Stefan Zatschler on behalf of the QUTEbits collaboration
Laurentian University, University of Toronto, SNOLAB

Radiopurity assays and radiation projections for qubit measurements at SNOLAB

York, UK, September 24th 2026

QUTEbits project overview

- **International research partnership**
  - Chalmers University of Technology in Sweden
  - Institute for Quantum Computing at UWaterloo
  - SNOLAB and Laurentian University in Sudbury
  - University of Toronto

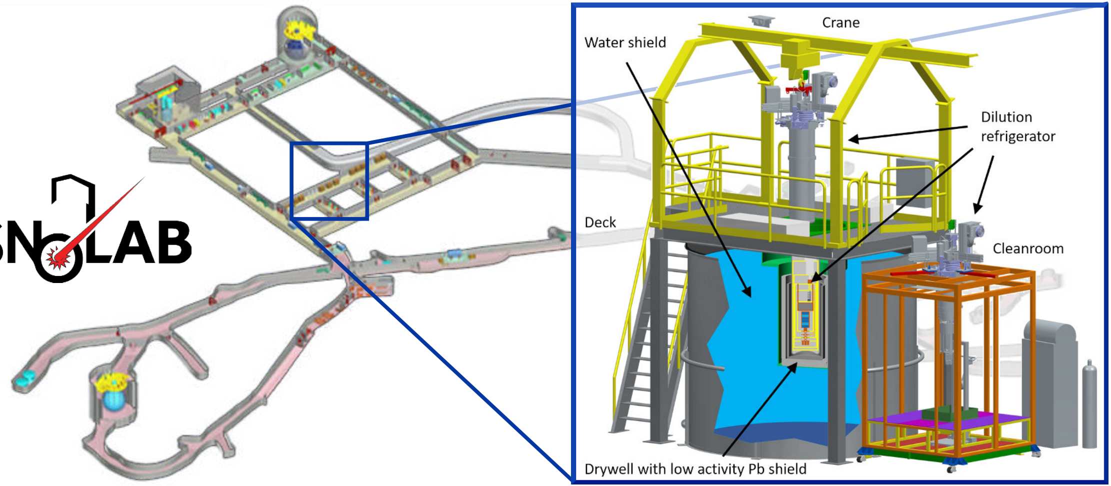
Project vision and goals

- Investigate performance of quantum sensors under low-radiation environment
- Identify factors that lead to decoherence of superconducting qubits
- Kick-off quantum device program at SNOLAB

This talk: Radiopurity assays & simulations!
Pre-print: arXiv:2607.16151

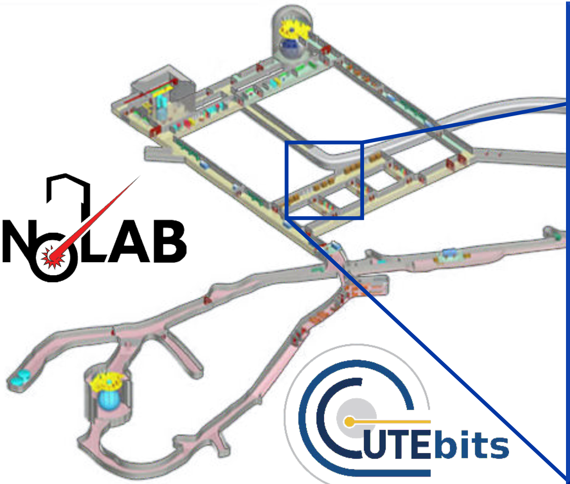
CUTE at SNOLAB

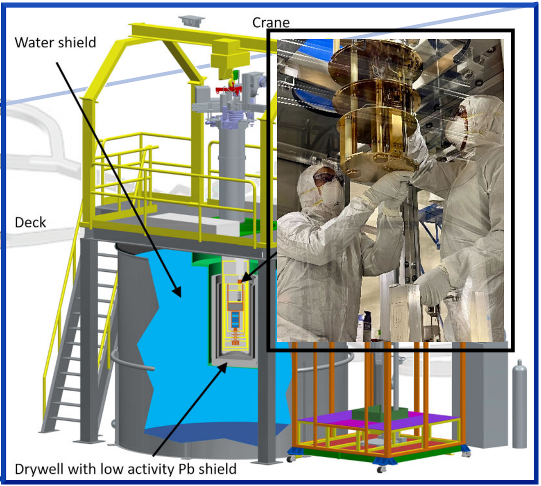
CUTE – Cryogenic Underground TEst Facility

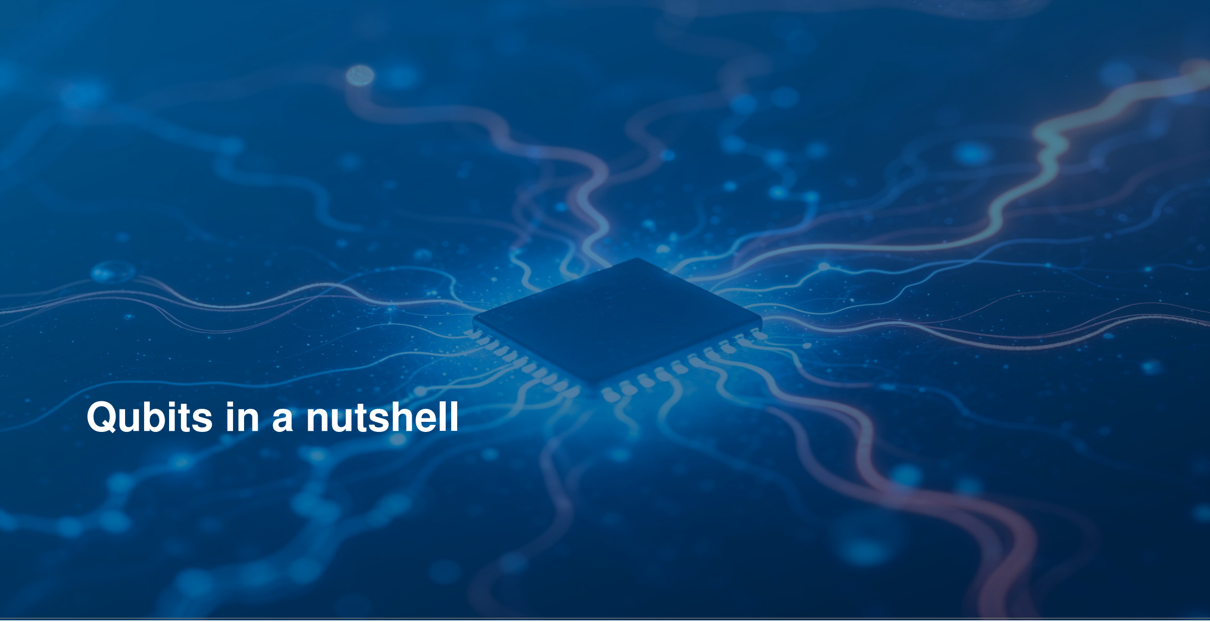


CUTE at SNOLAB

CUTE – Cryogenic Underground TEst Facility







Qubits in a nutshell

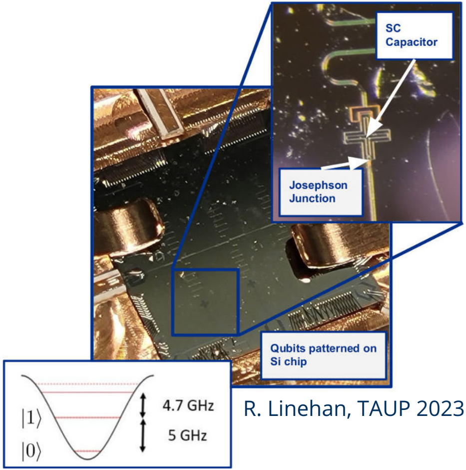
Superconducting qubits

What is a superconducting (SC) qubit?

- Anharmonic LC circuit in SC film
- "Qubit" = lowest two energy states
- Energy spacing typically in few GHz range (µeV)

Qubits are versatile sensors

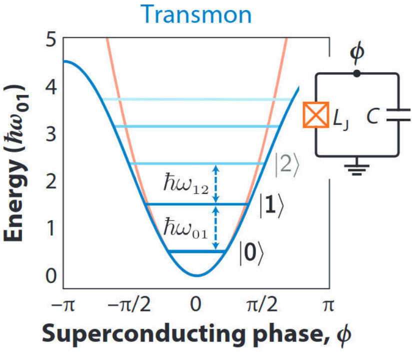
- State preparation, readout, and gates performed with microwave signals at $\mathcal{O}$(GHz)
- Design decisions enable flexibility in operation and noise susceptibility
- Coupling with other quantum systems allows for multiple detection schemes



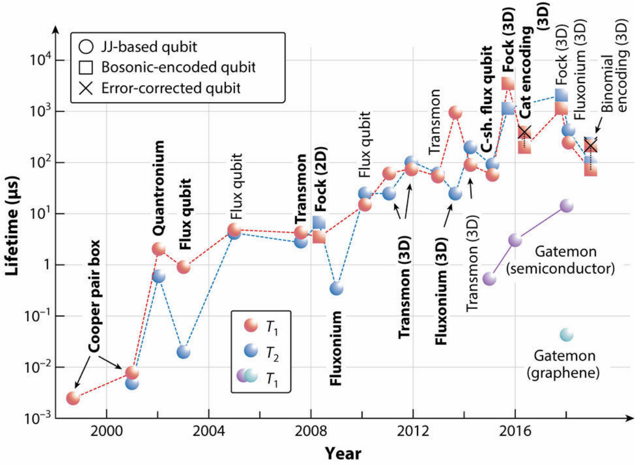
R. Linehan, TAUP 2023

Further reading: An Introduction to the Transmon Qubit for Electromagnetic Engineers, IEEE 65 (2), 8-20 (2022)

Evolution of quantum coherence times



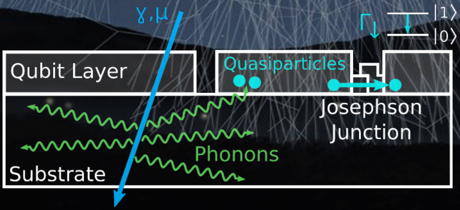
- Quantum harmonic oscillator
  - Equidistant energy levels
- Transmon: Josephson junction
  - Non-equidistant energy levels



Annu. Rev. Condens. Matter Phys. 2020. 11:369–95

Quantum coherence may be fundamentally limited by

- Cosmic rays ($\mu^{\pm}$, γ-rays, neutrons)
- Natural radioactivity (^{238}U, ^{232}Th, ^{222}Rn, ^{40}K)



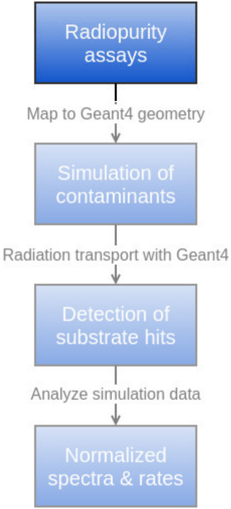
Mitigation strategies

- Go underground!
- Select radiopure materials!

McEwen *et al.*, Nature Physics 18, 107-111 (2022)

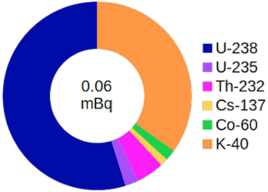
Radiation exposure modeling with GEANT4

Simulation pipeline

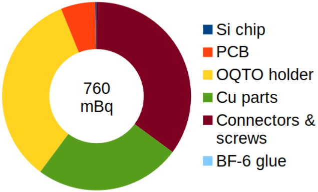


1.) Radiopurity assays

- Screened 60+ components near quantum device payload using HPGe spectroscopy at SNOLAB
  - Specific activities for long-lived radioactive isotopes of interest
- Selected materials and components based on assay results
- Assay results included in public radiopurity.org database hosted by SNOLAB



Si wafer



Qubit assembly

Simulation pipeline

Radiopurity assays

Map to Geant4 geometry

Simulation of contaminants

Radiation transport with Geant4

Detection of substrate hits

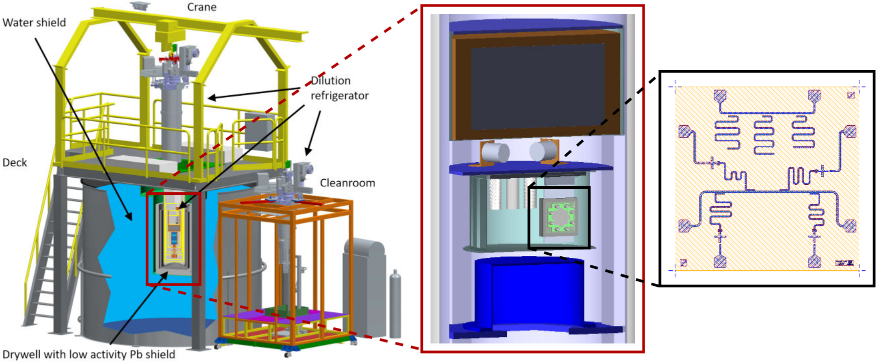
Analyze simulation data

Normalized spectra & rates

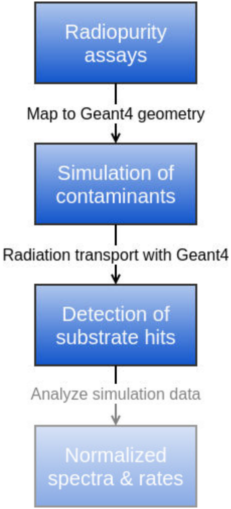
1.) **Radiopurity assays**

2.) **GEANT4 geometry implementation**

- Geometry includes cryostat and multi-layer shield
- Detailed model of qubit payload including magnetic shield



Simulation pipeline

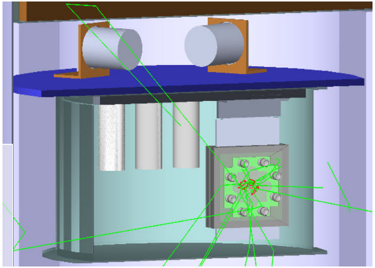


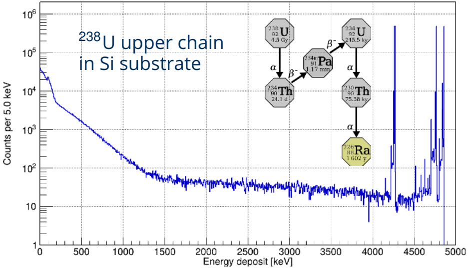
1.) Radiopurity assays

2.) GEANT4 geometry implementation

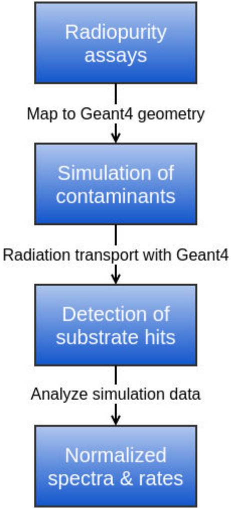
3.) Simulation of radioactive contaminants

- Distinguish bulk, surface and external contaminants
- Map assays onto representative geometry elements
  - Combinations: Bulk (482), surface (20), external (6)

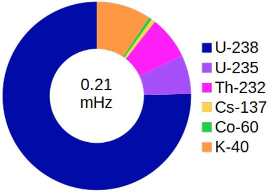




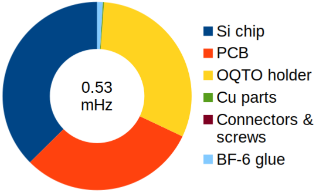
Simulation pipeline



1.) **Radiopurity assays**
2.) **GEANT4 geometry implementation**
3.) **Simulation of radioactive contaminants**
4.) **Analyze radiation hits and apply normalization**
   - Construct spectrum of radiation hits for each component
   - Apply normalization based on exposure history and assay results (specific activity per mass or surface area)

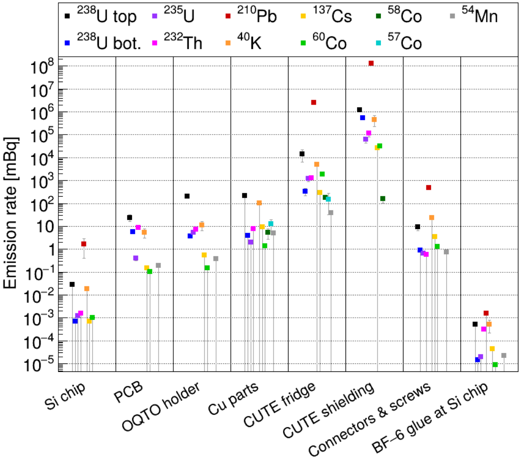


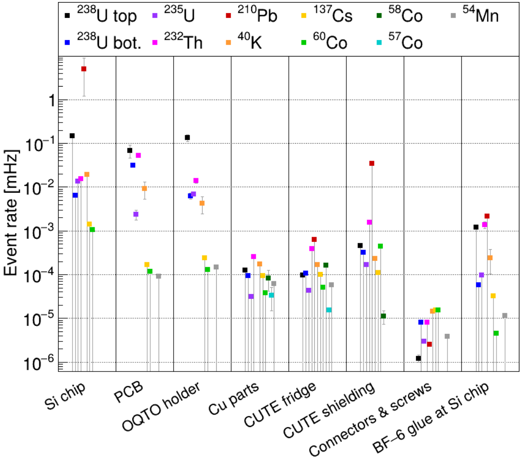
Si wafer



Qubit assembly

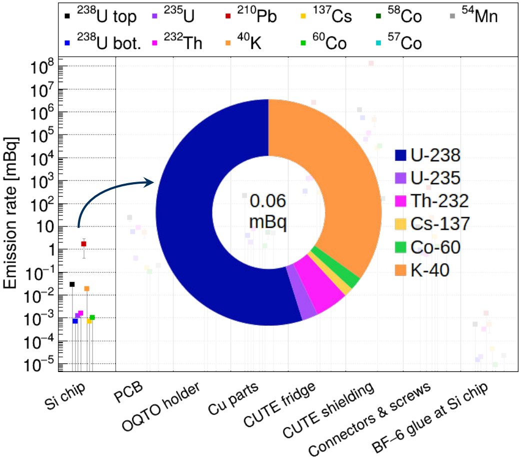
Material assays vs. simulation results

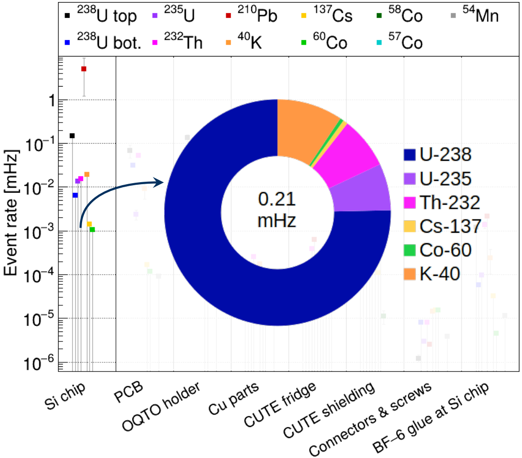




Notable finding: high ^{210}Pb assays $\rightarrow$ replace with estimate of radon exposure history

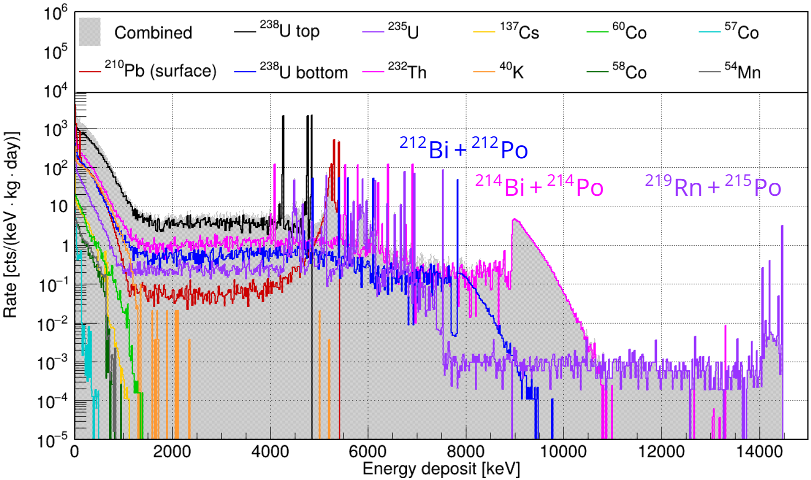
Material assays vs. simulation results



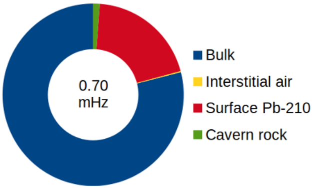


Notable finding: high ^{210}Pb assays $\rightarrow$ replace with estimate of radon exposure history

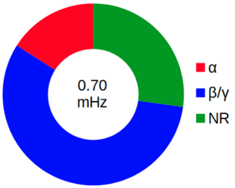
Spectral analysis of background components



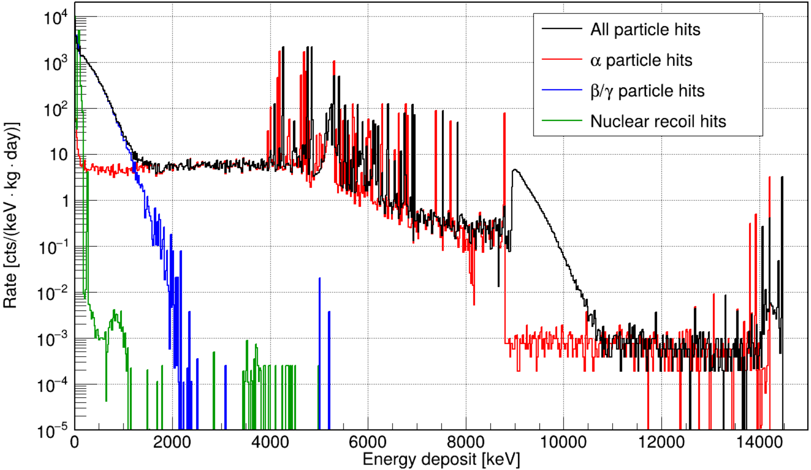
By contamination type



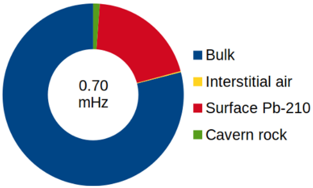
By particle type



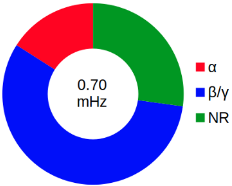
Spectral analysis of background components



By contamination type



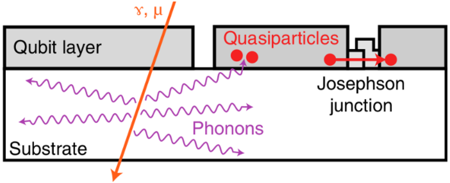
By particle type

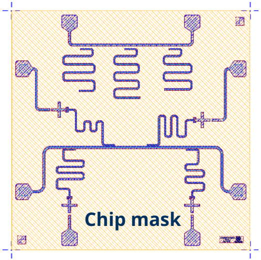


Crystal dynamics simulation with G4CMP

Motivation for using G4CMP

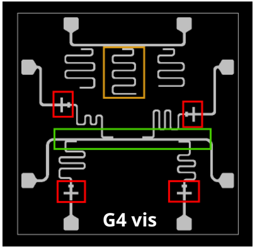
G4CMP – **C**ondensed **M**atter **P**hysics library for GEANT4





Fundamental questions

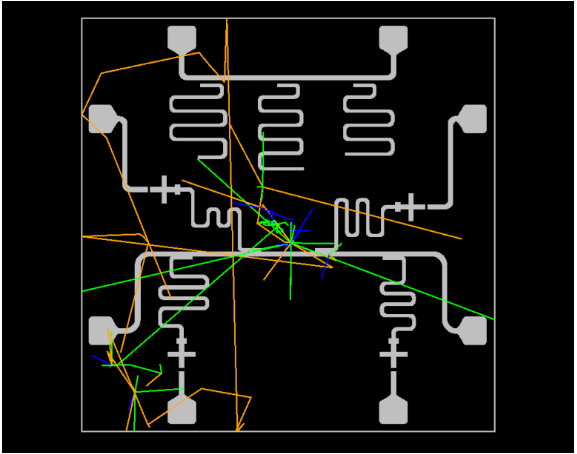
- How do radiation hits affect the quantum circuitry?
- How much energy gets dumped into circuit elements?
- Derive criteria that cause correlated qubit errors on same chip?



- **Layout:** 4-qubit chip design by Chalmers University
  - Elements: transmon crosses, resonators, tranmission line
  - **Superconducting circuitry** made of Al (300 nm film)

G4CMP case study: single phonon event

Primary particle: single 10 meV phonon at center of chip (isotropic emission)



Acoustic phonon modes in G4CMP:

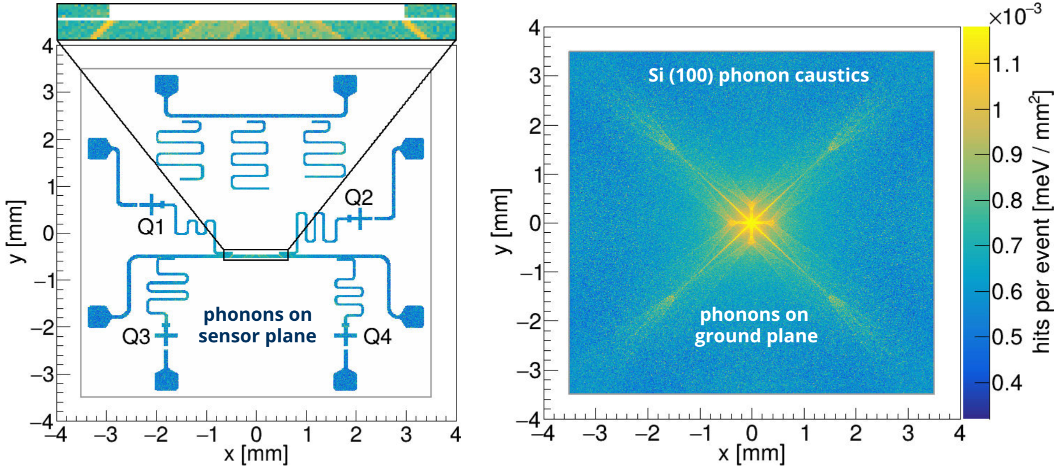
- Blue: longitudinal phonon
- Orange: transverse phonon (fast)
- Green: transverse phonon (slow)

Observations:

- Rapid downconversion via anharmonic phonon decay
- Ballistic transport of low-energy phonons
- Absorption on Al films

G4CMP case study: multiple phonon events

Primary particles: 4 meV phonons at center of chip (isotropic emission)



Summary of G4CMP studies

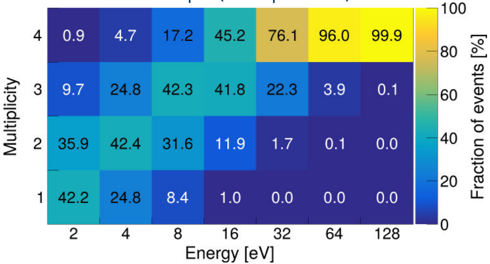
Source	Energy range	τ_{max} [μs]
Phonon	2 meV – 2 eV	14.7 ± 1.1
ER	2 eV – 192 eV	15.9 ± 1.6
NR	2 eV – 192 eV	16.1 ± 0.8
β electron	1 keV – 3000 keV	16.7 ± 2.6
α particle	1 keV – 8000 keV	16.0 ± 2.4

ER... electron recoil (e^-h^+ only)

NR... nuclear recoil (e^-h^+ + prompt phonons)

τ_{max}... phonon collection time (accounts for 99.9% of collected E_{ph})

ER example (NR equivalent)



Define qubit multiplicity $M \in [1, 2, 3, 4]$

Temporal distribution of phonon hits

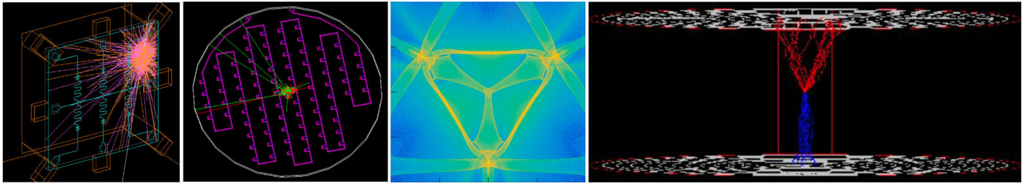
- Phonon collection time consistent across nine orders of magnitude!
  - Informs processing of GEANT4 events (ability to resolve delayed coincidences)

Spatial distribution of phonon hits

- Qubit hit multiplicity = correlated errors
  - Limits quantum algorithm execution time

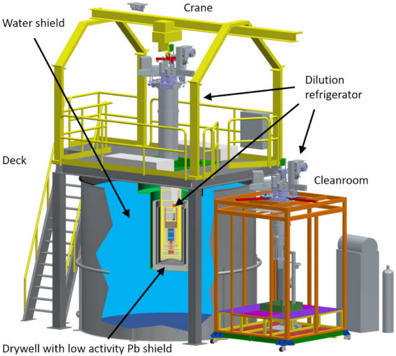
Advertisement: G4CMP consortium

- **Joint effort between CDMS developers and QIS community**
  - Coordinated by Laurentian/SNOLAB, Texas A&M, SLAC and FNAL
  - Initiated by VIEWS 2024 and RISQ 2024 workshops
- **Confluence web space:** G4CMP: GEANT for Condensed Matter Physics
  - Onboarding material, mailing list, documentation, workshops, etc.
  - Recommended: RISQ 2026 G4CMP workshop day
- **Regular consortium meetings**
  - Monthly high-level discussion and planning
  - Bi-weekly technical user meetings / office hours



Summary & Outlook

- **QUTEbits kicks off SNOLAB's quantum device program**
- **Completed material screening and background studies**
  - 60+ assay results published on radiopurity.org
  - Paper submitted to JINST: arXiv:2607.16151
- **Sophisticated Monte Carlo simulations**
  - Projections based on GEANT4 and G4CMP
    - Background in qubit chips: $< 1\,\mathrm{mHz}$
    - Rate with ^{133}Ba source: $\sim 40\,\mathrm{mHz}$
- **Qubit characterization measurements ongoing**



Our second QUTEbits run at SNOLAB is about to be wrapped up. Stay tuned!

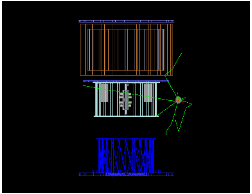
Appendix

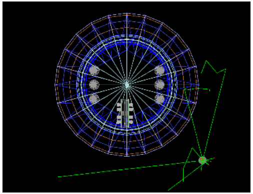
Expected backgrounds vs. calibration source

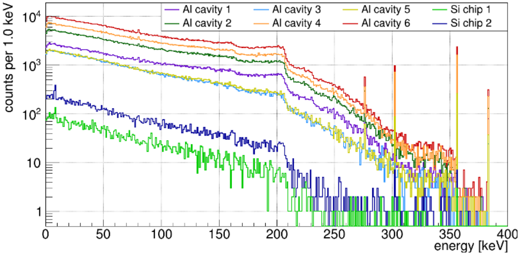
Background modeling

- Model for 2 Si chips and 6 Al cavities
- Rate from **bulk contaminants** in Si
  - Informed by assays: 0.6 mHz
- Rate from **surface contaminants** in Si
  - Different exposure scenarios (radon)
  - Surface time: 1 – 3 years
  - UG time at SNOLAB: 1 – 3 weeks
  - Expected rate: 0.1 – 0.3 mHz
- **Total expected background rate in Si**
  - Conservative estimate: 0.7 – 1.0 mHz
- **Expected ^{133}Ba rate in Si chips**
  - Expected rate: $\sim$ 40 mHz

^{133}Ba calibration source modeling







G4CMP – Crystal and phonon physics modeling

G4CMP – **C**ondensed **M**atter **P**hysics library for GEANT4

1.) **Production of e^-h^+ pairs and phonons from $\mathcal{O}$(keV) GEANT4 energy deposits**

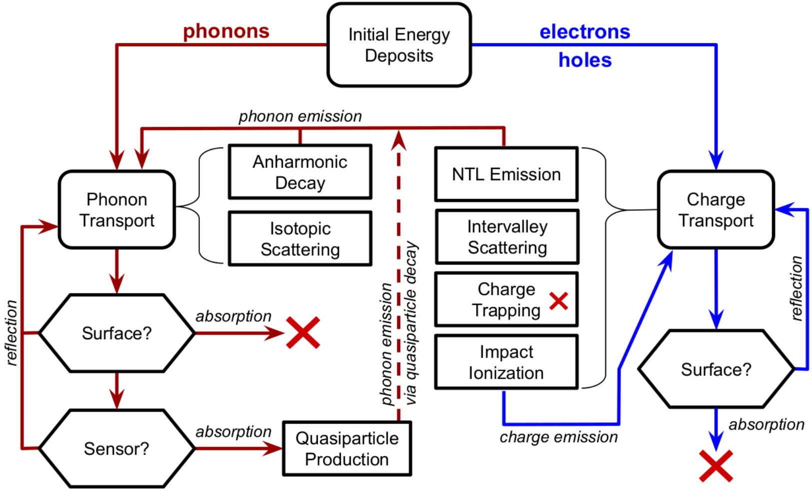
2.) **Transport of eV-scale** (conduction band) **electrons and holes** in crystals
   - Anisotropic transport of e^-, isotropic transport of h^+
   - Lattice scattering, phonon emission, impurity effects

3.) **Transport of meV-scale (acoustic) phonons** in deeply cryogenic crystals
   - Mode-specific relationship between wave vector and group velocity
   - Impurity scattering (mode mixing), anharmonic decays

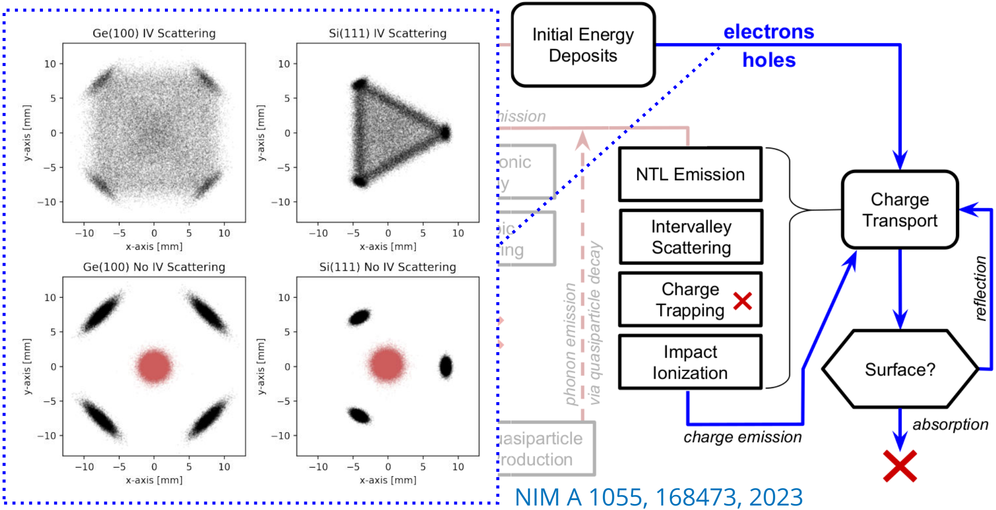
4.) **Sensor response modeling** (*G4CMPKaplanQP*)
   - User application implements phonon collection (absorption, reflection)
   - Phonons incident on sensor elements trigger thin-film simulation (QP physics)

More details: Kelsey *et al.*, NIM A 1055, 168473, 2023 (arXiv:2302.05998)
Source code: https://github.com/G4CMP/G4CMP

G4CMP – Event processing (simplified)

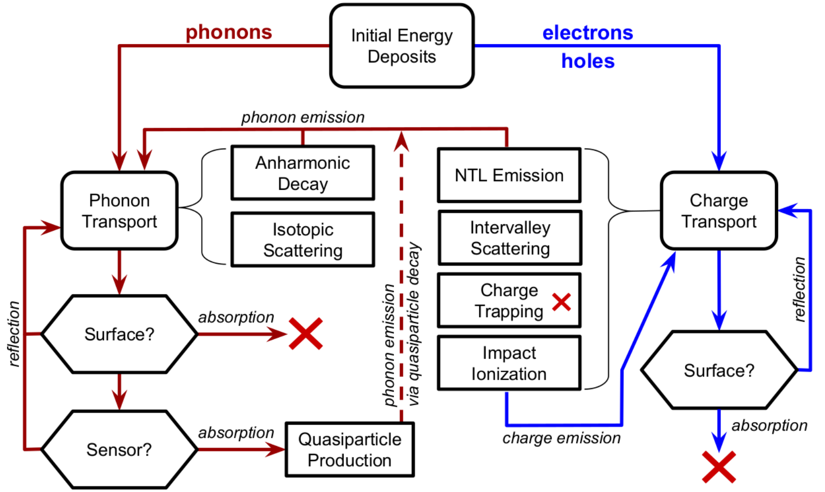


G4CMP – Event processing (simplified)

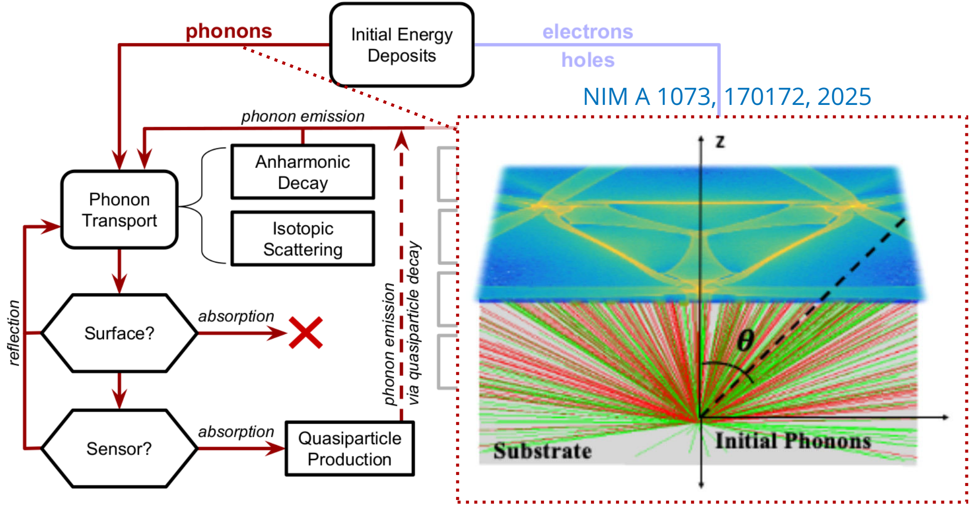


NIM A 1055, 168473, 2023

G4CMP – Event processing (simplified)



G4CMP – Event processing (simplified)



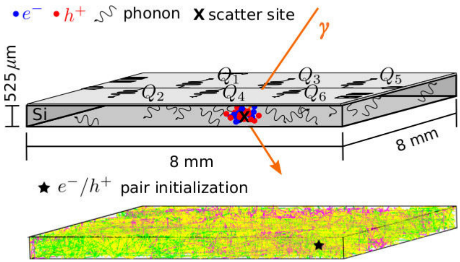
NIM A 1073, 170172, 2025

QIS studies using G4CMP

EDITORS' SUGGESTION

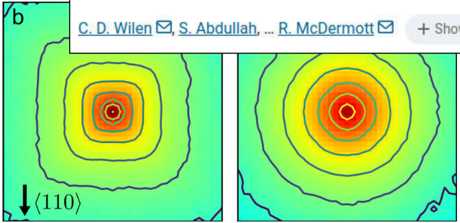
Modeling phonon-mediated quasiparticle poisoning in superconducting qubit arrays

E. Yelton[1], C. P. Larson[1], V. Iaia[1], K. Dodge[2], G. La Magna[3,4], P. G. Baity[5], I. V. Pechenezhskiy[1], R. McDermott[6], N. A. Kurinsky[7,8] *et al.*



Correlated charge noise and relaxation errors in superconducting qubits

C. D. Wilen, S. Abdullah, ... R. McDermott + Show authors



Estimating the energy threshold of phonon-mediated superconducting qubit detectors operated in an energy-relaxation sensing scheme

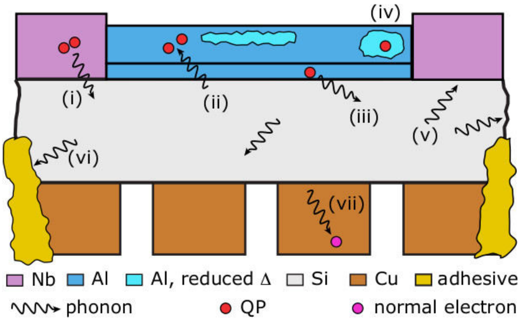
R. Linehan[1,*], I. Hernandez[2,1], D. J. Temples[1], S. Q. Dang[3,1], D. Baxter[1,4], L. Hsu[1], E. Figueroa-Feliciano[4,1], R. Khatiwada[2,1], K. Anyang[2,1] *et al.*

And many more...

Latest additions: QP tracking + new materials

Quasiparticle tracking

PRB 110, 024519, 2024

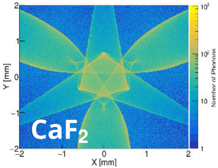


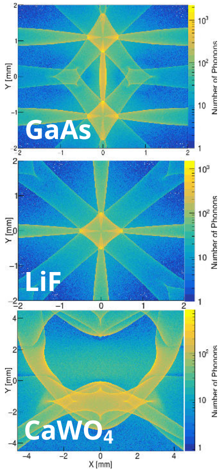
(i) QP recombination
(ii) Cooper pair-breaking
(iii) QP relaxation
(iv) QP trapping
(v) phonon transmission
(vi) phonon escape
(vi) phonon interaction in normal metal

Phonon propagation

- **Substrates**
  - Previously: Si, Ge
  - New: Al_2O_3, GaAs, LiF, $CaWO_4$, CaF_2, SiO_2
- **Superconductors**
  - Previously: Al
  - New: Nb, (Ta)

NIM A 1073, 170172, 2025





G4CMP workshop at RISQ 2026

RISQ – Radiation Impact on Superconducting Qubits

Venue (UW Madison, June 15–18)

- Conference website
- Indico (talks)
- Confluence

RISQ 2026

Access to SLAC S3DF cluster

- Open to G4CMP consortium members
- Dedicated hardware repository
- Containerized G4CMP software

SLAC | S3DF APPTAINER

New G4CMP tutorials

- **Quasiparticle tracking**
  - Demonstrate QP tracking (G4CMP-V10)
- **G4beginner example**
  - Add G4CMP to your own GEANT4 app