TRIUMF

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Quantum Sensing Applications in Particle Physics

P. Giampa, March 2024
TRIUMF Quantum Workshop

Discovery, accelerated

What Are We Covering?

- Introduction

- How Can We Bring Quantum Sensing Into Particle Physics?
- Where Are Our Strongest Capabilities To Fit Within This Global Effort?

- Conclusions

INTRODUCTION

Introduction

2022 @ TRIUMF
2023 @ Université de Montreal
2024 @ Toronto

TRIUMF
Arthur B. McDonald
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SNOLAB

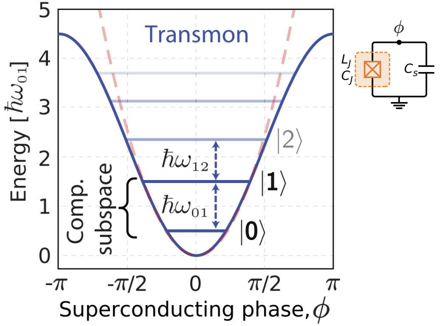
GUINEAPIG: GeV and Under Invisibles with New Experimental Assays for Particles In the Ground

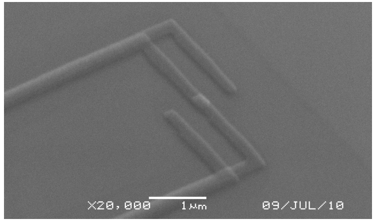
https://indico.cern.ch/event/1345184/

SNOLAB
Queen Mary
University of London

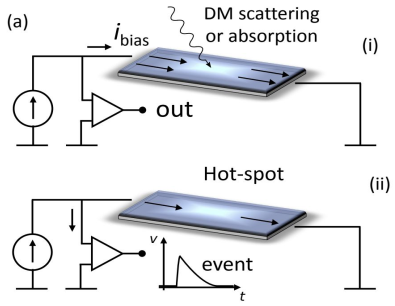
Superconducting Quantum Sensors

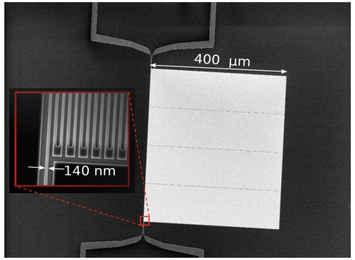
Charge/Flux Qubits



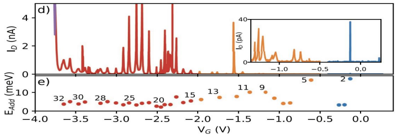


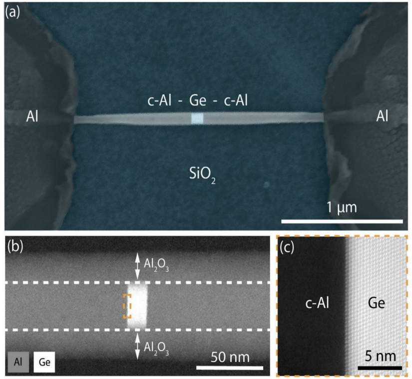
SC Nanowires





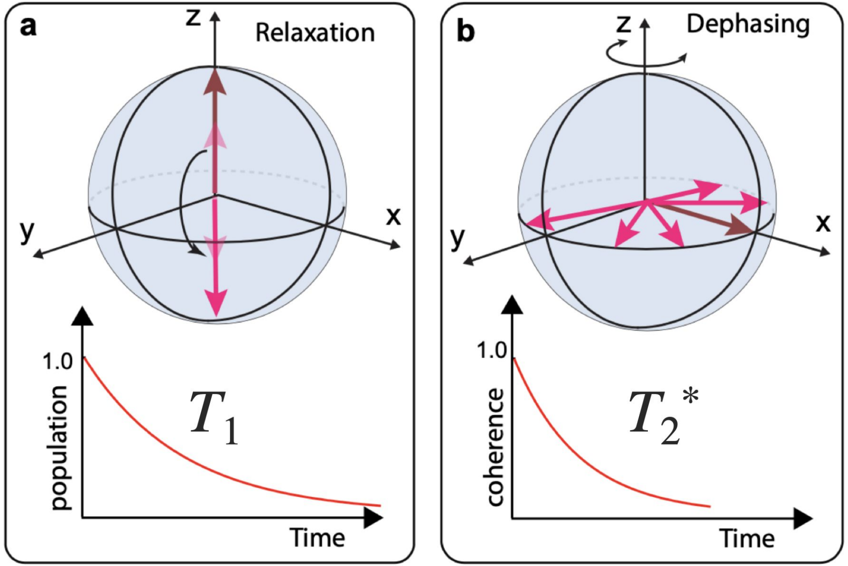
Quantum Dots





How Can We Bring Quantum Sensing Into particle Physics?

Qubits As Radiation Detectors?



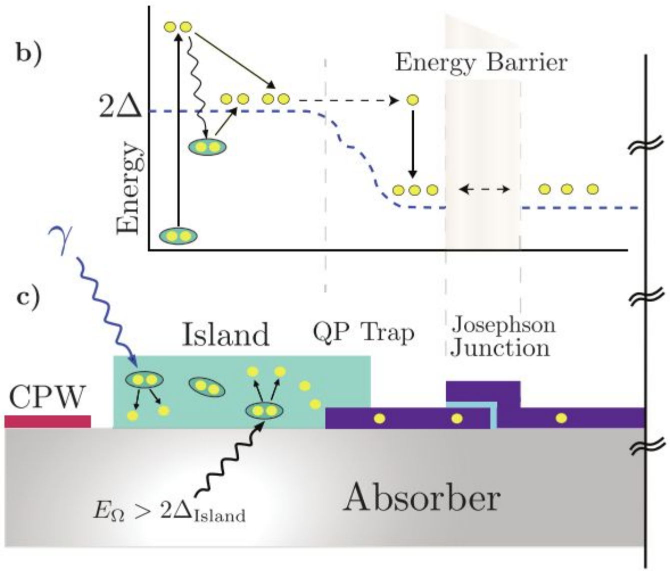
Mahdi Naghiloo, (2019) [arXiv:1904.09291]

Decoherence – loss of the set up state in the qubit (relaxation/dephasing)

- Bad for QIS
- Good for Detecting Low Energy Depositions

T_1: Relaxation Time
timescale for loss of the energy of the qubit state (1 to 0)
T_2*: Dephasing Time
timescale for loss of the coherence of the qubit state

Qubits As Radiation Detectors?



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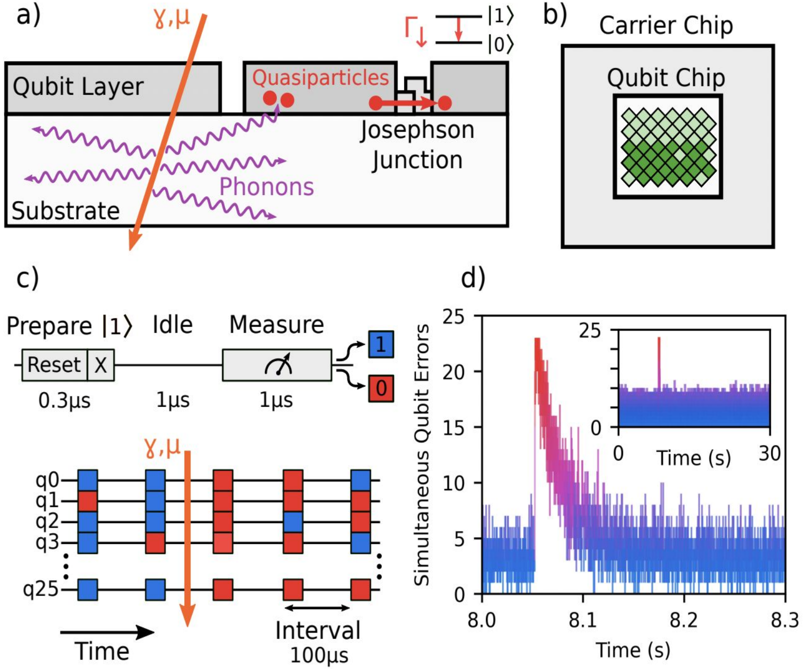
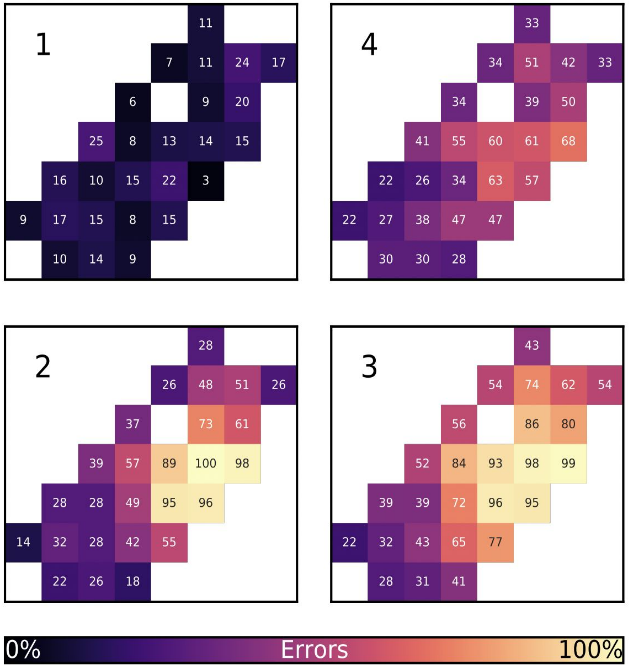
Google The First To Notice Something …

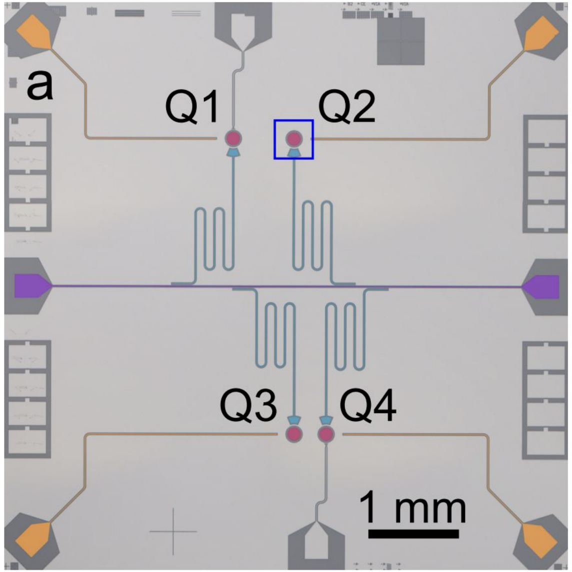
Nature Physics 18, 107-111

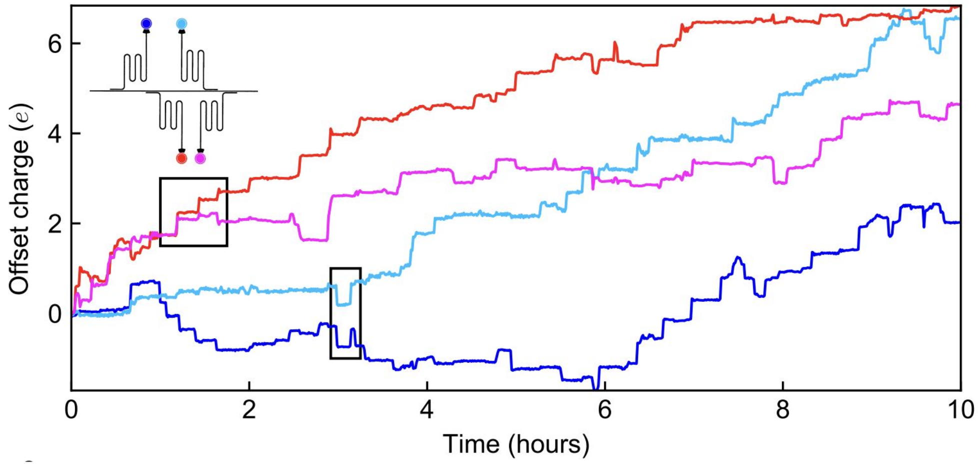




Impact of Cosmogenic Radiation On Qubits

Nature 594, 369--373 (2021)

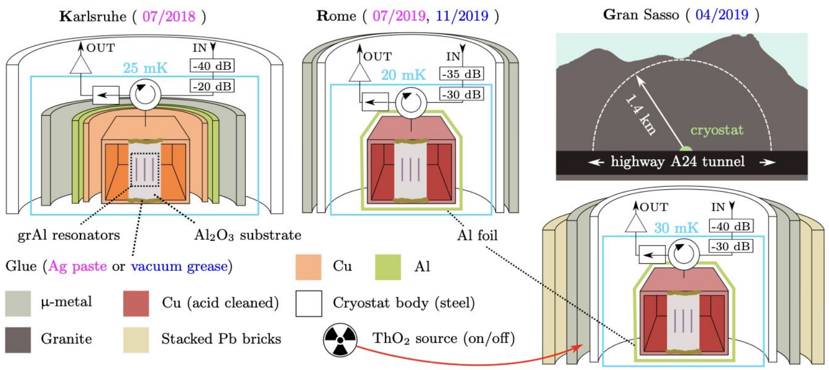




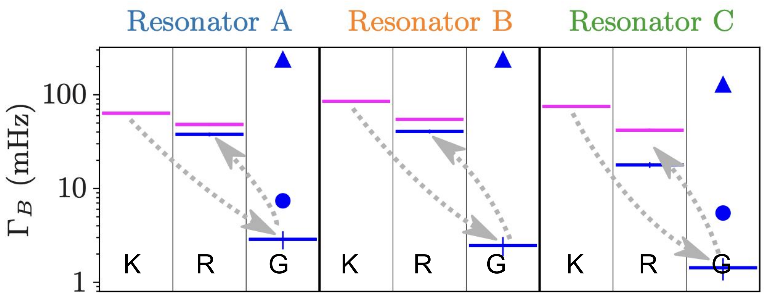
"Discrete charge jumps in qubits, induced by phonon-mediated quasiparticle poisoning associated with absorption of gamma rays and cosmic-ray muons in the qubit substrate"

Impact of Cosmogenic Shielding

Nat. Commun. 12, 2733 (2021)

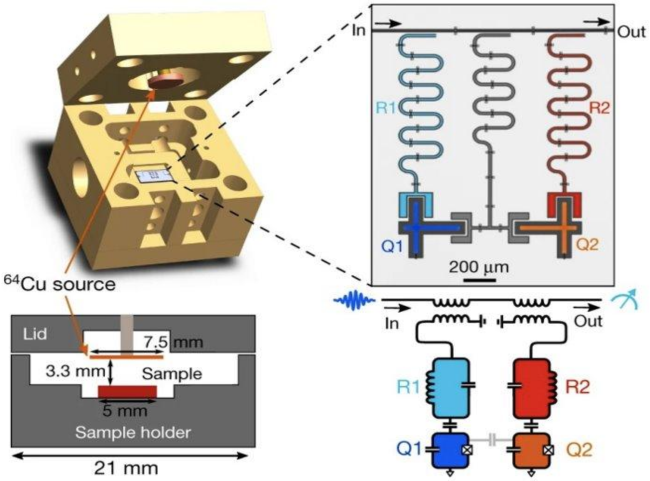


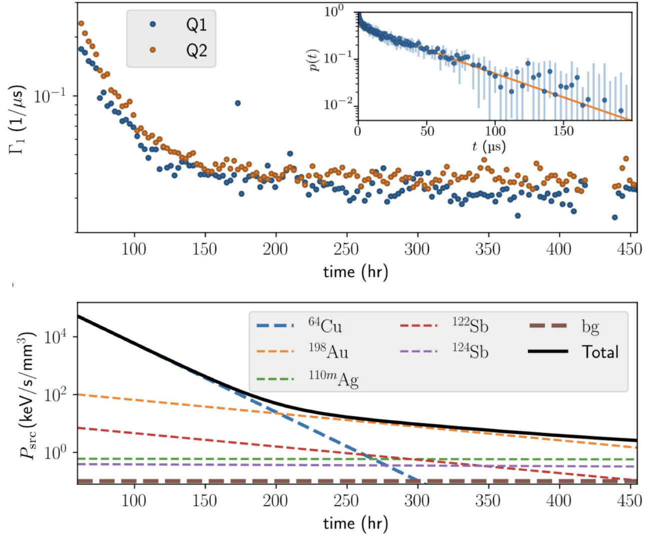
"Operating in a deep-underground lead-shielded cryostat decreases the quasiparticle burst rate by a factor fifty and reduces dissipation up to a factor four, showcasing the importance of radiation abatement in future solid-state quantum hardware"



Impact Radioactive Sources On Qubits

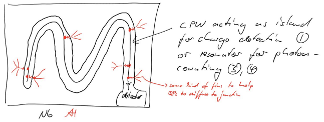
Nature 584, 551-556 (2020)



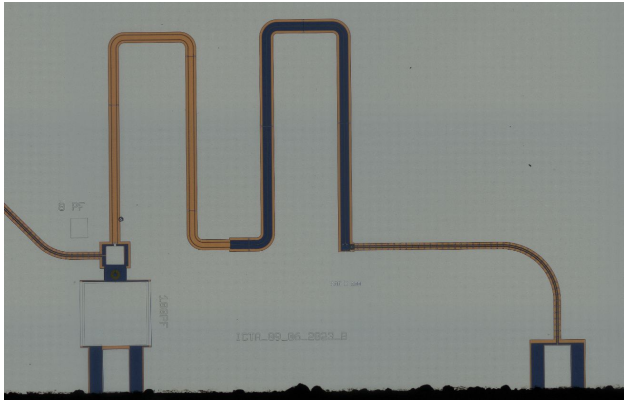


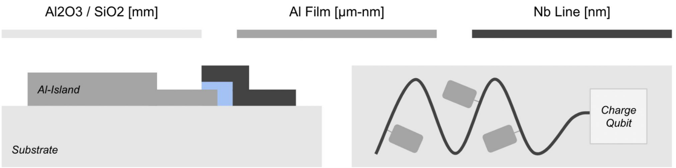
Measurements of decoherence relaxation rates ($1/T_1$) in the presence of a ^{64}Cu source. Strong evidence that quasiparticle poisoning due to radiation breaking Cooper pairs is a limiting factor in superconducting qubits for QIS.

Quasiparticle Count/Charge Readout



UNIVERSITÉ DE SHERBROOKE

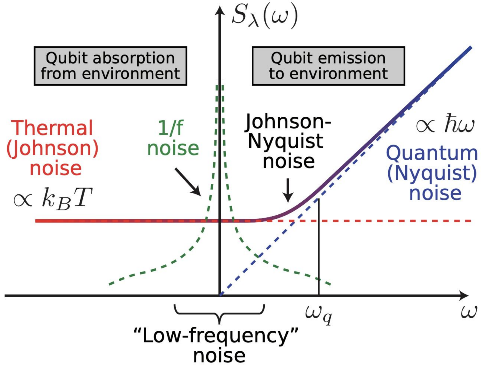




- Collaboration with Sherbrooke.
- Use of Al-Nb heterojunction, and charge qubits, to measure the charge of quasiparticle from phonon-induced Copper pair breaking on Al-islands.
- Same chip design, two different substrate thicknesses and materials (Al_2O_3 & SiO_2).
- Prove of principle for this type of detection (alpha source) & first characterization of noise. [Summer 2024]

Biggest Challenges - Reduce Overall Noise

Applied Physics Reviews 6, 021318 (2019)

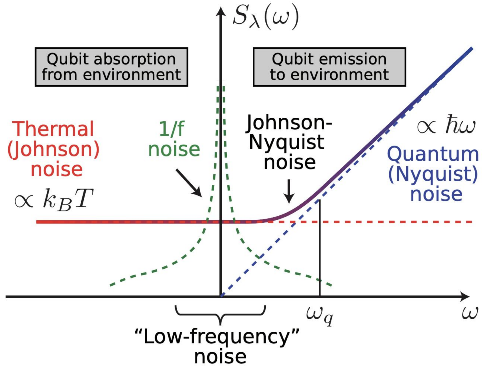


- Better understanding of the Phonon-Induced Cooper-Pair breaking model.
- Phonon transport models.
- Cosmogenic & Radiopurity activities.
- Impact of fabrication processes.
- Material selection.
- Induction of thermal stress.
- ………

Discovery, accelerated

Biggest Challenges - Reduce Overall Noise

Applied Physics Reviews 6, 021318 (2019)



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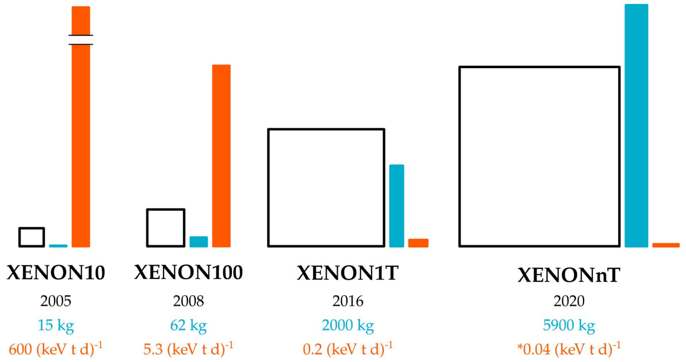

Example: LXe Dual-Phase Time-Projection-Chambers:

- Early 2000s identified as a great technique to measure nuclear recoils with thresholds of the order of few 10s of keV.
- Today, "Low-Background" LXe TPC are multi-tonne in size and operate with energy thresholds of of a few keV.

Achieved By Backgrounds Modeling

Surface alphas, general surface effects, PMT flasher, Radon pollution, Tritium pollution, unexpected fluorescences, unexplained nuclear mechanisms, quenching ....

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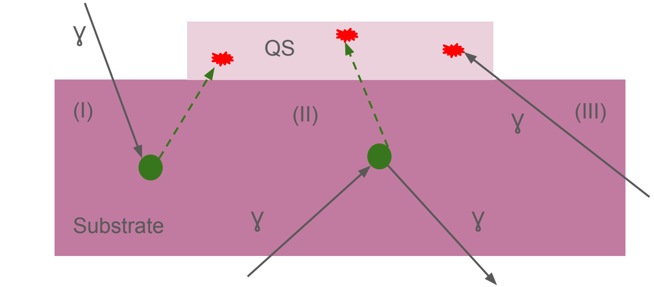
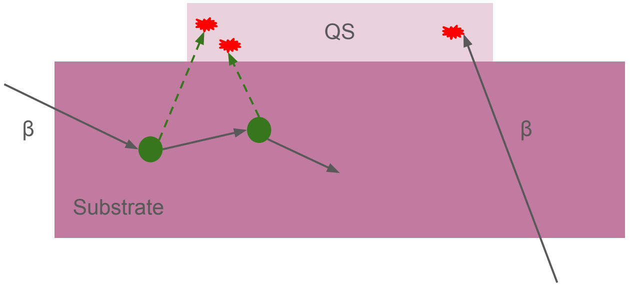
Biggest Challenges - Model Impact of IR

Phys. Rev. D ***106****, 023026*

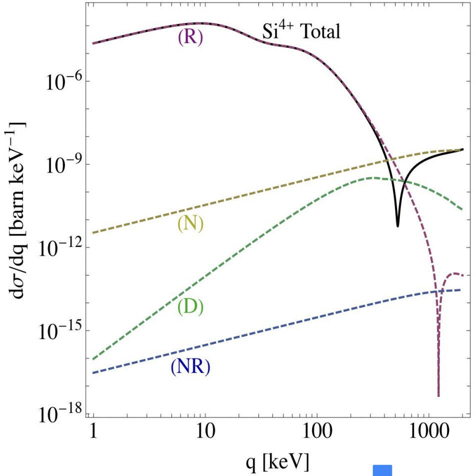
Photons

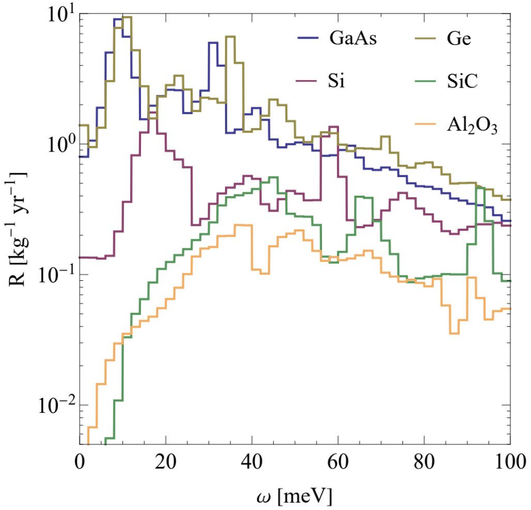


Electrons



Photon-ion scattering cross section in Si





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Where Are Our Strongest Capabilities To Fit Within This Global Effort?

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TRIUMF Capabilities & Synergies

Material Selection:

Optimization of these devices requires good handle on material properties and radiopurity.

Capability: uSR/b-NMR
Synergy: SNOLAB

uSR and b-NMR as quantum sensors.
I. McKenzie - 14:45

Particle Radiation:

Calibration is needed to properly understand the underlying physics in this techniques. Surface and bulk effect need separate models. (Phonon transport modeling)

Capability: Ion implantation, Dedicated Radioactive Sources
Synergy: IQC, Sherbrooke University, UBC

The BeEST and SALER - Experiments with rare isotopes.
C. Ruiz - 12:15

IR Optical Characterization:

Crucial to understand, and consequently limit, the impact of IR emission from the environment on quantum sensors.

Capability: SuperCDMS/nEXO/ARGO Infrastructure.
Synergy: IQC, Fermilab

Quantum opportunities with single photon detector.
H. Lewis - 14:30

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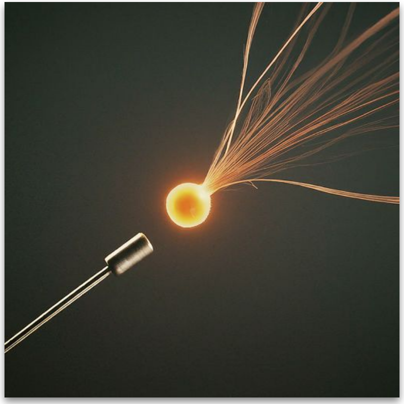
Conclusions

Conclusions

- The ongoing effort to study and characterize the impact of particle radiation in quantum sensors has potential to strongly benefit the QiS community and it's showing signs of very promising prospects for a meV-eV calorimetry.

- Understand "backgrounds" down to meV is key, but we have the combined expertise to fully characterize this in the coming years (Solid State + Condensed Matter + Particle Physics + Low Background Techniques) Not much different than the DM problem that requires PP,NP,Chem,Astro

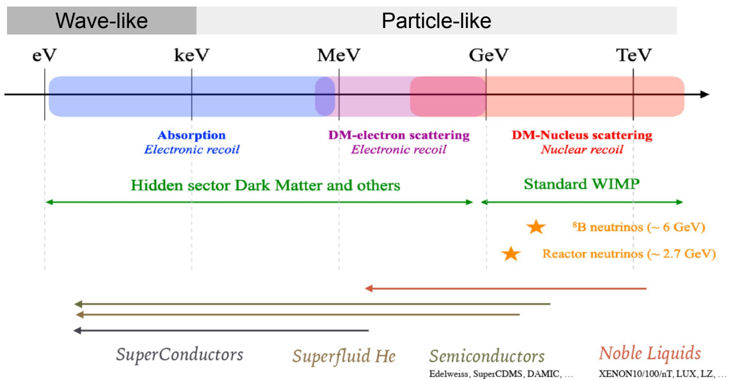
- We are just starting to see some real particle physics applications for Quantum Technologies (Dark Matter, Neutrinos, Rare Isotopes and more) … Most interesting time.

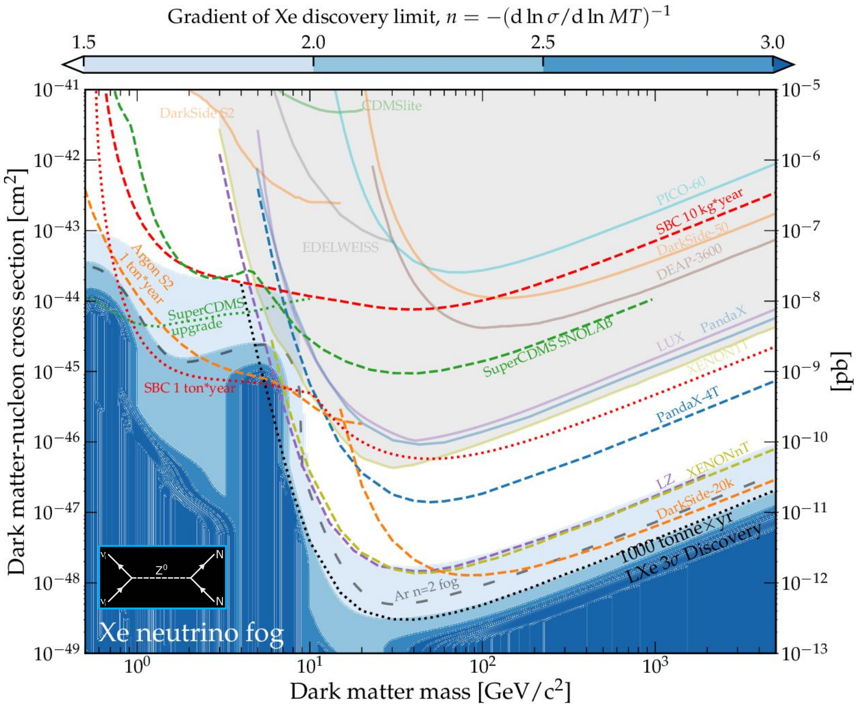


What a particle interaction with a qubit looks like according to Gemini A.I. :)

Backup

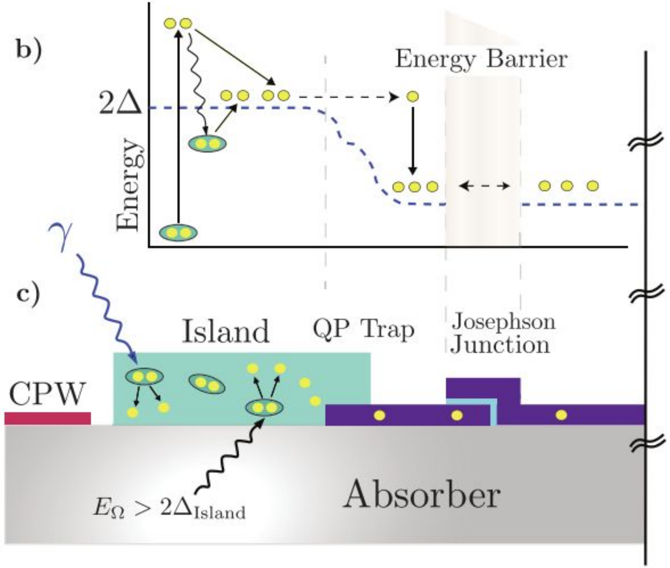
Introduction

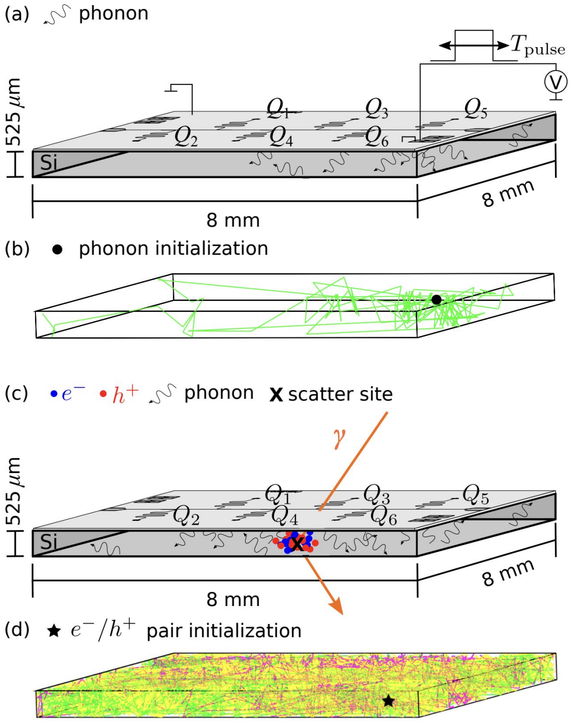




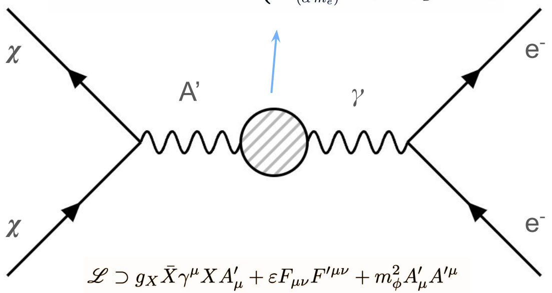
Phonon Induced Cooper-Pair Breaking

https://arxiv.org/abs/2402.15471





Dark Matter Scattering



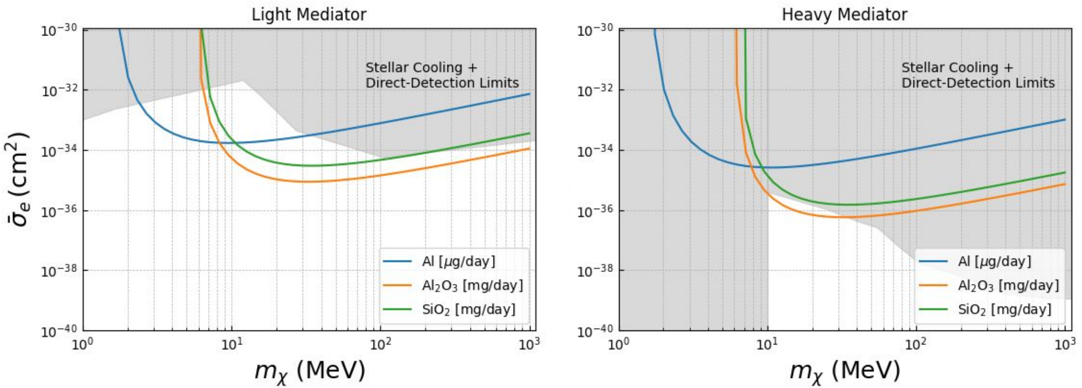
$$\bar{\sigma}_e = \frac{16\pi\mu_{\chi e}^2\alpha\alpha_D\varepsilon^2}{(m_{A_D}^2+\alpha^2 m_e^2)^2} \simeq \begin{cases} \frac{16\pi\mu_{\chi e}^2\alpha\alpha_D\varepsilon^2}{m_{A_D}^4}, & m_{A_D} \gg \alpha m_e \\ \frac{16\pi\mu_{\chi e}^2\alpha\alpha_D\varepsilon^2}{(\alpha m_e)^4}, & m_{A_D} \ll \alpha m_e \end{cases}$$

$$\mathscr{L} \supset g_X \bar{X}\gamma^\mu X A'_\mu + \varepsilon F_{\mu\nu}F'^{\mu\nu} + m_\phi^2 A'_\mu A'^\mu$$

Consider a fermonic DM particle, χ, charged under a new Abelian gauge group $U(1)_D$ with gauge coupling g_D. The $U(1)_D$ gauge boson A_D can obtain a small coupling εe to ordinary charged particles through kinetic mixing with the photon, mediating DM–electron scattering.

$$F_{DM}(q) = \frac{m_{A_D}^2+\alpha^2 m_e^2}{m_{A_D}^2+q^2} \simeq \begin{cases} 1, & m_{A'} \gg \alpha m_e \\ \frac{\alpha^2 m_e^2}{q^2}, & m_{A_D} \ll \alpha m_e \end{cases}$$

Phys. Rev. Lett. 123, 151802 (2019)



Feasibility for a Small Al2O3 or SiO2 wafer with single Quasiparticle Readout (JJ-based). Assuming meV Threshold, and no background counts (this should be fixed based on HE gamma flux).

Bulk of the calculations was done using the DarkELF code available on GitHub at the following link: DarkELF

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