Studies of radioactive background from environment for a potential LXe dark matter experiment at Boulby

Jemima Tranter [1, 2], Vitaly Kudryavtsev [1] and Paul Scovell [2]

[1] Department of Physics and Astronomy, The University of Sheffield, Sheffield S3 7RH, UK
[2] Boulby Underground Science Facility, Boulby Mine, Saltburn-by-the-Sea, Cleveland, TS13 4UZ, UK

Project overview

- The next-generation dark matter detector will look for WIMP interactions and evidence of 0νββ decay.
- Using a LXe target, the detector will have at least a magnitude greater sensitivity than predicted limits for current LXe detectors.
- One of the critical challenges for success is minimising sources of background.
- Going underground shields the detector from cosmic rays, but the rock provides a gamma-ray background from traces of ^{238}U, ^{232}Th and ^{40}K.
- This project aims to assess the shielding thickness for G3 and also the suitability of Boulby Mine, North Yorkshire, as a potential location.

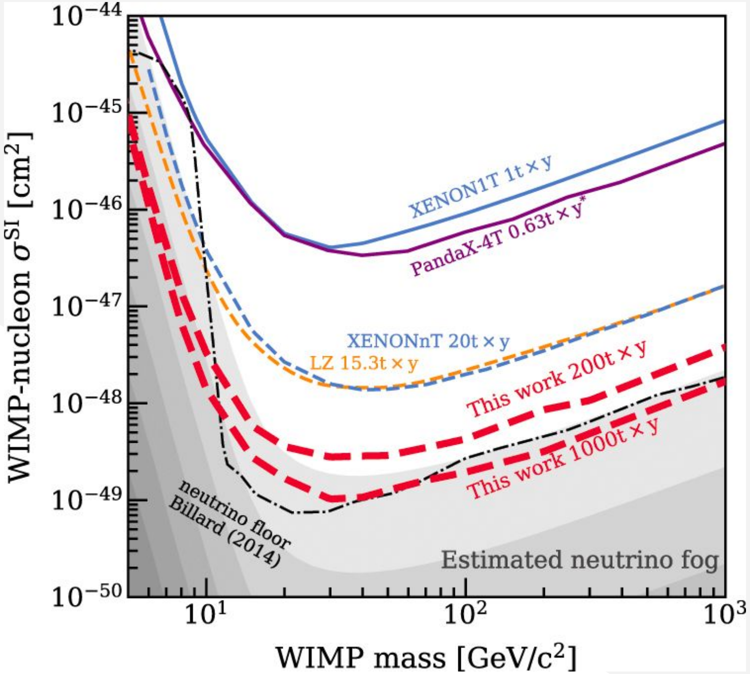
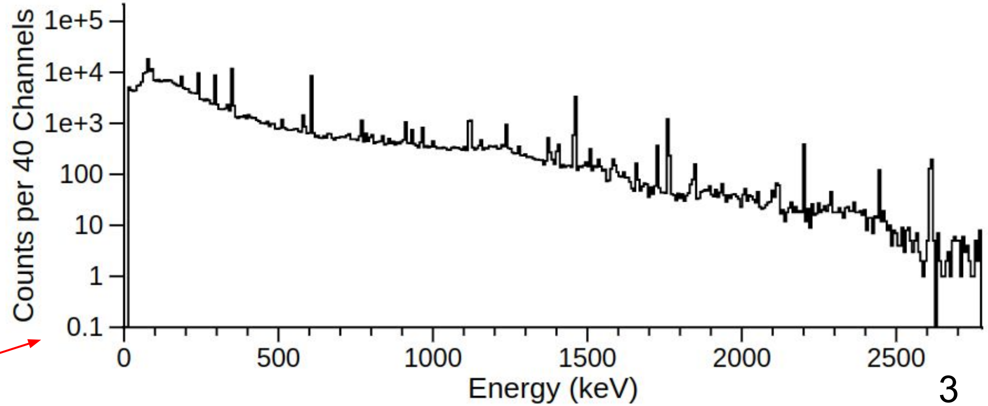


Image: J Aalbers *et al.*, *J. Phys. G: Nucl. Part. Phys. 2023,* **50** 013001, 10.1088/1361-6471/ac841a

Gamma-ray background from rock

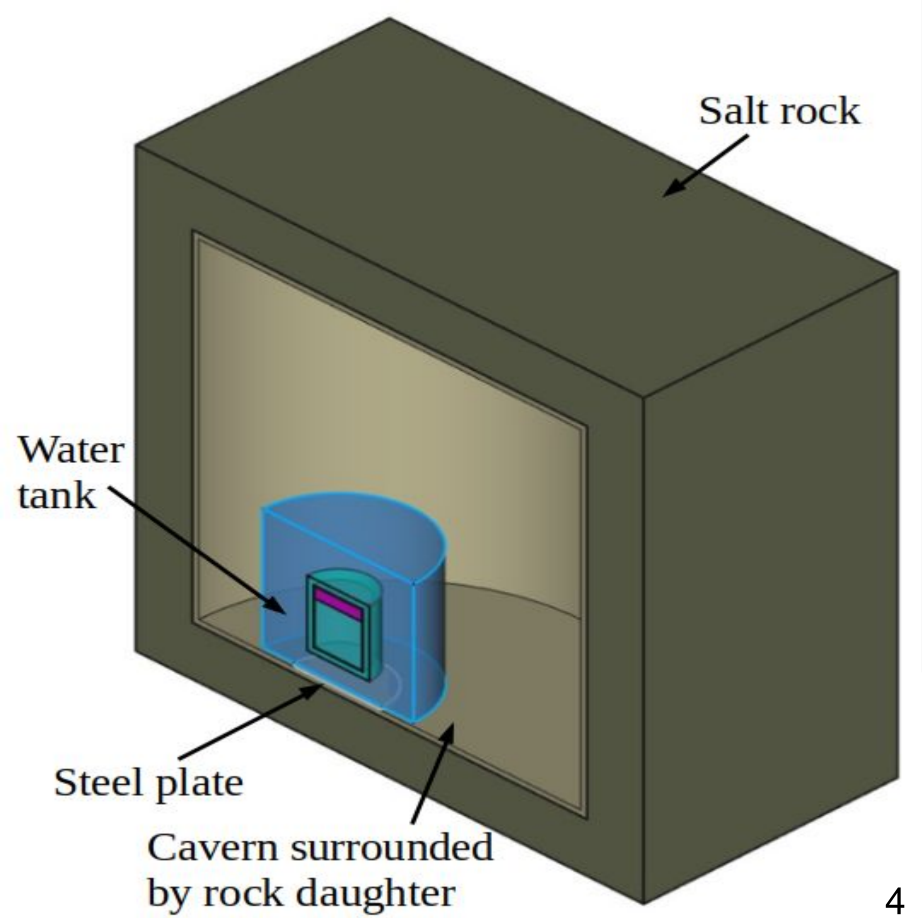
- Natural radionuclides ^{238}U, ^{232}Th and ^{40}K are found in rock and construction materials. Daughter isotopes in their decay chains emit gamma-rays of a broad range of energies.
- WIMP ROI: 0 - 20 keV, Q-value of 0νββ decay of ^{136}Xe: 2458 keV, we use an ROI of ± 50 keV.
- Low-energy gammas are a background for WIMP search, gammas with higher energies are a background for 0νββ decay and WIMP search.
- Water can be used as shielding against neutrons and gamma rays. Gadolinium-loaded liquid scintillator (GdLS) can be used as shielding and as a neutron veto.
- To investigate the necessary shielding thickness a simulation has been developed in Geant4.



Example rock gamma spectrum, measured with HPGe detector.

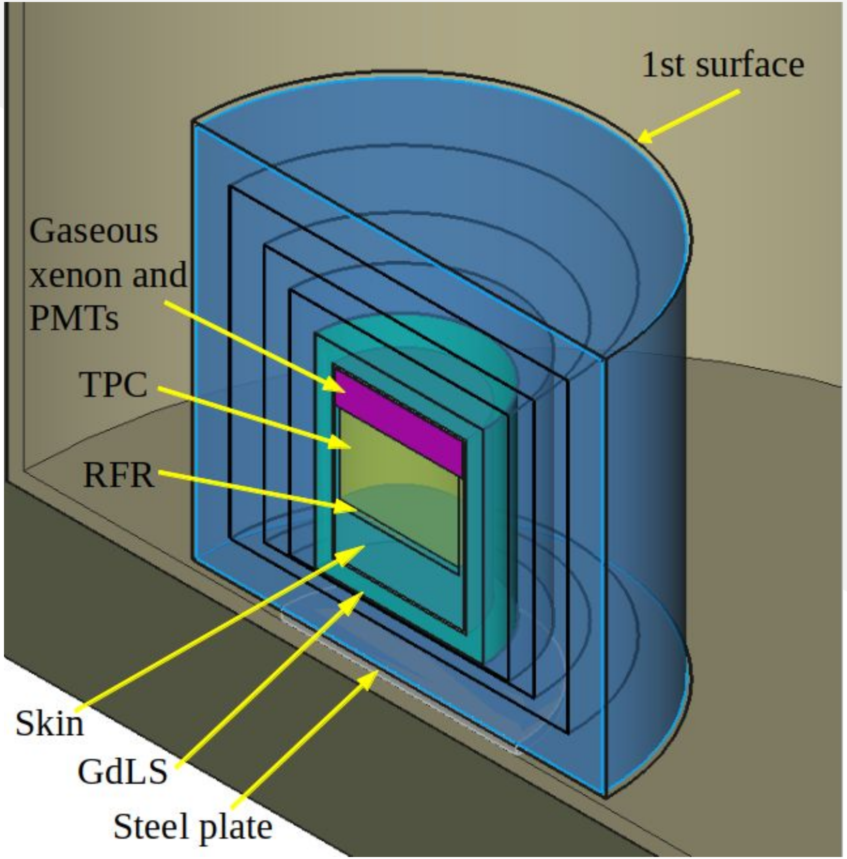
Simulation geometry

- The simulation geometry is based on a potential cavern in Boulby mine.
- 40 x 40 x 40 m^3 cube of salt rock surrounding a cylindrical cavern that is 30 m in both height and diameter.
- 30 cm thick stainless steel plate beneath the water tank.
- 71 tonnes of LXe in the TPC ($\rho = 2.953$ g cm^{-3}).
- There is a thin (0.5 m) layer of salt rock ($\rho = 2.17$ g cm^{-3}) surrounding the hall, from which gamma-rays were generated, simulating ^{238}U, ^{232}Th and ^{40}K decays.



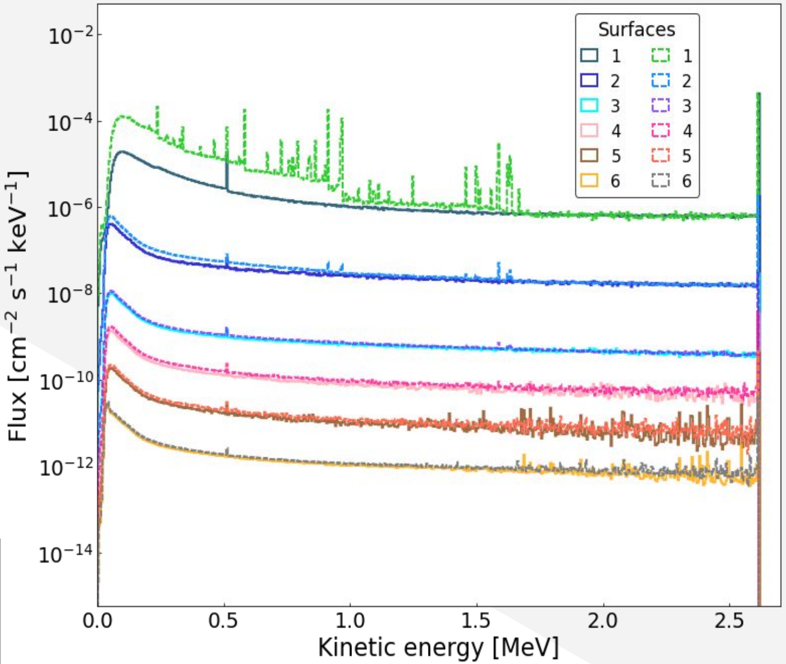
Water tank and detector

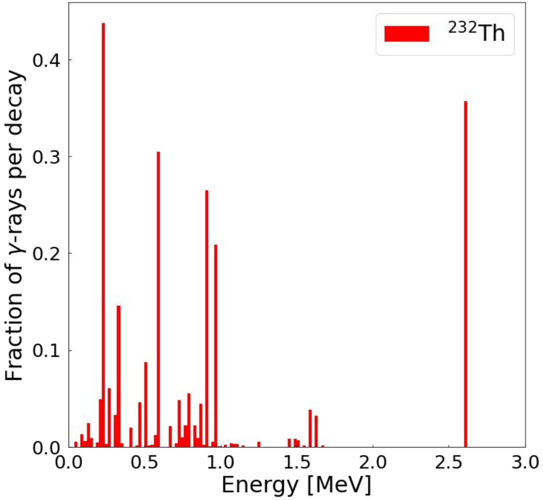
- 3.5 m of water on the top and sides of the detector, 1.5 m of water below the TPC.
- 0.5 m of GdLS around the TPC.
- GXe and PMTs above TPC, reverse field region (RFR) below TPC.
- Skin of LXe acts as a gamma-ray veto, 8 cm thick around the sides of the TPC, 78 cm thick below RFR.
- Surfaces throughout the water tank to stop and repropagate gammas to boost statistics.
- A multi-stage process is required because over several trillion gamma-rays need to be generated to attain statistically acceptable data.

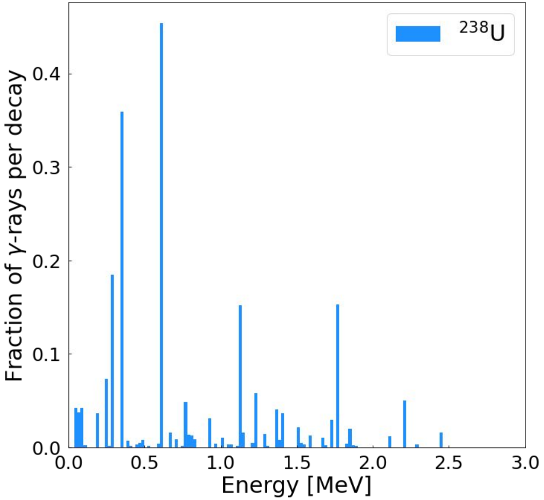


Propagation

- ^{208}Tl (2.615 MeV γ) and ^{40}K (1.461 MeV γ) generated as monoenergetic gammas.
- ^{232}Th and ^{238}U decay chains generated as gamma lines of highest intensity.
- The decay rate of the parent nuclide was normalised to 1 Bq kg^{-1}.





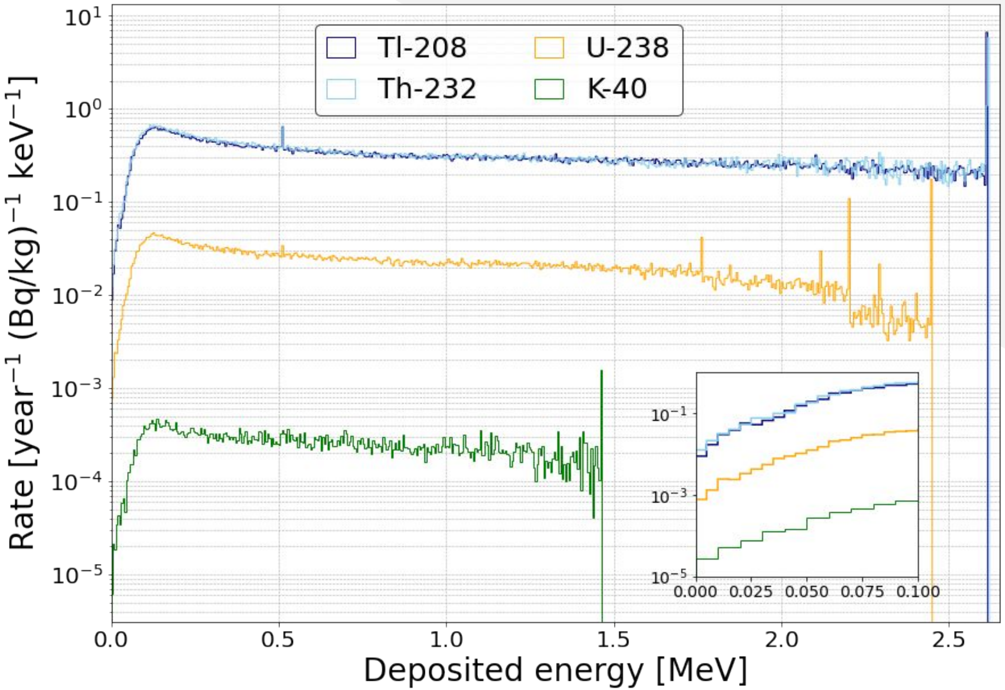


Above: The ^{208}Tl line from the ^{232}Th chain is all that is needed to be simulated due to higher attenuation of lower energy gamma-rays.

Left: Initial energy spectra of gamma rays for the ^{232}Th and ^{238}U decay chains.

Energy deposits in the TPC

- The final stage of the simulation involves propagating the gamma rays once more from the final surface.
- Information is collected from every particle that deposits > 0.1 keV in the TPC, Skin and GdLS volumes.
- These particles are primarily electrons with occasional positrons.
- Information recorded includes energy deposits and their positions and time, as well as the parameters of the particles.



Multiple scatter rejection

$$\sigma_z^* = \sqrt{\frac{\sum_{i=1}^{N} w_i (z_i - \overline{z}^*)^2}{\sum_{i=1}^{N} w_i}}$$

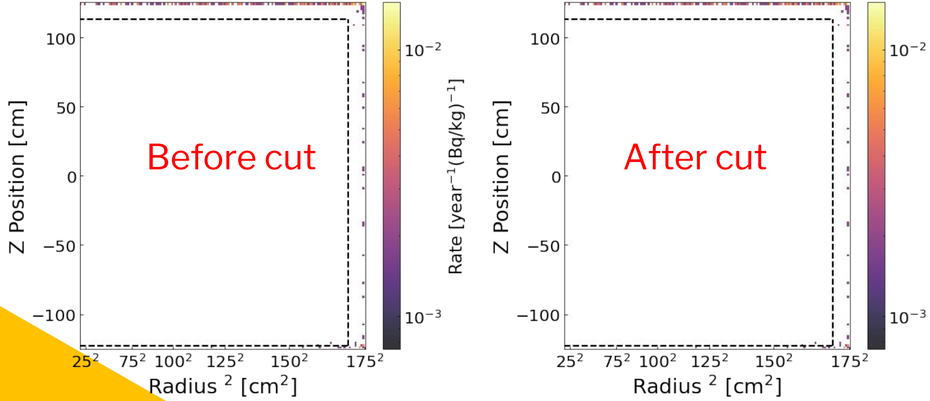
$$\sigma_r^* = \sqrt{\frac{\sum_{i=1}^{N} w_i ((x_i - \overline{x}^*)^2 + (y_i - \overline{y}^*)^2)}{\sum_{i=1}^{N} w_i}}$$

N = Number of entries in x_i x_i = array of data

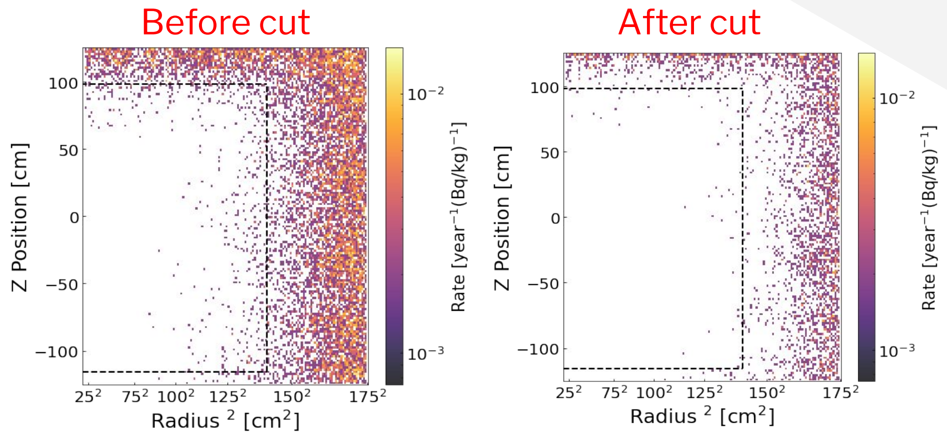
w_i = array of weights $\overline{x}^*$ = weighted mean of array

σ_R and σ_Z are the energy-weighted standard deviations of energy deposits within an event.

Ability of detector to resolve individual signals defines the MS cut: $\sigma_R < 5$ cm, $\sigma_Z < 0.5$ cm



Energy deposited in TPC =< 100 keV (WIMP ROI)



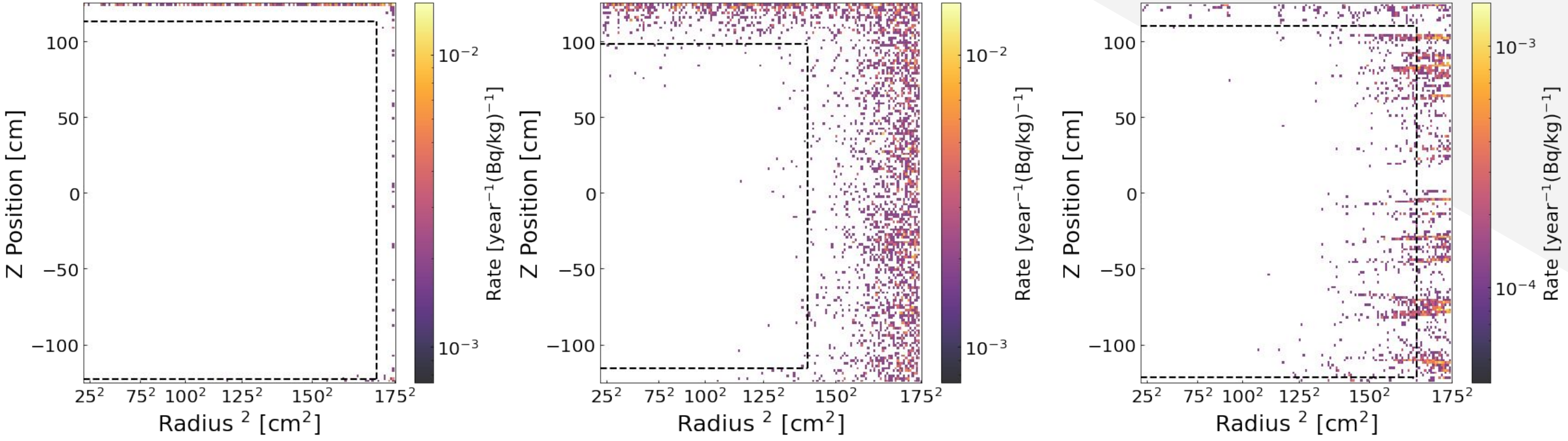
Energy deposited in TPC 2458 ± 50 keV ($0\nu\beta\beta$ ROI)

Fiducial volume cut

WIMP ROI: 0 - 20 keV
0νββ ROI: 2458 ± 50 keV.

WIMP FV: $-123 < z < 113$ cm, $r < 170$ cm
^{232}Th 0νββ FV: $-115.75 < z < 98.5$ cm, $r < 141$ cm
^{238}U 0νββ FV: $-121.75 < z < 110.5$ cm, $r < 165$ cm

Mean positions of energy deposits for each event in the TPC, in the WIMP ROI and the 0νββ ROI.



WIMP FV | ^{232}Th 0νββ FV | ^{238}U 0νββ FV

Results

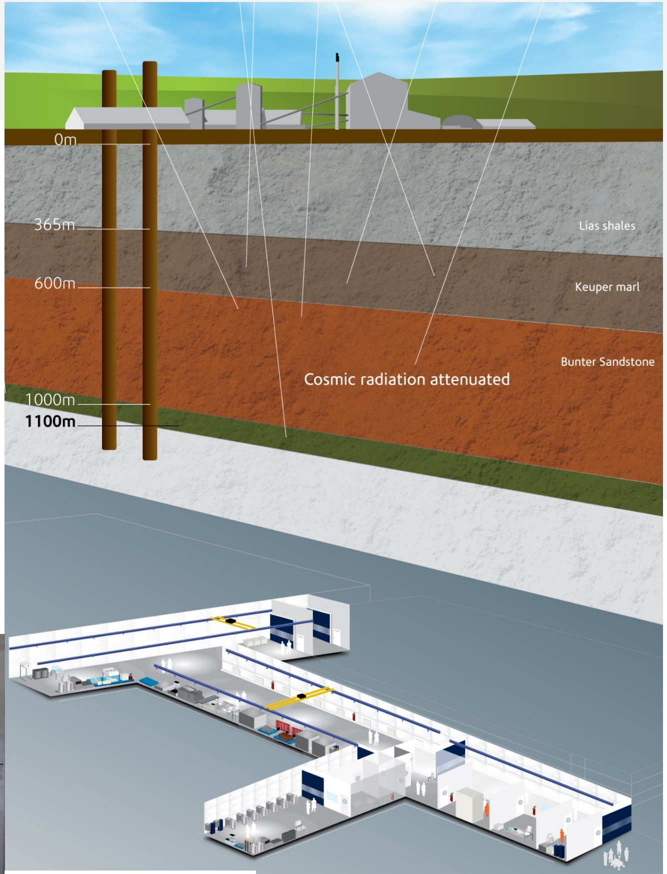
- These results represent rates of events in the TPC for 1 Bq kg^{-1} each of ^{238}U, ^{232}Th and ^{40}K, with all analysis cuts applied.
- The 0 - 100 keV rates are presented here because this covers an extended range of energies of interest for WIMP-nucleon effective field theory couplings.
- For WIMP search we need < 1 event $year^{-1}$ and for 0νββ decay we need < 0.1 event $year^{-1}$

	0 - 20 keV		0 - 100 keV		2408 - 2508 keV	
Isotope	**Events**	**Rate [$year^{-1}$ $(Bq/kg)^{-1}$]**	**Events**	**Rate [$year^{-1}$ $(Bq/kg)^{-1}$]**	**Events**	**Rate [$year^{-1}$ $(Bq/kg)^{-1}$]**
^{208}Tl	$1^{+1.75}_{-0.63}$	$(1.9^{+3.3}_{-1.2}) \times 10^{-3}$	$9^{+3.79}_{-2.67}$	$(1.70^{+0.72}_{-0.51}) \times 10^{-2}$	56 ± 7.5	0.106 ± 0.014
^{232}Th	$2^{+2.25}_{-1.26}$	$(3.8^{+4.3}_{-2.4}) \times 10^{-3}$	$8^{+3.32}_{-2.70}$	$(1.53^{+0.64}_{-0.52}) \times 10^{-2}$	52 ± 7.2	0.100 ± 0.014
^{238}U	$0^{+2.44}_{-0}$	$(0^{+2.9}_{-0}) \times 10^{-4}$	$7^{+3.30}_{-2.75}$	$(8.3^{+3.8}_{-3.2}) \times 10^{-4}$	793 ± 28	$(9.35 \pm 0.33) \times 10^{-2}$
^{40}K	$0^{+2.44}_{-0}$	$(0^{+3.8}_{-0}) \times 10^{-5}$	$0^{+2.44}_{-0}$	$(0^{+3.8}_{-0}) \times 10^{-5}$	n/a	n/a

For non-zero event rates, the statistical uncertainties are shown at 1 σ. For zero events, an upper limit of 90 % C.L. is quoted for the event rate.

Boulby underground lab

- Deepest mine in England at a depth of 1.1 km.
- Houses many experiments spanning multiple scientific disciplines.
- There is a class 1000 cleanroom called the Boulby UnderGround Screening facility (BUGS).
- Potential location for the next gen detector, in the layer of polyhalite: $K_2Ca_2Mg(SO_4)_4 \cdot 2H_2O$
- Polyhalite is high in ^{40}K, but low in ^{238}U and ^{232}Th.



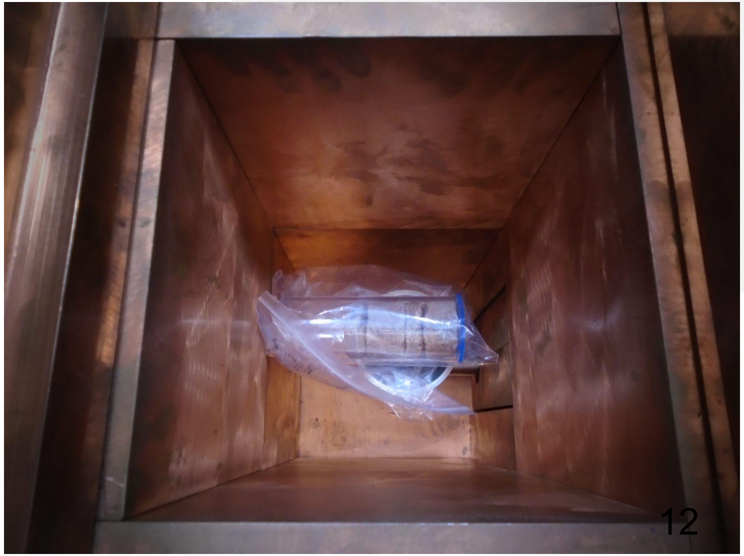
Science and Technology Facilities Council
Boulby Underground Laboratory

Measuring samples

Chaloner

- **Detector Type:** P-Type
- **Configuration:** BEGe
- **Crystal Weight:** 0.8 kg
- **Relative Efficiency:** 48%
- **Background Status:** Very Low Background

BEGe detectors offer high energy resolution, making them suitable for identifying and quantifying gamma-ray energies, particularly at low energies (3 keV - 3 MeV).



Rates normalised to Boulby polyhalite

- Averaged measurements of multiple polyhalite samples from Boulby mine.

95 % C.L.

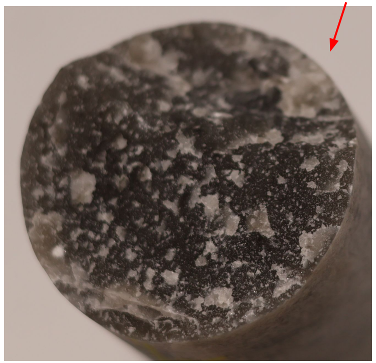
Rock type	^{40}K activity [Bq kg^{-1}]	^{232}Th activity [Bq kg^{-1}]	^{238}U activity [Bq kg^{-1}]	^{235}U activity [Bq kg^{-1}]
Polyhalite	$2500 \pm 1 \pm 287$	$(1.14 \pm 0.37 \pm 0.10) \times 10^{-2}$	$0.356 \pm 0.008 \pm 0.054$	$< 3.4 \times 10^{-2}$

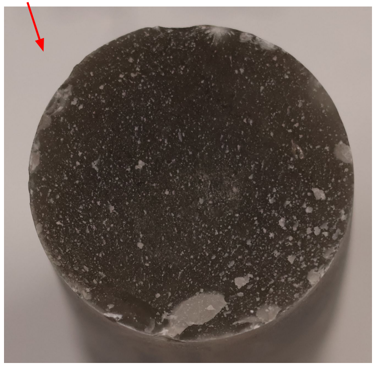
(Uncertainties are quoted as stat. then sys.)

- Rates of simulated events depositing energy in the TPC with analysis cuts applied, normalised to polyhalite.

Isotope	0 - 20 keV Rate [year^{-1}]	0 - 100 keV Rate [year^{-1}]	2408 - 2508 keV Rate [year^{-1}]
^{232}Th	$(4.3^{+4.9}_{-2.7}) \times 10^{-5}$	$(1.74^{+0.73}_{-0.59}) \times 10^{-4}$	$(1.14 \pm 0.37) \times 10^{-3}$
^{238}U	$(0^{+1.0}_{-0}) \times 10^{-4}$	$(3.0^{+1.4}_{-1.1}) \times 10^{-4}$	$(3.33 \pm 0.14) \times 10^{-2}$
^{40}K	$(0^{+9.5}_{-0}) \times 10^{-2}$	$(0^{+9.5}_{-0}) \times 10^{-2}$	n/a

Polyhalite samples



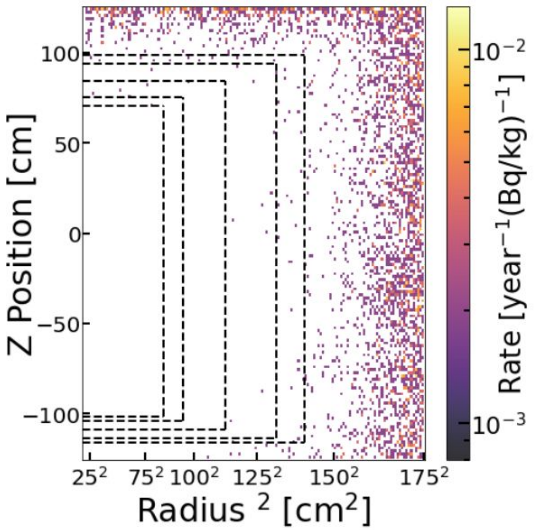


Other rock types have been screened and the results, which are soon to be published, are intended for use by any prospective experiments that Boulby Mine may host.

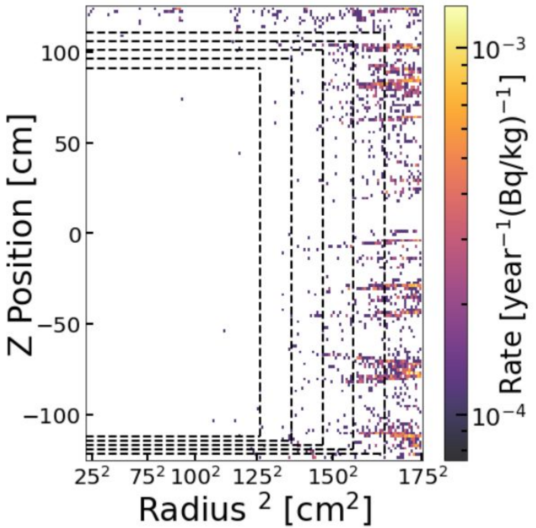
Reducing shielding

- Reducing the water shielding by 1 m from the top, sides and bottom of the detector will increase the rate by a factor of 80.9 for ^{232}Th and 111.9 for ^{238}U.
- At 1 Bq kg^{-1} the increased background is still within sensitivity limits for WIMP search, but 0νββ will require a reduced FV.
- Each of the dotted outlines represents a FV for 25 cm less shielding from the original FV to 1 m less water shielding.
- Reduction of xenon mass:
  - ^{232}Th: 39.5 → 11.5 tonnes
  - ^{238}U: 58.7 → 29.9 tonnes
- The FV will need to be reduced regardless due to background from detector materials.

^{232}Th



^{238}U



Conclusions

- A simulation to propagate gamma-rays through a simplified geometry of a next generation dark matter experiment housed in Boulby mine has been created.
- The simulation demonstrates that for 1 Bq kg^{-1}, the thickness of water shielding is sufficient for WIMP search, but a smaller FV is needed for 0νββ decay. These results are applicable to any location with correct normalisation relative to the site's radioactivity levels.
- Measurements of Boulby polyhalite have shown very low rates of gammas from ^{232}Th and ^{238}U decay chains.
- Despite the rates from ^{40}K decay being much higher, the ^{40}K gamma rays will not affect the 0νββ decay search, and the rate is still < 1 event per year in the WIMP ROI.
- If the next-generation detector were to come to Boulby, the shielding is sufficient for WIMP search and 0νββ decay with respect to rock gammas and also neutrons (as they are more easily attenuated). No detector materials were taken into account in this project.
- Investigation into reduction of shielding suggests it would not affect the WIMP background if background from rock is 1 Bq kg^{-1} or lower, but would lead to a significant decrease in FV for 0νββ decay.

Science and Technology Facilities Council
Boulby Underground Laboratory

Acknowledgements

We would like to thank STFC for funding this project and the ICL Mining Company for access to Boulby mine, their rock samples and two of their geologists, P. Edey and D. Webb, who provided us with materials to understand the geology of Boulby. We would also like to thank the whole team from the Boulby Underground Laboratory.

Backup slides

WIMP ROI

- In a LXe-based detector, WIMPs will interact with a Xe nucleus, producing an nuclear recoil.
- Within the energy region of interest for WIMP searches, this can be difficult to distinguish from electron recoils from processes like Compton scattering.

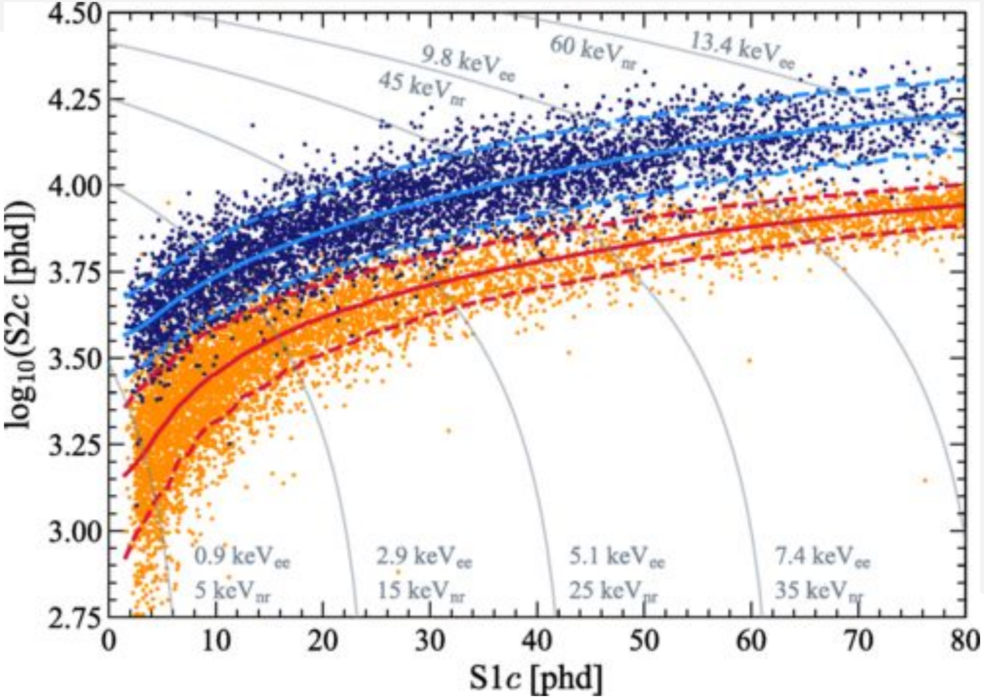
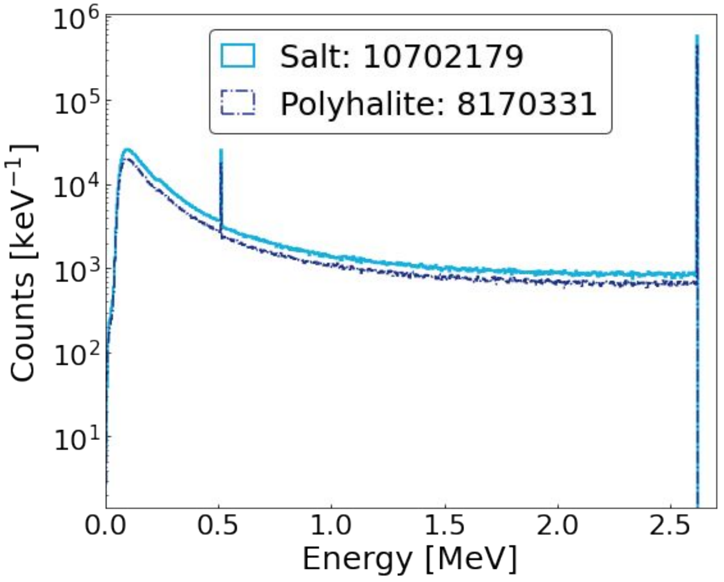
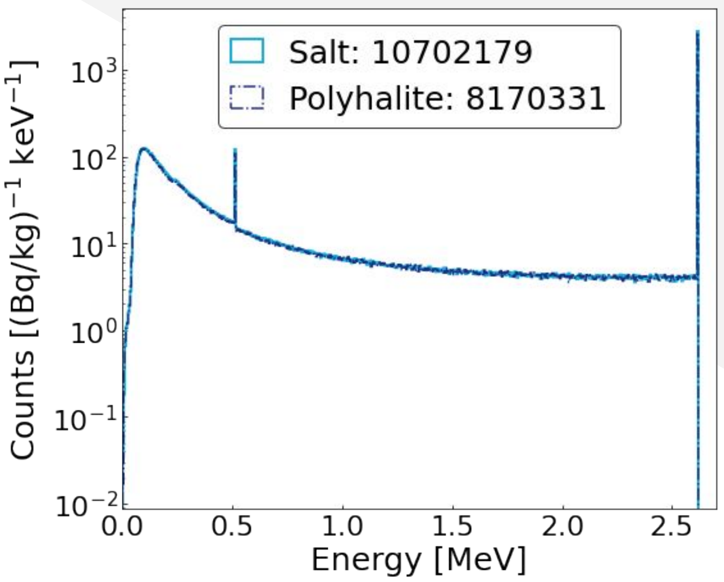


Image: LUX-ZEPLIN Collaboration. Phys. Rev. Lett. 131, 041002, 2023, https://doi.org/10.1103/PhysRevLett.131.041002

Effect of density

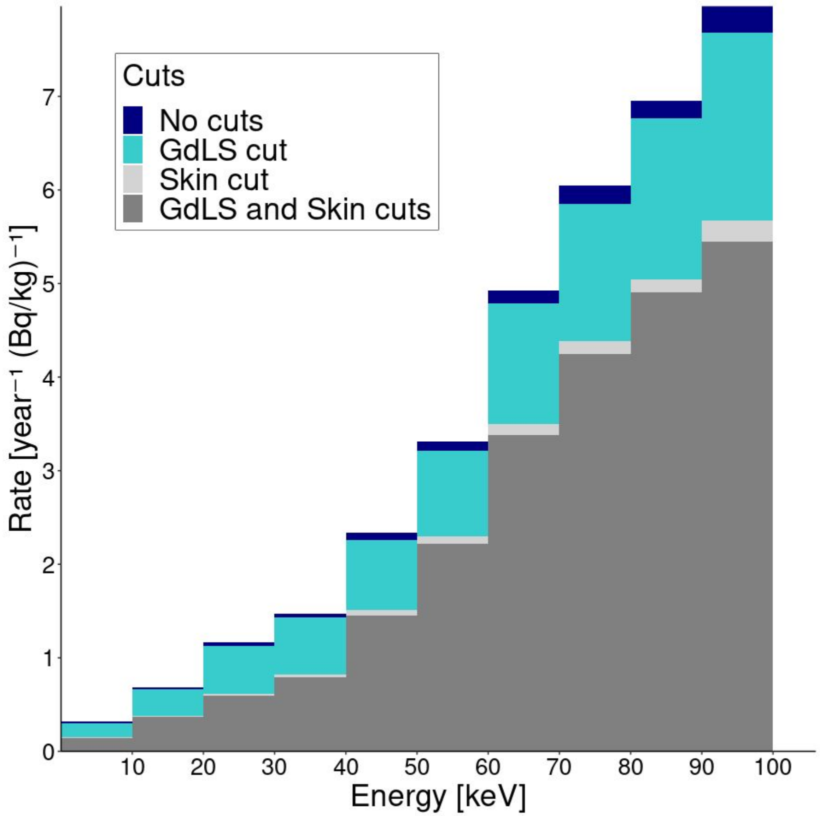


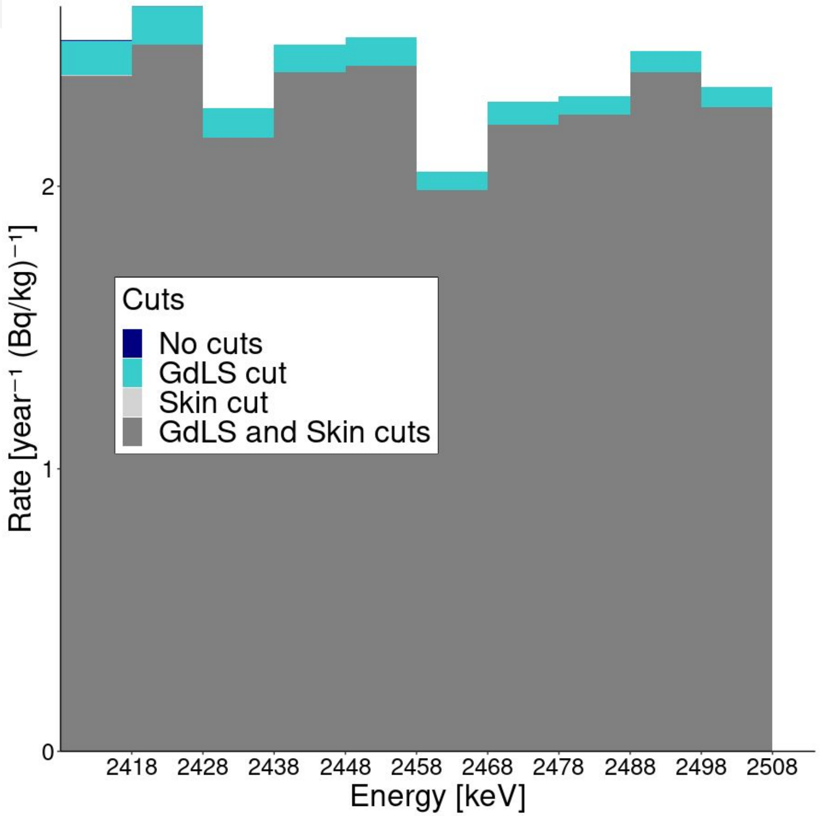


Additional analysis cuts

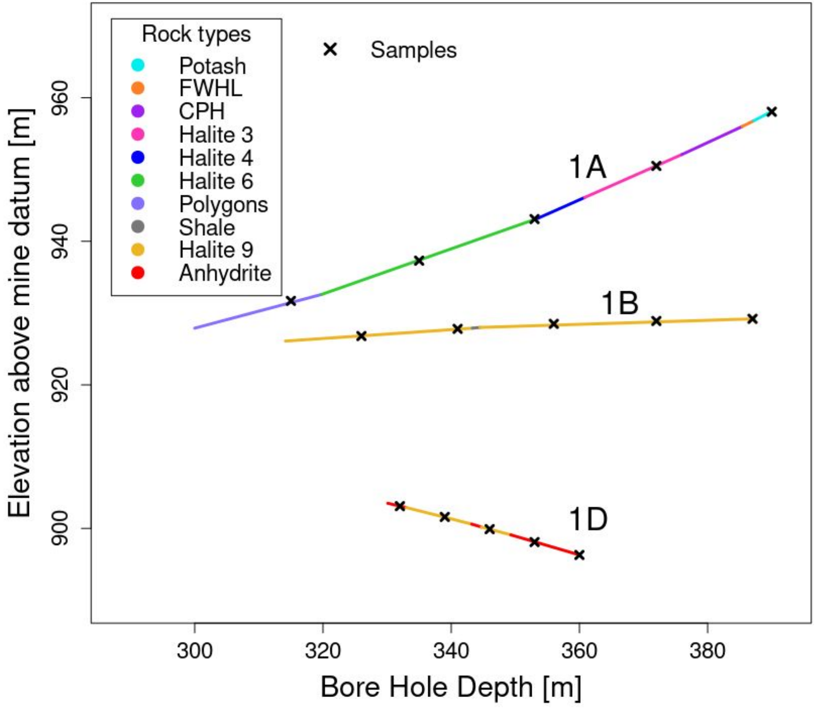
^{232}Th deposits in TPC, 0 - 100 keV and 2408 - 2508 keV

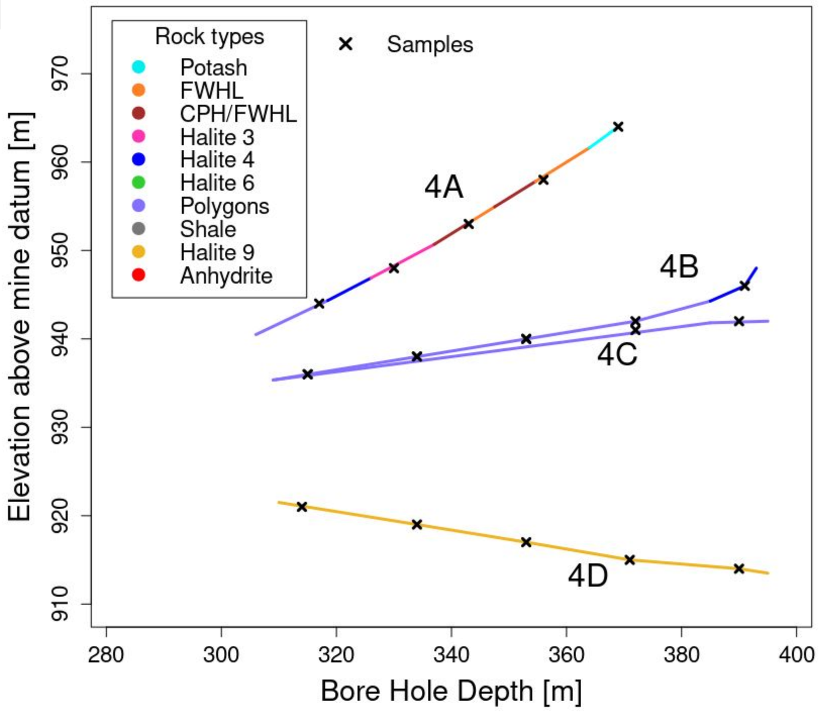
- 200 keV threshold for deposits in the GdLS.
- 100 keV threshold for deposits in the skin.
- 1 μs anti-coincidence time window.





Boulby rock samples





Locations of samples