# Quantum Devices for Dark Matter Studies


Prof. Adrian Bevan
a.j.bevan@qmul.ac.uk

Queen Mary University of London


Also see recent workshops and conferences including:
- QMUL-SNOLab workshop: https://indico.cern.ch/event/1345184/overview (SNOLab)
- Pisa Meeting on Advanced Detectors: https://agenda.infn.it/event/37033/overview (Elba)
- Identification of Dark Matter: https://agenda.infn.it/event/39713/overview (L'Aquila)
- GUINEAPIG 2024: https://indico.triumf.ca/event/521/timetable/#20240820 (Toronto)

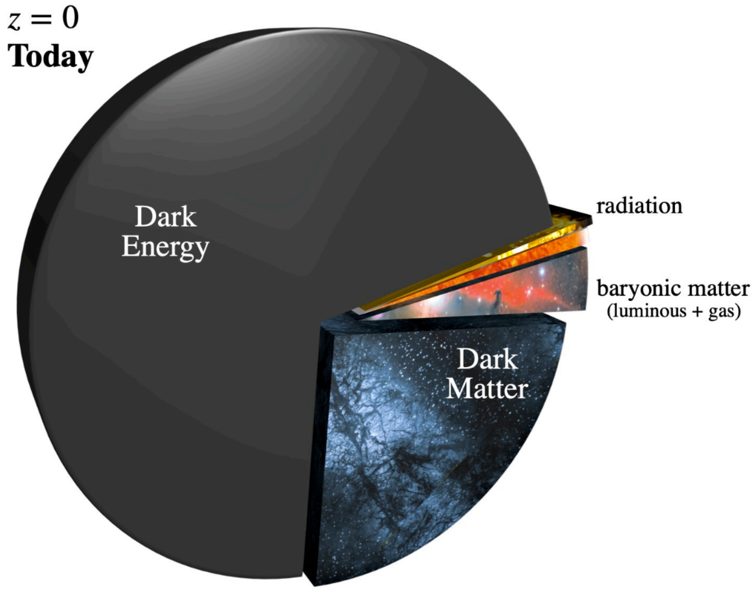
# Overview

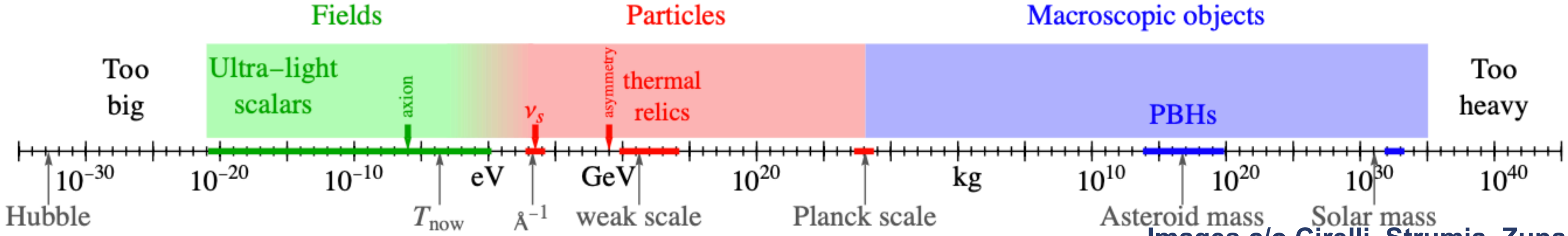
- Motivation
- Substrates
- Technologies
  - Transition Edge Sensors (TES)
  - Kinetic Induction Detectors (KIDs)
  - Coulomb Blockade Thermometers (CBTs)
  - Superconducting nanowire single photon detectors (SNSPDs)
  - Nanotube resonators
- Requirements
- Summary

# Motivation

# What is the nature of dark matter?

- We still don't have an answer to this question after almost 100 years.
- Is it a particle ?
  - If so what: WIMP, Axion, something else?
- Is it an astrophysical dark object?
  - Primordial Black Hole, domain wall, … ?
- Is it a combination of things?
  - 5% of the energy of the universe is visible
  - About 23% is dark matter
- We have plenty of candidates that could contribute to the solution



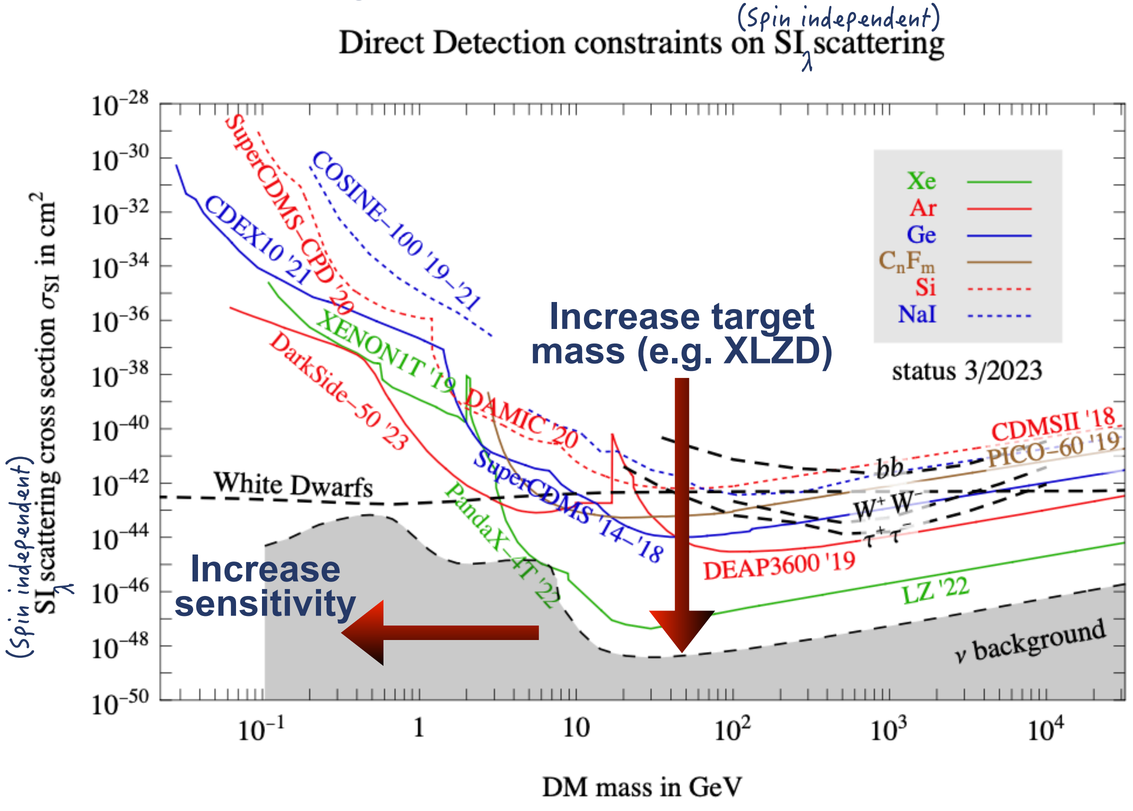



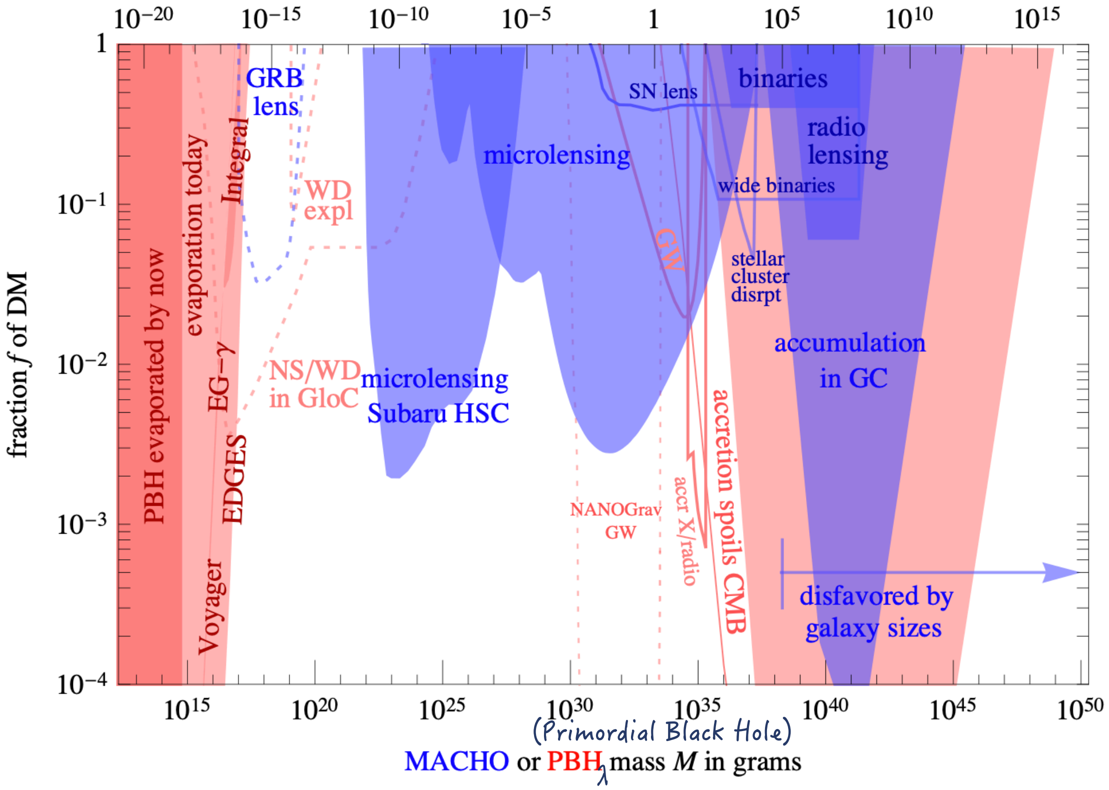

Images c/o Cirelli, Strumia, Zupan, arXiv:2406.01705

ORCID-0000-0002-4105-9629

# Existing constraints on dark matter

- **Model dependent direct search constraints for particle and astrophysical DM rule out much of model parameter space**



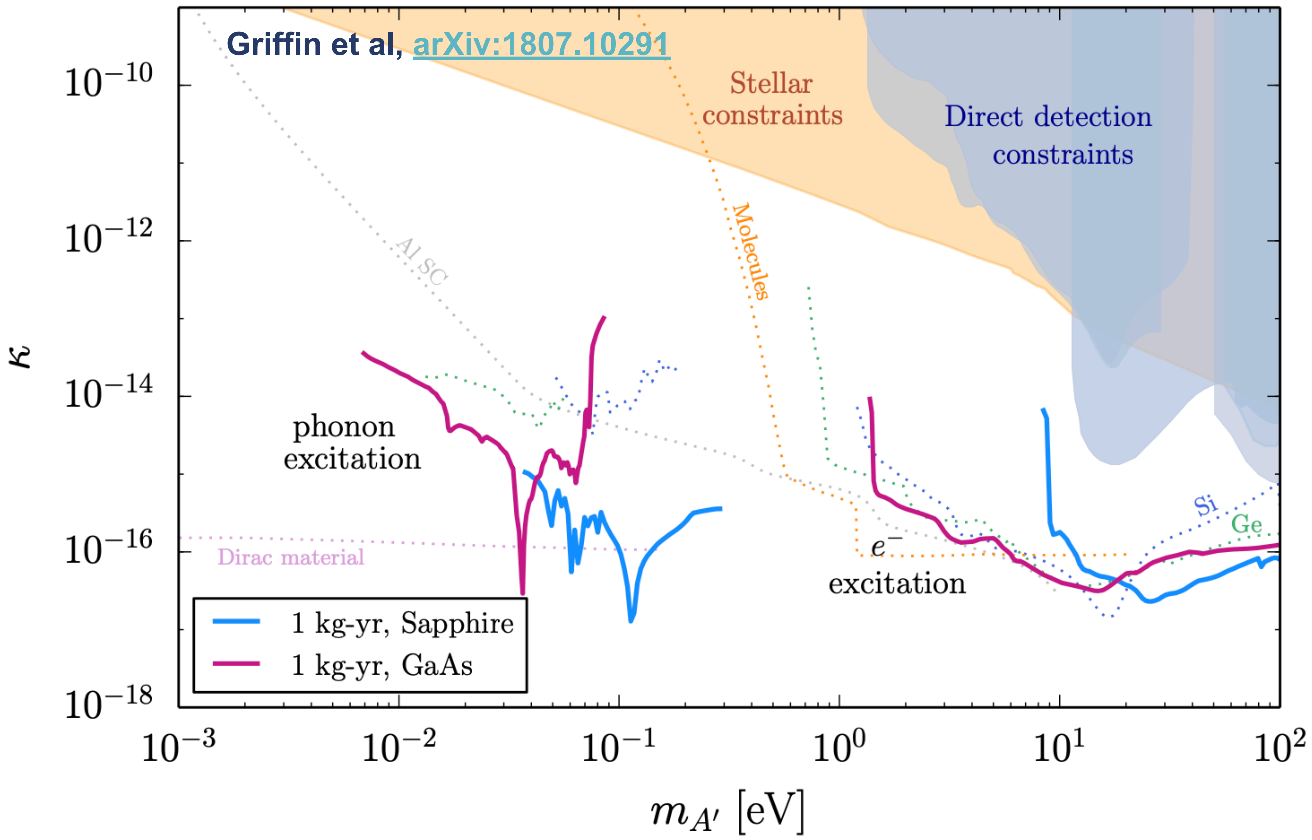




Cirelli, Strumia, Zupan, arXiv:2406.01705

ORCID-0000-0002-4105-9629

# Existing constraints on dark matter

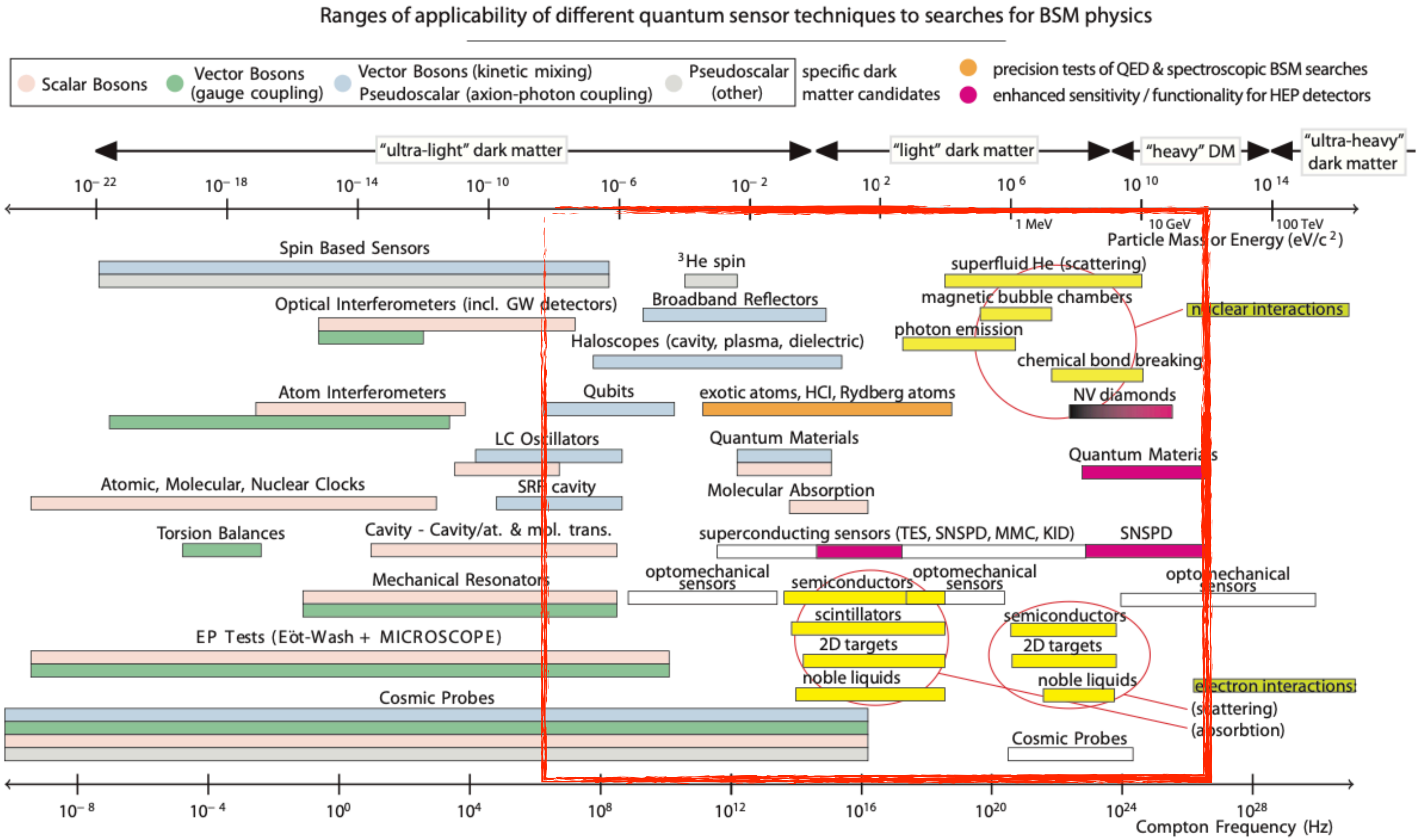
- **Model dependent direct search constraints for particle and astrophysical DM rule out much of model parameter space**




- **Dark photon sensitivity to different crystals cover the ~0.01 eV to 100's eV range**
- **Complements large direct detection experiments**
- **Huge amount of interest and growing activity in this area**
- **Quantum tech enables this paradigm shift**
- **Plot assumes 25meV sensitivity - a challenge for current technologies**

ORCID-0000-0002-4105-9629

# Sensitive to (ultra)dark matter




https://arxiv.org/pdf/2305.11518

ORCID-0000-0002-4105-9629

Adrian Bevan

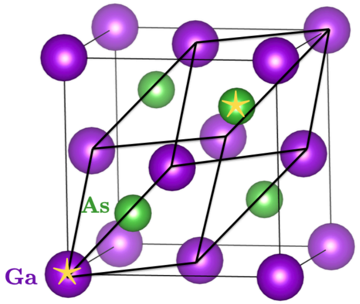
# Substrates

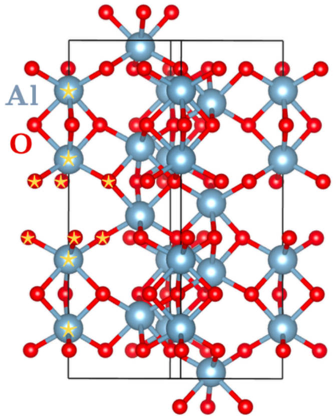
ORCID-0000-0002-4105-9629

Adrian Bevan

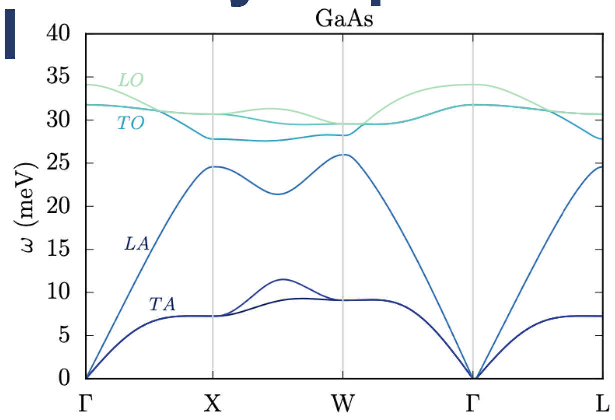
# Substrates

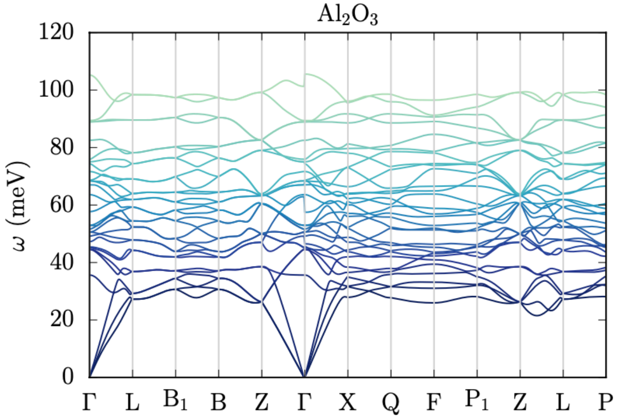
- Various crystal lattices are proposed: Si, GaAs, Sapphire ($Al_2O_3$)




- Energy sensitivity depends on the band structure ion the crystal




- Isotropic crystals are blind to dark matter direction

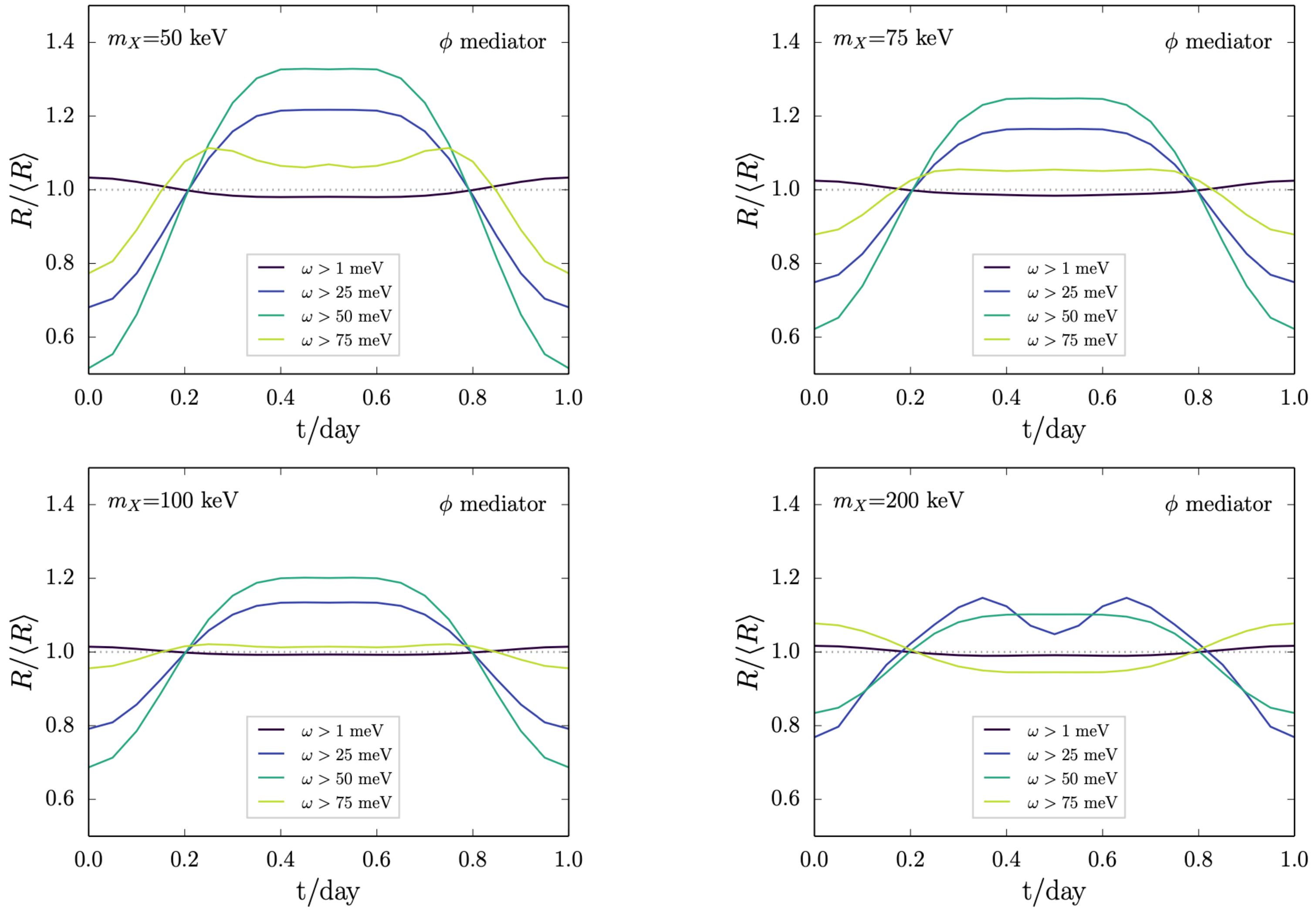
- Anisotropic crystals like sapphire, are directionally dependent
  - Directional detection is highly desirable for many reasons including background rejection

Griffin et al, arXiv:1807.10291

ORCID-0000-0002-4105-9629
Adrian Bevan

# Substrates

- **Anisotropic signal detection could enable directional dark matter detection**
- **Would allow to probe into the neutrino fog, scaling better than $\sqrt{t}$**
- **Daily modulation of any dark matter signal has mass sensitivity**




Griffin et al, arXiv:1807.10291

ORCID-0000-0002-4105-9629

# Transition Edge Sensors (TES)

ORCID-0000-0002-4105-9629

# TES

- Use the temperature dependent resistance of a superconducting material to sense the passage of radiation

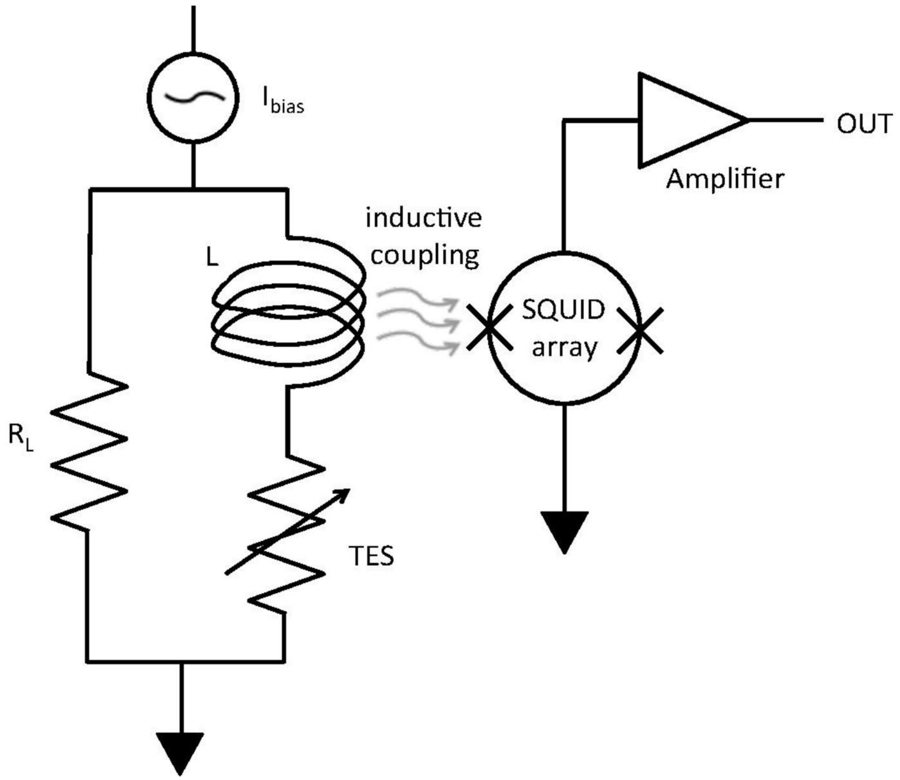


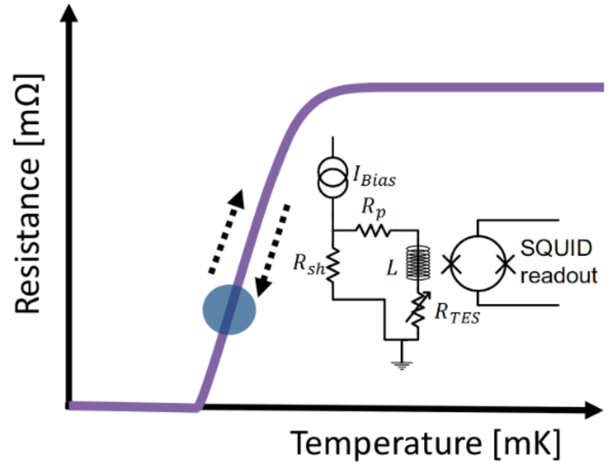

Image: Wikipedia (Creative Commons License)

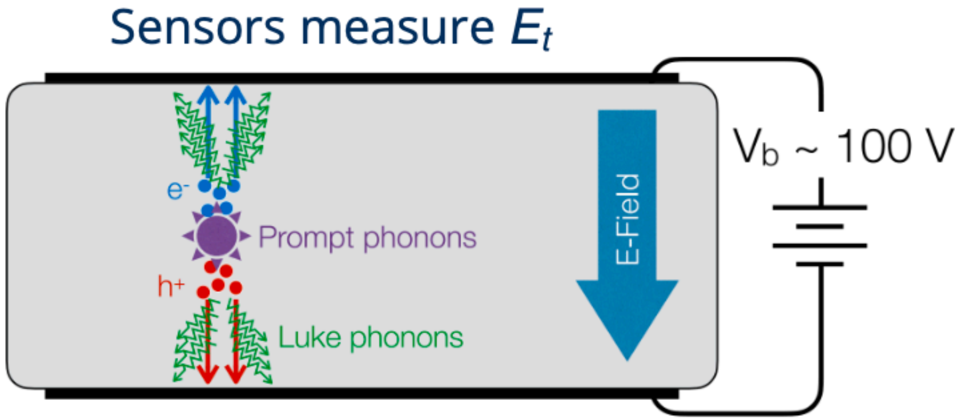
- Under normal conditions power dissipated is constant
- Interaction with dark matter adds energy that changes the power
- TES resistance increases, current drops
- e.g. Use inductor to couple TES to a squid array to sense change in current & read out / amplify signal

ORCID-0000-0002-4105-9629

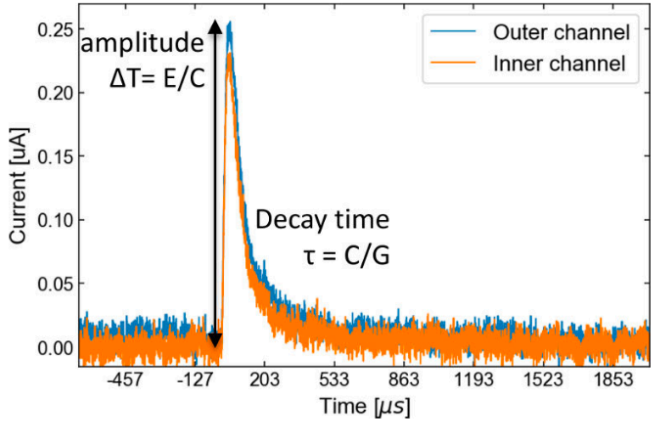
# Example: SuperCDMS

- **Experiment at SNOLab based on TES Technology (Si/Ge crystals)**

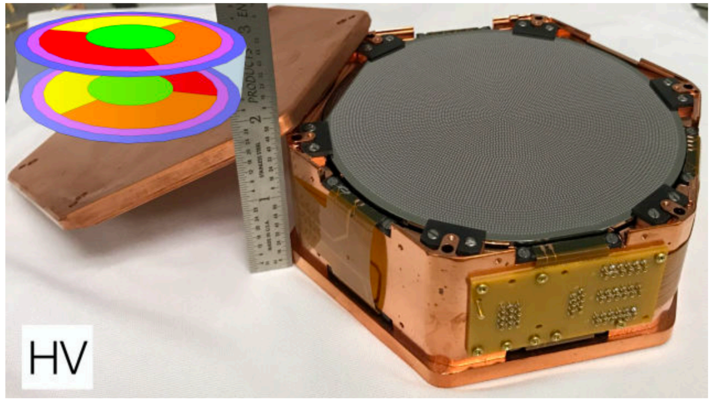



Zatschler, GUINEAPIG 2024



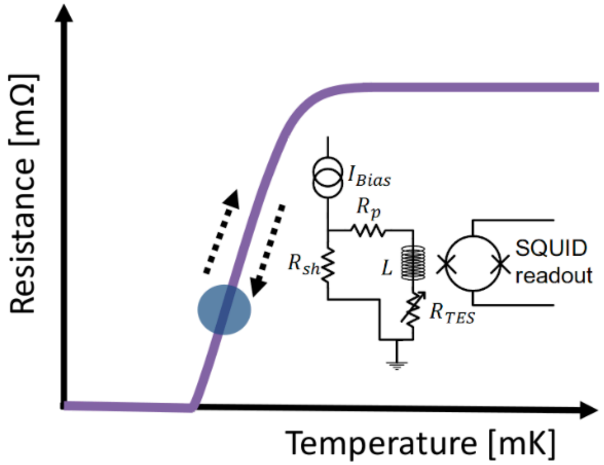

- **10 - 15 mK athermal phonon sensors**
- **Detect Luke phonons in the TES**
- **Amplify and process signals to extract energy**

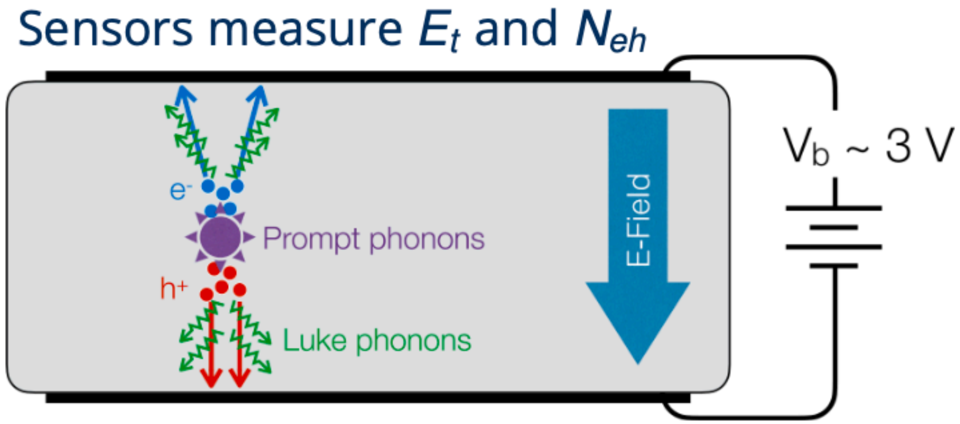



ORCID-0000-0002-4105-9629

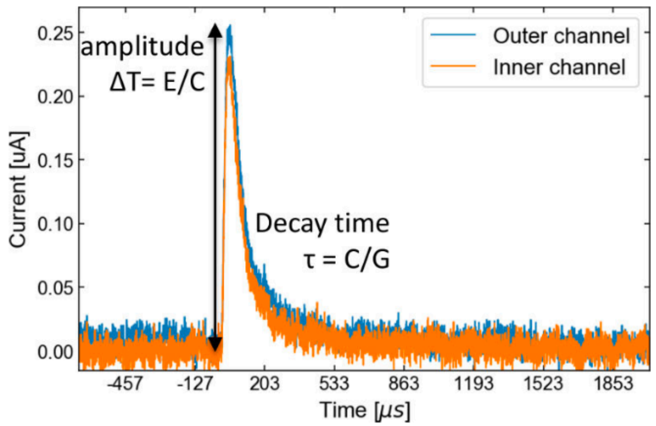
# Example: SuperCDMS

- Experiment at SNOLab based on TES Technology (Si/Ge crystals)

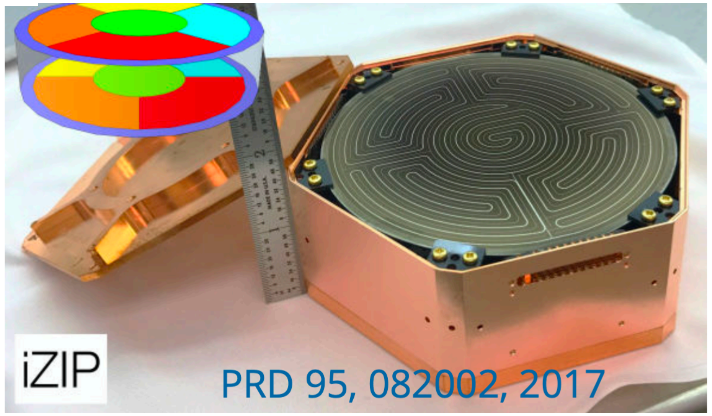



Zatschler, GUINEAPIG 2024

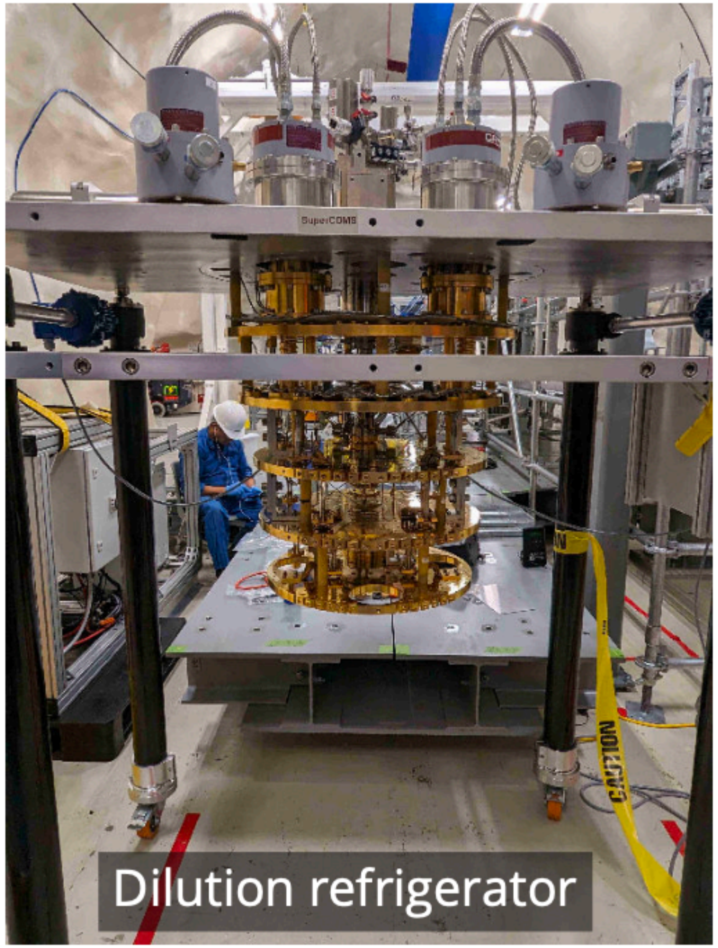


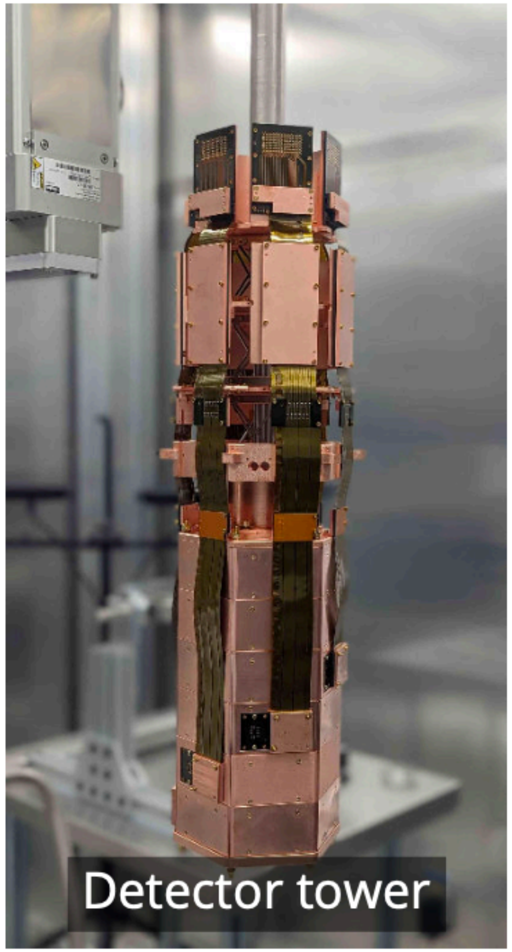

- 10 - 15 mK athermal phonon sensors
- Detect Luke phonons in the TES
- Amplify and process signals to extract energy

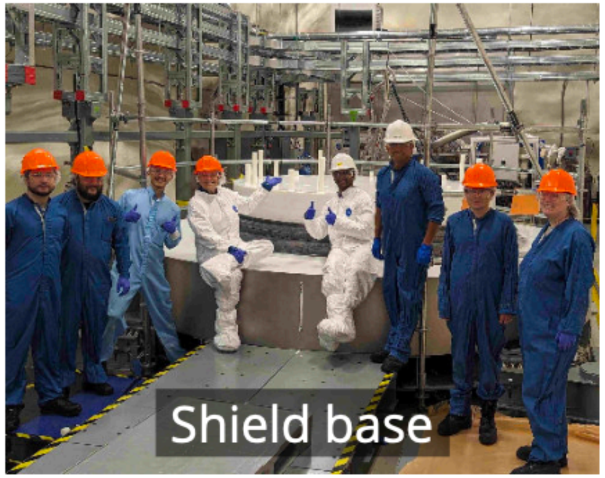



ORCID-0000-0002-4105-9629

# SuperCDMS construction at SNOLAB




LaurentianUniversity UniversitéLaurentienne | UNIVERSITY OF TORONTO

SuperCDMS SNOLAB
LU, UofT // S. Zatschler
August 20, 2024

17/26

SUPER CDMS

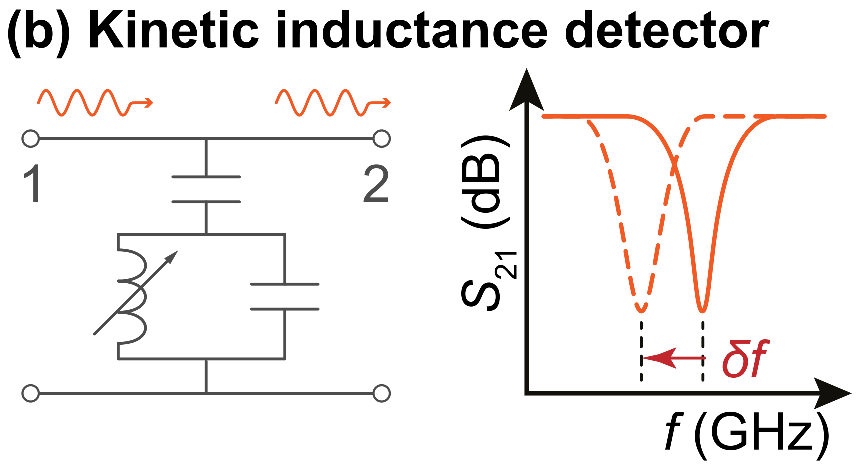
ORCID-0000-0002-4105-9629

# Kinetic Induction Detectors (KIDs)

ORCID-0000-0002-4105-9629

# KIDs

- **Superconducting phonon detectors for single phonon counting with a high temporal precision**
- **Used for X-ray astronomy, gaining traction in particle physics**
- **Change in surface impedance resulting from an incoming phonon breaking up a cooper pair**




- **Energy deposits result in a frequency shift that can be measured**
- **Can provide a rate measurement for any dark matter signal**

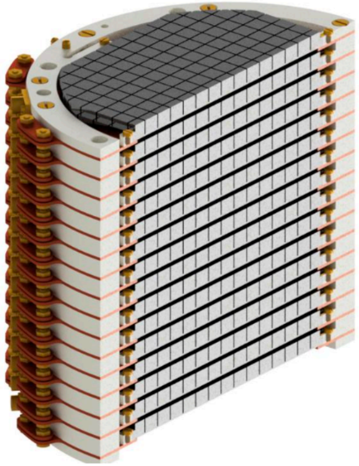
ORCID-0000-0002-4105-9629

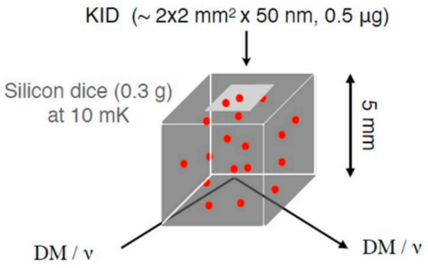
# BULLKID-DM

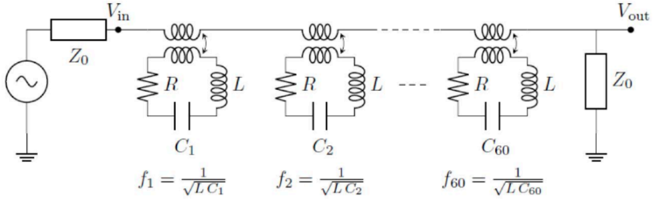
- **Example: silicon detector based KID array for DM searches**

**BULLKID: Kinetic Inductance Detectors coupled to silicon absorbers [1]**

- **Phonon-mediated** detection of nuclear recoils
- **Scalable** and **highly segmented** silicon absorber
- **145** 5x5x5 mm$^3$ **silicon cubes per 4' wafer**
- Target **mass is 0.6 Kg (16x 4' wafers)**

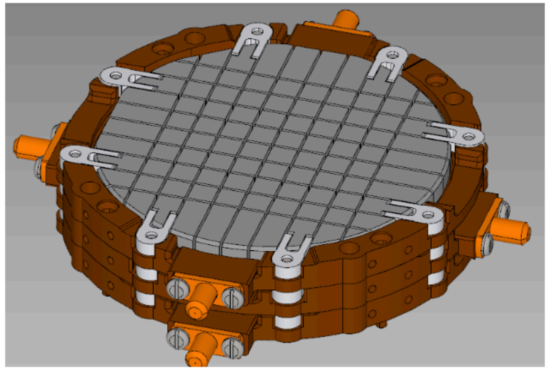




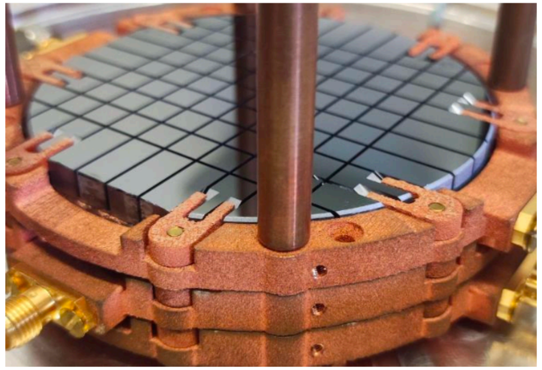




**3x 3-inch Demonstrator**

- **Intermediate step** before moving to a **full scale array**
- 3x **3-inch** silicon wafers for a total of **180 units and 61g of active silicon**



**KIDs on Ge**



**4-inch design**

Same detection

Delicato, Pisa Instrumentation Meeting, 2024

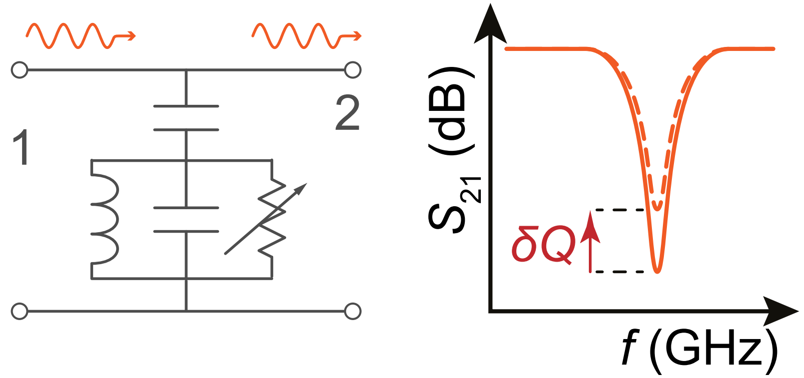
ORCID-0000-0002-4105-9629

# Coulomb Blockade Thermometers (CBTs)

# CBTs

- Amplitude shift related to phonon energy measured in a detector
- Tailor designs to control thresholds with theoretical range down to 25 meV sensitivity (thickness of superconducting layer)
- Can provide an energy measurement for any dark matter detected
- Relaxation times of ~1µs possible

(c) Coulomb blockade thermometer



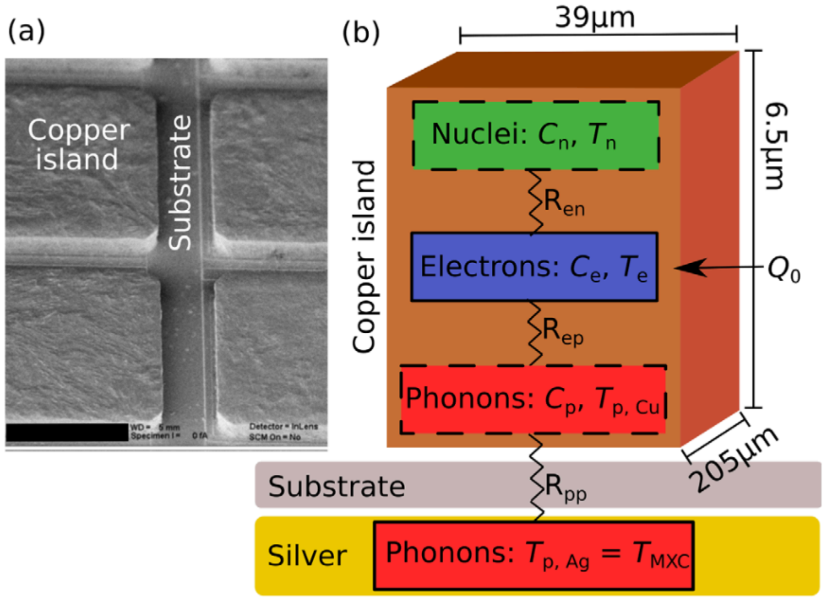



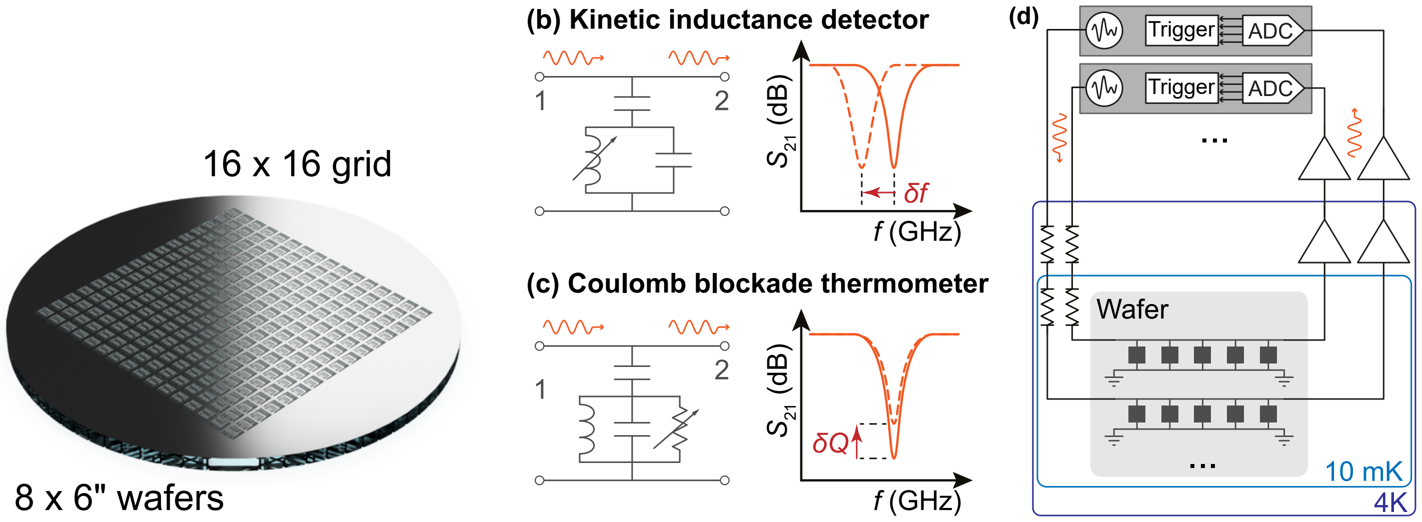

Illustration of heat capacity of an island and energy flow from nuclei to the silver platform in the cryostat mixing chamber.

Autti et al., PRL 131.077001

ORCID-0000-0002-4105-9629

# Example: QuaDMOS

- **Proposed experiment using a 1.2kg stack of sapphire substrates with 2048 KID and CBT pixels**




- **Potential to test new technologies in Boulby and work toward improving dark matter limits, aligned with mass regions of interest for dark photon models.**

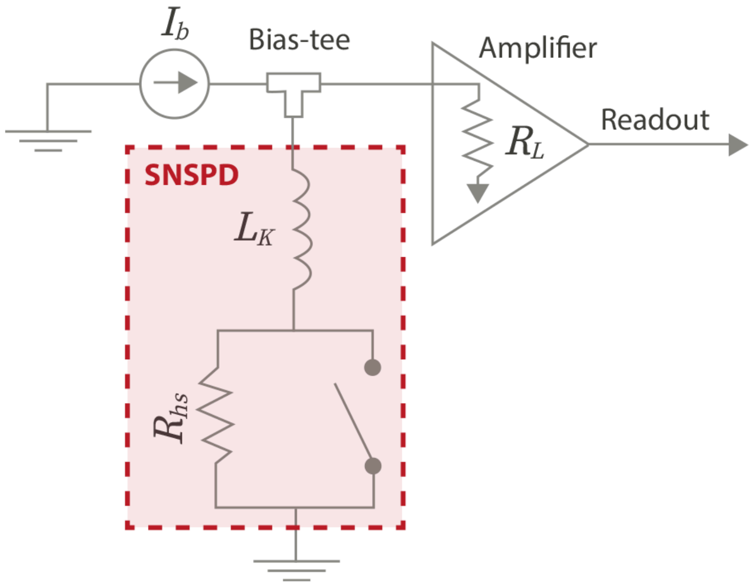
Bevan, GUINEAPIG 2024

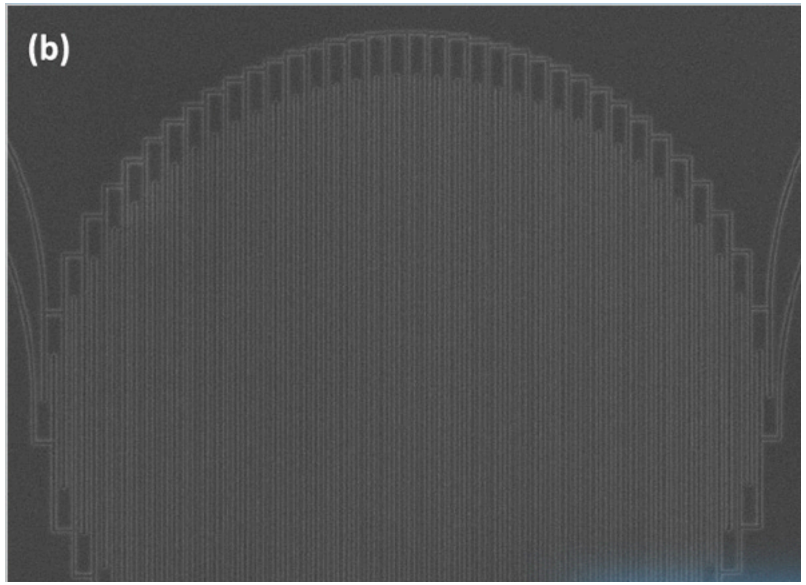
ORCID-0000-0002-4105-9629

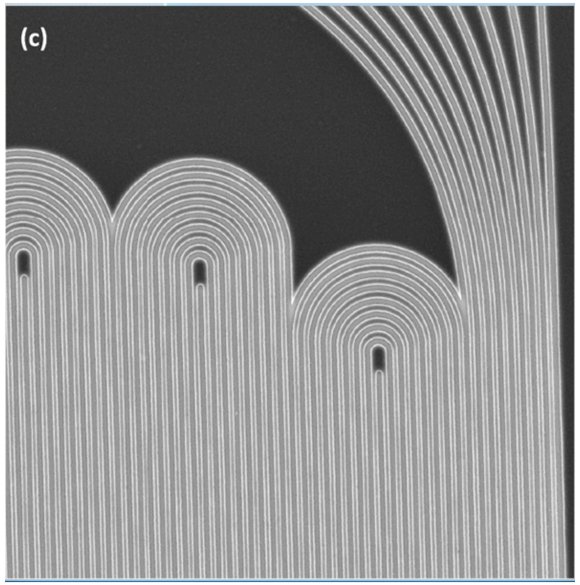
# Superconducting nanowire single photon detector (SNSPD)

# SNSPD

- **Nanowire change in resistance from signal is amplified by an impedance amplifier to generate signal pulses**



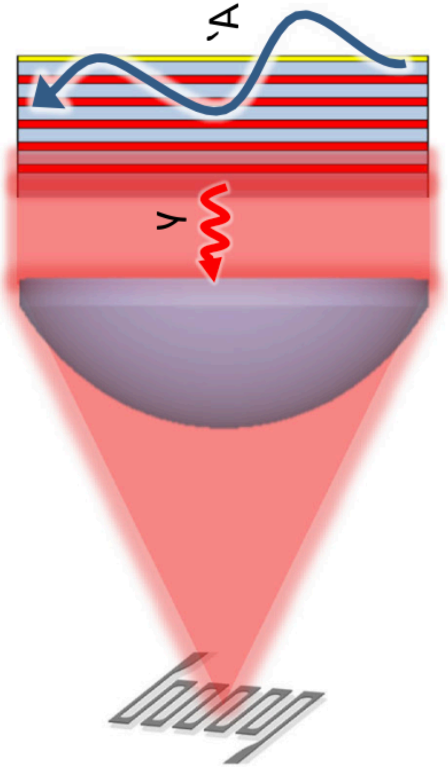

https://www.idquantique.com/ An Overview,a two-dimensional detector plane.

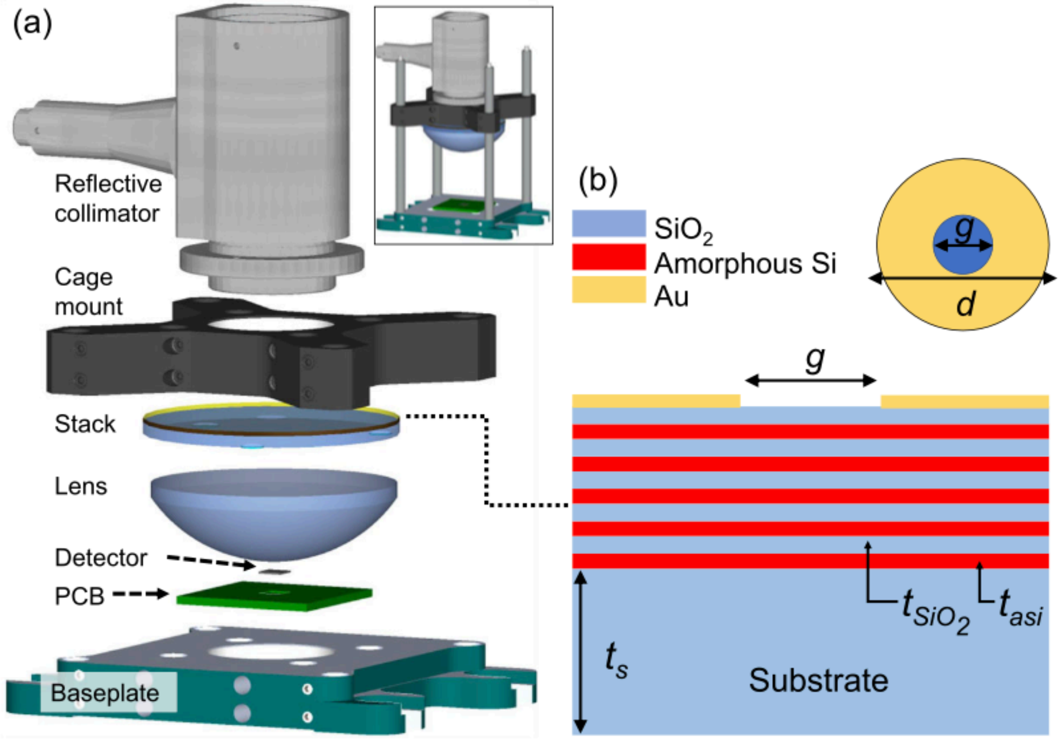
ORCID-0000-0002-4105-9629

Adrian Bevan 

# Example using the LAMPOST* concept

- **Focus light converted from a dark photon conversion to a $\gamma$ onto the SNSPD**






- **Device sandwiched layers of $SiO_2$ and amorphous silicon.**
- **Dark count rate ~$10^{-6}$**
- $\epsilon \sim 30\,\%$ **(achieved close to maximum theoretical efficiency)**

*Light A Multilayer Periodic Optical SNSPD Target

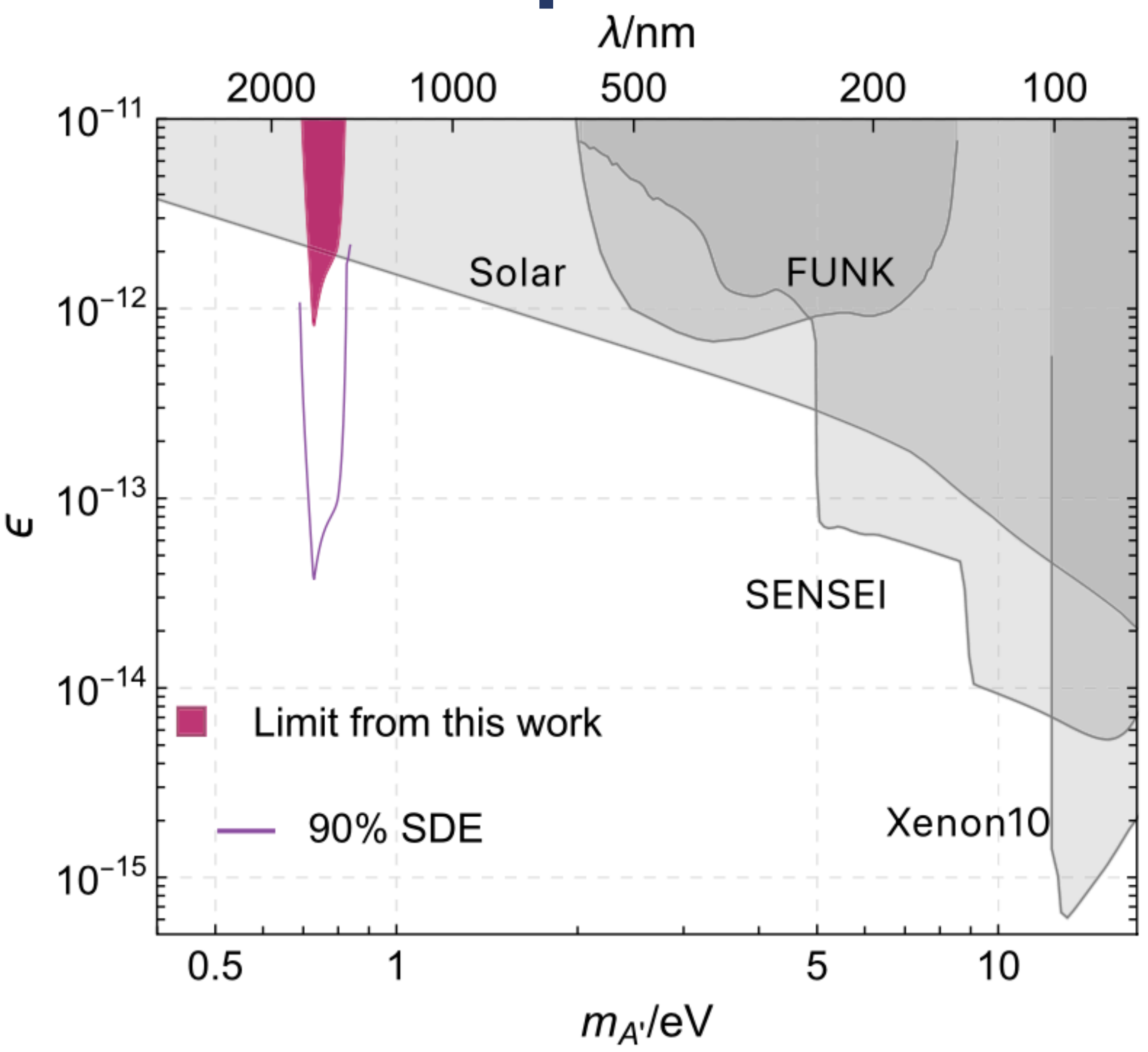
Chiles et al. PRL 128 231802

ORCID-0000-0002-4105-9629

# Example using the LAMPOST concept

Queen Mary University of London

- Able to improve limits by a factor of 2 for a specific low mass dark photon hypothesis
- Stacking construct of this experiment gives approximately x30 improvement over earlier designs
- Validates the efficacy of SNSPDs as a dark matter detector technology

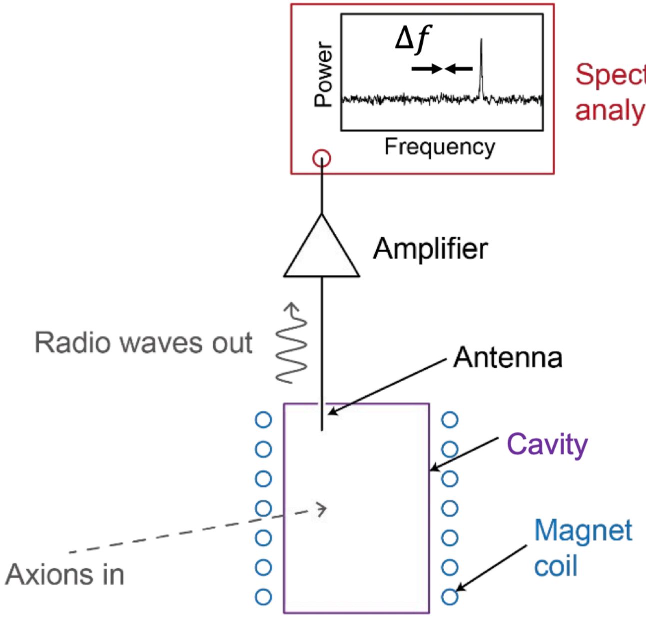



Chiles et al. PRL 128 231802

# Nanotube resonators

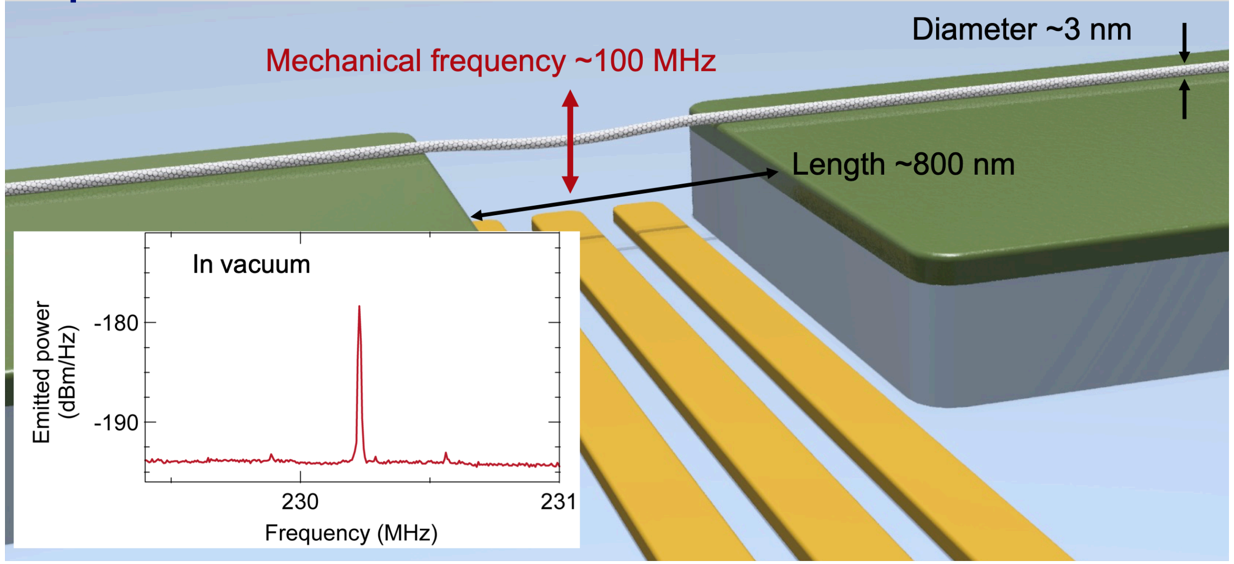
# Quantum Sensors for the Hidden Sector

- QSHS focusing on axion search using quantum sensors
- quantum amplifiers key component for detecting signals




- Also looking for other ways to detect signals, e.g. nanotube resonators in superfluid He

Carbon nanotube resonators for measuring superfluid helium




Laird QMUL-SNOLab Workshop

ORCID-0000-0002-4105-9629

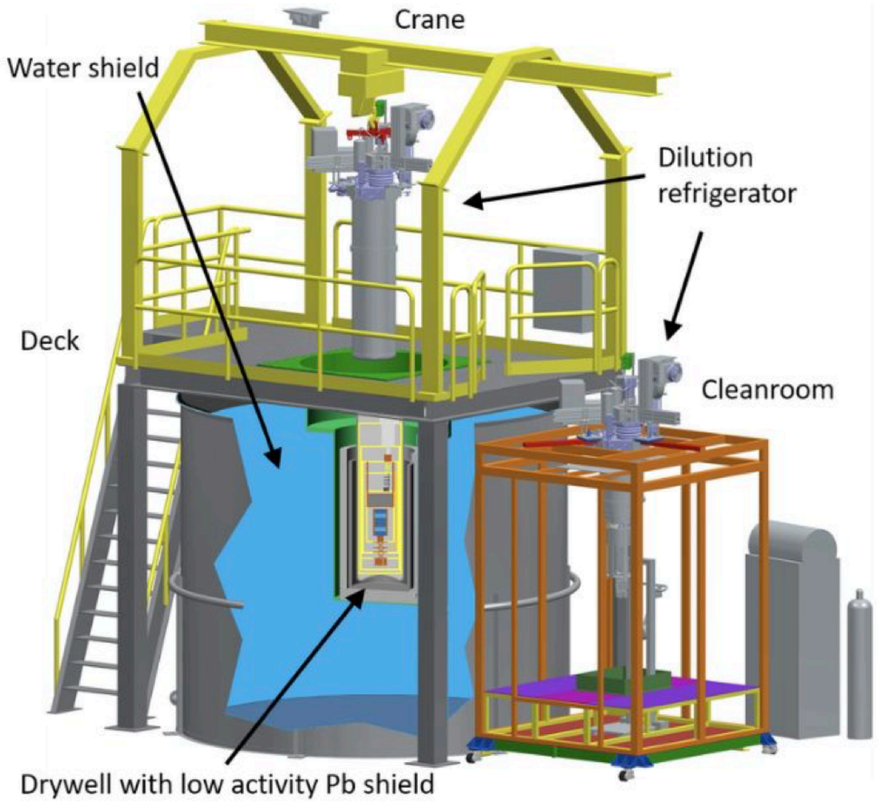
# Requirements

# Requirements

- Different technologies have different requirements, but some common infrastructure needed
- Dilution fridge running down to ~10 mK
- Understanding of the intrinsic radiation background of the lab, the setup and detector material
  - Good design to ensure radio purity of detector and key infrastructure components
  - Neutron background constraints: both fast and thermal neutrons
  - Radon background constraints
- (beyond axions) low background environment to search for signals
- + ideally an underground facility to fabricate detector components prior to installation (minimise cosmogenic activation)

# e.g. CUTE facility at SNOLab

## CUTE: Cryogenic Underground TEst facility




- Located 2 km underground at SNOLAB
- Includes water, lead, and HDPE shielding to achieve a background level of less than 10 DRU
- Custom designed suspension system proven to significantly reduce vibrational noise

Facility managed and maintained by SNOLAB; made available to the community through a proposal process

c/o Yan Liu (UBC/TRIUMF)

# Summary

# Summary

- Quantum sensing technology is already making an impact on dark matter direct detection for light and ultra light systems
- The active mass of detectors is small compared to the Nobel liquid detectors, so not competitive for WIMP searches
- Plenty of other opportunities to explore, including directional detectors
- Need dilution fridges (preferably modified) in a low background environment like the Stage 1 expansion
- Some technologies are "established" and others are concepts for DM detectors
- Lots of promise… just need funding to match the problem space

ORCID-0000-0002-4105-9629

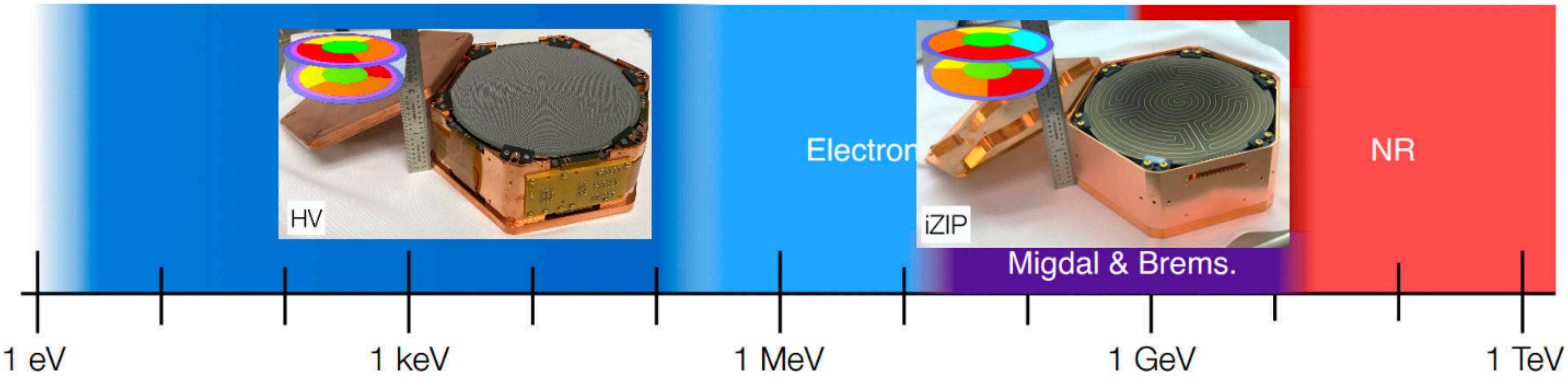
# Backup

# SuperCDMS

## SuperCDMS: A broadband DM search

c/o Stefan Zatschler (Laurentian/Toronto)

| | | |
|---|---|---|
| Absorption (Dark Photon, ALP): | $\sim$ 1 eV – 0.5 MeV | peak search (HV) |
| Electron Recoil (ER): | $\sim$ 0.5 MeV – 10 GeV | no NR/ER discrim. (HV) |
| Migdal & Bremsstrahlung: | $\sim$ 0.01 – 10 GeV | no NR/ER discrim. (HV + iZIP) |
| HV Detector (LT, NR): | $\sim$ 0.3 – 10 GeV | no NR/ER discrim. (HV) |
| Low Threshold (LT) NR: | $\gtrsim$ 1 GeV | limited NR/ER discrim. (iZIP) |
| Traditional Nuclear Recoil (NR): | $\gtrsim$ 5 GeV | full NR/ER discrim. (iZIP) |

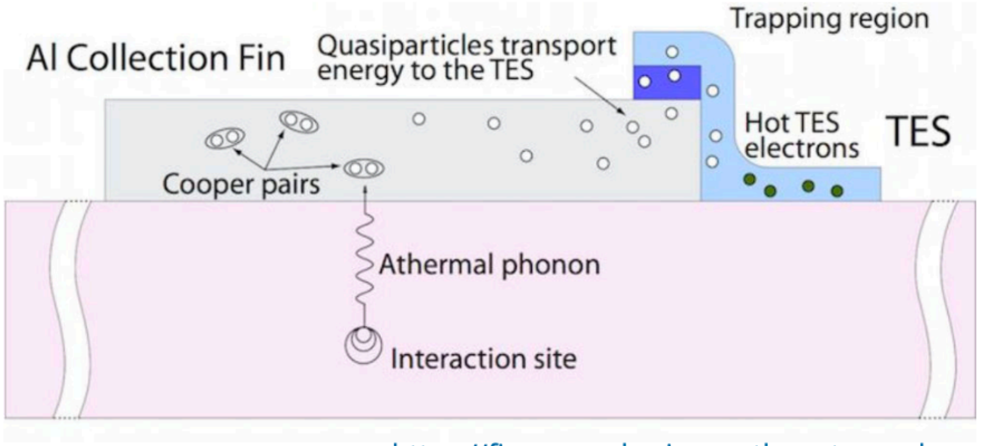



ORCID-0000-0002-4105-9629

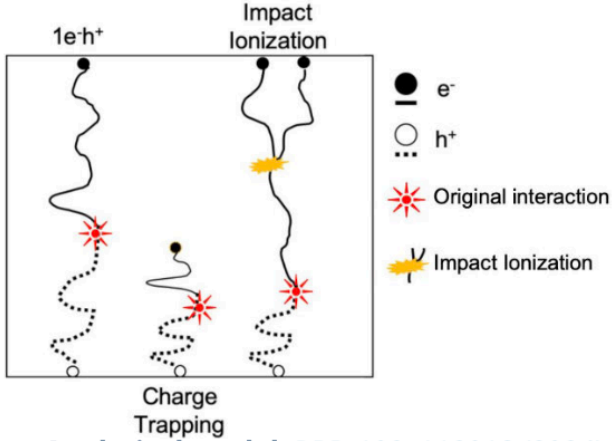
# SuperCDMS

- **Lots of detailed work on simulation: See: Zatschler, GUINEAPIG 2024**

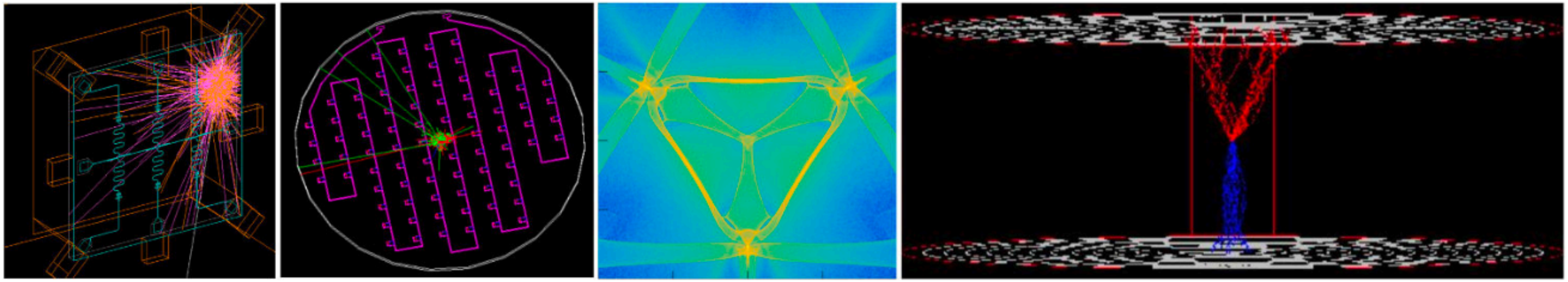
QET – **Q**uasiparticle trap assisted **E**lectrothermal feedback **T**ransition edge sensor




https://figueroa.physics.northwestern.edu




**Analytical model:** PRD 109, 112018 (2024)

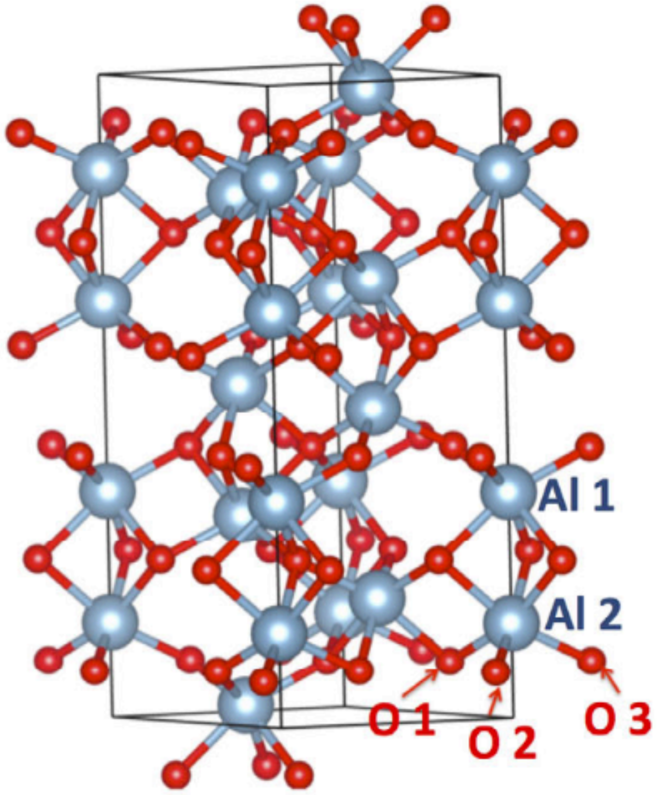


ORCID-0000-0002-4105-9629

S. Griffin et al., Phys. Rev. D **98**, 115034 (2018).

# Why sapphire?

- Anisotropic polar crystal
  - 10 atoms in a primitive cell, so 30 phonon modes: 3 acoustic and 27 optical modes
  - Directional detection capability that would lead to daily modulation with sidereal time
- “broad” range of energies accessible in the meV range for DM scattering producing optical phonons
- Able to detect dark photon interactions that kinetically mix with the standard model photon




ORCID-0000-0002-4105-9629

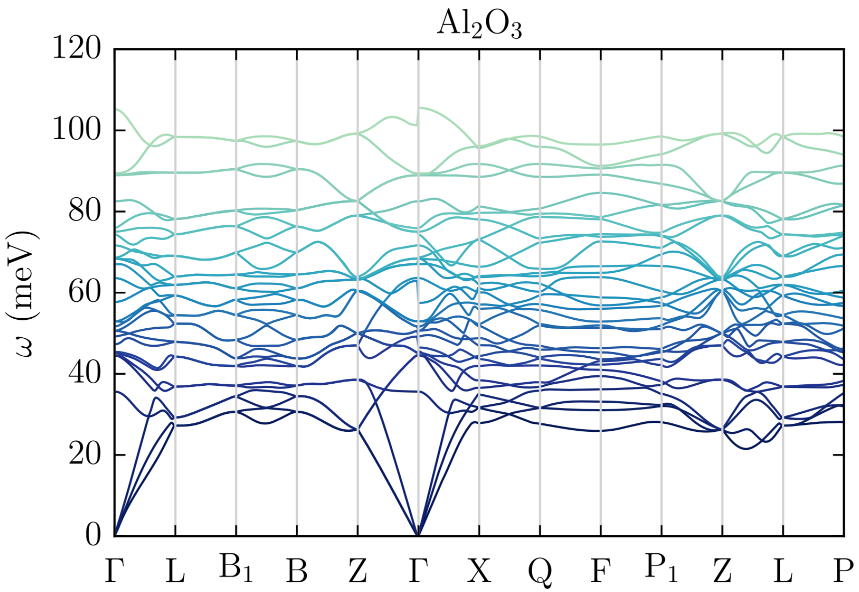
Adrian Bevan

S. Griffin et al., Phys. Rev. D **98**, 115034 (2018).

Queen Mary University of London

# Why sapphire?

- Anisotropic polar crystal
  - 10 atoms in a primitive cell, so 30 phonon modes: 3 acoustic and 27 optical modes
  - Directional detection capability that would lead to daily modulation with sidereal time
- "broad" range of energies accessible in the meV range for DM scattering producing optical phonons
- Able to detect dark photon interactions that kinetically mix with the standard model photon




Phonon band structure for Sapphire (Al2O3) computed using PHONOPY, from S. Griffin et al.

$$\omega = c_s |\mathbf{q}| \lesssim 2 c_s m_X \sim 7\, meV \times \frac{m_X}{100\, keV}$$

$c_s$ speed of sound in material
$\mathbf{q}$ is the wavevector
$v$ is the DM velocity
$m_X$ DM candidate mass

$$c_s(Al_2O_3, |\mathbf{q}| \sim 0) = 10^4\, (m/s)$$

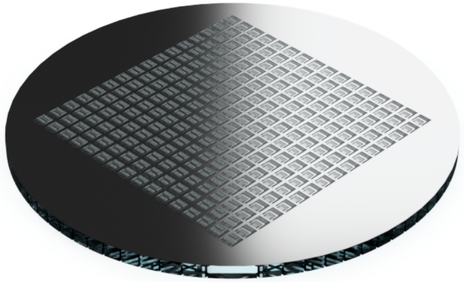
ORCID-0000-0002-4105-9629

# e.g. QuaDMOS detector concept

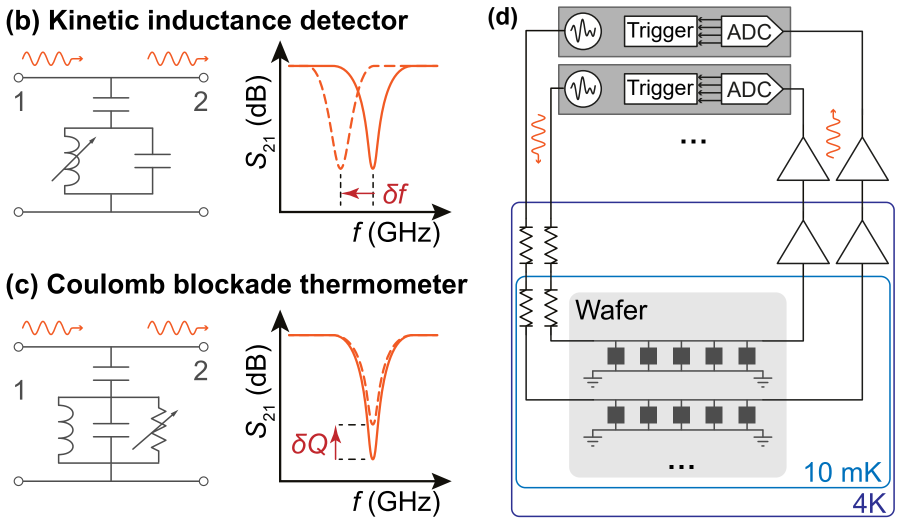
- A 1.2 kg Sapphire detector comprising of a stack of 8 wafers with:
  - Kinetic Induction Detectors
  - + Coulomb Blockade Thermometers

  on a graphene-based circuit

16 x 16 grid



8 x 6" wafers




- Measure athermal phonons from dark matter interactions with the sapphire
- KID detection limit is governed by the small energy gap of Cooper pairs
- CBT detection limit is governed by raising the electron temperature
- Use a frequency multiplexed sensor array of 2048 pixels in 1.2 kg of $Al_2O_3$

- Working with the custom foundry on wafer production

ORCID-0000-0002-4105-9629

# QuaDMOS detector concept

- Dilution fridge:
  - Operate at sub 10mK temperatures
  - Copper electroplating of key components to mitigate background to help develop a new product for the dilution fridge supplier
  - Standardise readout for a test facility to test at surface and prepare for the mine
  - Detector made and tested on surface; loom transferred to the mine.
  - If Boulby had an underground quantum lab we would assemble the detector underground to mitigate material activation; instead plan to use a surface lab at QMUL.
  - Minimal maintenance required for operation

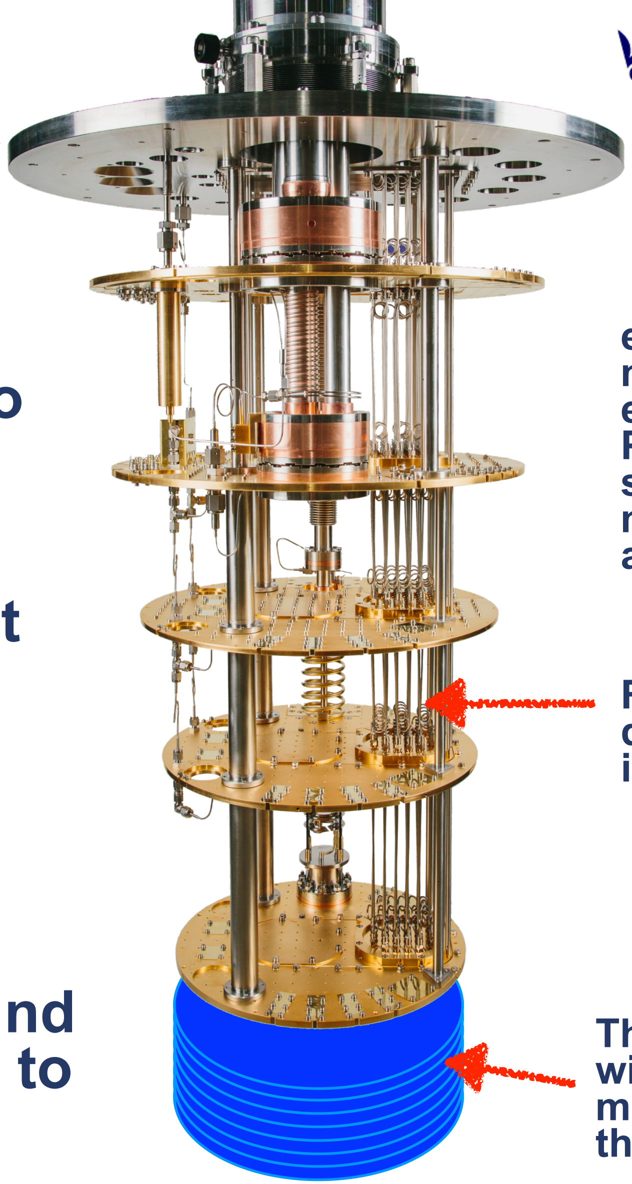


Image: Courtesy of Oxford Instruments NanoScience, © 2024

e.g. the standard multi stage heat exchanger for a Proteox system is shown (other manufactures are available)

RF and DC lines run down this removable insert

The 1.2 kg detector will be operated at 10 mK, suspended from this plate.

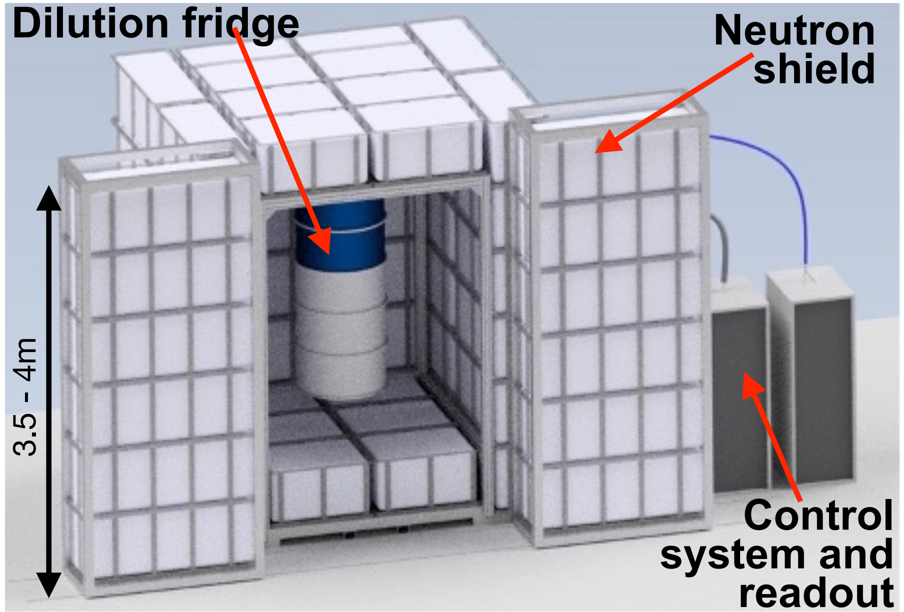
ORCID-0000-0002-4105-9629

Adrian Bevan

# QuaDMOS detector concept

- **Boulby is a low background environment, however neutron background will mimic signals**
- **Measurements of fast neutrons have been made previously, but the thermal neutron background is not known**

V. A. Kudryavtsev et al., hep-ex/0301038. (2003)




- **Use a well established approach for neutron shielding using commercial off the shelf parts from a nuclear industry supplier (modular plastic water tanks).**
- **Develop novel technology for "real time" thermal neutron measurements using existing commercial off the shelf DAQ; tailoring sensors to the low background environment.**

ORCID-0000-0002-4105-9629

Adrian Bevan

S. Griffin et al., Phys. Rev. D **98**, 115034 (2018).

Queen Mary University of London

# Directional detection

- The anisotropic sapphire crystal results in directional dependence of the cross section, leading to sidereal time daily modulations of signal

- Example plots from Griffin et al.

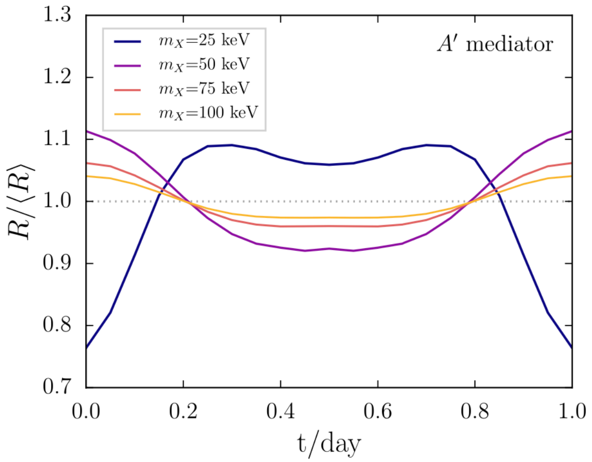



FIG. 6. Modulation of the scattering rate for sapphire over a sidereal day, assuming a 25 meV threshold.

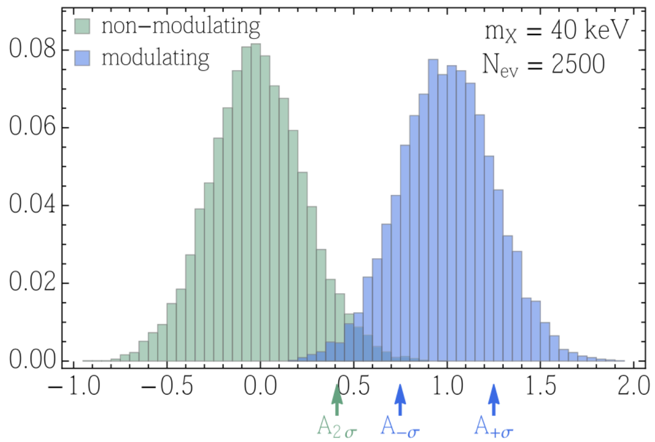



FIG. 16. Distributions of the modulation amplitude, assuming 2500 expected events.

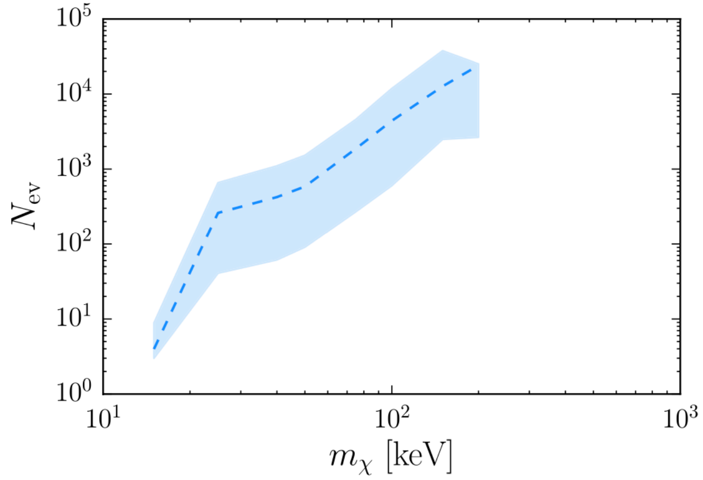



FIG. 17. Expected number of events needed for $2\sigma$ observation of the daily modulation.