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

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Project overview

- The next generation detector (G3) will look for WIMP interactions and evidence of 0νββ decay.
- G3, based on LXe, will have at least a magnitude greater sensitivity than predicted limits for current LXe detectors.
- Critical challenge for success is minimising sources of background.
- Building G3 underground shields it 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.

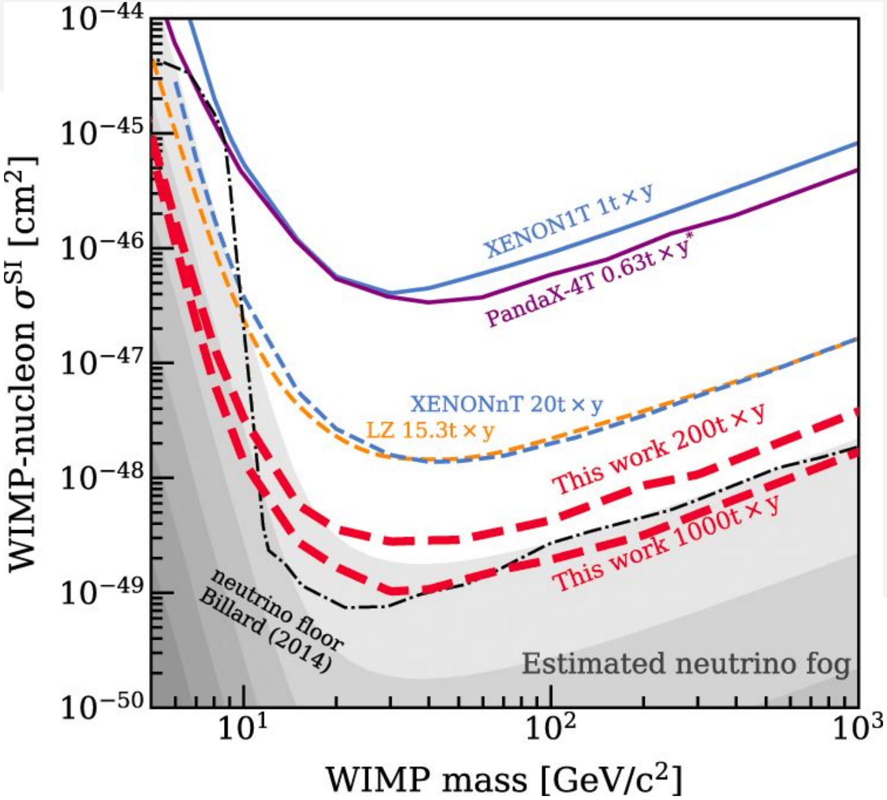
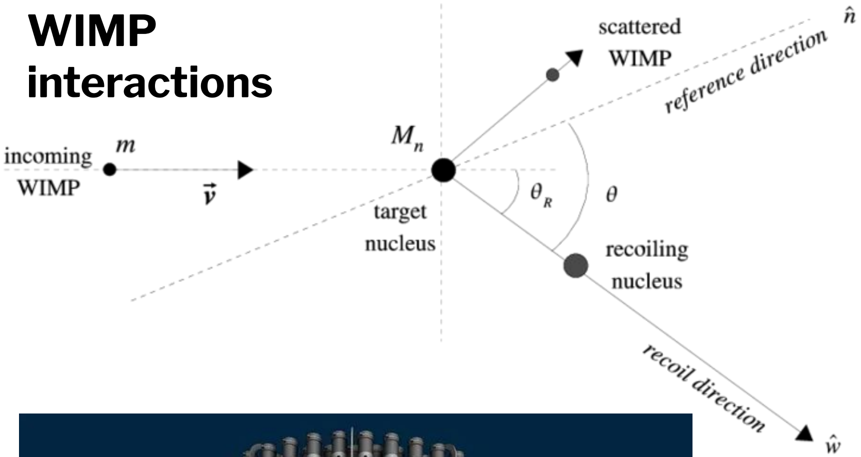
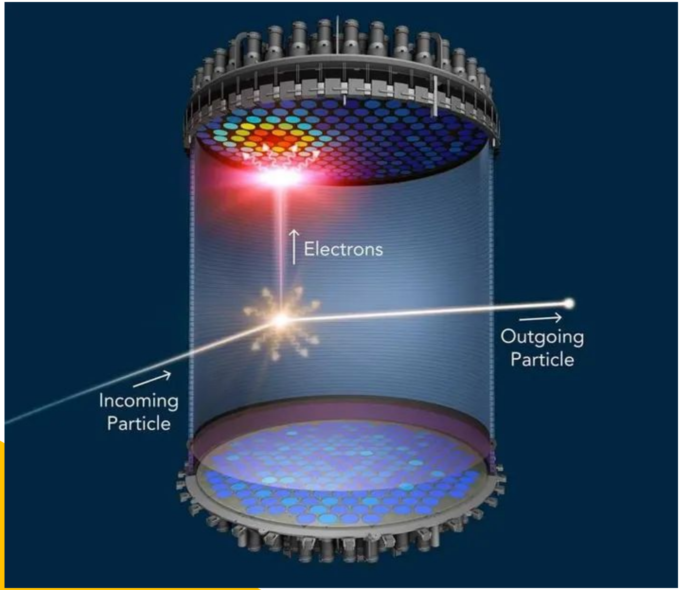


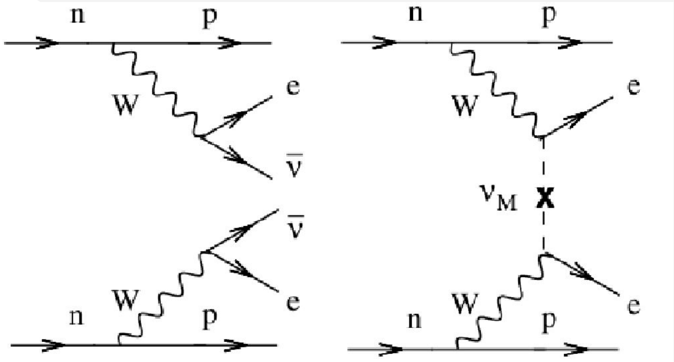
Image: J Aalbers *et al* 2023 *J. Phys. G: Nucl. Part. Phys.* **50** 013001, 10.1088/1361-6471/ac841a

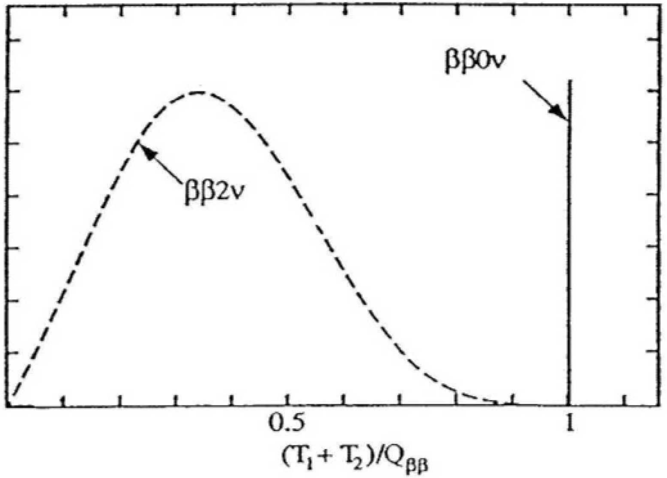
WIMP interactions





0νββ decay





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 which contribute to the electron recoil background.
- WIMP ROI: 0 - 20 keV, 0νββ decay of ^{136}Xe: 2458 keV.
- From LZ experience, water and gadolinium-doped liquid scintillator (GdLS) are used as shielding against neutrons and gamma-rays, with gamma-rays the more difficult of the two to attenuate.
- To investigate the shielding thickness required for G3, a simulation has been developed in Geant4. This will affect the design of the cavern.

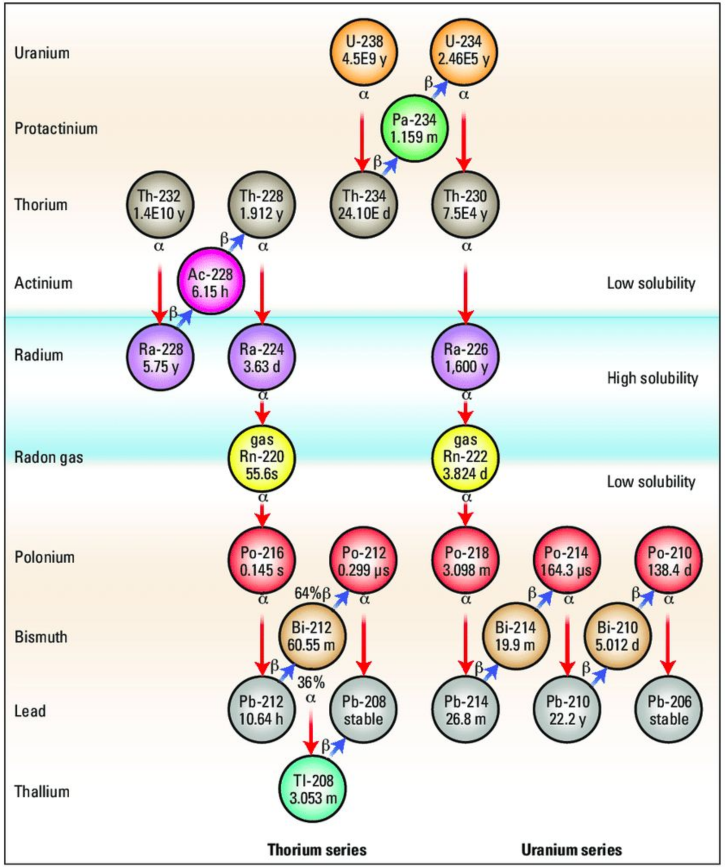
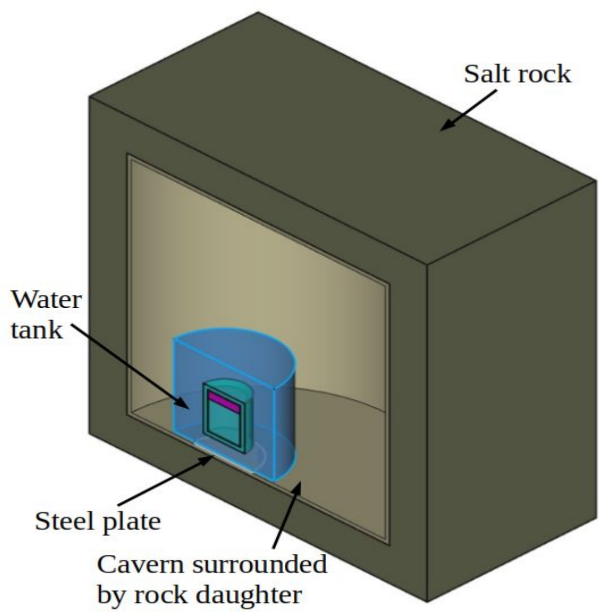
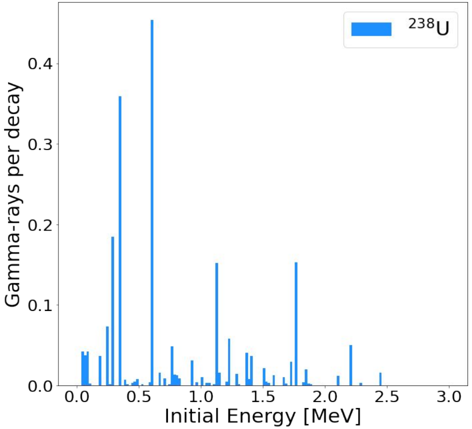


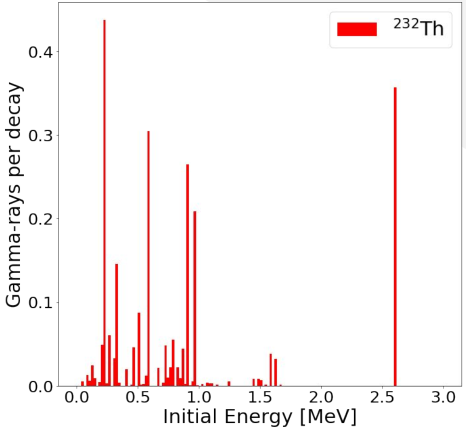
Image: Nelson, Andrew et al. (2015). Environmental health perspectives. 123. 10.1289/ehp.1408855.

The Simulation

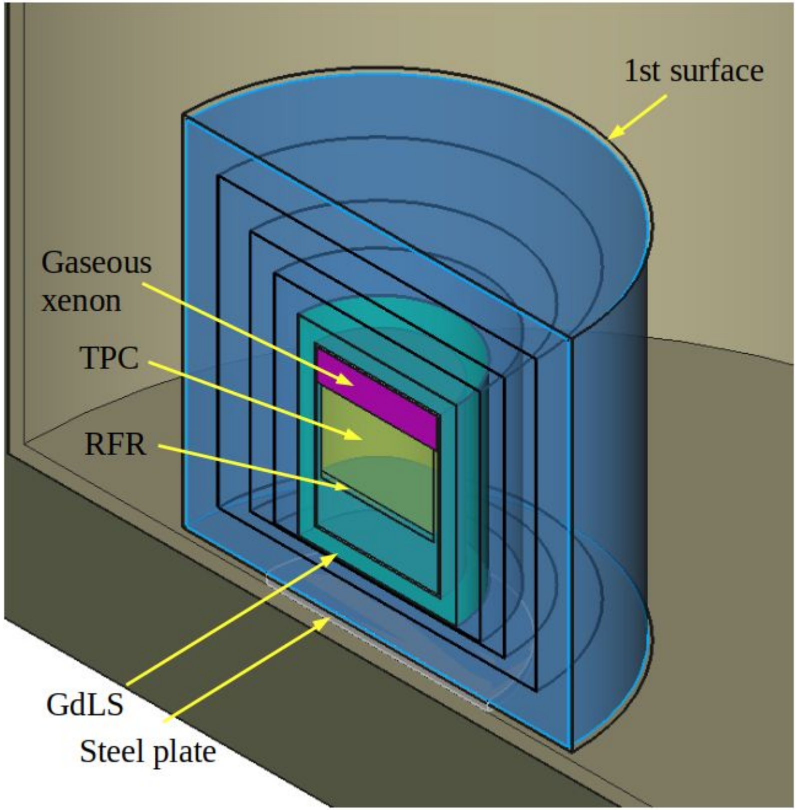
- The simulation geometry is based on a potential cavern in Boulby mine.
- 40 x 40 x 40 m size cube of rock surrounding a 30 x 30 m size cylindrical cavern.
- 3.5 m of water on the top and sides, 1.5 m of water below the TPC. 0.5 m GdLS around the TPC.
- 30 cm thick steel plate beneath the water tank.
- 71 tonnes of liquid xenon in the TPC.
- There is a thin (0.5 m) layer of salt rock (ρ = 2.17 g cm^{-3}) surrounding the hall, from which gamma-rays were generated, simulating ^{238}U and ^{232}Th decays.
- A multi-stage process is required because upwards of several billion gamma-rays need to be generated to attain statistically acceptable data.

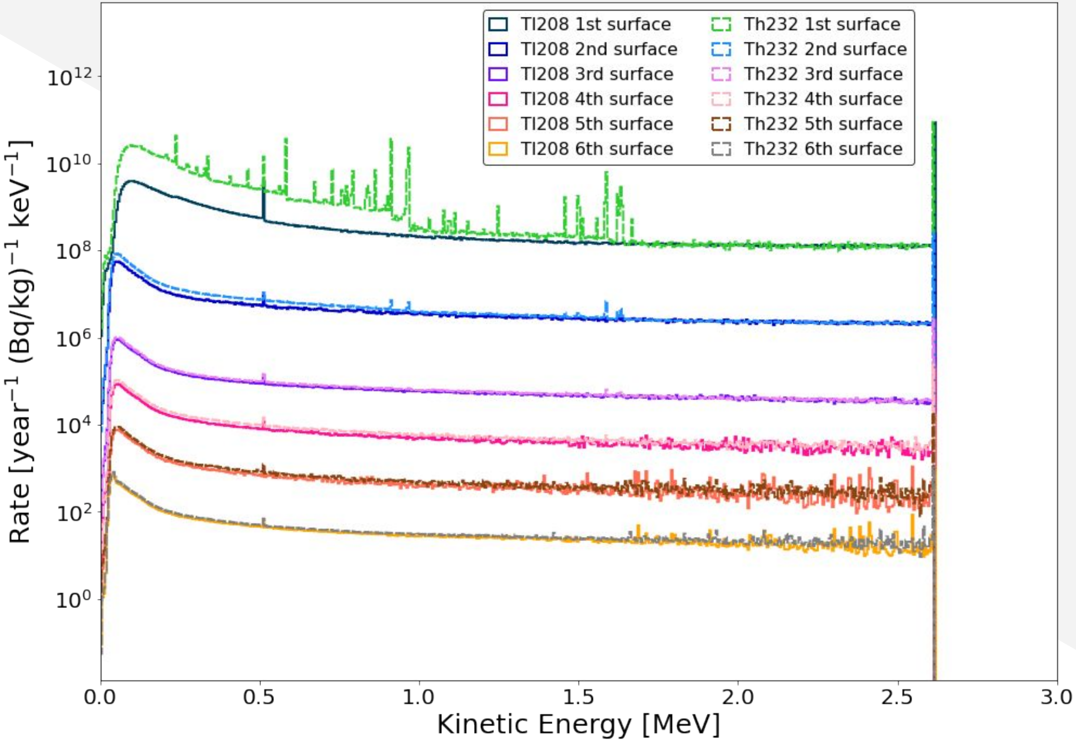






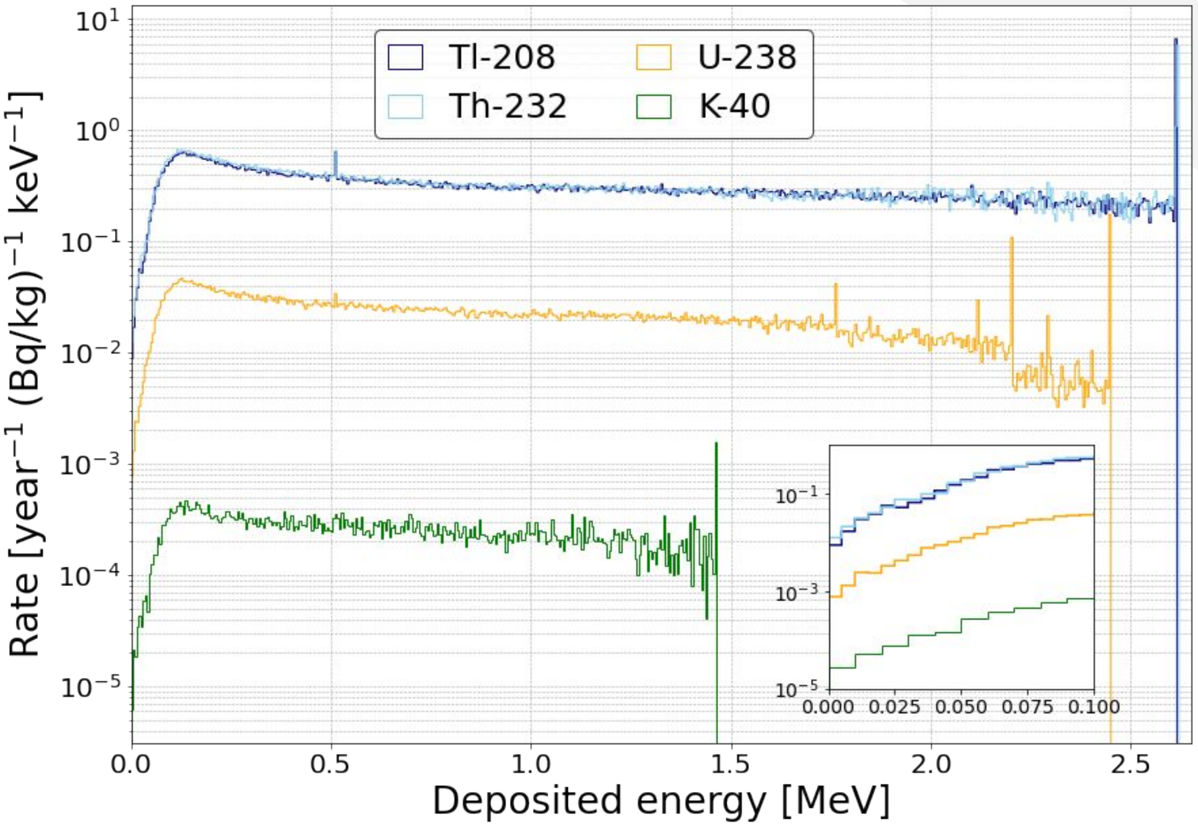
Through the water tank





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

Energy deposits



Multiple scatter and Fiducial Volume cuts

^{232}Th deposits in the TPC, 2408 - 2508 keV
(± 50 keV around the 0νββ Q-value, 2458 keV)

Black dotted line shows fiducial volume, ~63 tonnes.

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

$N =$ Number of entries in x_i $\quad x_i =$ array of data

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

MS:

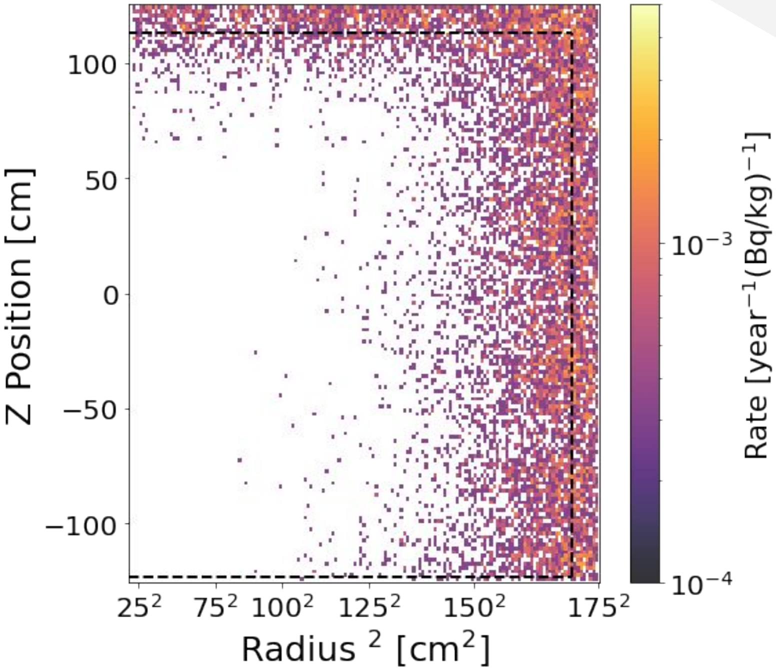
$\sigma_R < 5$ cm

$\sigma_Z < 0.5$ cm

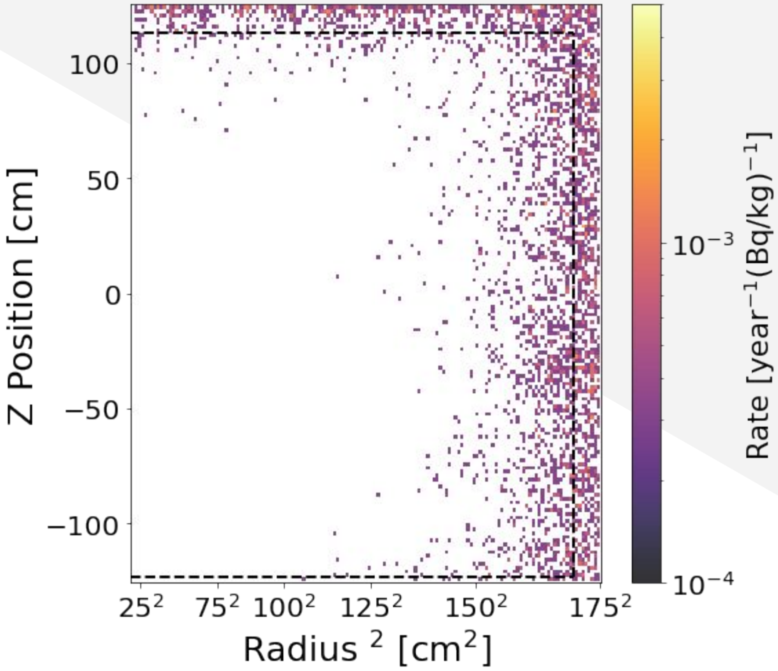
FV:

-123 < Z < 113 cm

radius < 170 cm



Before multiple scattering cut



After multiple scattering cut

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.

For WIMP search we need < 1 event year^{-1} and for 0νββ decay we need < 0.1 event year^{-1}

± 50 keV around the 0νββ Q-value

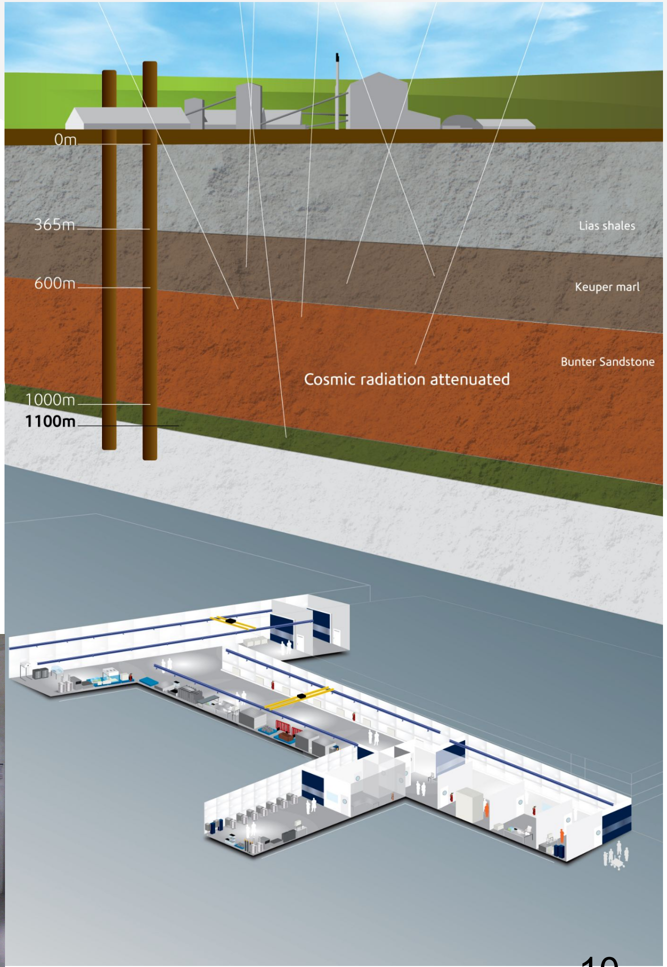
WIMP search ROI

Isotope	0 - 20 keV events	0 - 20 keV rate [year^{-1} (Bq/kg)$^{-1}$]	0 - 100 keV events	0 - 100 keV rate [year^{-1} (Bq/kg)$^{-1}$]	2408 - 2508 keV events	2408 - 2508 keV rate [year^{-1} (Bq/kg)$^{-1}$]
^{208}Tl	$1^{+1.75}_{-0.63}$	$0.0019^{+0.0033}_{-0.0012}$	$9^{+3.79}_{-2.67}$	$0.017^{+0.007}_{-0.005}$	1593 ± 40	3.01 ± 0.08
^{232}Th	$2^{+2.25}_{-1.26}$	$0.0038^{+0.0043}_{-0.0024}$	$8^{+3.32}_{-2.7}$	$0.015^{+0.006}_{-0.005}$	1579 ± 40	3.02 ± 0.08
^{238}U	$0^{+2.44}_{-0}$	$0^{+0.0007}_{-0}$	$2^{+2.25}_{-1.26}$	$0.0006^{+0.0007}_{-0.0004}$	633 ± 25	0.186 ± 0.074
^{40}K	$0^{+2.44}_{-0}$	$0^{+0.00004}_{-0}$	$0^{+2.44}_{-0}$	$0^{+0.00004}_{-0}$	n/a	n/a

Asymmetric uncertainties are quoted at 68.27 % confidence level (C.L) intervals for the Poisson signal mean and 90 % C.L intervals for 0 values.

Boulby Underground Mine

- 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 called BUGS.
- Potential location for G3, in the layer of polyhalite (1300 m): $K_2Ca_2Mg(SO_4)_4{\cdot}2H_2O$
- Polyhalite is high in ^{40}K, but low in ^{238}U and ^{232}Th.

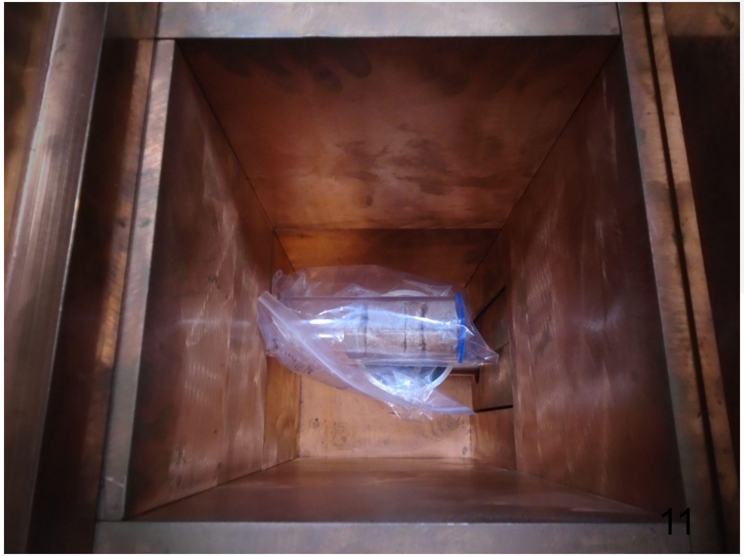


Measuring samples

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).



11

Boulby rock

Average measurements of radioactive isotopes in rock samples from Boulby Mine. An * denotes an upper limit at 95% confidence interval.

ICL mining company gave us samples of rock from boreholes ~1100 m below sea level.

Key:

FWHL = footwall halite
CPH = clear pink halite
LG = low grade

The difference in the halites is mainly down to composition, contaminants and grain size.

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 1100 m	3583 ± 3	0.0091 ± 0.0004	0.134 ± 0.020	< 0.019*
Polyhalite 1300 m	2498 ± 1	0.019 ± 0.005	0.382 ± 0.009	< 0.008*
Salt polygons	58.6 ± 0.3	0.190 ± 0.005	0.199 ± 0.006	0.021 ± 0.002
LG potash	3578 ± 3	3.38 ± 0.03	2.54 ± 0.027	0.140 ± 0.009
Potash	1508 ± 3	2.86 ± 0.02	2.36 ± 0.04	0.118 ± 0.011
FWHL	282 ± 1	1.19 ± 0.01	1.16 ± 0.02	0.059 ± 0.005
CPH	1709 ± 3	0.417 ± 0.024	0.535 ± 0.026	< 0.042*
Anhydrite	13.6 ± 0.1	0.660 ± 0.005	3.93 ± 0.01	0.192 ± 0.002
Halite 3	587 ± 2	0.894 ± 0.022	0.877 ± 0.023	0.047 ± 0.008
Halite 4	480 ± 1	4.31 ± 0.02	2.36 ± 0.02	0.129 ± 0.004
Halite 9	37.5 ± 0.2	0.302 ± 0.005	0.595 ± 0.007	0.035 ± 0.002

Rates normalised to Boulby rock

- Rates of events in the TPC with analysis cuts applied, normalised to measurements of polyhalite from Boulby mine, 1300 m underground.
- Note that these are only cavern backgrounds and do not include backgrounds from other sources such as detector materials.
- Reducing the shielding by 0.5 m will increase the rate by a factor of 8.5, which at 1 Bq kg^{-1} is still within sensitivity limits for WIMP search, but $0\nu\beta\beta$ will require a reduced FV.

Normalised to 1 Bq kg^{-1}

	0 - 20 keV	0 - 100 keV	2408 - 2508 keV
Isotope	Rate [year^{-1}]	Rate [year^{-1}]	Rate [year^{-1}]
^{232}Th	$(3.8^{+4.3}_{-2.4}) \times 10^{-3}$	$(1.5^{+0.6}_{-0.5}) \times 10^{-2}$	3.02 ± 0.08
^{238}U	$0^{+0.0007}_{-0}$	$(5.9^{+6.6}_{-3.7}) \times 10^{-4}$	0.186 ± 0.074
^{40}K	$0^{+0.00004}_{-0}$	$0^{+0.00004}_{-0}$	n/a

Normalised to Boulby measurements

	0 - 20 keV	0 - 100 keV	2408 - 2508 keV
Isotope	Rate [year^{-1}]	Rate [year^{-1}]	Rate [year^{-1}]
^{232}Th	$(7.2^{+8.2}_{-4.6}) \times 10^{-5}$	$(2.9^{+1.1}_{-0.9}) \times 10^{-4}$	0.057 ± 0.014
^{238}U	$0^{+0.00027}_{-0}$	$(2.3^{+2.5}_{-0.8}) \times 10^{-4}$	0.071 ± 0.003
^{40}K	$0^{+0.1}_{-0}$	$0^{+0.1}_{-0}$	n/a

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.
- Rates of < 1 year^{-1} (Bq/kg)$^{-1}$ have been found for each the radionuclides, ^{232}Th, ^{238}U and ^{40}K at from simulated data in the WIMP search ROI.
- The simulation demonstrates that for 1 Bq kg^{-1}, the shielding is sufficient for WIMP search, but a smaller FV is needed for 0νββ decay. Reducing the shielding by 0.5 m will increase the rate by a factor of 8.5, which at 1 Bq kg^{-1} is still within sensitivity limits for WIMP search, but 0νββ will require a reduced FV.
- Measurements at Boulby have shown the following rates in the 1300 m polyhalite layer:
  - ^{232}Th: 0.019 ± 0.005 Bq kg^{-1}
  - ^{238}U: 0.382 ± 0.009 Bq kg^{-1}
  - ^{40}K: 2498 ± 1 Bq kg^{-1}
- If G3 were to come to Boulby, the shielding is sufficient for WIMP search and 0νββ decay, but again, this takes only gamma-rays from the cavern into account (and neutrons as they are more easily attenuated), and not gamma-rays from detector materials.

Acknowledgements

I would like to thank STFC for funding this project and the ICL Mining Company for access to Boulby mine, their rock samples and their knowledgeable geologists.

I would also like to thank the whole team from the Boulby Underground Laboratory who assisted me in my data collection.

Any questions?

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.

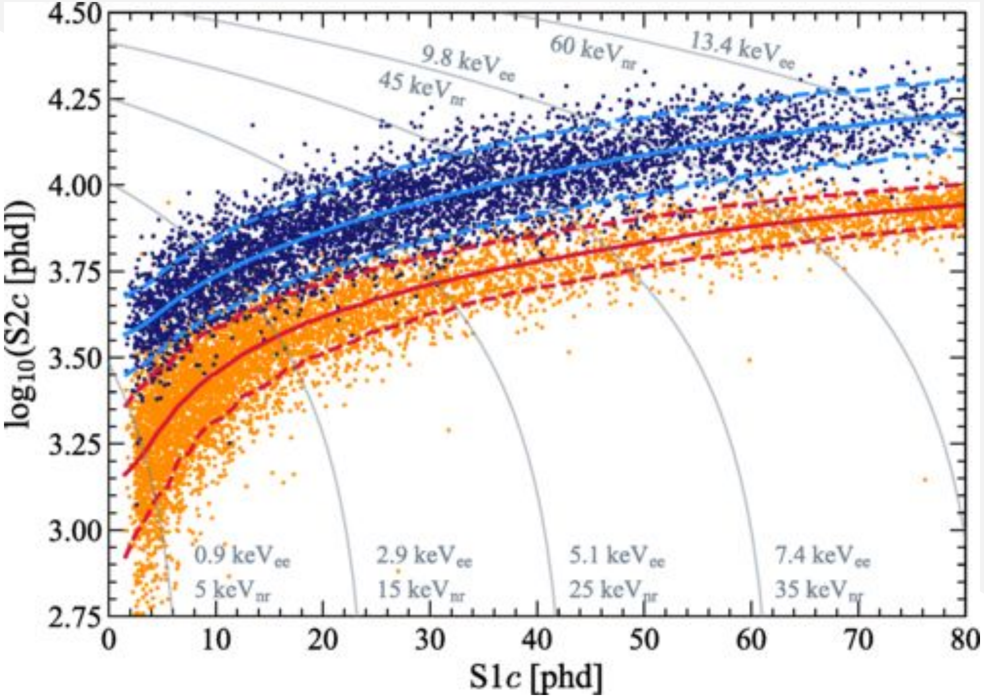
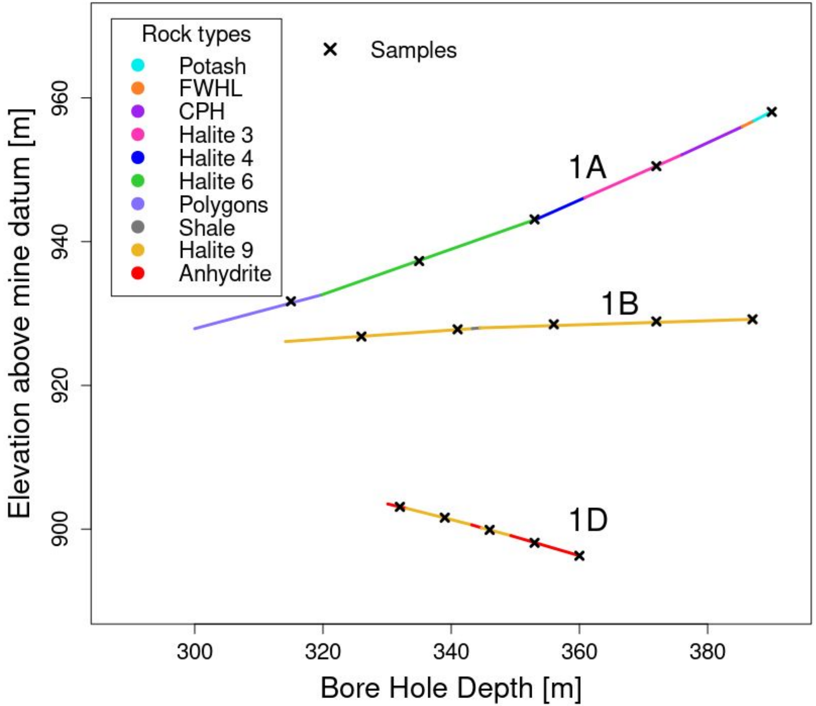
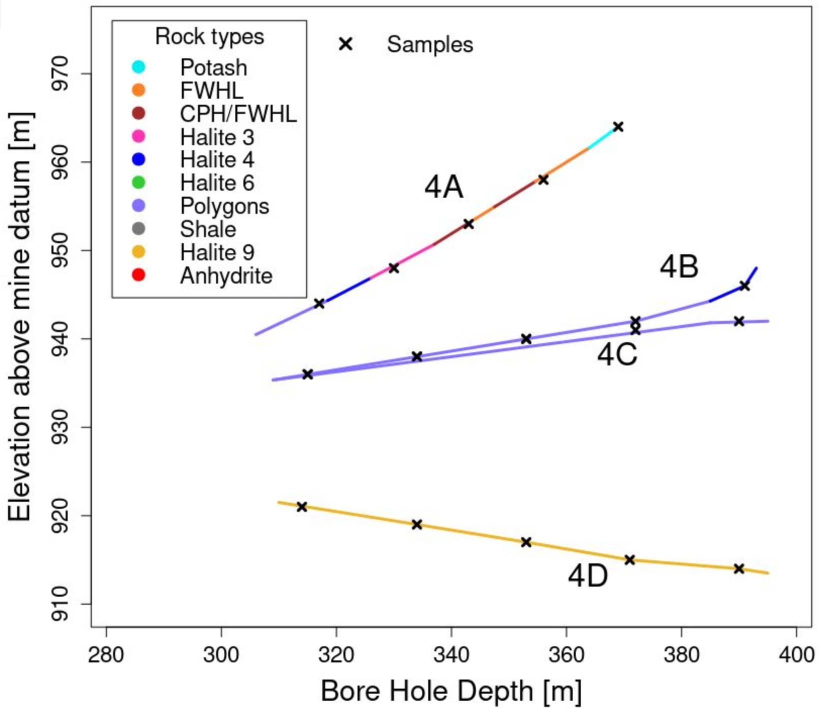


Image: LUX-ZEPLIN Collaboration. Phys. Rev. Lett. 131, 041002, 2023, https://doi.org/10.1103/PhysRevLett.131.041002

Back-up slides

Boulby rock samples





Analysis cuts

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

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