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

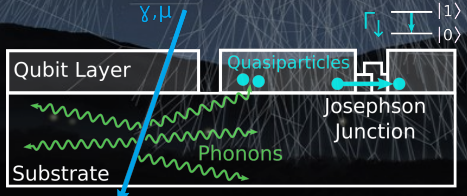
CAP Congress 2026, June 23rd 2026

Quantum technology and dark matter experiments 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)

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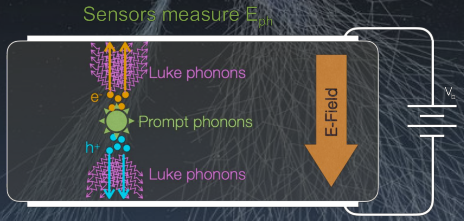

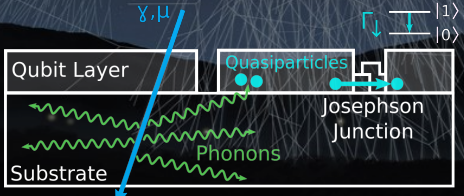

McEwen *et al.*, Nature Physics 18, 107-111 (2022)

SUPER CDMS

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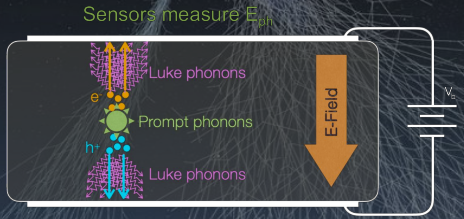
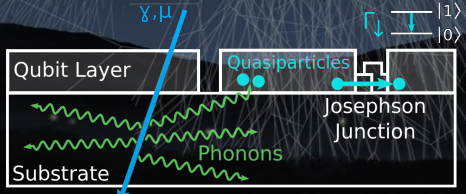




McEwen *et al.*, Nature Physics 18, 107-111 (2022)

GEANT4 A SIMULATION TOOLKIT

G4CMP

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**

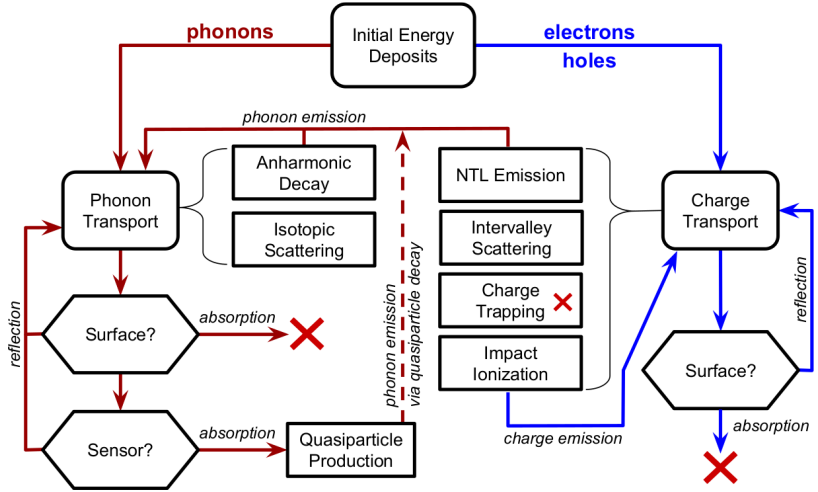
2.) **Transport of eV-scale** (conduction band) **electrons and holes** in crystals
- Anisotropic transport of e^-, isotropic transport of h^+
- Lattice scattering, phonon emission, impurity effects

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

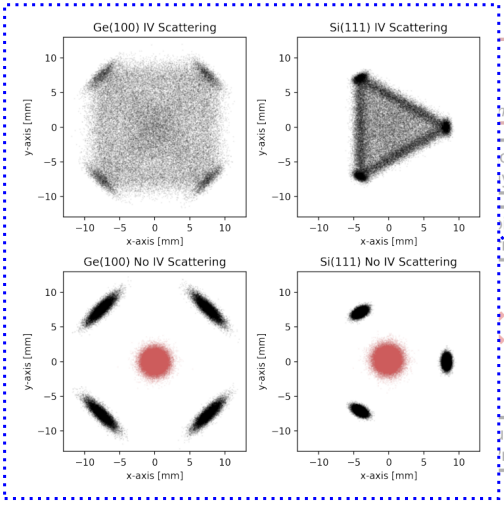
4.) **Sensor response modeling** (*G4CMPKaplanQP*)
- Phonons incident on sensor elements trigger thin-film simulation
- **New in G4CMP V10:** optional tracking of Bogoliubov QPs!

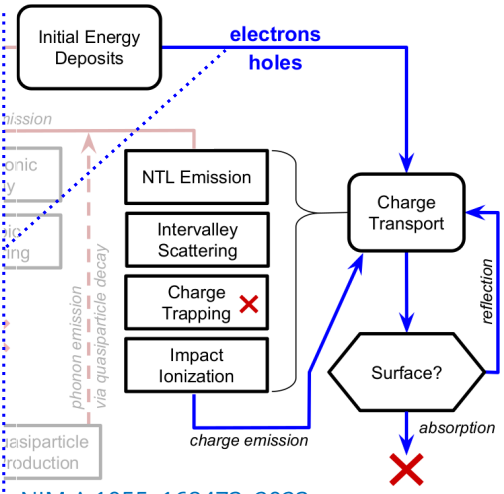
More details: M. Kelsey *et al.*, NIM A 1055, 168473, 2023
Source code: https://github.com/G4CMP/G4CMP

G4CMP – Event processing (simplified)



G4CMP – Event processing (simplified)





NIM A 1055, 168473, 2023

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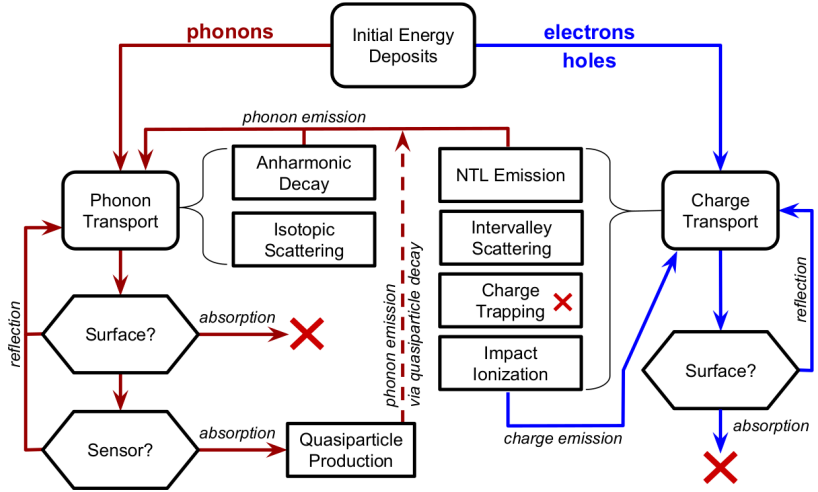

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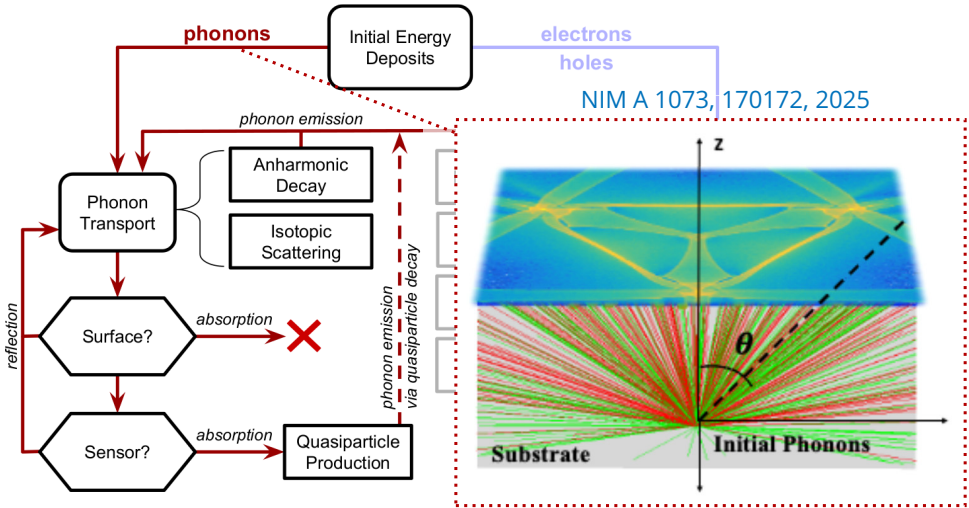
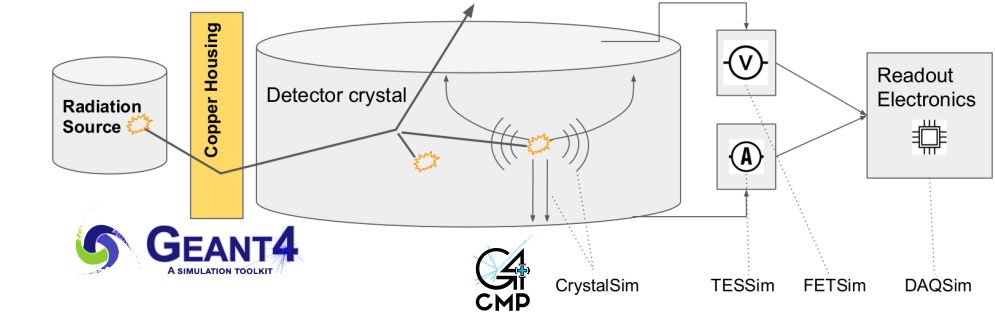


SuperCDMS detector response modeling

SuperCDMS phonon sensor – QET

QET – **Q**uasiparticle trap assisted **E**lectrothermal feedback **T**ransition 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

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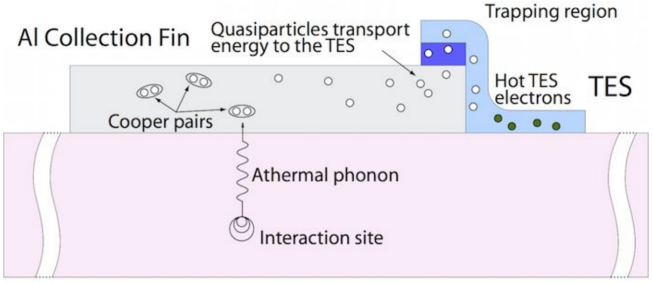
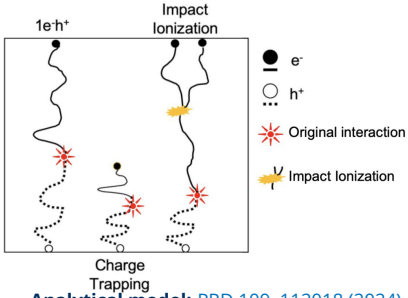


https://figueroa.physics.northwestern.edu



Analytical model: PRD 109, 112018 (2024)

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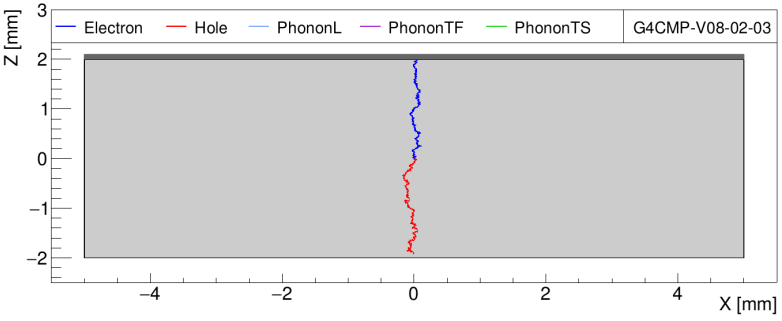
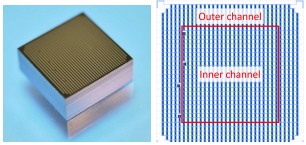
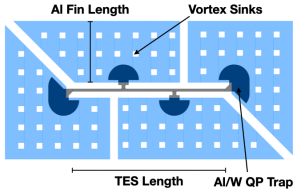
SuperCDMS Si-HVeV modeling



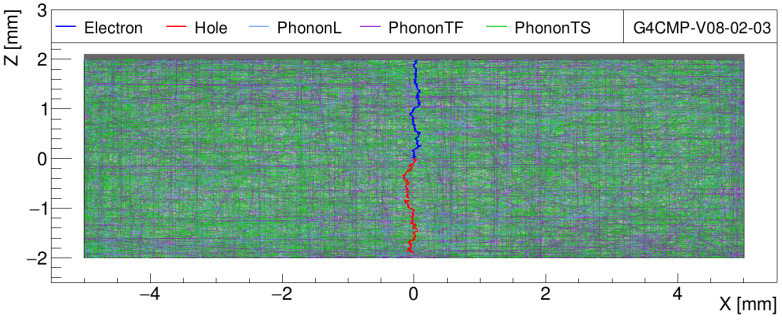


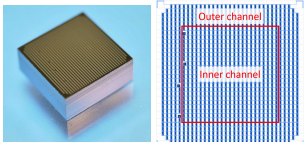
PRD 104, 032010 (2021)



- **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 ∼5-10k steps for charge tracks in this configuration (mainly Luke scattering)
  - About ∼50k phonon tracks with $\mathcal{O}(100) - \mathcal{O}(1000)$ steps each (mainly surface reflections)

SuperCDMS Si-HVeV modeling





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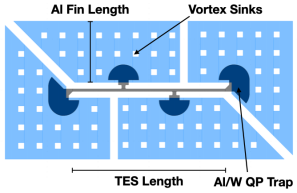

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SuperCDMS @ CAP 2026

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

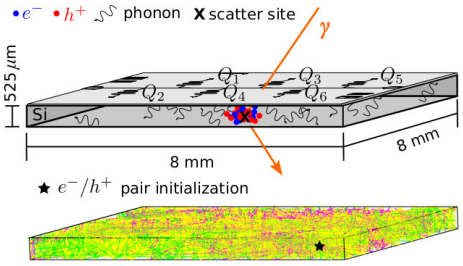
G4CMP applications in QIS

QIS studies using G4CMP

EDITORS' SUGGESTION

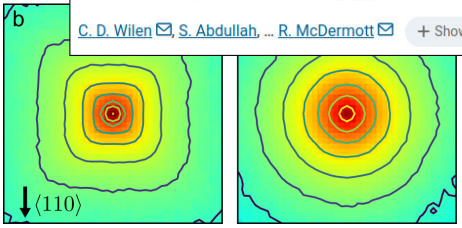
Modeling phonon-mediated quasiparticle poisoning in superconducting qubit arrays

E. Yelton[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

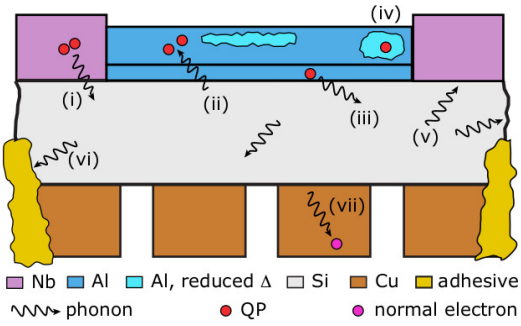
R. Linehan[1,*], I. Hernandez[2,1], D. J. Temples[1], S. Q. Dang[3,1], D. Baxter[1,4], L. Hsu[1], E. Figueroa-Feliciano[4,1], R. Khatiwada[2,1], K. Anyang[2,1] *et al.*

And many more...

Latest additions: QP tracking + new materials

Quasiparticle tracking

PRB 110, 024519, 2024

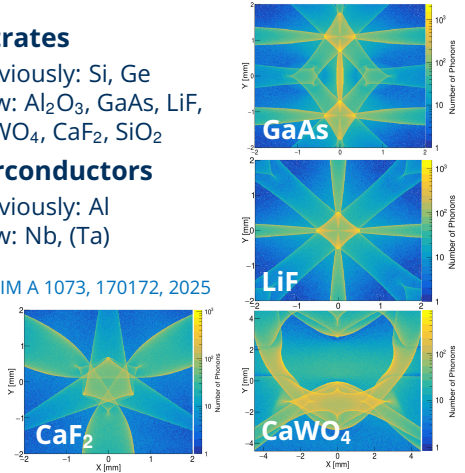


(i) QP recombination
(ii) Cooper pair-breaking
(iii) QP relaxation
(iv) QP trapping
(v) phonon transmission
(vi) phonon escape
(vi) phonon interaction in normal metal

Phonon propagation

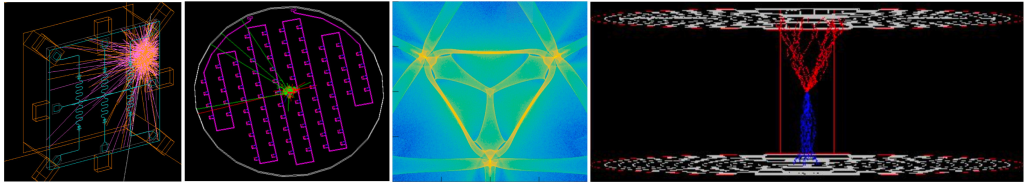
- **Substrates**
  - Previously: Si, Ge
  - New: Al_2O_3, GaAs, LiF, $CaWO_4$, CaF_2, SiO_2
- **Superconductors**
  - Previously: Al
  - New: Nb, (Ta)

NIM A 1073, 170172, 2025



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

RISQ 2026

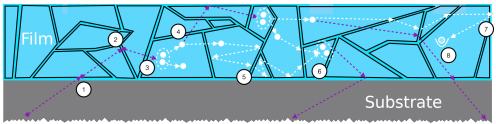
Access to SLAC S3DF cluster

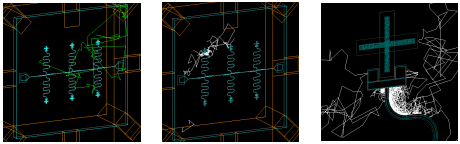
- Open to G4CMP consortium members
- Dedicated hardware repository
- Containerized G4CMP software

SLAC S3DF APPTAINER

New G4CMP tutorials

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



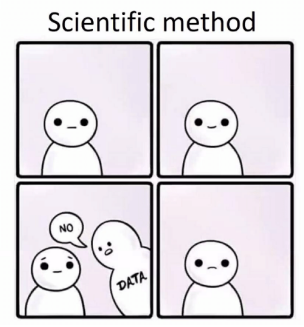


Summary & Outlook

- **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)



Appendix

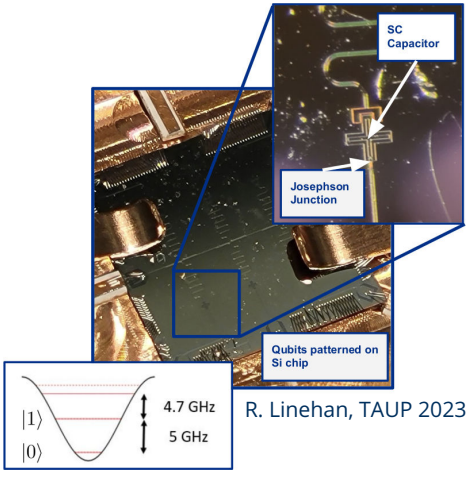
Superconducting qubits

What is a superconducting (SC) qubit?

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

Qubits are versatile sensors:

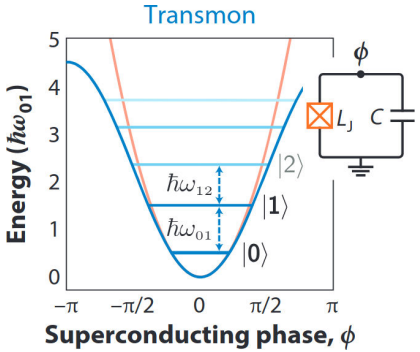
- State preparation, readout, and gates performed with microwave signals at $\mathcal{O}$(GHz)
- Design decisions enable flexibility in operation and noise susceptibility
- Coupling with other quantum systems allows for multiple detection schemes



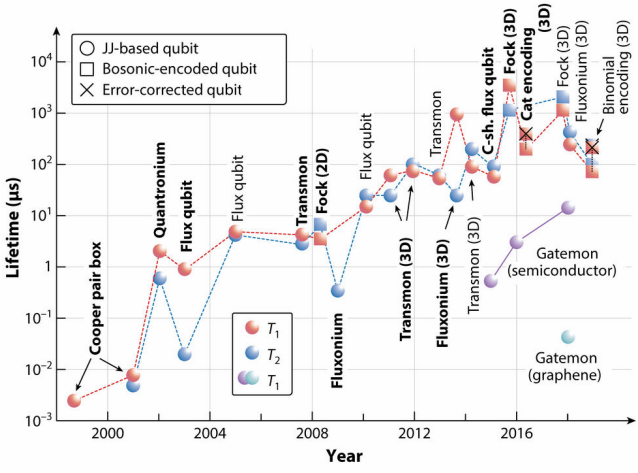
R. Linehan, TAUP 2023

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

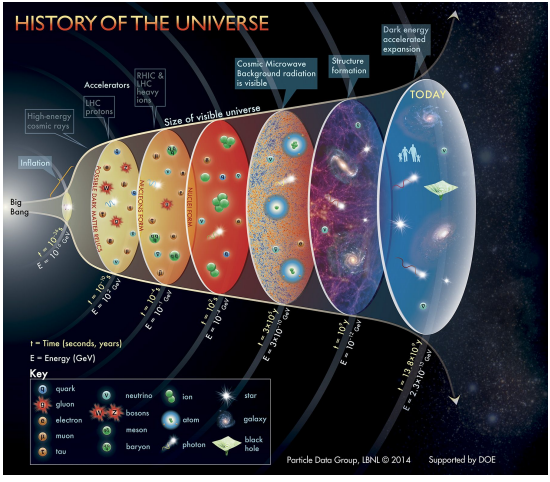
Dark Matter in a nutshell

What do we know about Dark Matter?

The true nature of Dark Matter (DM) remains a mystery to the present day!

- **DM is (likely) <u>not</u> ordinary matter**
  - Atoms, known particles, black holes[a], etc.
- **DM is (almost) invisible** $\rightarrow$ "dark"
  - Does not interact via electromagnetism
  - New elusive particle(s)? Dark sector?
- **Best guess: ΛCDM model of cosmology**
  - Non-baryonic = no "known" particle
  - Cold = non-relativistic velocity distribution
  - Collisionless = interaction mainly via gravity (and possible weak force)
- **Alternatives to ΛCDM?**
  - Modified Newtonian Dynamics (MOND)

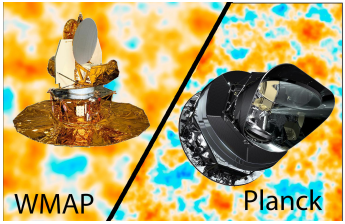
[a] except for (hypothetical) primordial black holes



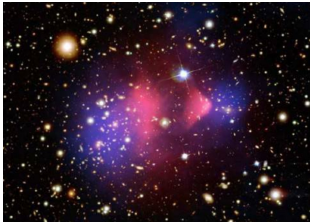
Cosmological evidence for Dark Matter

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

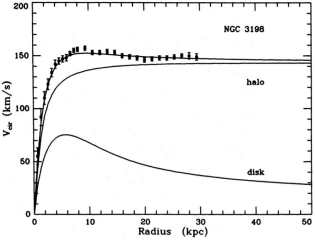
CMB surveys



Large-scale structures



Galaxy rotation curves

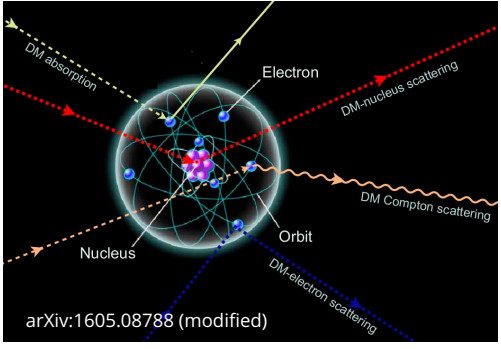


And many more… But no direct detection (yet)!

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

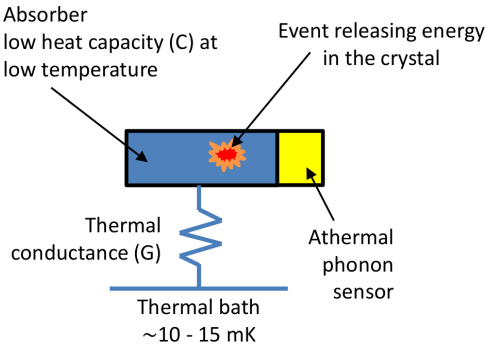
→ **119 000 DM particles per cm^2 per s**

- DM Density: 0.3 GeV/cm^3
- DM Mass: 60 GeV
- Relative velocity: 238 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

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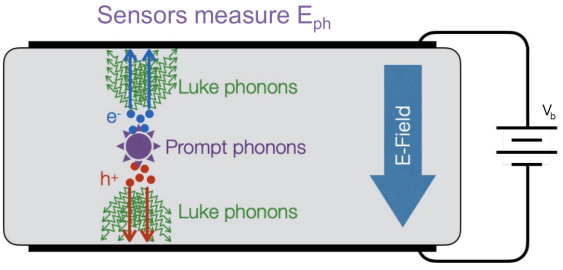

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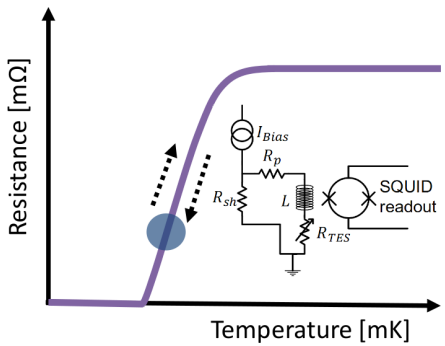

Signal formation

- 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

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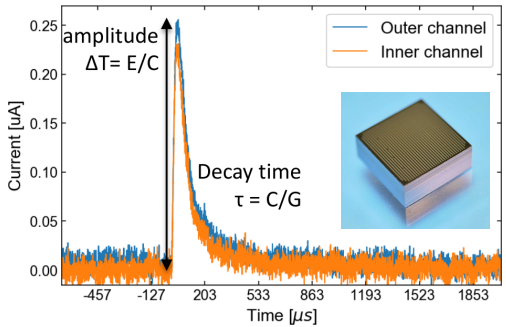

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