

Stefan Zatschler on behalf of the G4CMP consortium  
Laurentian University, SNOLAB, University of Toronto

# **G4CMP – Simulating condensed matter physics with GEANT4 in dark matter research and QIS**

CAP Congress 2026, June 23<sup>rd</sup> 2026

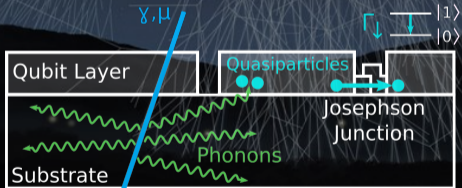


Quantum technology and dark matter experiments may be fundamentally limited by:

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

### Mitigation strategies

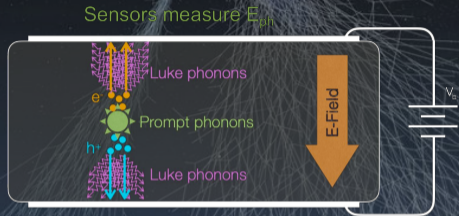
- Go underground!
- Select radiopure materials!



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

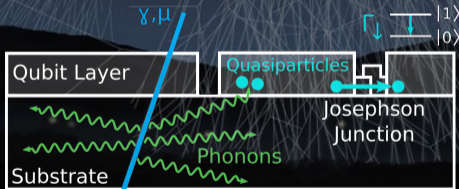
Quantum technology and dark matter experiments may be fundamentally limited by:

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



### Mitigation strategies

- Go underground!
- Select radiopure materials!

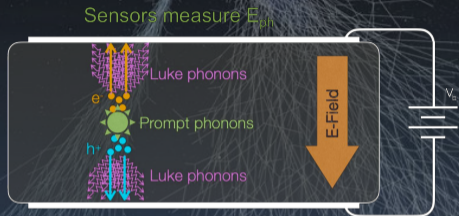


McEwen *et al.*, Nature Physics 18, 107-111 (2022)



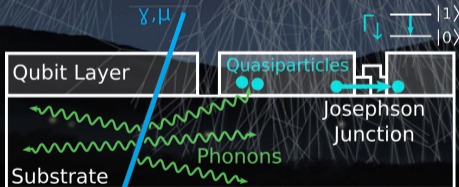
Quantum technology and dark matter experiments may be fundamentally limited by:

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



Mitigation strategies

- Go underground!
- Select radiopure materials!



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

GEANT4  
A SIMULATION TOOLKIT



# G4CMP – Crystal and phonon physics modeling

G4CMP – Condensed Matter Physics library for GEANT4

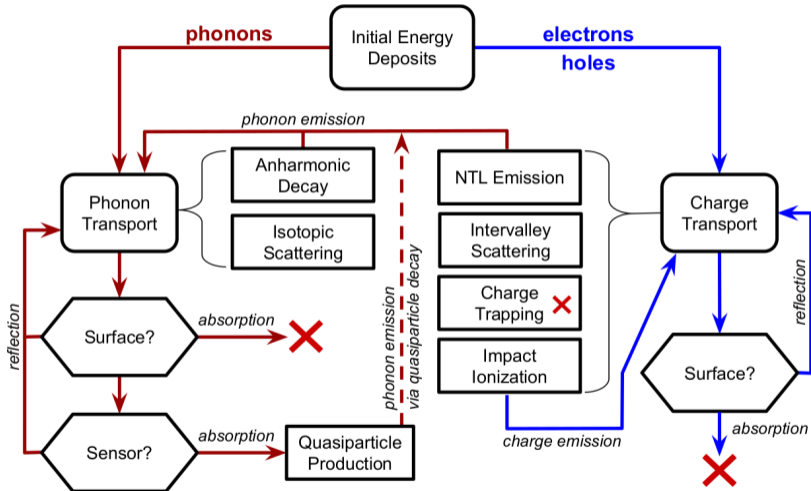
- 1.) **Production of  $e^- h^+$  pairs and phonons from  $\mathcal{O}(\text{keV})$  GEANT4 energy deposits**
- 2.) **Transport of eV-scale (conduction band) electrons and holes** in crystals
  - ▶ Anisotropic transport of  $e^-$ , isotropic transport of  $h^+$
  - ▶ Lattice scattering, phonon emission, 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*)**
  - ▶ Phonons incident on sensor elements trigger thin-film simulation
  - ▶ **New in G4CMP V10:** optional tracking of Bogoliubov QPs!

**More details:** M. Kelsey *et al.*, NIM A 1055, 168473, 2023

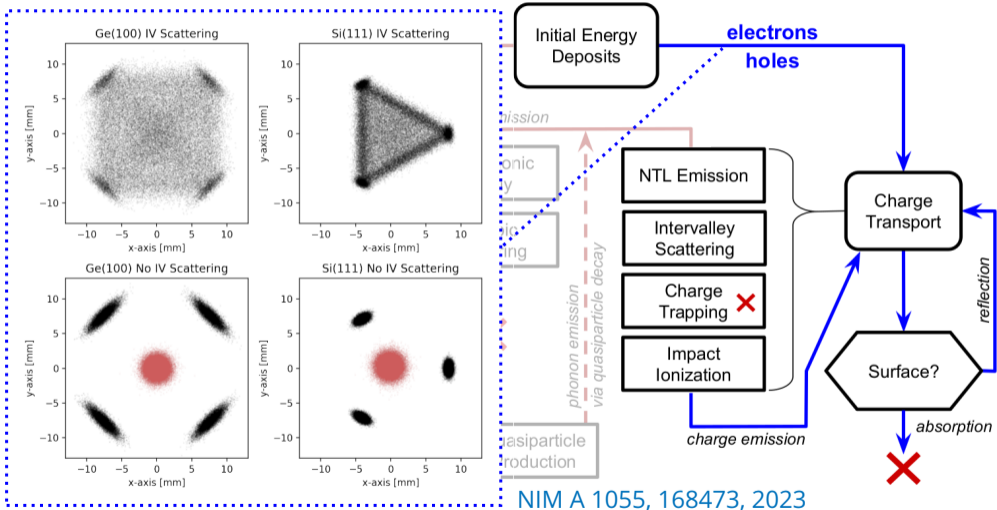
**Source code:** <https://github.com/G4CMP/G4CMP>



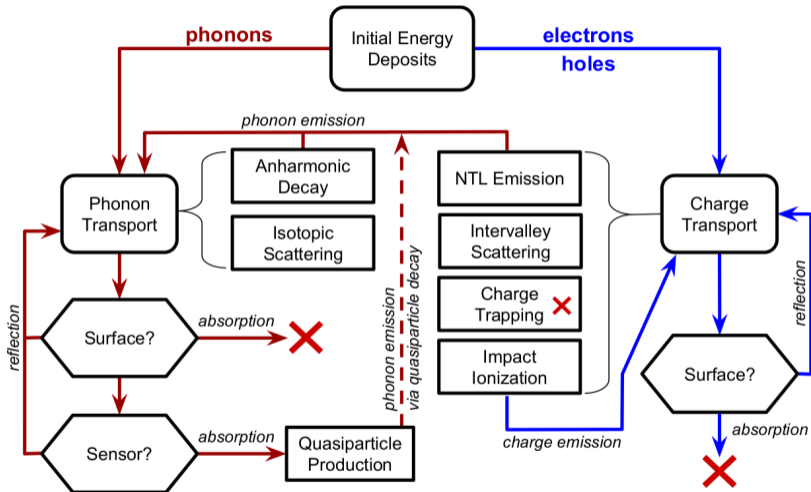
# G4CMP – Event processing (simplified)



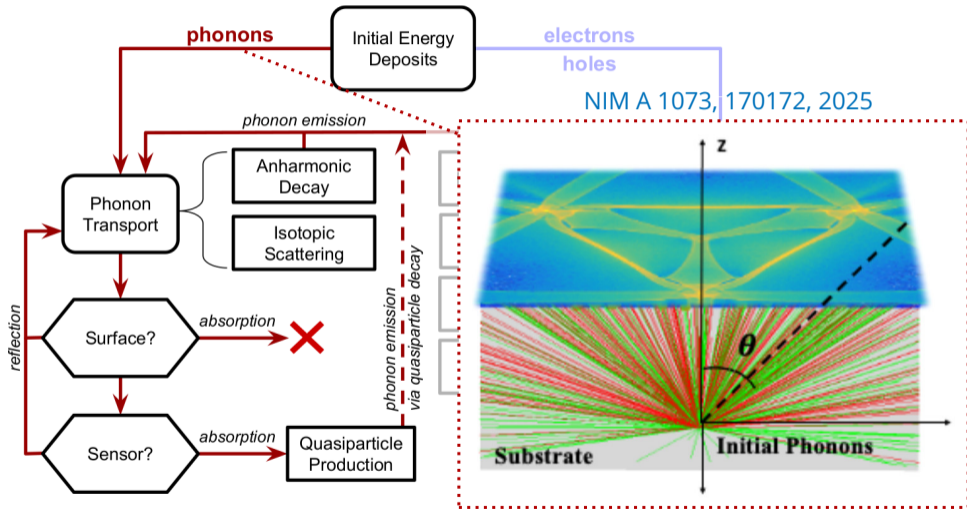
# G4CMP – Event processing (simplified)



# G4CMP – Event processing (simplified)



# G4CMP – Event processing (simplified)

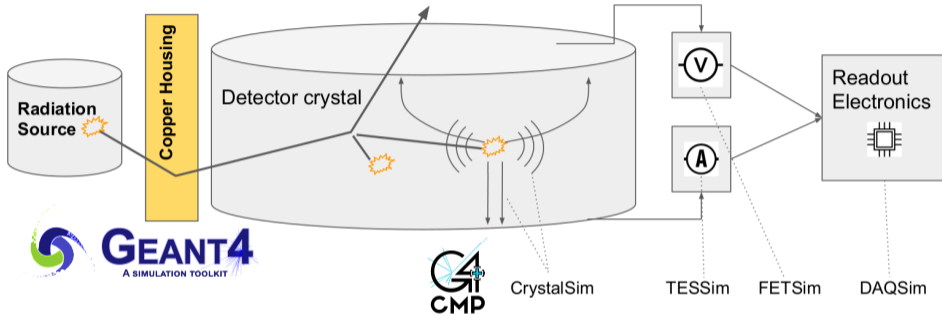




# SuperCDMS detector response modeling

# SuperCDMS phonon sensor – QET

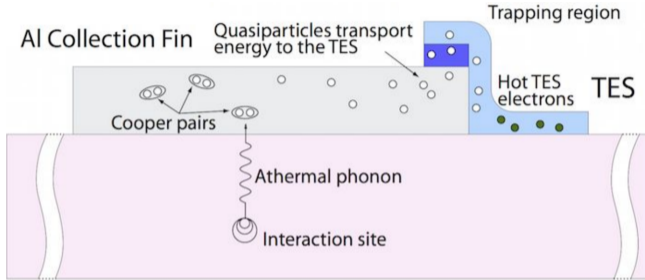
QET – Quasiparticle trap assisted Electrothermal feedback Transition edge sensor



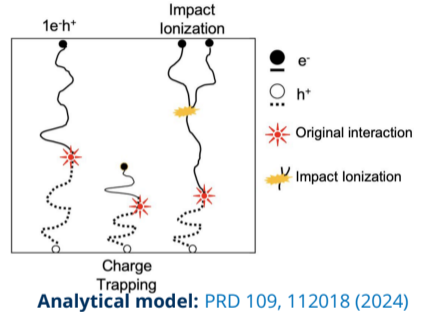
- **Sophisticated GEANT4-based framework** to model crystal and sensor response
  - ▶ **Crystal dynamics:** lattice definition, charge and phonon scattering, etc.
  - ▶ **Impurity effects:** charge trapping, impact ionization
  - ▶ **TES configuration:** physical layout, circuitry and electro-thermodynamics

# SuperCDMS phonon sensor – QET

QET – Quasiparticle trap assisted Electrothermal feedback Transition edge sensor

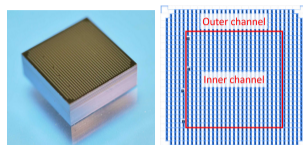


<https://figueroa.physics.northwestern.edu>

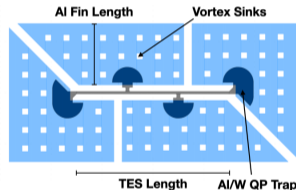


- **Sophisticated GEANT4-based framework** to model crystal and sensor response
  - ▶ **Crystal dynamics:** lattice definition, charge and phonon scattering, etc.
  - ▶ **Impurity effects:** charge trapping, impact ionization
  - ▶ **TES configuration:** physical layout, circuitry and electro-thermodynamics

# SuperCDMS Si-HVeV modeling

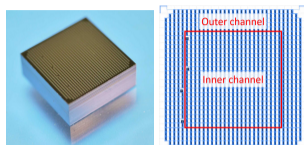
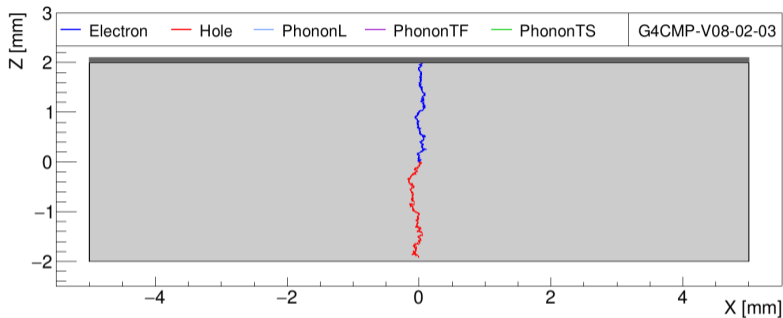


PRD 104, 032010 (2021)

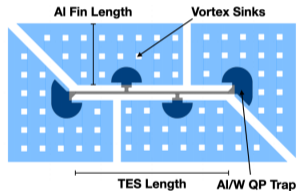


- **Si-HVeV** = prototype HV detector with eV-scale resolution (one-sided QET readout)
- **Tracking of single  $e^-h^+$  pair** created at center in electric field of  $\mathcal{O}(10)$  V/cm
  - ▶ About  $\sim 5$ - $10$ k steps for charge tracks in this configuration (mainly Luke scattering)
  - ▶ About  $\sim 50$ k phonon tracks with  $\mathcal{O}(100)$  –  $\mathcal{O}(1000)$  steps each (mainly surface reflections)

# SuperCDMS Si-HVeV modeling

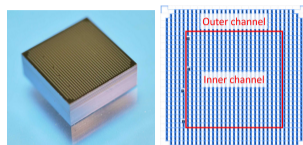


PRD 104, 032010 (2021)

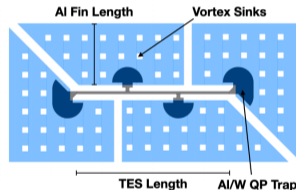


- **Si-HVeV** = prototype HV detector with eV-scale resolution (one-sided QET readout)
- **Tracking of single  $e^-h^+$  pair** created at center in electric field of  $\mathcal{O}(10)$  V/cm
  - ▶ About  $\sim 5$ - $10$ k steps for charge tracks in this configuration (mainly Luke scattering)
  - ▶ About  $\sim 50$ k phonon tracks with  $\mathcal{O}(100)$  –  $\mathcal{O}(1000)$  steps each (mainly surface reflections)

# SuperCDMS Si-HVeV modeling

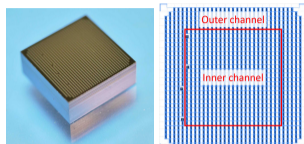
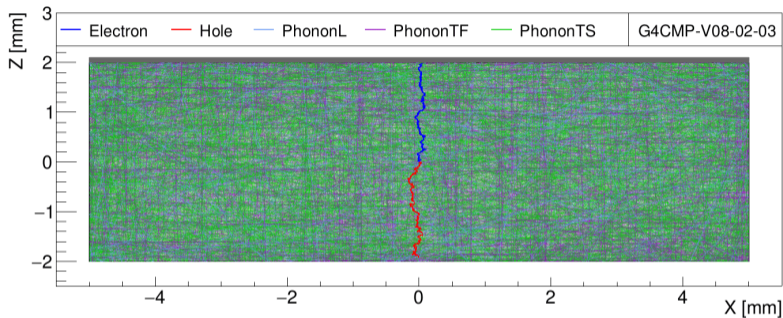


PRD 104, 032010 (2021)

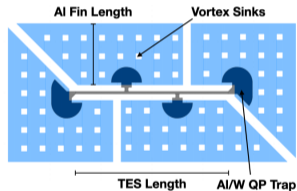


- **Si-HVeV** = prototype HV detector with eV-scale resolution (one-sided QET readout)
- **Tracking of single  $e^-h^+$  pair** created at center in electric field of  $\mathcal{O}(10)$  V/cm
  - ▶ About  $\sim 5$ - $10$ k steps for charge tracks in this configuration (mainly Luke scattering)
  - ▶ About  $\sim 50$ k phonon tracks with  $\mathcal{O}(100)$  –  $\mathcal{O}(1000)$  steps each (mainly surface reflections)

# SuperCDMS Si-HVeV modeling



PRD 104, 032010 (2021)



- **Si-HVeV** = prototype HV detector with eV-scale resolution (one-sided QET readout)
- **Tracking of single  $e^-h^+$  pair** created at center in electric field of  $\mathcal{O}(10)$  V/cm
  - ▶ About  $\sim 5$ - $10$ k steps for charge tracks in this configuration (mainly Luke scattering)
  - ▶ About  $\sim 50$ k phonon tracks with  $\mathcal{O}(100)$  –  $\mathcal{O}(1000)$  steps each (mainly surface reflections)

# SuperCDMS @ CAP 2026



## Talks:

- ▶ **Ge-HV detector testing at CUTE** by Ruchi Soni → Mon, 3:30 pm, C408, CRX
- ▶ **SuperCDMS overview** by Sukee Dharani → Tue, 4:15 pm, 241, LMX
- ▶ **HVeV Run 5** by Mason Buchanan → Thu, 2:45 pm, C308, CRX
- ▶ **Background modeling** by Madeleine Zurowski → Thu, 3:00 pm, C308, CRX
- ▶ **Background simulations** by Birgit Zatschler → Thu, 3:30 pm, C308, CRX

## Posters:

- ▶ **Event reconstruction (POS-18)** by Antoine Rehberg → Tue, 6:00 pm, Lobby, CRX
- ▶ **PLC system (POS-77)** by Cassandra Harms → Tue, 6:00 pm, Lobby, CRX










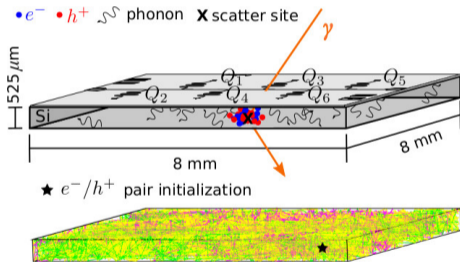
# G4CMP applications in QIS

# QIS studies using G4CMP

EDITORS' SUGGESTION

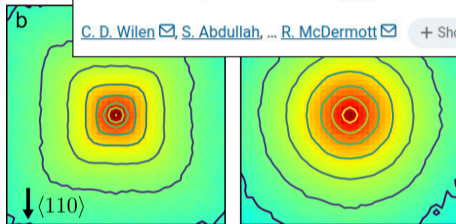
## Modeling phonon-mediated quasiparticle poisoning in superconducting qubit arrays

[E. Yelton](#) <sup>1</sup>, [C. P. Larson](#) <sup>1</sup>, [V. Iaiia](#) <sup>1</sup>, [K. Dodge](#) <sup>2</sup>, [G. La Magna](#) <sup>3,4</sup>, [P. G. Baity](#) <sup>5</sup>, [I. V. Pechenezhskiy](#) <sup>1</sup>, [R. McDermott](#) <sup>6</sup>, [N. A. Kurinsky](#) <sup>7,8</sup> *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

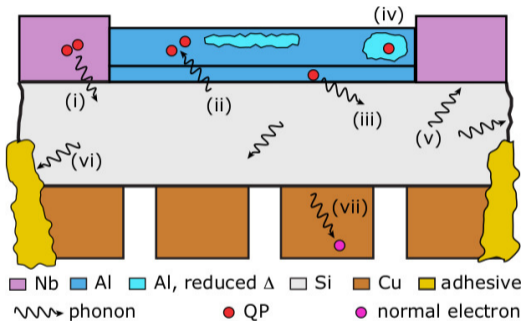
[R. Linehan](#) <sup>1,\*</sup>, [I. Hernandez](#) <sup>2,1</sup>, [D. J. Temples](#) <sup>1</sup>, [S. Q. Dang](#) <sup>3,1</sup>, [D. Baxter](#) <sup>1,4</sup>, [L. Hsu](#) <sup>1</sup>, [E. Figueroa-Feliciano](#) <sup>4,1</sup>, [R. Khatiwada](#) <sup>2,1</sup>, [K. Anyang](#) <sup>2,1</sup> *et al.*

And many more...

# Latest additions: QP tracking + new materials

## Quasiparticle tracking

PRB 110, 024519, 2024



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

## Phonon propagation

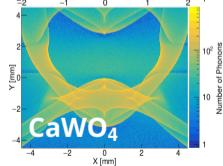
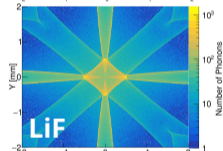
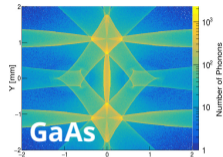
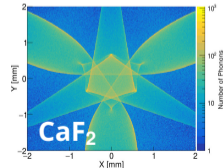
### ■ Substrates

- ▶ Previously: Si, Ge
- ▶ New:  $\text{Al}_2\text{O}_3$ , GaAs, LiF,  $\text{CaWO}_4$ ,  $\text{CaF}_2$ ,  $\text{SiO}_2$

### ■ Superconductors

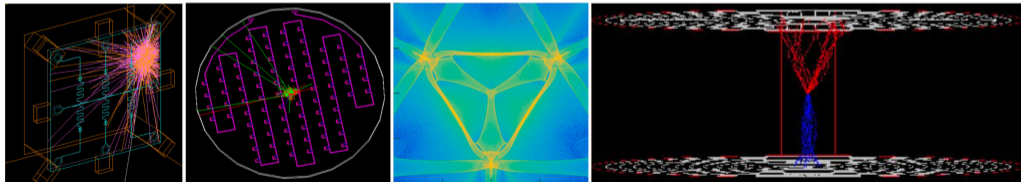
- ▶ Previously: Al
- ▶ New: Nb, (Ta)

NIM A 1073, 170172, 2025



# 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.
- **Regular consortium meetings**
  - ▶ Monthly high-level discussion and planning
  - ▶ Bi-weekly technical user meetings / office hours



# G4CMP workshop at RISQ 2026

RISQ – Radiation Impact on Superconducting Qubits

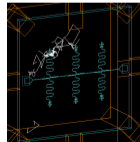
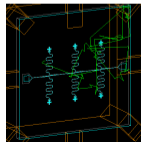
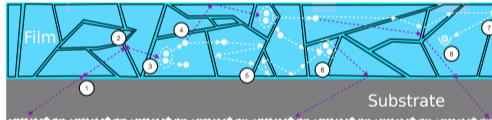
## Venue (UW Madison, June 15–18)

- Conference website
- Indico (talks)
- Confluence



## New G4CMP tutorials

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



**SLAC** | **S3DF**



# Summary & Outlook

- **G4CMP is a versatile tool to model cryogenic devices**
  - ▶ Very active development and feature implementation
- **Growing user community in DM research and QIS**
  - ▶ Join the G4CMP consortium – It's free!
- **Established resources to support user community**
  - ▶ **Web:** GitHub, Confluence, Jira, Slack
  - ▶ **SLAC S3DF:** software and hardware

**We are always looking for new users  
and ways to validate our physics models!**



Logo credit:  
Selby Dang  
(SLAC)

Scientific method



# Appendix

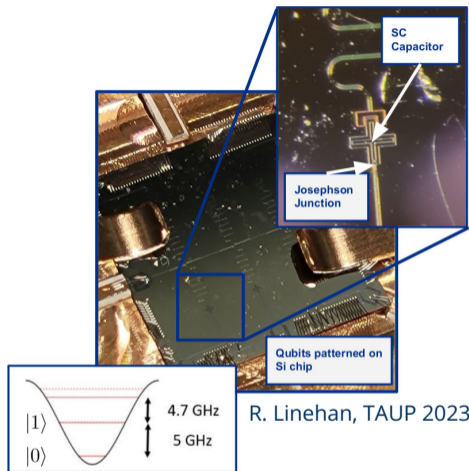
# Superconducting qubits

## What is a superconducting (SC) qubit?

- Anharmonic LC circuit in SC film
- "Qubit" = lowest two energy states
- Energy spacing typically in few GHz range ( $\mu\text{eV}$ )

## Qubits are versatile sensors:

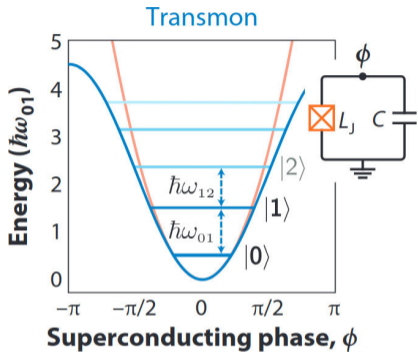
- State preparation, readout, and gates performed with microwave signals at  $\mathcal{O}(\text{GHz})$
- Design decisions enable flexibility in operation and noise susceptibility
- Coupling with other quantum systems allows for multiple detection schemes



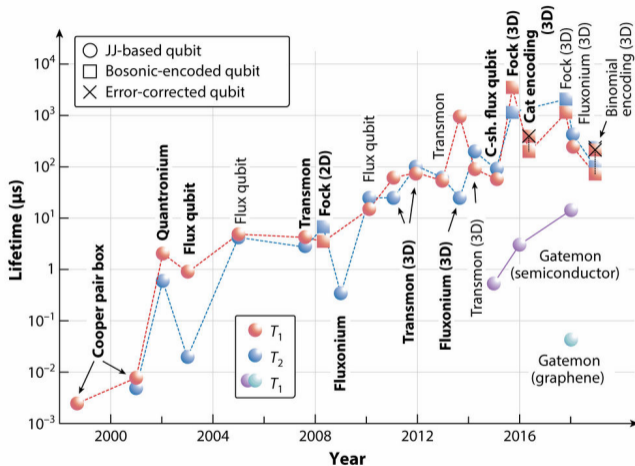
R. Linehan, TAUP 2023

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

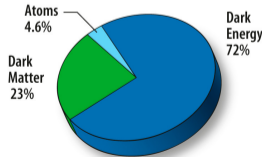
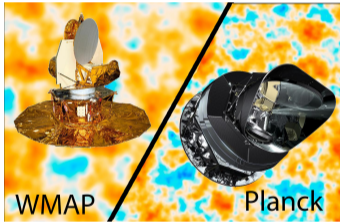
# Dark Matter in a nutshell



# Cosmological evidence for Dark Matter

Astrophysical observations provide strong evidence for Dark Matter (DM).

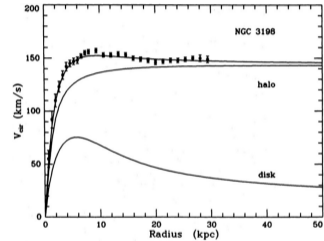
## CMB surveys



## Large-scale structures



## Galaxy rotation curves



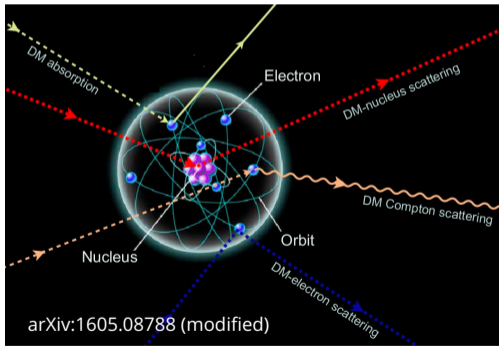
**And many more... But no direct detection (yet)!**

# Dark Matter direct detection

**Principal idea:** DM is made of **particles** which **interact** with atoms in different ways.

## ■ Any observable interaction counts!

- ▶ NR = nuclear recoil
- ▶ ER = electronic recoil



## Estimate of DM flux on Earth

→ **119 000 DM particles per cm<sup>2</sup> per s**

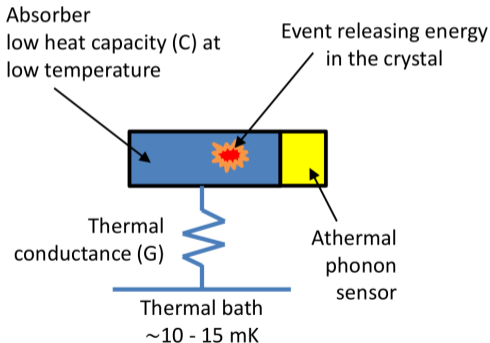
- ▶ DM Density:  $0.3 \text{ GeV/cm}^3$
- ▶ DM Mass:  $60 \text{ GeV}$
- ▶ Relative velocity:  $238 \text{ km/s}$



# How to measure Dark Matter interactions?

**Setting:** Low-energy deposit of DM particle recoiling on detector lattice

- Cryogenic calorimeter held at temperature of 10 – 15 mK
- Equipped with athermal phonon sensor – Transition Edge Sensor (TES)



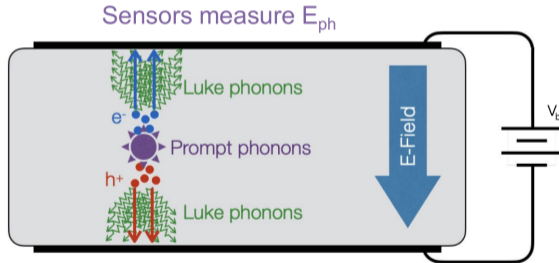
## Signal formation

- Energy deposit creates  $e^-h^+$  pairs and prompt phonons in crystal
- Charges drift in external electric field
- Drifting charges emit Luke phonons
  - ▶ Signal amplification
  - ▶ Sensitivity to single  $e^-h^+$  pairs
- Phonon collection with TES
  - ▶ Pulse reconstruction
  - ▶ Measure of energy deposit

# How to measure Dark Matter interactions?

**Setting:** Low-energy deposit of DM particle recoiling on detector lattice

- Cryogenic calorimeter held at temperature of 10 – 15 mK
- Equipped with athermal phonon sensor – Transition Edge Sensor (TES)



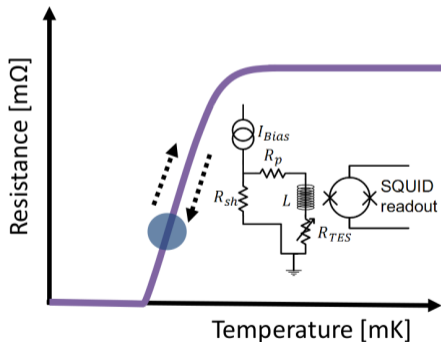
## Signal formation

- Energy deposit creates  $e^-h^+$  pairs and prompt phonons in crystal
- Charges drift in external electric field
- Drifting charges emit Luke phonons
  - ▶ Signal amplification
  - ▶ Sensitivity to single  $e^-h^+$  pairs
- Phonon collection with TES
  - ▶ Pulse reconstruction
  - ▶ Measure of energy deposit

# How to measure Dark Matter interactions?

**Setting:** Low-energy deposit of DM particle recoiling on detector lattice

- Cryogenic calorimeter held at temperature of 10 – 15 mK
- Equipped with athermal phonon sensor – Transition Edge Sensor (TES)



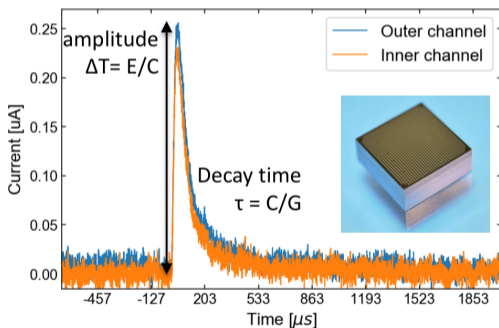
## Signal formation

- Energy deposit creates  $e^-h^+$  pairs and prompt phonons in crystal
- Charges drift in external electric field
- Drifting charges emit Luke phonons
  - ▶ Signal amplification
  - ▶ Sensitivity to single  $e^-h^+$  pairs
- Phonon collection with TES
  - ▶ Pulse reconstruction
  - ▶ Measure of energy deposit

# How to measure Dark Matter interactions?

**Setting:** Low-energy deposit of DM particle recoiling on detector lattice

- Cryogenic calorimeter held at temperature of 10 – 15 mK
- Equipped with athermal phonon sensor – Transition Edge Sensor (TES)



## Signal formation

- Energy deposit creates  $e^-h^+$  pairs and prompt phonons in crystal
- Charges drift in external electric field
- Drifting charges emit Luke phonons
  - ▶ Signal amplification
  - ▶ Sensitivity to single  $e^-h^+$  pairs
- Phonon collection with TES
  - ▶ Pulse reconstruction
  - ▶ Measure of energy deposit