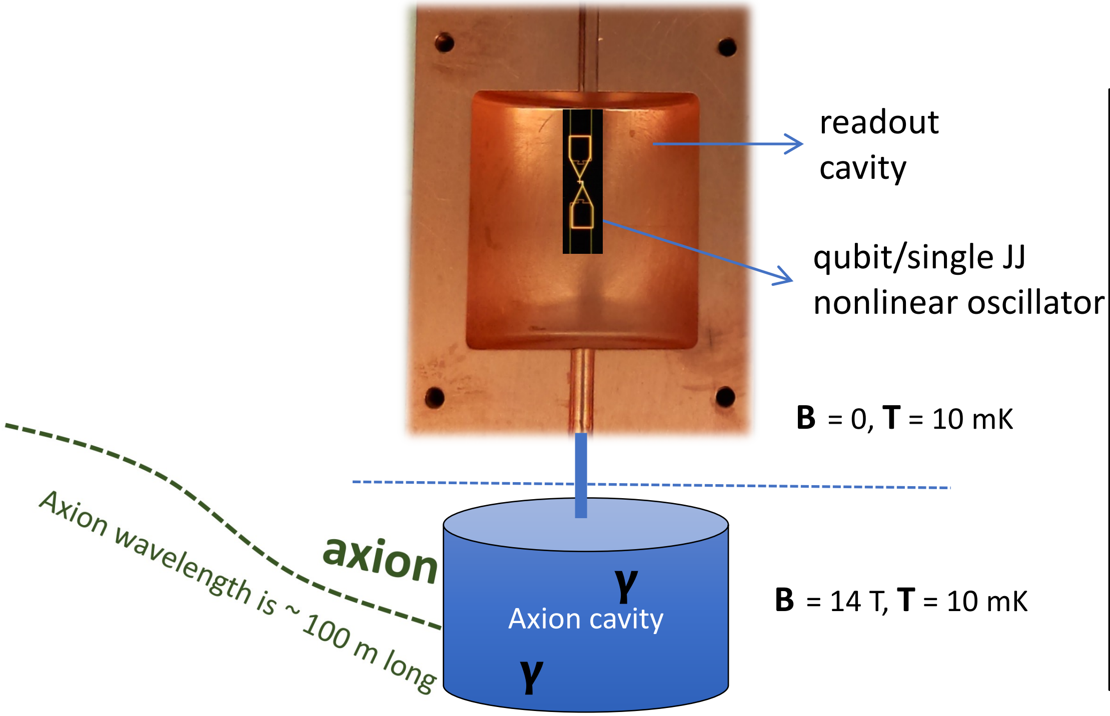
Challenges:

* Superconducting cavity not good at high B field
-- Photonic Bandgap (PBG) cavity

* Coupling of storage cavity with the readout cavity tricky

Photon # counting evades the quantum noise limit

Qubit based axion detector



Ways of enhancing the signal:

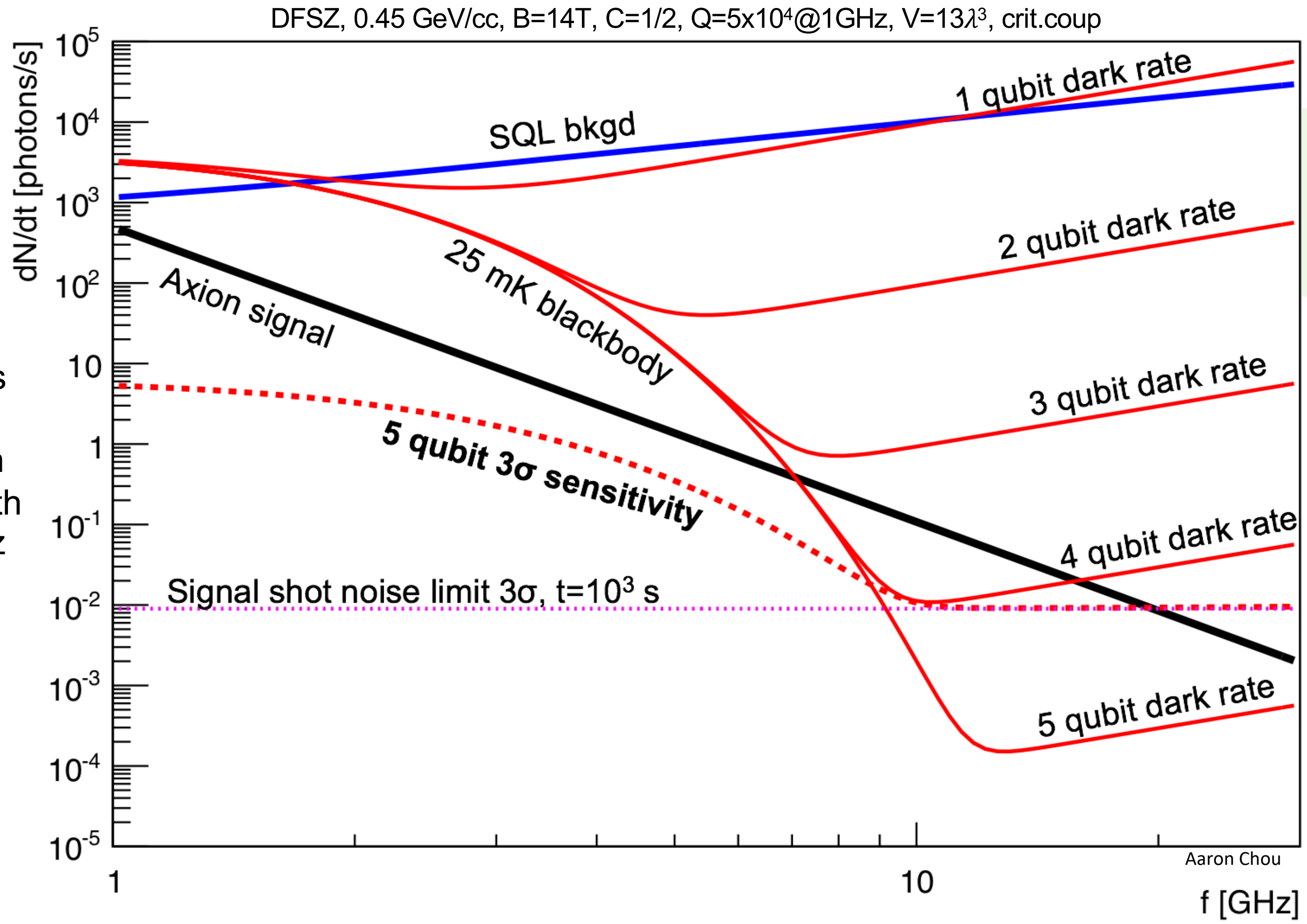
→ Multiple measurements:
Mulitple qubits:

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

→ Stimulated emission (N+1 enhancement)

Photon # counting evades the quantum noise limit

Signal and noise rate



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

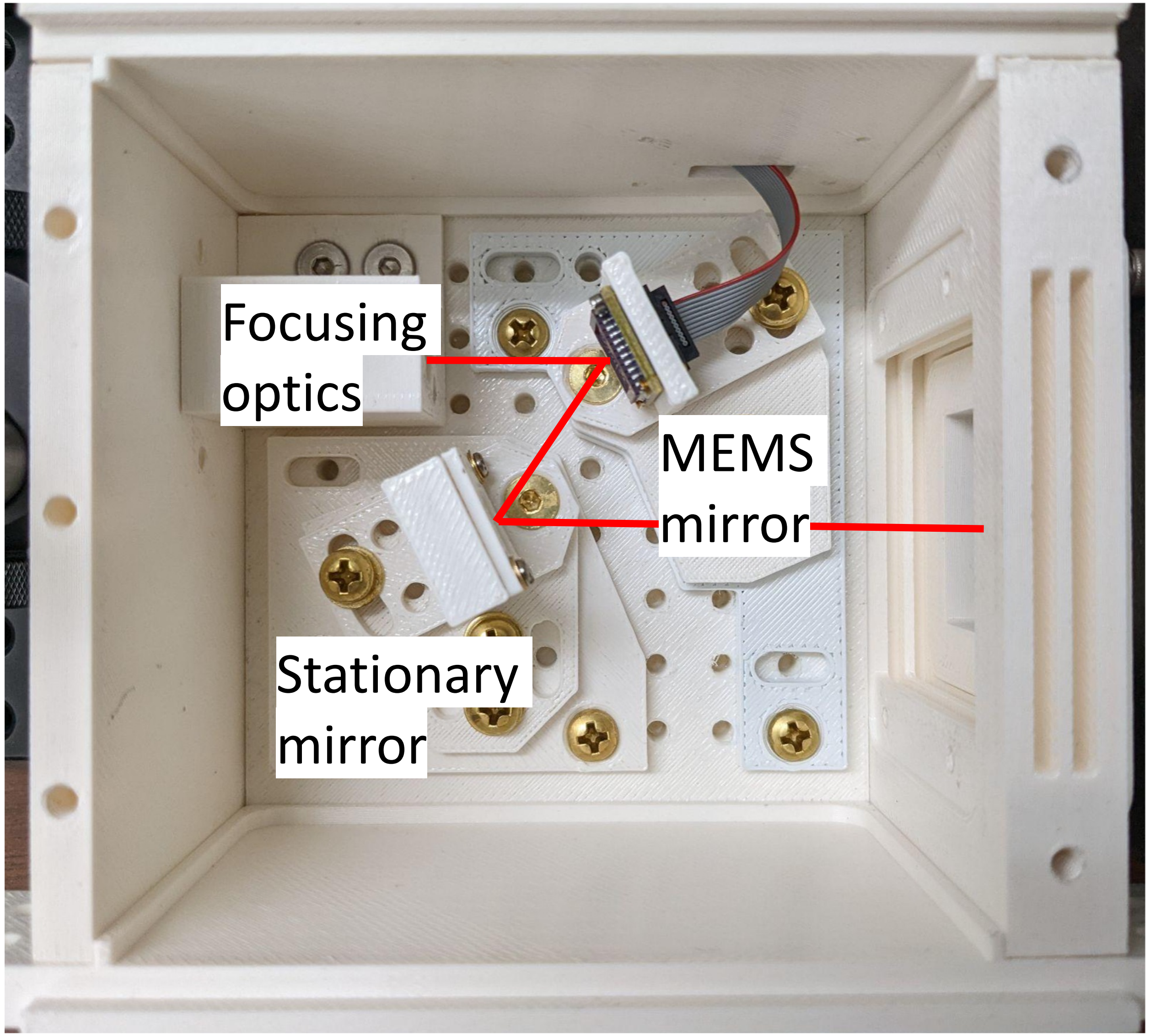
N QND measurements **dark rate = $(10^{-2})^N \Delta f$**

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).

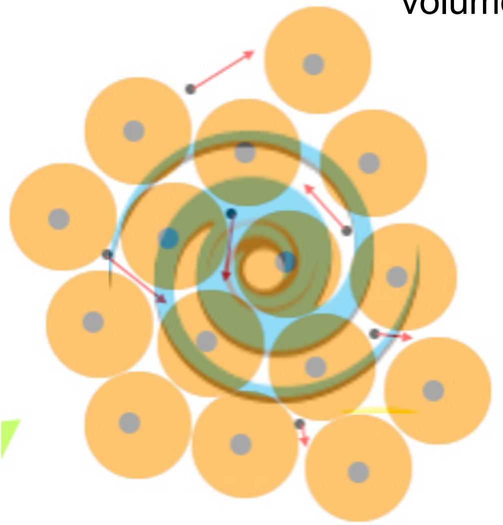
MEMS mirror allows for desired operating specifications:



- ~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

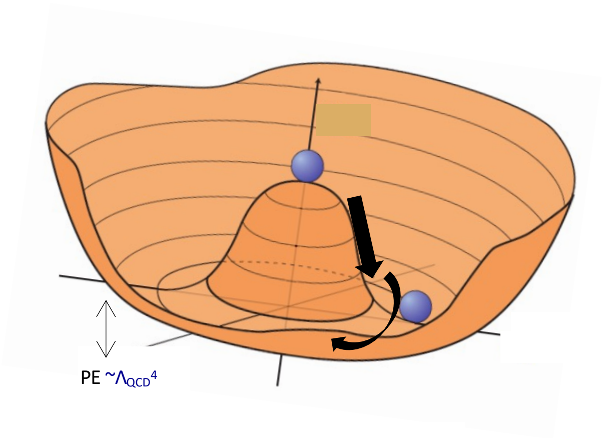
- Global symmetry broken at scale f_a
  -- axion produced through misalignment mechanism
  -- during QCD phase transition, trough tilted by Λ_{QCD}^4
- PE $\sim\Lambda_{QCD}^4$ released, makes up dark matter

-- 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

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



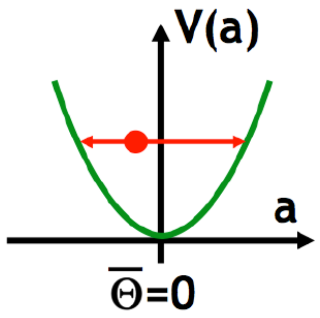
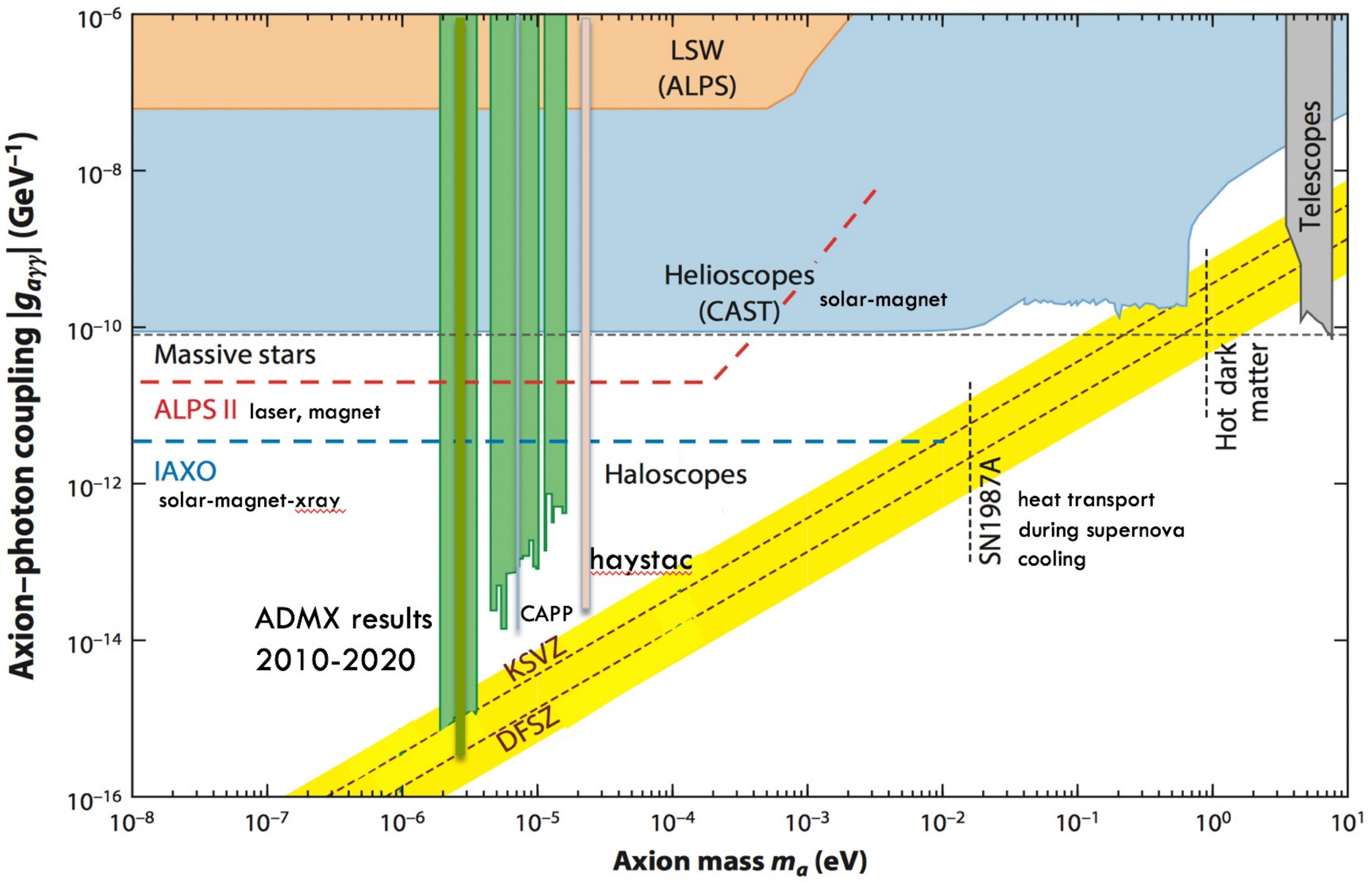


Fig 1:J. Ellis et al; arxiv:1201.6045v1

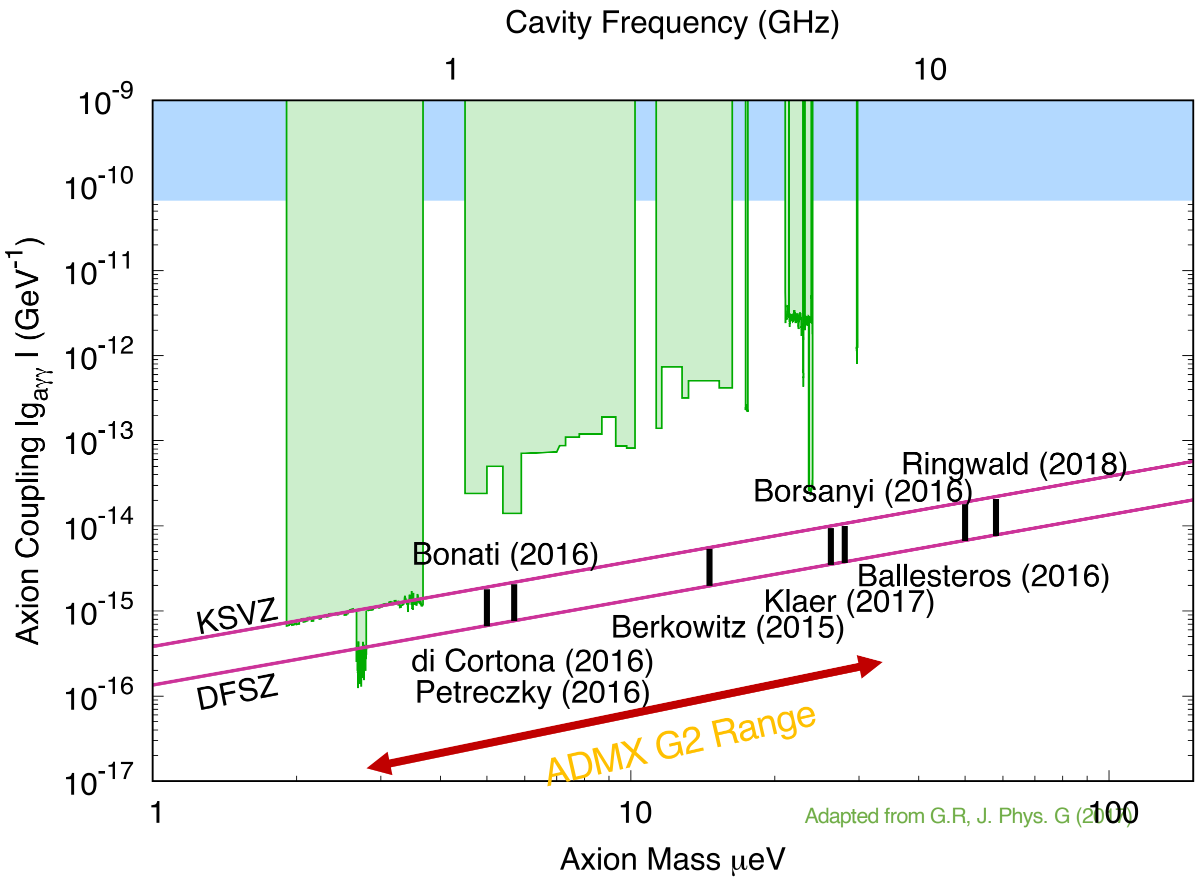
Axion searches overview



Graham, et. al (2016)

Axion searches overview contd.

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



Quantum amplifiers

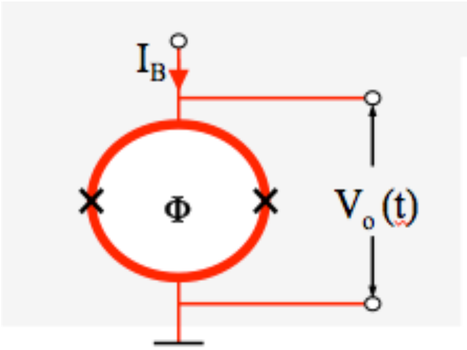
Why quantum amps.?

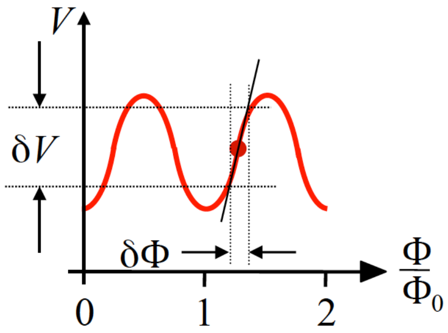
Intrinsically low noise (superconducting technology)
⇒ low resistance elements
⇒ low thermal dissipation
⇒ Add very low added noise during amplification
=> Tunable in frequency

Josephson Parametric Amplifier

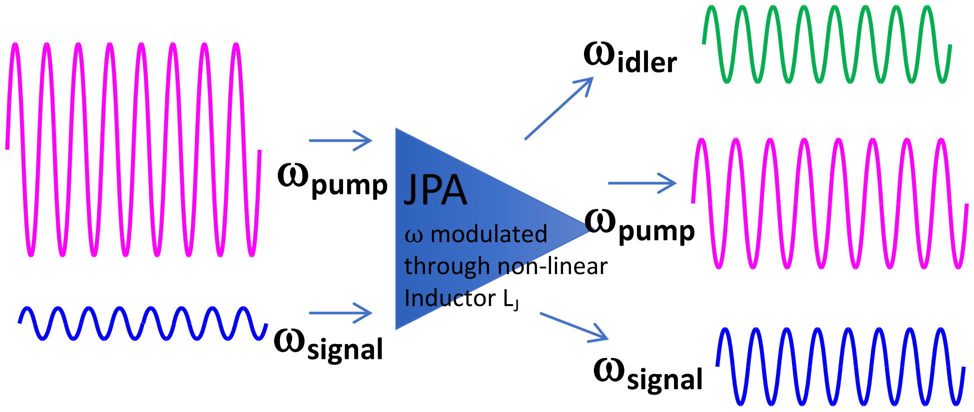
JPA

dc SQUID





- Energy transfer from pump to two normal modes of swing



Only limited by Quantum Noise

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)

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

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

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