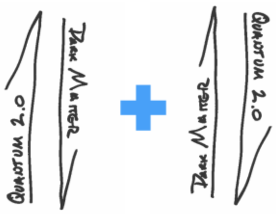
Quantum Workshop – Introduction Flash Talk

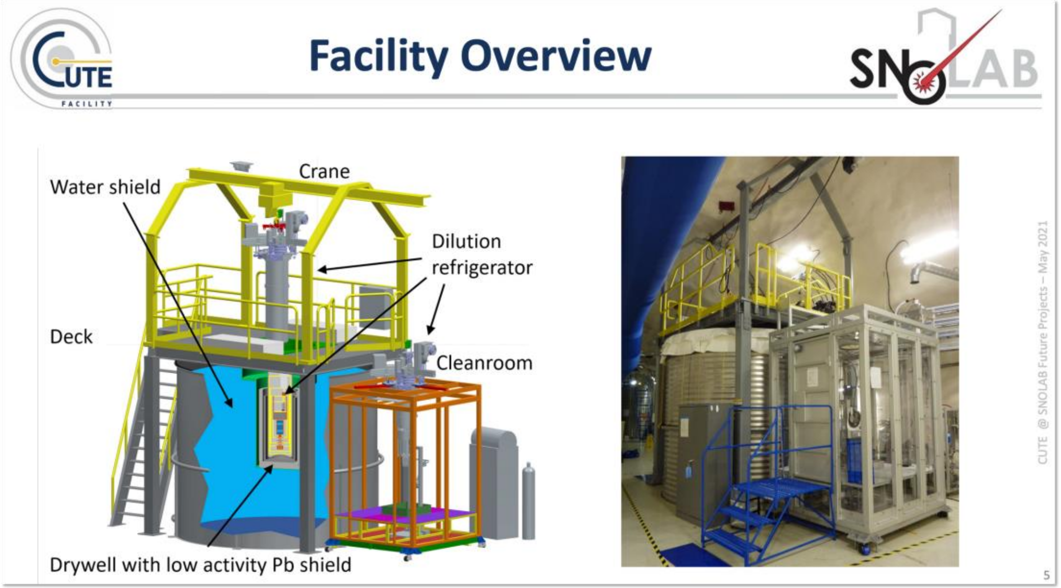
15th January 2024 14:00-14:45

Jeter Hall – Director of Research, SNOLAB

Research interests:

- Exploring the new energy frontier of 1 meV – 1 eV
  - What are the natural sources of quanta in this energy range?
- Improving quantum bit performance by controlling environmental backgrounds
  - Is dark matter a fundamental limitation to certain quantum tech?



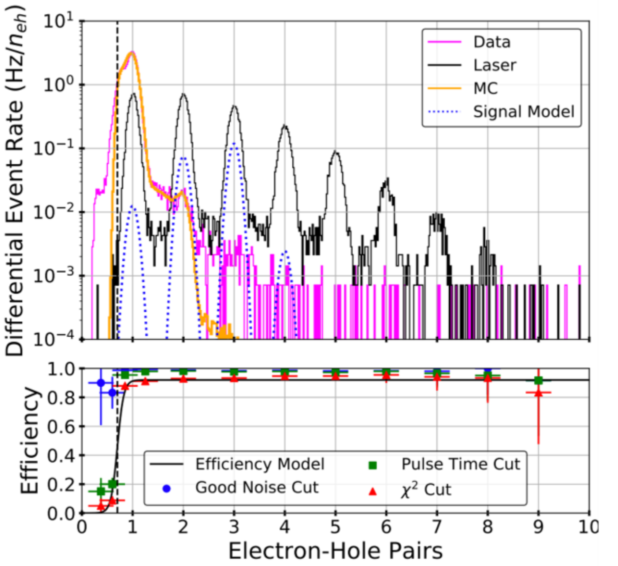


Facility Overview

CUTE @ SNOLAB Future Projects – May 2021

5

SuperCDMS Collaboration, PRL 121 (2018) 051301, arXiv:1804.10697



Queen Mary University of London

Jeter Hall
jeter@snolab.ca

Stephen Sekula – Research Group Manager, SNOLAB

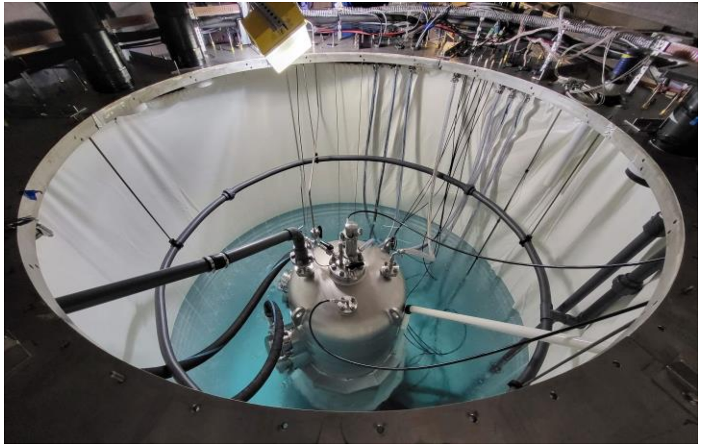
Rare Interaction Detection

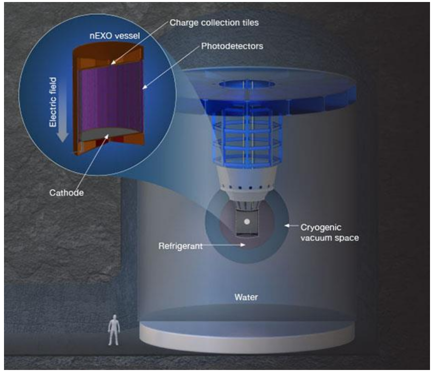
Helium and Lead Observatory (HALO)

- 79 tonnes of lead and 128 embedded cylindrical He-3 counters
- Shielded from cosmic ray radiation and ambient neutrons
- Detects burst of neutrons from neutrino-Pb interactions
- Galactic supernova early warning detector
- Long periods of stable operation (>99% uptime)

PICO – superheated liquid detector

- Currently 70kg freon target at 12C and 27.5psia
- Shielded from cosmic ray radiation and ambient neutrons
- Detects bubbles from nuclear interactions (alphas, neutrons, dark matter) using cameras, fast pressure sensors, and acoustic sensors
- Active data-taking program, commissioned in 2023.





nEXO – next-gen. neutrinoless double beta decay

- Liquid Xenon TPC enriched in Xe-136 (~5000kg)
- Aimed toward CD-1 process in U.S. Scoped for construction at SNOLAB-like underground lab.
- Focus on radon reduction during construction and radioisotope mitigation in material fabrication.

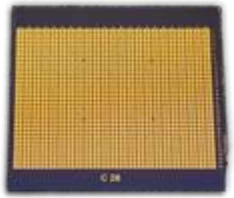
Queen Mary
University of London

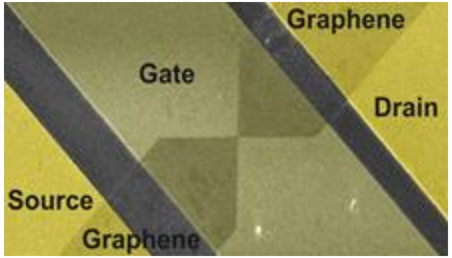
James Thomas – Lecturer in Quantum Technology, QMUL

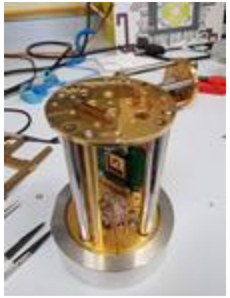
Research interests:

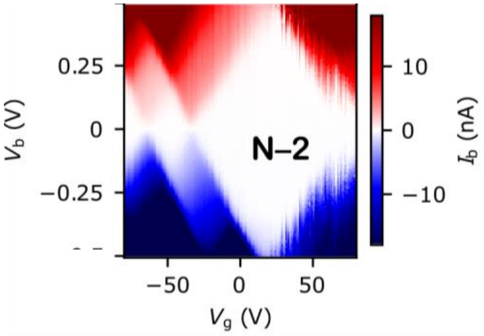
- Exploring molecular species and 2D materials for quantum transport and information processing
- Increasing transistor performance through quantum interference effects

Devices

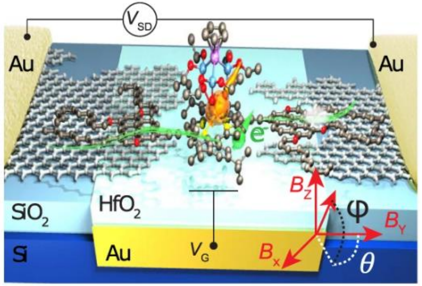


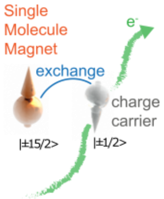


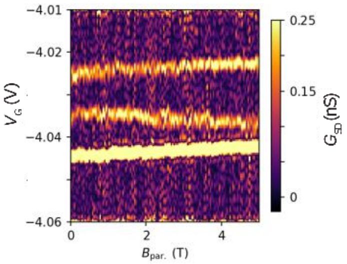




Spin and phonon effects





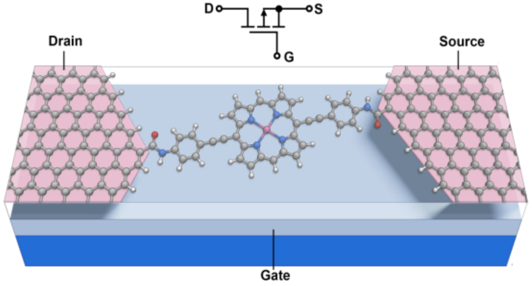


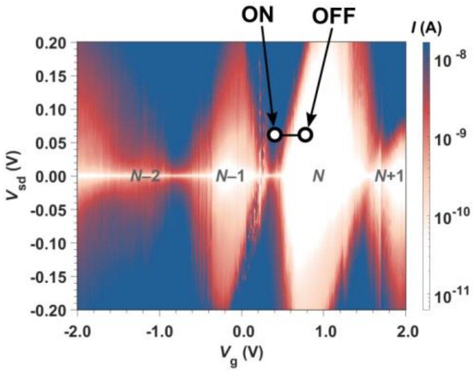
James Thomas
j.o.thomas@qmul.ac.uk

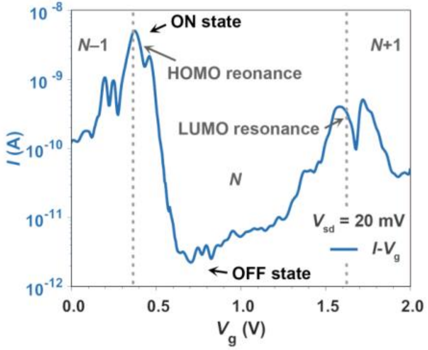
Nat. Commun., **13**, 4506 (2022)

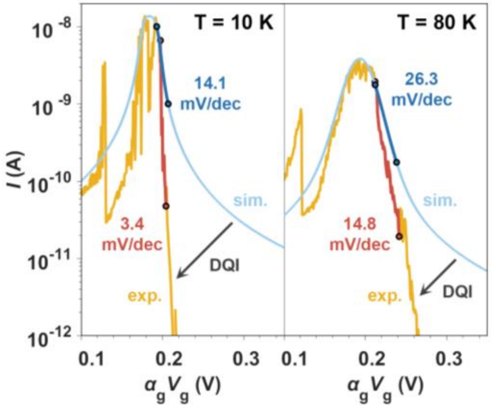
Research interests:

- Exploring molecular species and 2D materials for quantum transport and information processing
- Increasing transistor performance through quantum interference effects









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University of London

James Thomas
j.o.thomas@qmul.ac.uk

arXiv:2304.08535

Lancaster University

Rich Haley

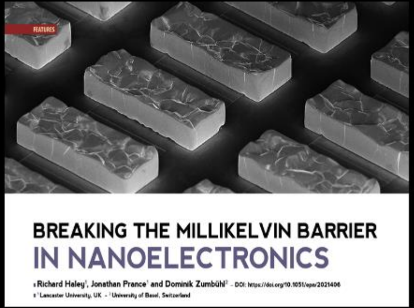
Ultra Low Temperature

Lancaster University

Rich Haley

Ultra Low Temperature

Cooling & measurement
Techniques & technology


FEATURES

BREAKING THE MILLIKELVIN BARRIER
IN NANOELECTRONICS

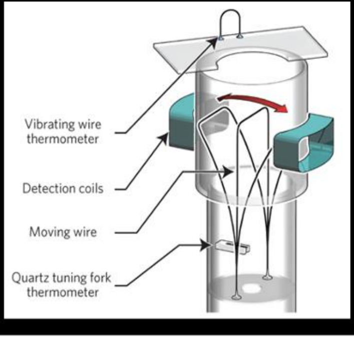
Richard Haley[1], Jonathan Prance[1] and Dominik Zumbühl[2] – DOI: https://doi.org/10.1051/epn/2021406

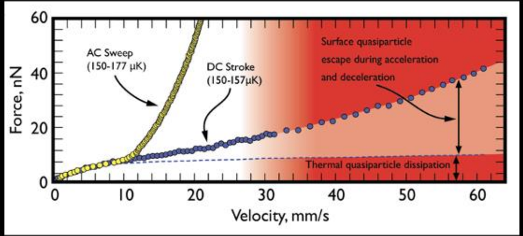
[1] Lancaster University, UK – [2] University of Basel, Switzerland

Haley *et al: EuroPhysics News (2021)*
Autti *et al: Phys. Rev. Lett. (2023)*

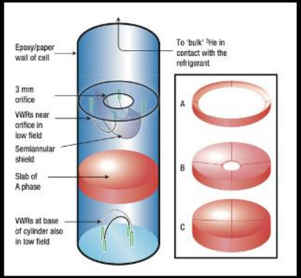
IsoLab

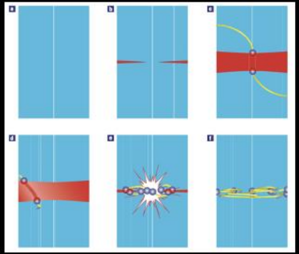
Superfluid helium-3
Fundamental physics & analogue systems



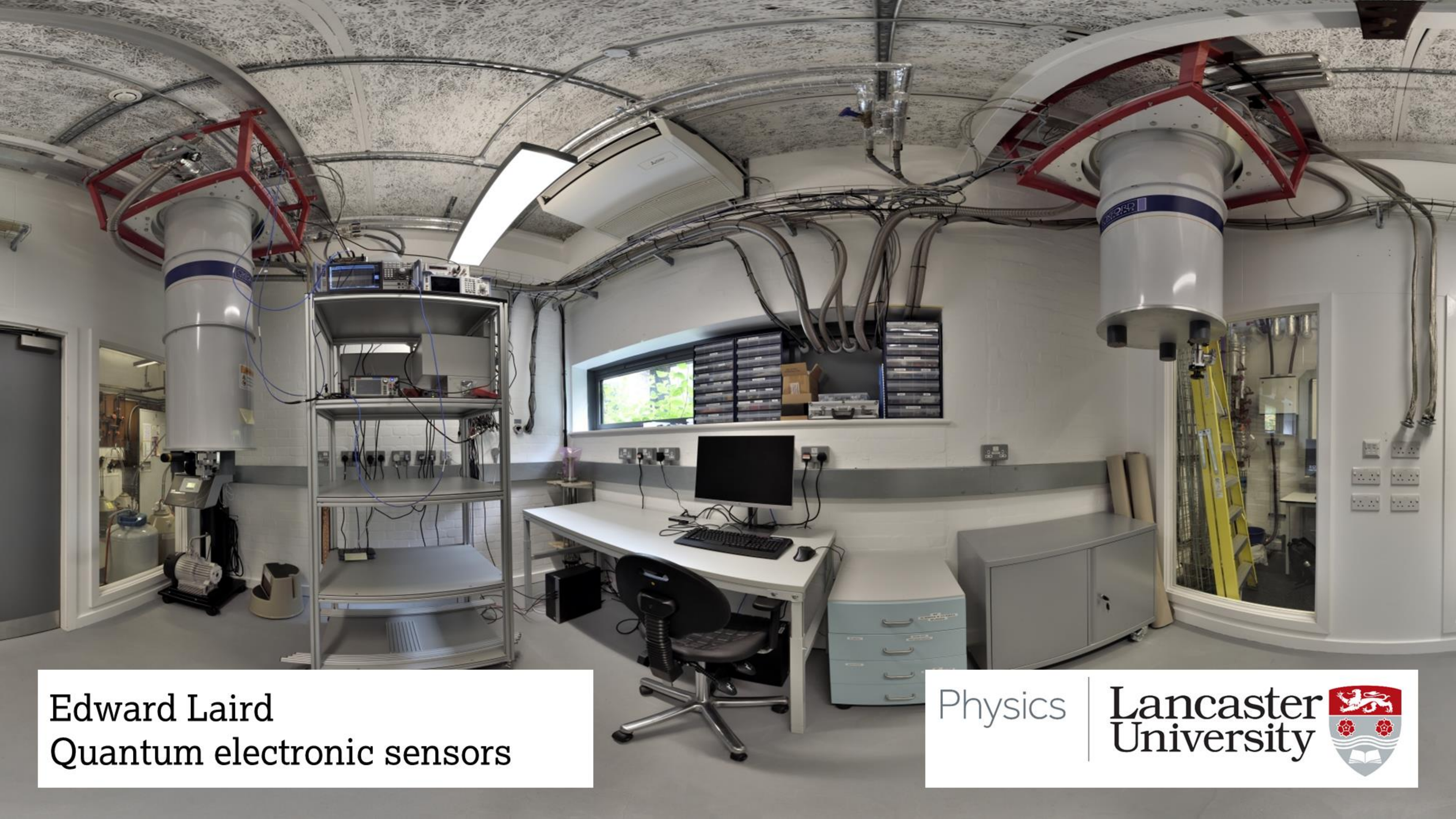


Breaking the superfluid speed limit
in a fermionic condensate
Nat. Phys. 12, 1017 (2016)





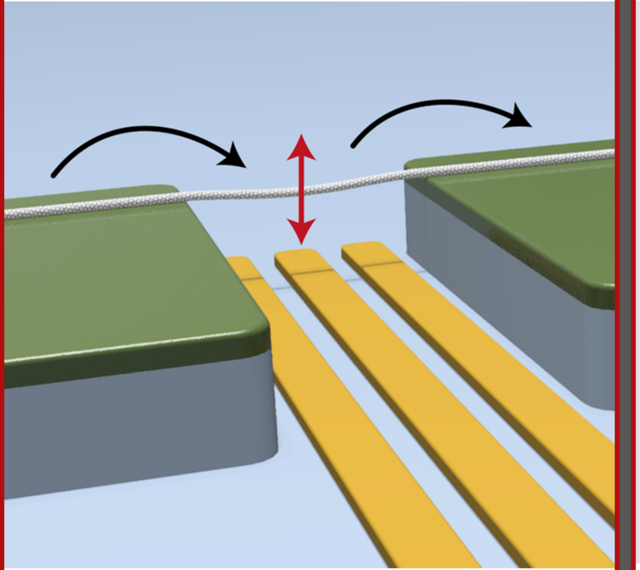
Relic topological defects
from brane annihilation
simulated in superfluid ^{3}He
Nat. Phys. 4, 46 (2008)



Edward Laird
Quantum electronic sensors

Physics | Lancaster University

Sensing force and motion

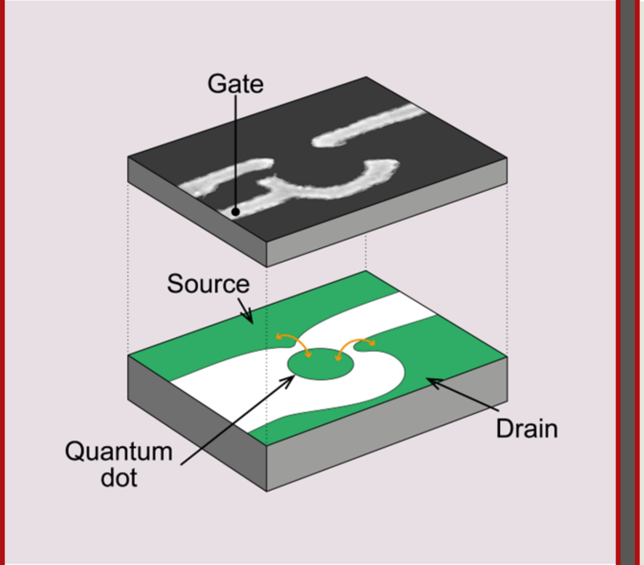


"A coherent nanomechanical oscillator driven by single-electron tunnelling"

Wen et al.

Nature Physics (2020)

Sensing qubits

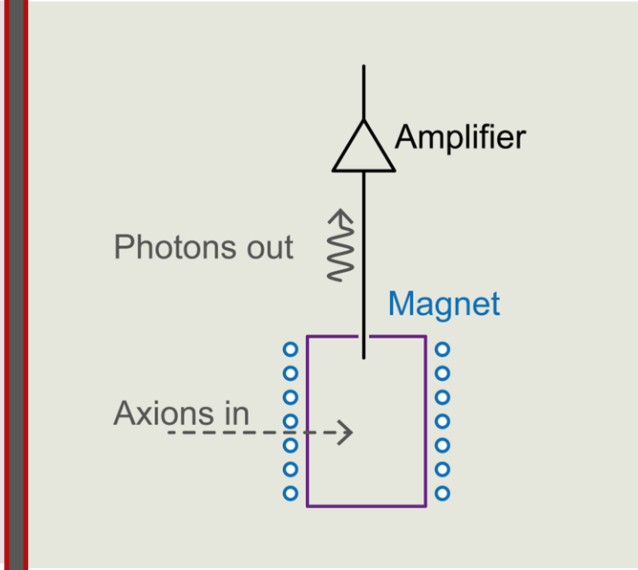


"Sensitive radio-frequency readout of quantum dots using an ultra-low-noise SQUID amplifier"

Schupp et al.

Journal of Applied Physics (2020)

Sensing dark matter



"Searching for wave-like dark matter with QSHS"

Bailey et al.

SciPost Physics Proceedings (2023)

Pietro Giampa – Science & Technology TRIUMF / McDonald Institute

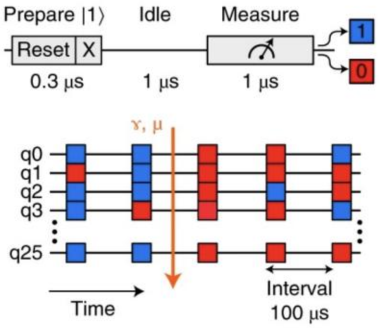
15-Jan-2024

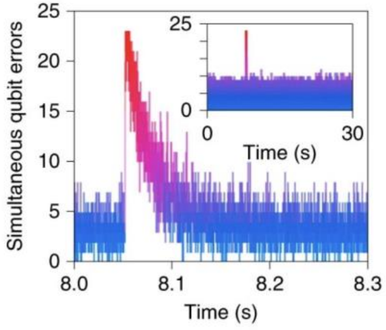
Beyond The Standard Model Research

Strong Emphasis on Dark Matter Detection

Research Targets:

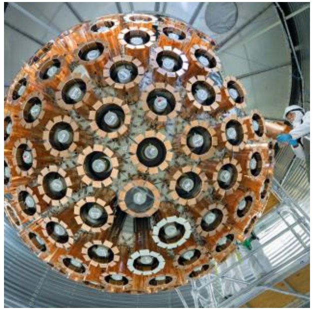
- Dark Matter searches for ultra-low masses, which require detectors with sensitivity in the meV-eV energy deposition range.
- Photo-detection techniques with sub-ns timing.

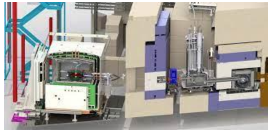


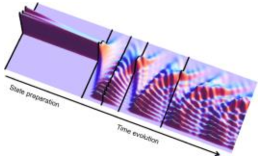


Historic Research:

- In the past I mostly focused on Liquid Nobles and Silicon based detectors for Dark Matter detections.
- DEAP-3600, SBC, LoLX, SiPM R&D
- Also involved in precision physics with Ultracold Neutrons (UCNs). Neutron Lifetime & Quantum Gravity.







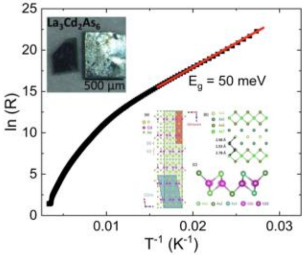
Caleb Fink – Los Alamos National Laboratory, NM

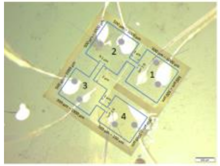
cwfink@lanl.gov

Novel Quantum Materials and Qubit Sensors for Low Mass Dark Matter

- Detector physicist focusing on developing meV scale sensitive charge and phonon sensors using novel materials and superconducting qubits
- Collaborative effort between LANL, SLAC, and UIUC
- Formerly part of SuperCDMS and Tesseract

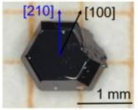
Quantum Materials for Low Mass Dark Matter Detection

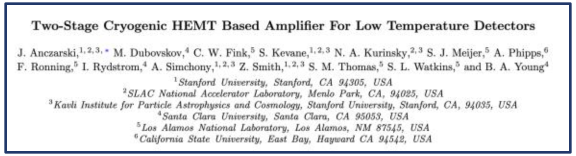




$Eu_5In_2Sb_6$

EuZ_2P_2



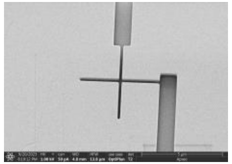


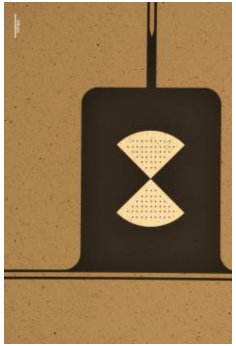
Two-Stage Cryogenic HEMT Based Amplifier For Low Temperature Detectors

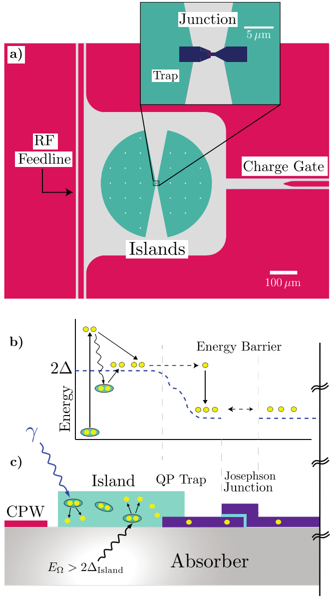
J. Anczarski,[1,2,3,*] M. Dubovskov,[4] C. W. Fink,[5] S. Kevane,[1,2,3] N. A. Kurinsky,[2,3] S. J. Meijer,[5] A. Phipps,[6] F. Ronning,[5] I. Rydstrom,[4] A. Simchony,[1,2,3] Z. Smith,[1,2,3] S. M. Thomas,[5] S. L. Watkins,[5] and B. A. Young[4]

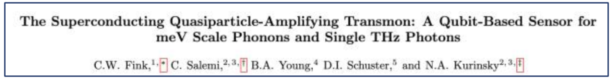
[1] *Stanford University, Stanford, CA 94305, USA*
[2] *SLAC National Accelerator Laboratory, Menlo Park, CA, 94025, USA*
[3] *Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA, 94035, USA*
[4] *Santa Clara University, Santa Clara, CA 95053, USA*
[5] *Los Alamos National Laboratory, Los Alamos, NM 87545, USA*
[6] *California State University, East Bay, Hayward CA 94542, USA*

Qubit Based Sensors for meV Scale Phonon Sensing









The Superconducting Quasiparticle-Amplifying Transmon: A Qubit-Based Sensor for meV Scale Phonons and Single THz Photons

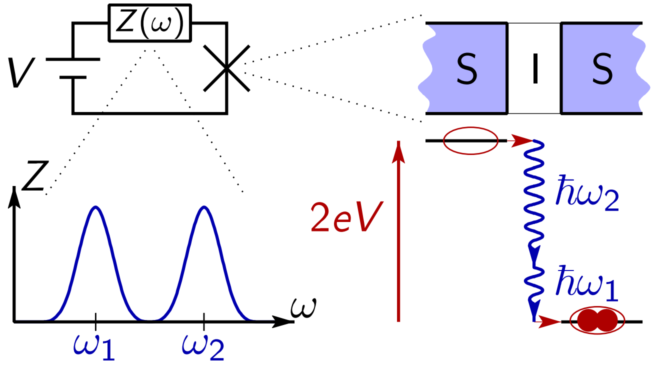
C.W. Fink,[1,*] C. Salemi,[2,3,†] B.A. Young,[4] D.I. Schuster,[5] and N.A. Kurinsky[2,3,‡]

Caleb Fink – cwfink@lanl.gov

Max Hofheinz – Institut quantique, Université de Sherbrooke

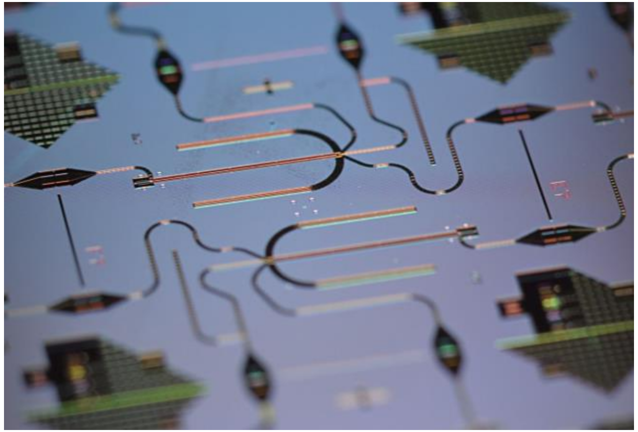
max.hofheinz@usherbrooke.ca

Josephson photonics



Devices

- Amplifiers
- Photon counters
- Photon sources
- ...



Working principle

- Based on inelastic Cooper-pair tunneling
- Matrix element depends on $Z(\omega)$
- $Z(\omega)$ can be engineered at will
- Operation kT to gap: µeV (GHz) to meV (THz)

Related activities at IQ

- Impact of ionizing radiation on superconducting qubits: Mathieu Juan, Alexandre Blais
  - Single-photon avalanche detectors: Serge Charlebois, Jean-François Pratte

Max Hofheinz
max.hofheinz@usherbrooke.ca

Michel Calame – Empa & University of Basel

Transport at Nanoscale Interfaces Laboratory, Empa, Switzerland
Department of Physics, University of Basel, CH, Switzerland
www.empa.ch/tnilab
michel.calame@empa.ch

Transport at Nanoscale Interfaces Lab

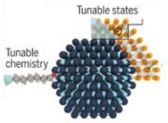
Materials to Devices

Transport & Devices

Nanofabrication, quantum transport,
(opto-)electronic, thermoelectric properties

Low dimensional materials Integration

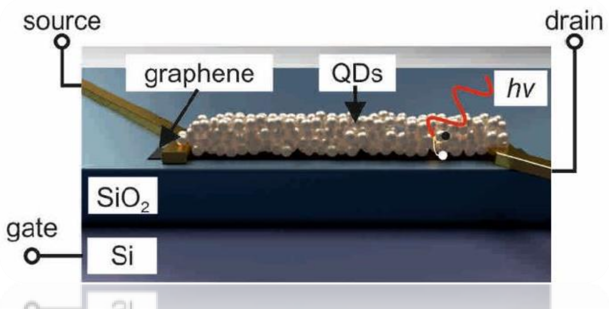
Synthetic Quantum Dots



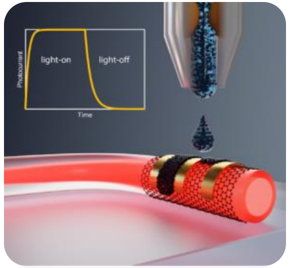
de Arquer *et al.* Science (2021)

IR Photodetectors
Nanoprinted colloidal QDots
Integration in miniaturized Spectrometer
Integration on optical fibers

I. Shorubalko *et al.*



Shorubalko *et al.,* : Adv. Optical Mater. (2019); Adv. Science (2021); ACS Appl. Mater. Interfaces (2021), Nat. Photonics (2022, 2023);



Kara *et al.,* Adv. Mater. Technol. (2023)

Transport at Nanoscale Interfaces Lab

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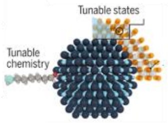
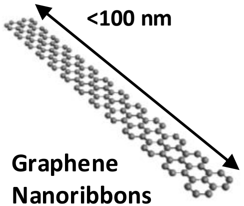


Synthetic Quantum Dots

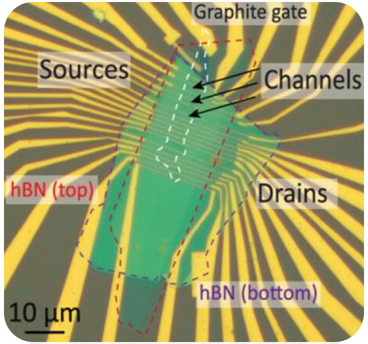
de Arquer *et al.* Science (2021)



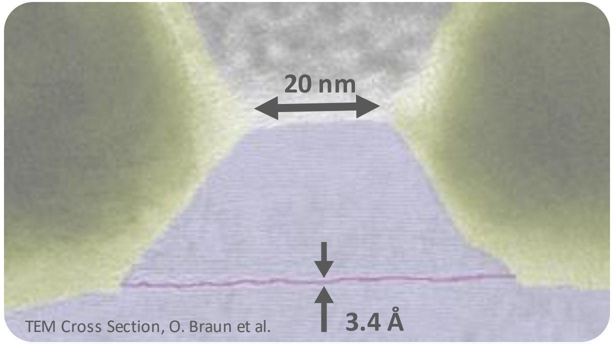
Graphene Nanoribbons

Nanocarbons (GNRs, CNTs) integration
QDot physics and mesoscopic transport
Edge contacts to GNRs
Encapsulation in hBN

M. Perrin *et al.*



Huang et al., ACS Nano (2023)



TEM Cross Section, O. Braun et al.

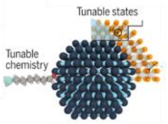
Transport at Nanoscale Interfaces Lab

Materials to Devices

Transport & Devices

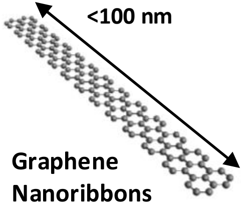
Nanofabrication, quantum transport,
(opto-)electronic, thermoelectric properties

Low dimensional materials
Integration

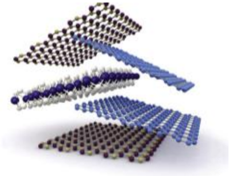


**Synthetic
Quantum Dots**

de Arquer *et al.* Science (2021)



**Graphene
Nanoribbons**



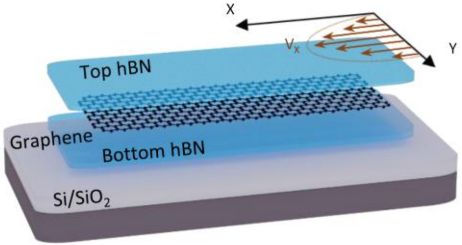
Novoselov *et al.* Science (2016)

2D Materials

2D materials integration
Mesoscopic transport
Hydrodynamic regime, Strong e-e correlations
Moiré structures

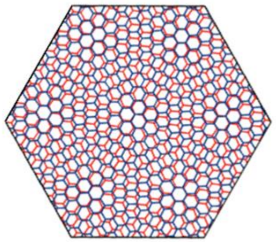
M. Perrin *et al.*

Graphene: Viscous charge flow



Huang et al., Phys Rev. Res (2023)

**Twisted
n-layer graphene**



Zhang et al., under review

Transport at Nanoscale Interfaces Lab

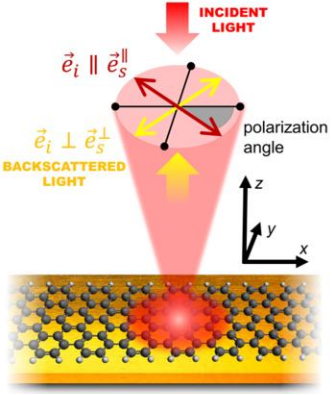
Materials to Devices

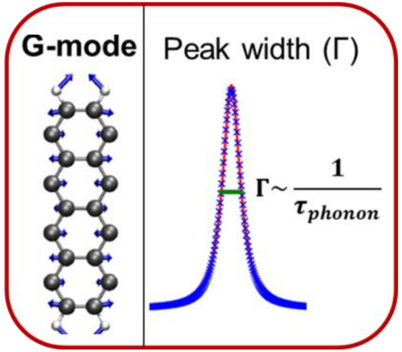
Imaging & Spectroscopy

Structural & Chemical (Optical, Raman & THz, Atomic Force Microscopy, Electron and Ion-beam)

Raman Spectroscopy, Photoluminescence, THz-TDS & Imaging

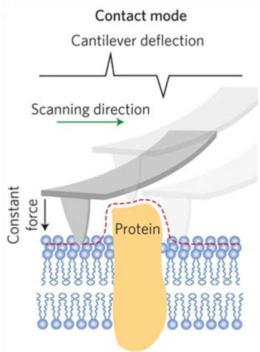
M. Dimitirievska *et al.*

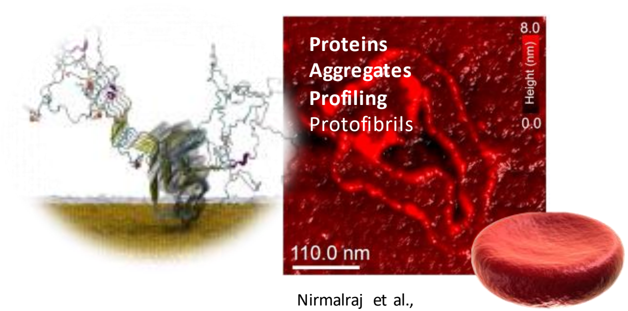




Liquid-based Atomic Force Microscopy (AFM), Infrared (IR)-AFM, Raman Spectroscopy

P. Nirmalraj *et al.*





Nirmalraj et al., Science Advances (2021)

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Jan Mol – Queen Mary University of London

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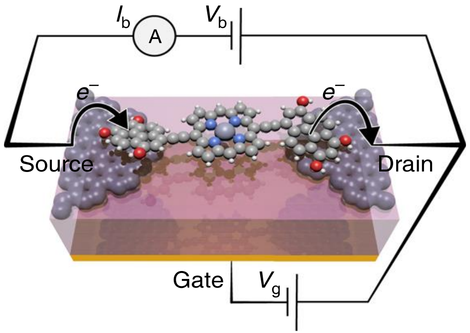
Measuring quantum *transport*

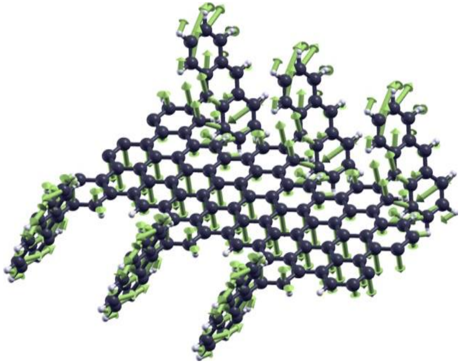


Understanding resonant charge transport through weakly coupled single-molecule junctions.

Thomas *et al.*

Nat. Commun. **10**, 4628 (2019)

Measuring quantum *motion*

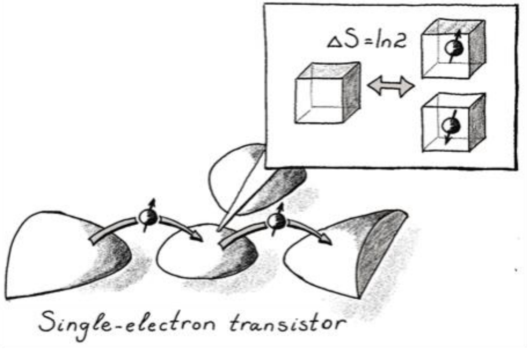


Exceptionally clean single-electron transistors from solutions of molecular graphene nanoribbons.

Niu *et al.*

Nat. Mater. **22**, 180–185 (2023)

Measuring quantum *entropy*



Electronic measurements of entropy in meso- and nanoscale systems.

Pyurbeeva *et al.*

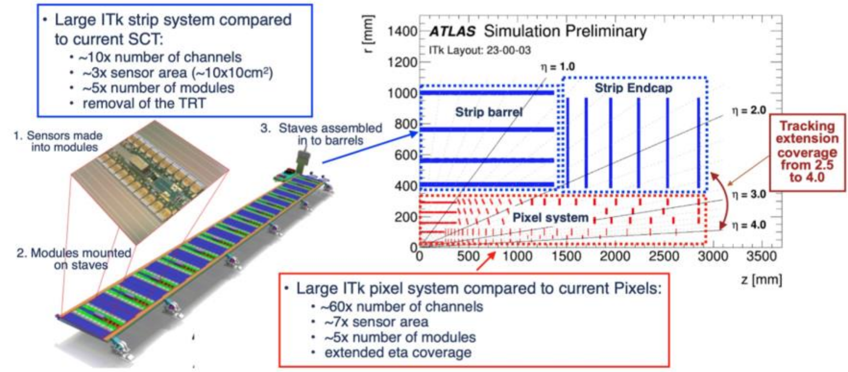
Chem. Phys. Rev. **3**, 041308 (2022)

Adrian Bevan – Queen Mary University of London

a.j.bevan@qmul.ac.uk

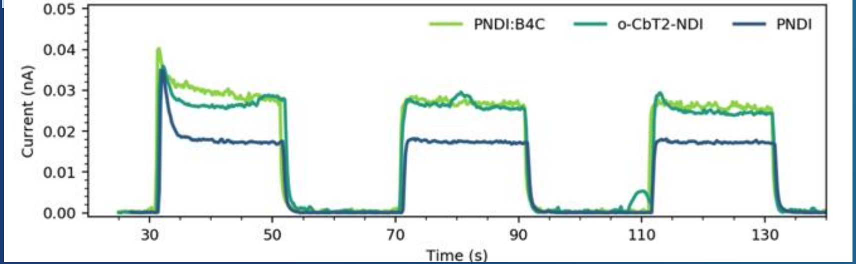
Developing new technologies and building new detectors for fundamental science applications

e.g. ATLAS tracker upgrade systems for the High Luminosity Large Hadron Collider at CERN.


- Large ITk strip system compared to current SCT:
  - ~10x number of channels
  - ~3x sensor area (~10x10cm²)
  - ~5x number of modules
  - removal of the TRT

- Large ITk pixel system compared to current Pixels:
  - ~60x number of channels
  - ~7x sensor area
  - ~5x number of modules
  - extended eta coverage

e.g. Organic semiconductor radiation detectors targeting fast and thermal neutron detection.

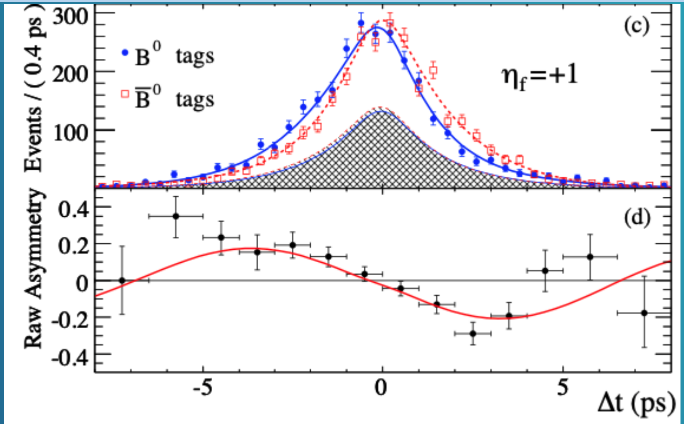


Focus on:

- Silicon detectors
- Diamond detectors
- Novel detectors: solution processed systems including π-conjugated organic semiconductors

Searching for new phenomena and testing fundamental symmetries: CP, T, CPT tests, rare decay searches. (see more on Thursday)

Lots of experience in using entangled pairs of sub-atomic particles to test fundamental physics



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https://mcdonaldinstitute.ca/miriam-diamond/

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Direct detection of Beyond the Standard Model low-mass dark matter candidates

SuperCDMS detectors

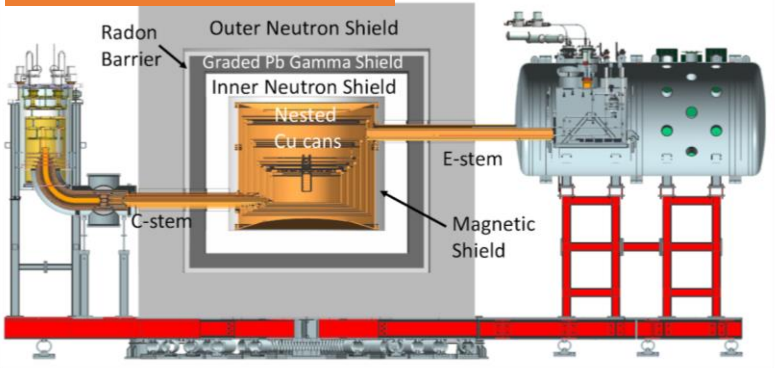
- Phonon and ionization channels
- Operation at <50 mK
- Readout with superconducting cables
- Thresholds as low as 10 eV

UToronto group:

- R&D devices at local lab
- Detector characterization at CUTE@SNOLAB
- Installing & commissioning of full SuperCDMS@SNOLAB experiment

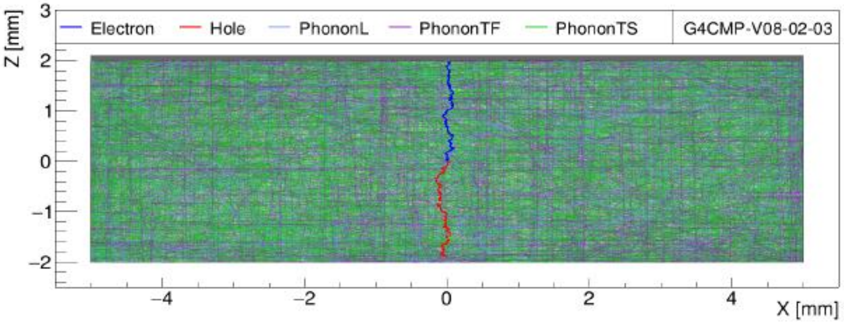
UToronto lab

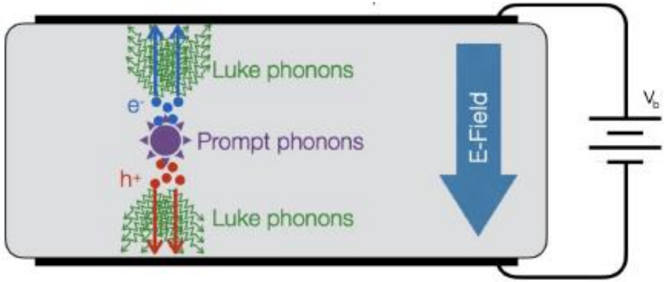
SuperCDMS SNOLAB

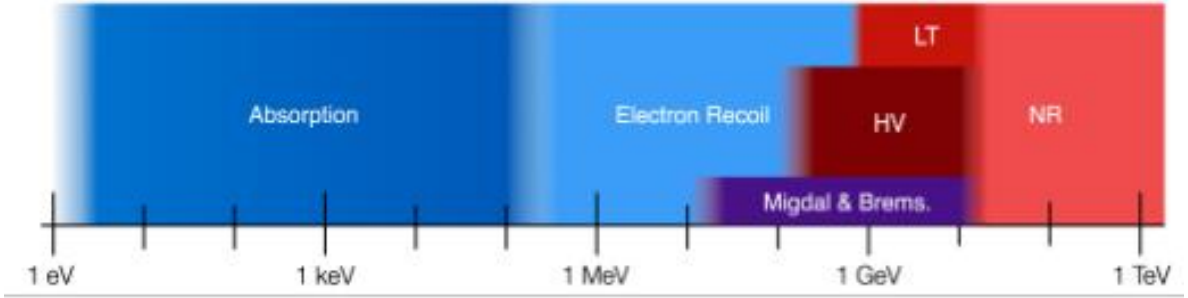


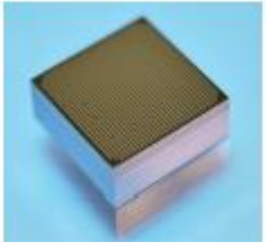
- "Super sensitive detectors require super precise modeling"
    - Phonon and charge propagation in cryogenic semiconductor crystals
    - Nuclear recoil, electron recoil, and dark absorption signals and low-energy backgrounds

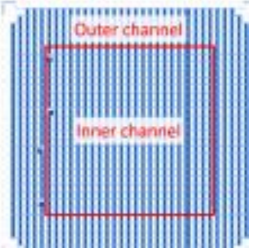
- "HVeV" gram-scale prototype devices feature single electron-hole pair sensitivity
- World-leading constraints on wide range of sub-GeV DM candidates
    - Axions, dark photons, lightly-ionizing particles, …











GUINEAPIG workshop co-organizer

GeV and Under Invisibles with New Experimental Assays for Particles in the Ground

V2 (summer 2023): https://indico.triumf.ca/event/348/overview V3 (summer 2024): coming to Toronto!

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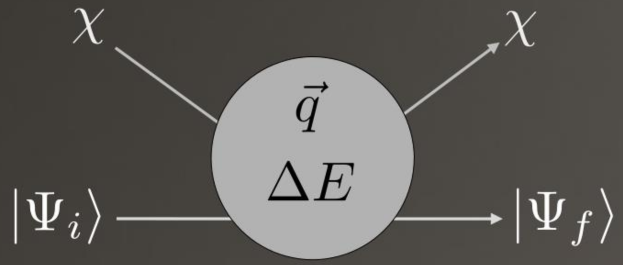
NASA

SPACE
TELESCOPE
SCIENCE
INSTITUTE

Oskar Klein
centre

Stockholm
University

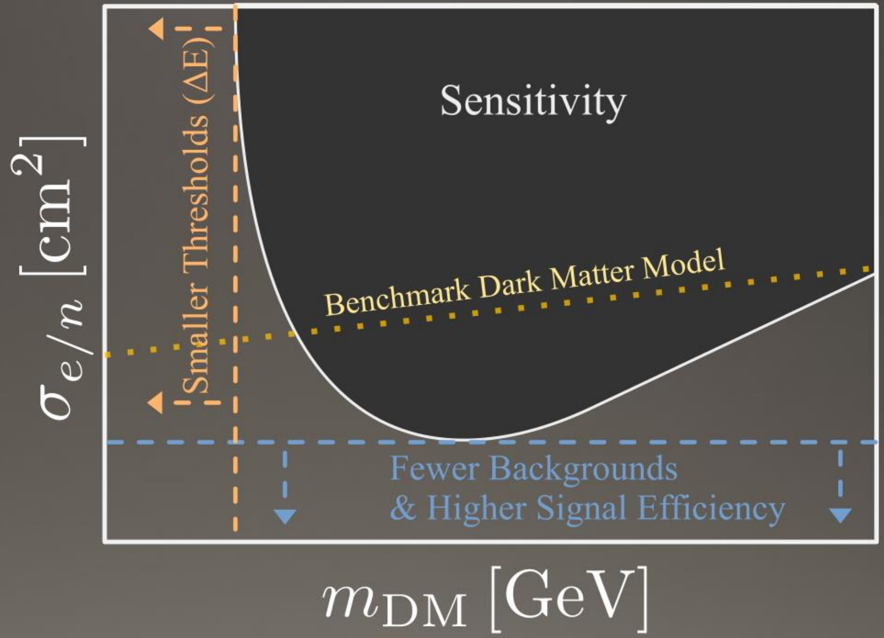
Direct detection



Novel Target Materials:

Molecular Crystals:
(Directionality → daily modulation)

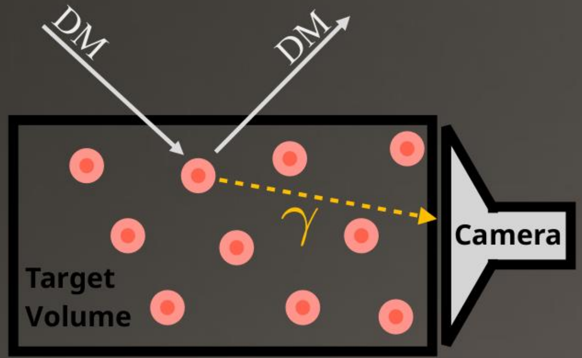
Nanomaterials:
(Confinement → tunable salient signals)



Direct Detection: New Materials & Methods

Drawing from *quantum chemistry* & *material science* to develop theoretical methods that describe the interactions between target and dark matter

Recoil-induced *fluorescense* (radiative deexcitation)



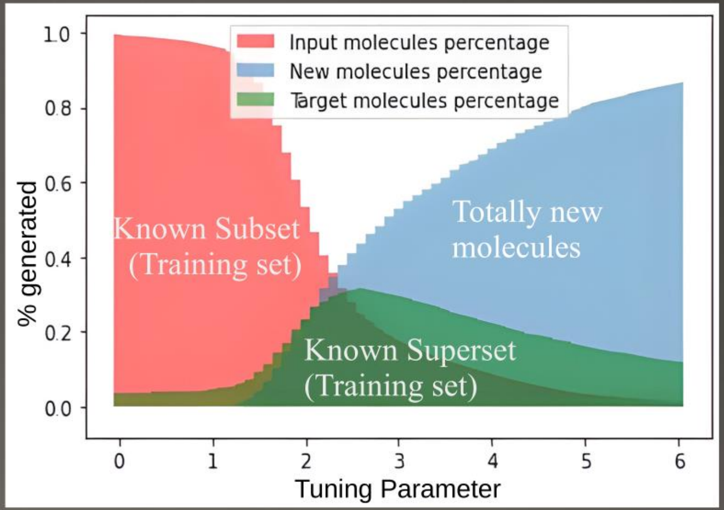
● :unit that de-excites by emitting a photon

Could be:

- Nanostructures (quantum dots)
- Molecules in ordered crystal
- Hybrid material (QDs in Molecular matrix)

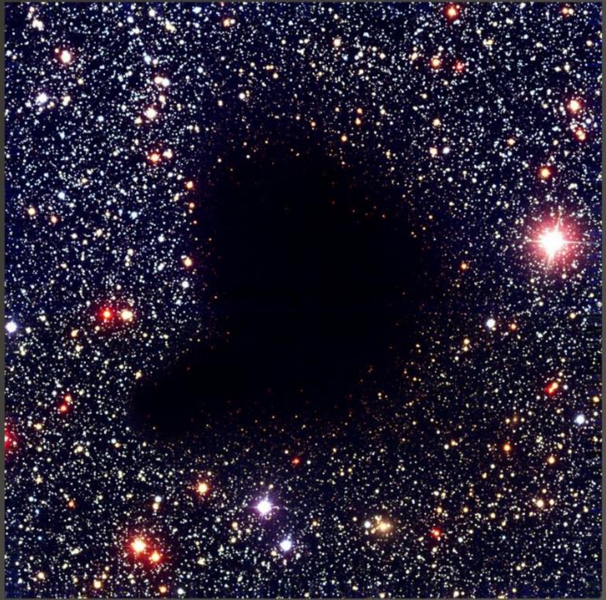
Proof of principle: First search for dark matter with organic scintillator (‘19)

ML to explore vast data of material space



Generative ML models will identify novel materials that maximize signals

Beyond direct detection



Cold molecular cloud

We can use the same theoretical techniques that I've developed to predict rates in detectors to predict rates in *astrophysical* objects

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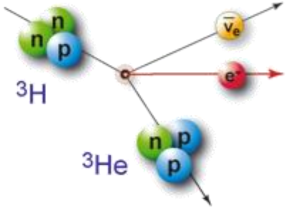
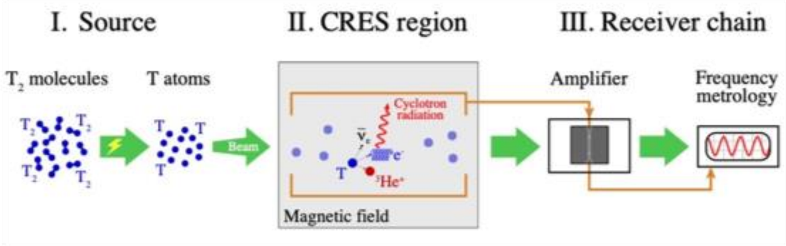
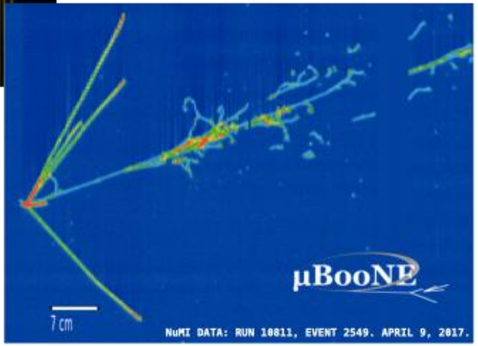
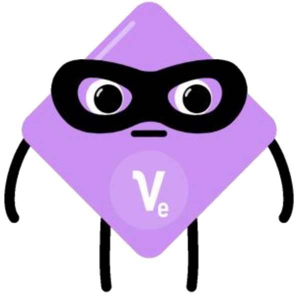


- Neutrino physicist and detector physicist
- Liquid argon neutrino detectors
- Neutrino mass measurement using quantum technology





QTNM
Quantum Technologies for Neutrino Mass



SHORT-BASELINE
SBND
NEAR DETECTOR

Adrian Lupascu

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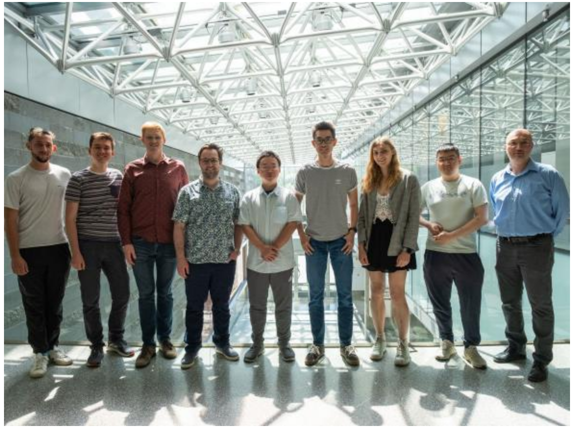


DRDC
RDDC
Canada

NSERC
CRSNG

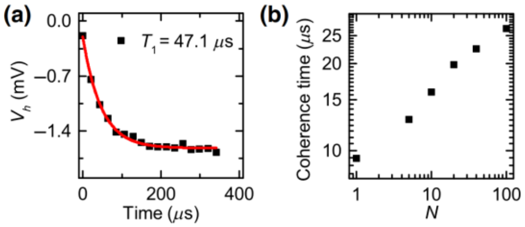
U.S. DEPARTMENT OF
ENERGY

IQC Institute for Quantum Computing

Quantum computing

Improving coherence of qubits

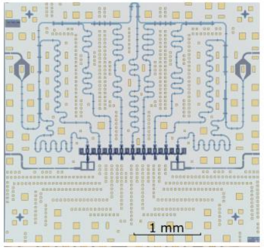
- Noise spectroscopy
- Improved materials – niobium (collaboration with Fermilab, Jefferson lab)

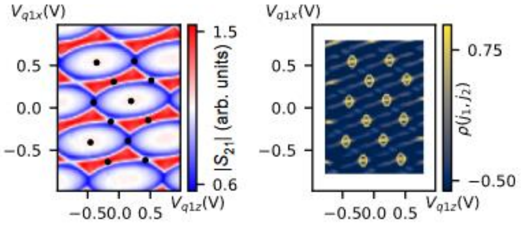


Yurtalan, M. A., J. Shi, G. J. K. Flatt, and A. Lupascu. Physical Review Applied 16, 054051 (2020).

Design of quantum processors

- Calibration and connectivity in coherent quantum annealers (DARPA collaboration)

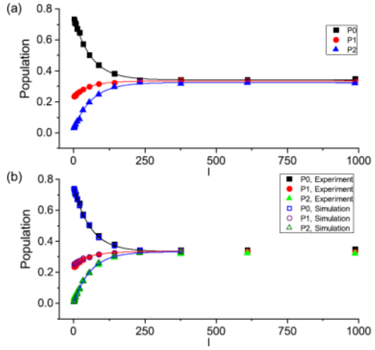




Dai et al., PRX Quantum 2, 040313 (2021).
Tennant *et al.*, acc. to npj Quantum Information (2022).

Qutrits

- quantum control (collaboration with Juelich, Sahel Ashhabe NICT)
- process characterization

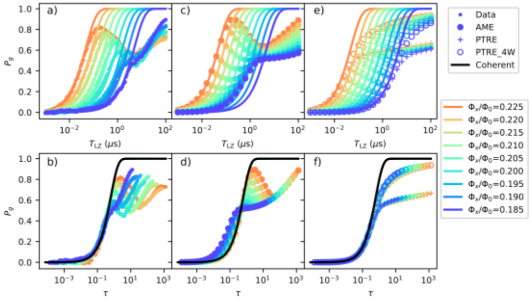


M. A. Yurtalan, J. Shi, M. Kononenko, A. L., S. Ashhab, Phys. Rev. Lett. **125**, 180504 (2020)
M. Kononenko, M. A. Yurtalan, S. Ren, J. Shi, S. Ashhab, A. L., Phys. Rev. Research **3**, L042007 (2021)

Fundamental topics in quantum dynamics

Unconventional environments

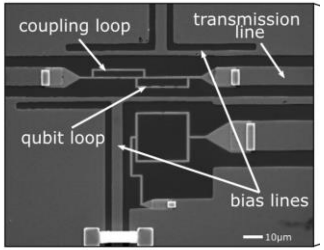
- **The weak to strong coupling crossover in Landau Zener tunneling (DARPA collaboration)**
- **The spin boson model with tunable coupling strength**

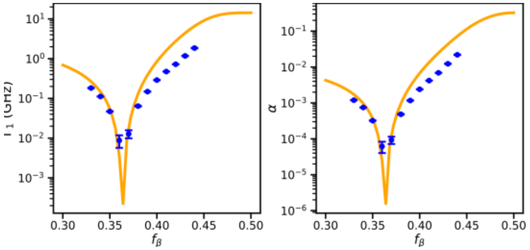


Dai et al., arXiv:2207.02017 (2022).

Relativistic quantum information

- **Entanglement harvesting (collaboration with Eduardo Martin Martinez at UW)**

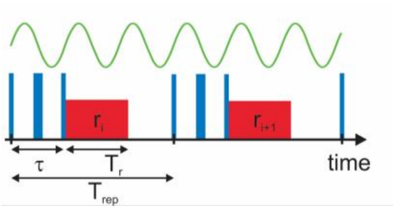


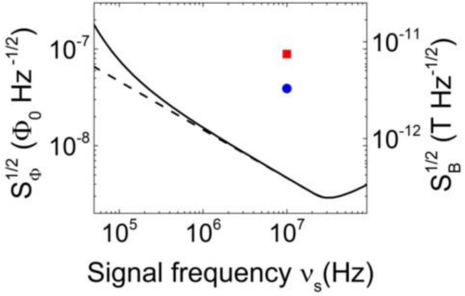


Janzen et al., Phys. Rev. Res. 5, 033155 (2023).

Quantum sensing

Artificial atom magnetometers

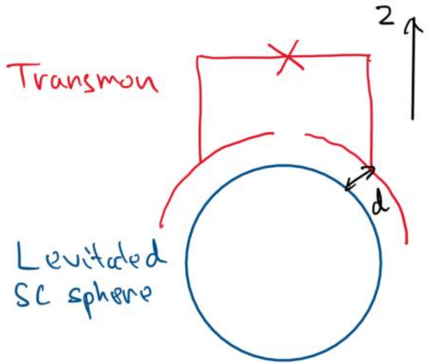




Bal et al., Nature Communications (2012).

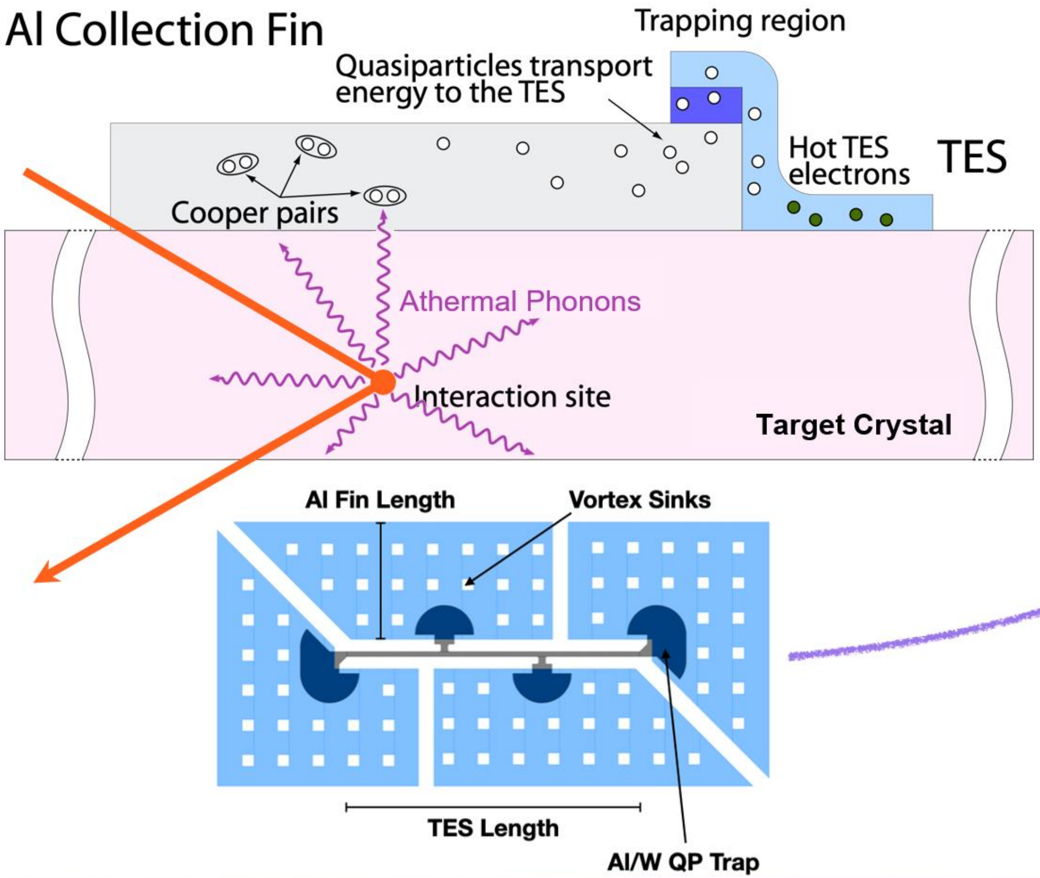
Quantum levitation

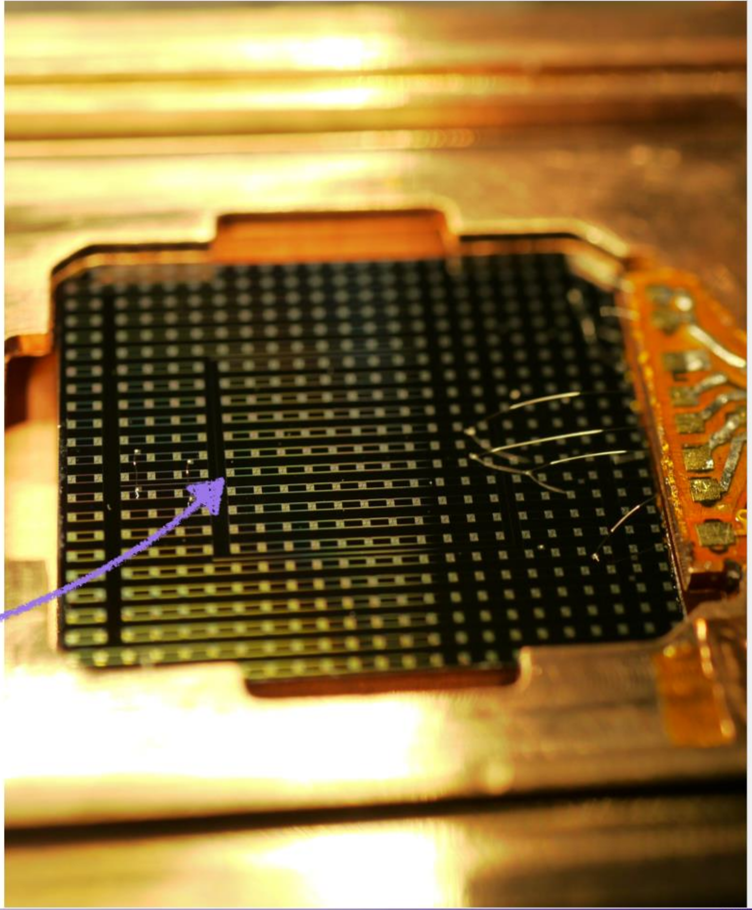
- **Hybrid systems formed of diamagnetically levitated spheres and superconducting qubits**
- **Applications in gravimetry, dark matter detection**



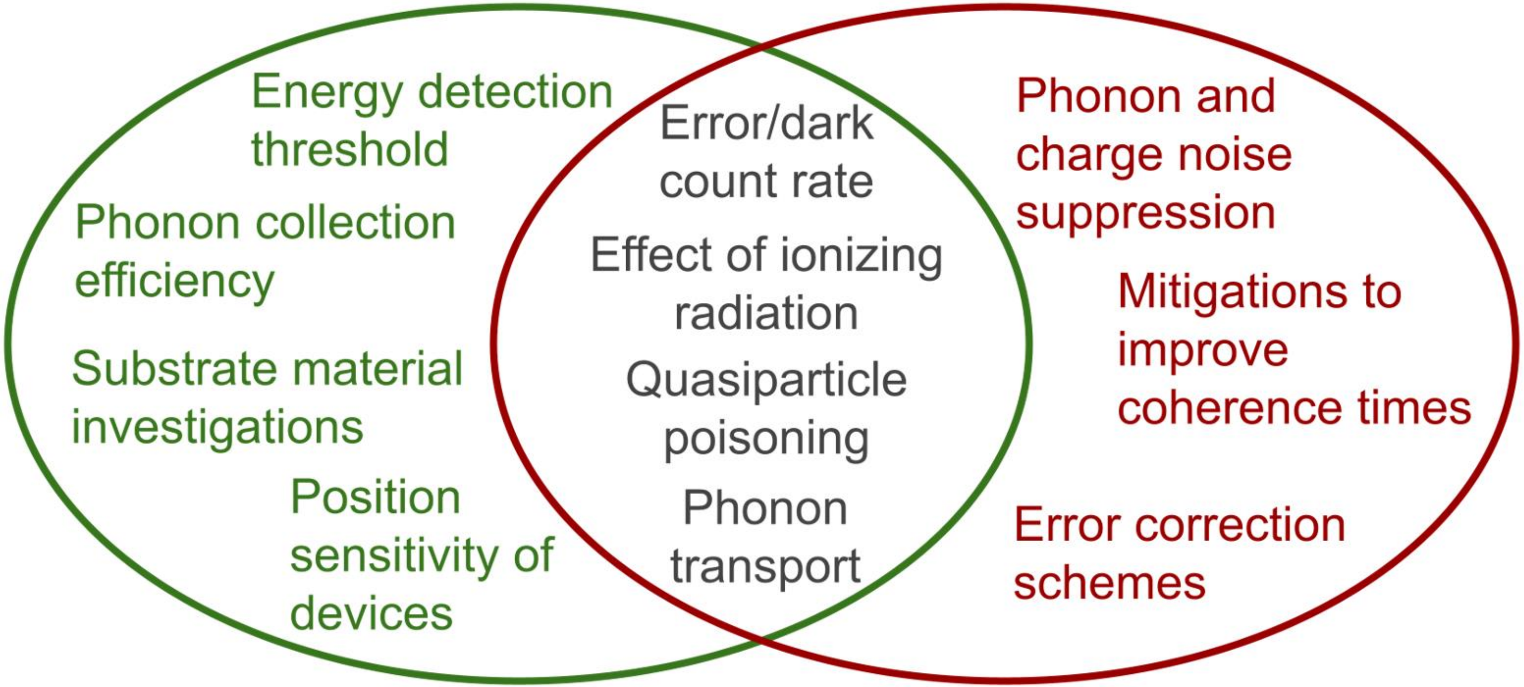
Transition-Edge Sensors vs. Superconducting Qubits for Particle Detection

Enectali Figueroa-Feliciano \ Northwestern





Transition-Edge Sensors vs. Superconducting Qubits for Particle Detection



SC Qubits for Dark Matter

- Energy detection threshold
- Phonon collection efficiency
- Substrate material investigations
- Position sensitivity of devices

SC Qubits for Dark Matter and SC Qubits for Quantum Computing

- Error/dark count rate
- Effect of ionizing radiation
- Quasiparticle poisoning
- Phonon transport

SC Qubits for Quantum Computing

- Phonon and charge noise suppression
- Mitigations to improve coherence times
- Error correction schemes