Proposal for a new quantum tech based dark matter experiment: QuaDMOS

Quantum Dark Matter Object Search: QuaDMOS

Prof. Adrian Bevan

Working with a range of industry and research partners:

STFC Boulby, SNOLab, IBM, Micron Semiconductor Ltd., Paragraf Ltd.

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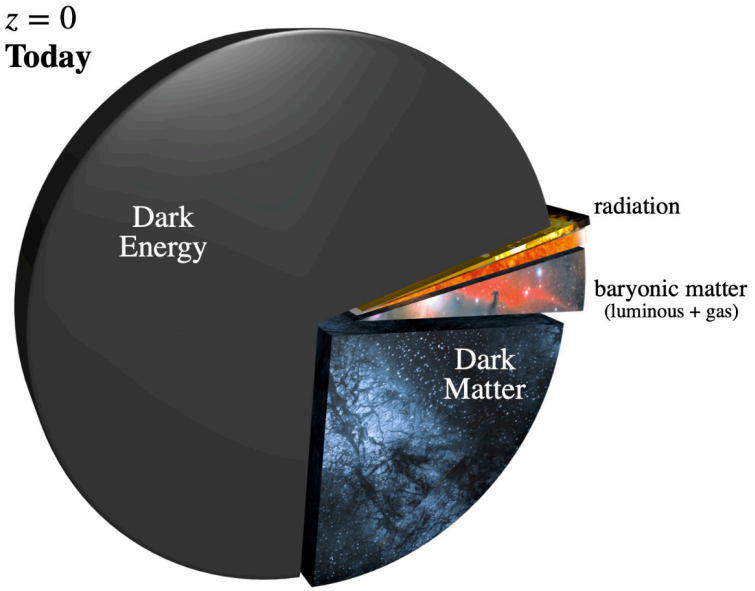
Motivation

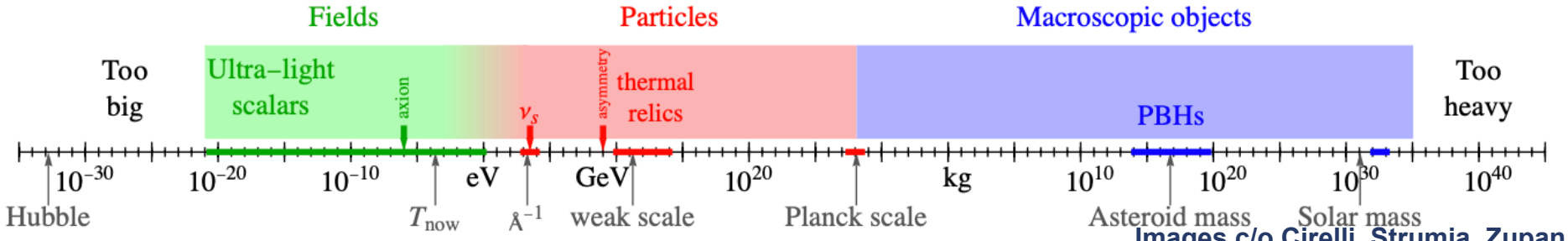
What is the nature of dark matter?

- 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

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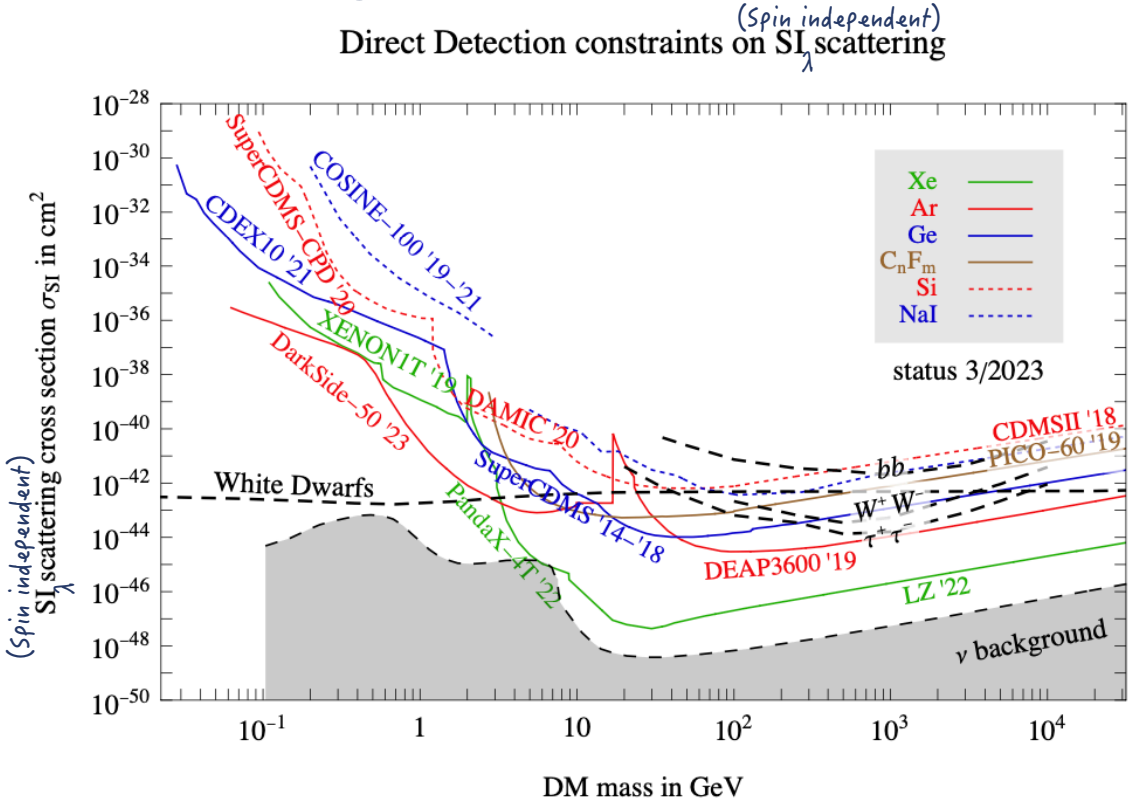
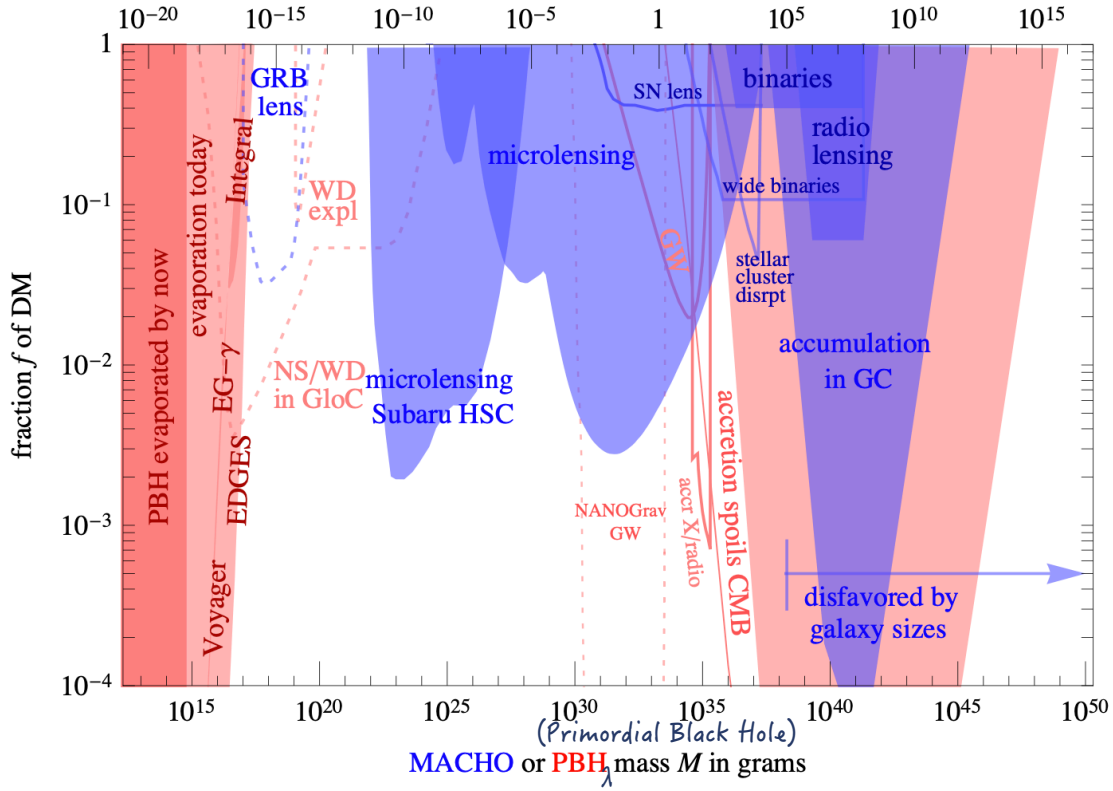
Existing constraints on dark matter

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





Cirelli, Strumia, Zupan, arXiv:2406.01705

Aims

The scientific aims of QuaDMOS

- Search for dark matter:
  - Light dark matter as particles
  - Explore the potential to search for macroscopic DM objects (small on the $m_{\odot}$ scale)
- Develop technology to map the (thermal) neutron background of the Boulby laboratory, with real time data acquisition
- For this we need to routinely operate a 2048 pixel 1.2 kg detector below 10 mK in a dilution fridge

The broader aims of QuaDMOS

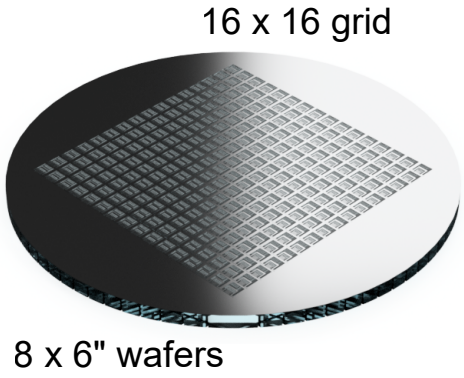
- Develop dilution fridge technology for low background environments working with our supply chain partners
- Operate a quantum computer compatible dilution fridge in Boulby
- Develop new quantum technology and radiation detection products for UK industry
- Commercial partners with interest include:
  - IBM, Micron Semiconductor Ltd., and Paragraf ltd
- Other stakeholders with interest in our project include the nuclear industry, where there is a neutron dosimetry need
- Collaborating with SNOLab to help strengthen links with Boulby

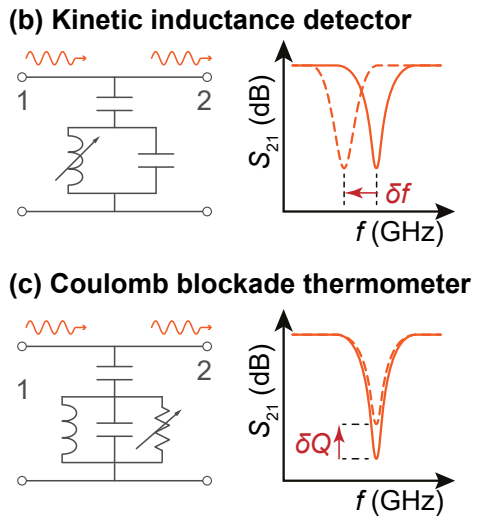
Approach

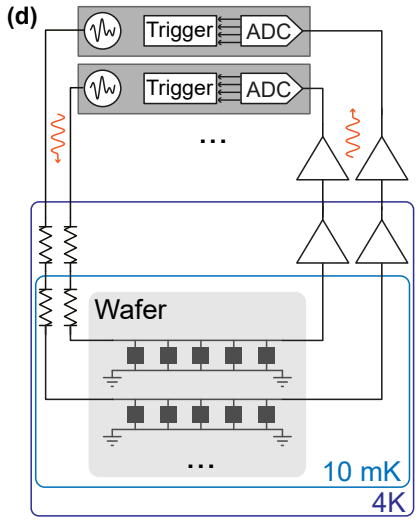
The detector

- 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







- 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 Paragraf on wafer production

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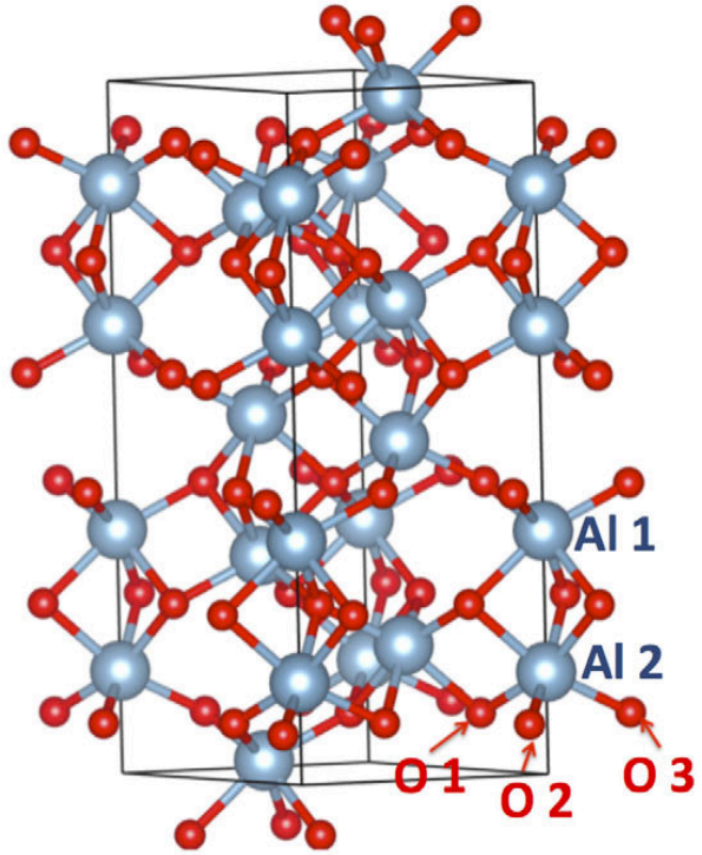
S. Griffin et al., Phys. Rev. D **98**, 115034 (2018).

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 photons via kinetic to standard model photons



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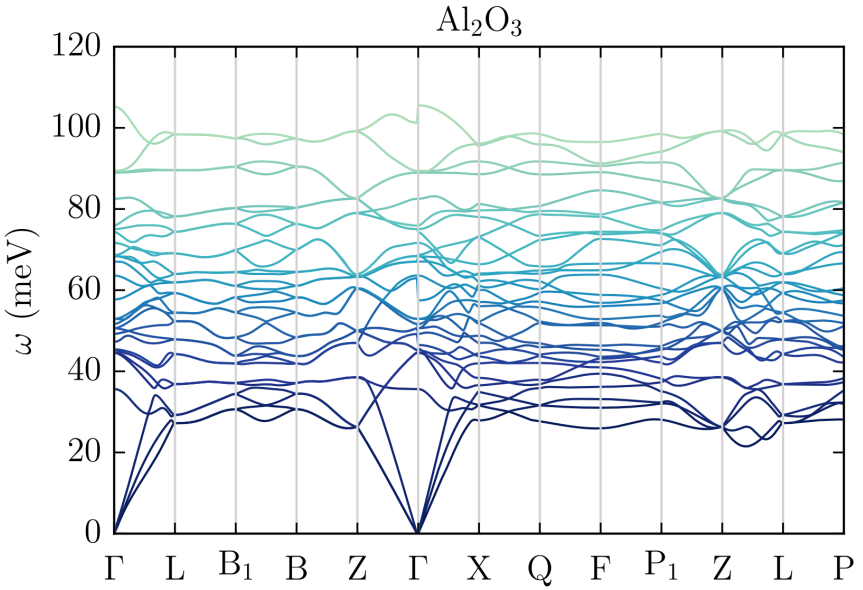

Phonon band structure for Sapphire (Al2O3) computed using PHONOPY, from S. Griffin et al.

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

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

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

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The environment

- 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

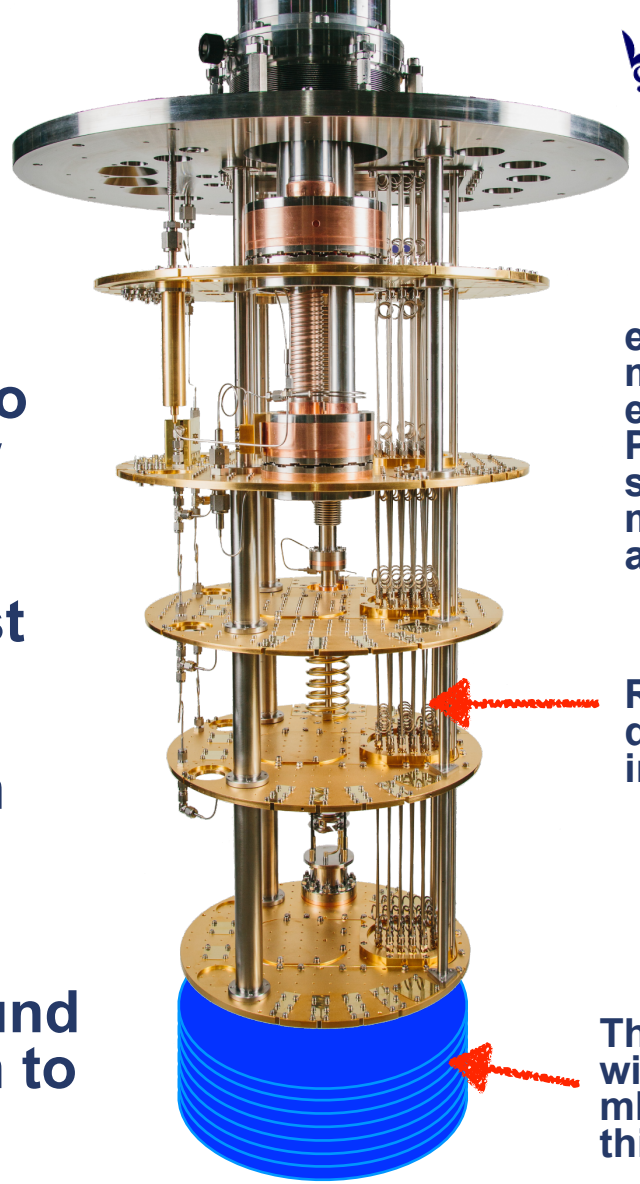

Image: Courtesy of Oxford Instruments NanoScience, © 2024

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.

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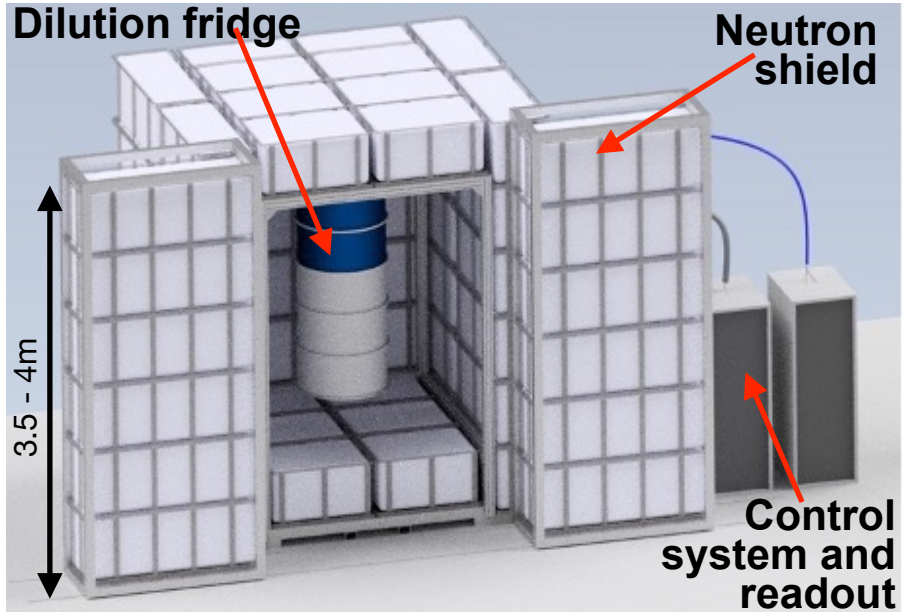
The environment

- **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.**

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Neutron measurements

- **Broad range of energies in the cavern**
- **$5.8 \times 10^{-10}\, cm^{-2} s^{-1}$ neutron flux (E>1MeV) at the lab depth (3km w.e.)**
- **Thermal neutron (n_{th}) flux dominates, but is not measured**
- **Will use technology developed by QM to measure neutron flux in real time**
- **Raspberry PI DAQ for reading out the system is available, now and will be used to map the n_{th} radiation field in the lab**

L. Vozdecky, A. Bevan, NuSec Annual Technical Workshop, London (2023)

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

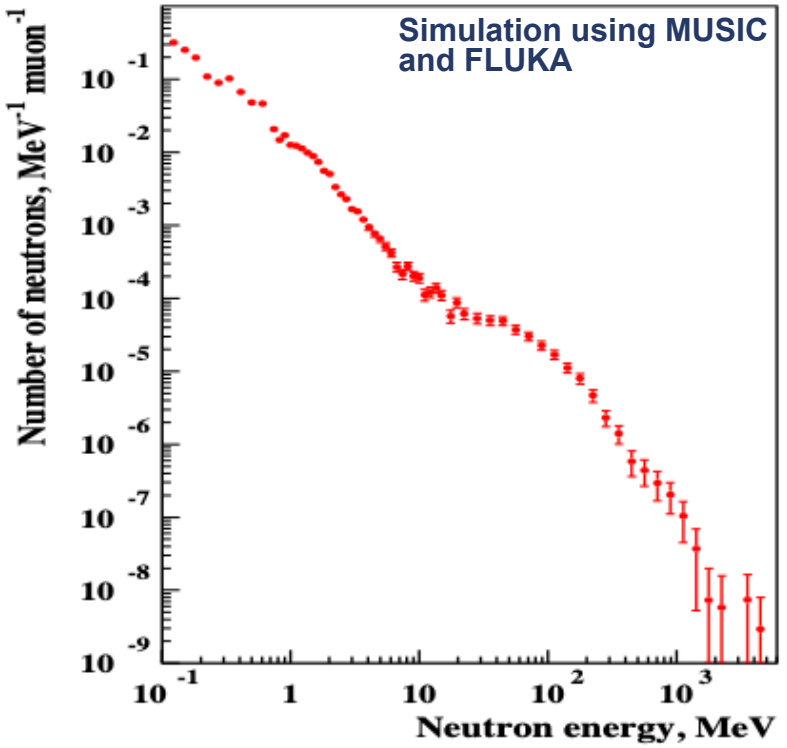
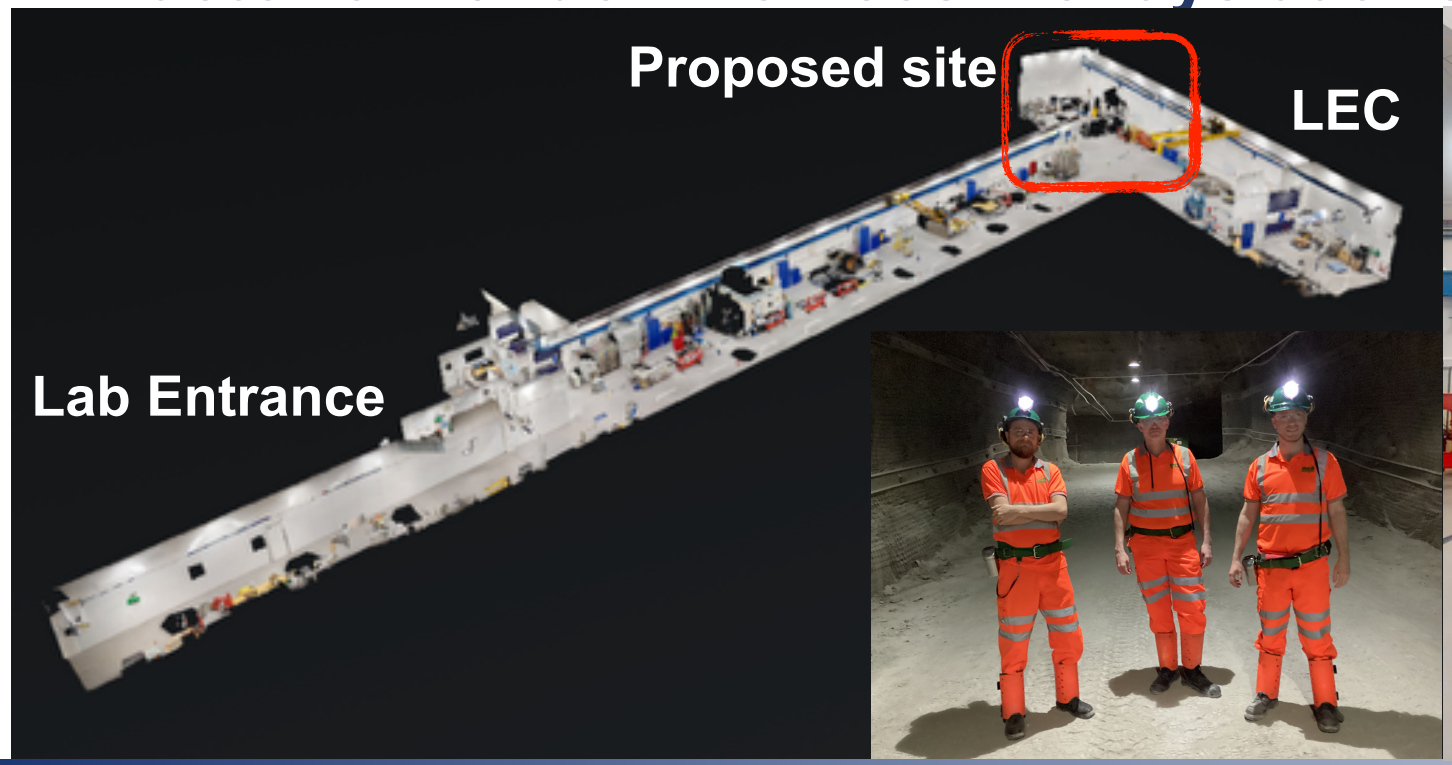


Figure 6. Neutron energy spectrum at the boundary between salt and cavern.

The environment

- Proposed location for the experiment is in the Large Experimental Cavern (LEC) in the Boulby Laboratory
- Lab constructed in a 250 million year old salt bed 1100 m underground
- Factor of 10^6 down on cosmic rays at this site compared to sea level



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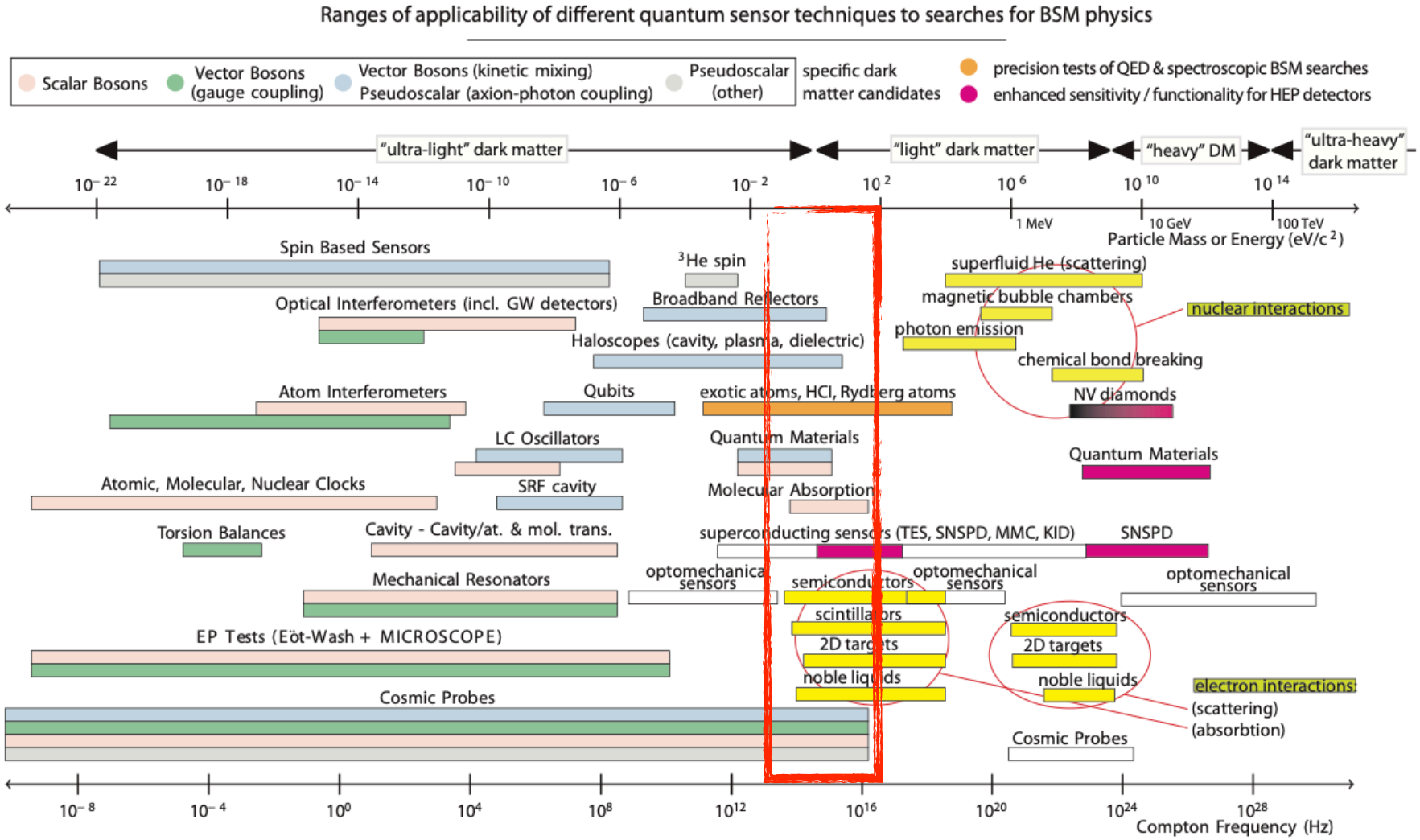
Project status

- Applying for funding from the STFC in the UK
- Aim to set up surface laboratory quickly to start developing the detector system, while working on the bespoke system for the Boulby Laboratory.
- Engineering run expected to start 2 years into the project to shake down any issues
- Optimistically we are aiming for 2 1/2 years of data taking
- Legacy use of the setup includes using the underground dilution fridge as a quantum technology test stand (like the CUTE facility @ SNOLab)

Potential

Sensitive to (ultra)light dark matter



https://arxiv.org/pdf/2305.11518

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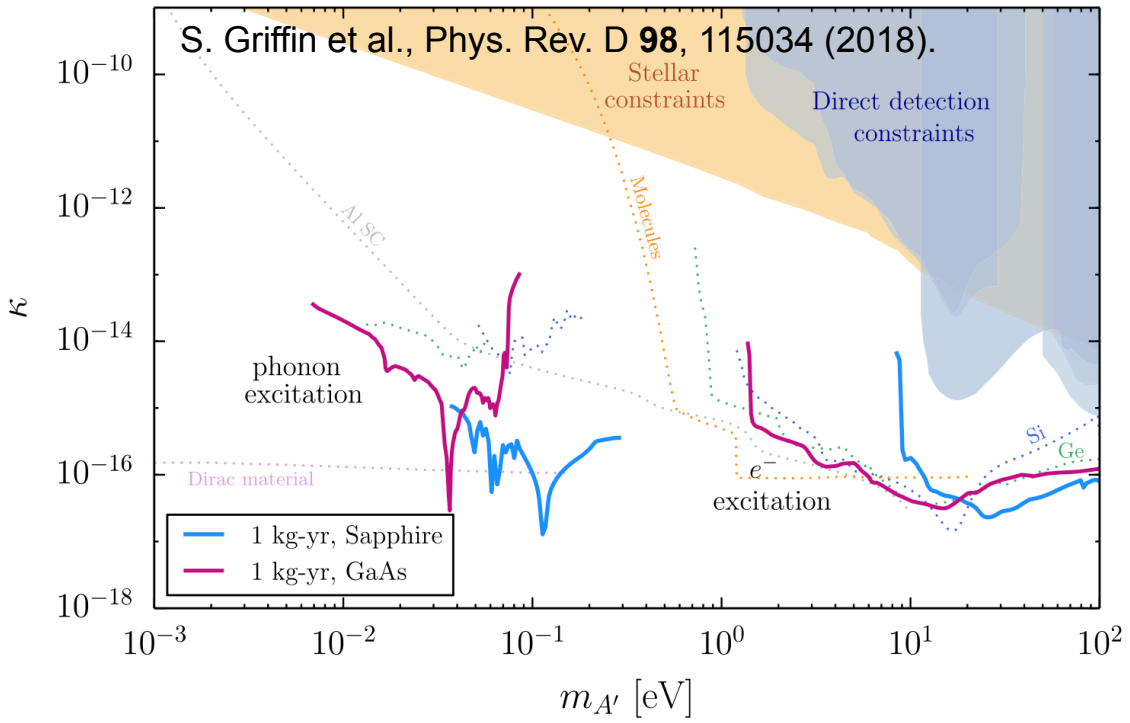
Estimated sensitivity

- Aiming for an engineering run, followed by operations for 2 1/2 years, corresponding to a physics run with a 3 kg-year sensitivity.



- Aim to produce search limits for dark matter masses O(0.1) eV, and for tens of eV.
- Detector has a modular design.
- QuaDMOS can inform future upgrades e.g. for Boulby's stage 1 expansion or at other laboratories.

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Other Science

- QuaDMOS is designed to have the requisite RF and DC readout capacity to be a quantum technology testbed in a low background environment.
  - e.g. to study the decoherence of qbits from cosmic rays
- Legacy options for this project include testing quantum devices, and evaluation of the feasibility quantum computers operating in the laboratory.
- It is also feasible to relocate the experiment in part or whole from the LEC at Boulby to the stage 1 expansion of the lab currently under construction, where the option of a quantum laboratory is being explored.

Summary

Summary

- QuaDMOS is a quantum experiment targeting 3kg-yr run
- Searching for light particle dark matter and explore potential to search for exotic astrophysical sources
- Strong interest from industry including IBM, Micron, Paragraf
- Several other stakeholders interested in neutron detection part of the project for industrial applications
- Aligned with the vision of developing a quantum lab at Boulby and benefiting from expertise of operating CUTE at SNOLab
- Work is ongoing to determine sensitivities for our system, and evaluate the potential for transient DM searches

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Please do get in touch if you are interested in finding out more, or are interested in joining our effort

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