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Muon-induced background in the next-generation dark matter experiment based on liquid xenon

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on behalf of the Boulby Feasibility Study team

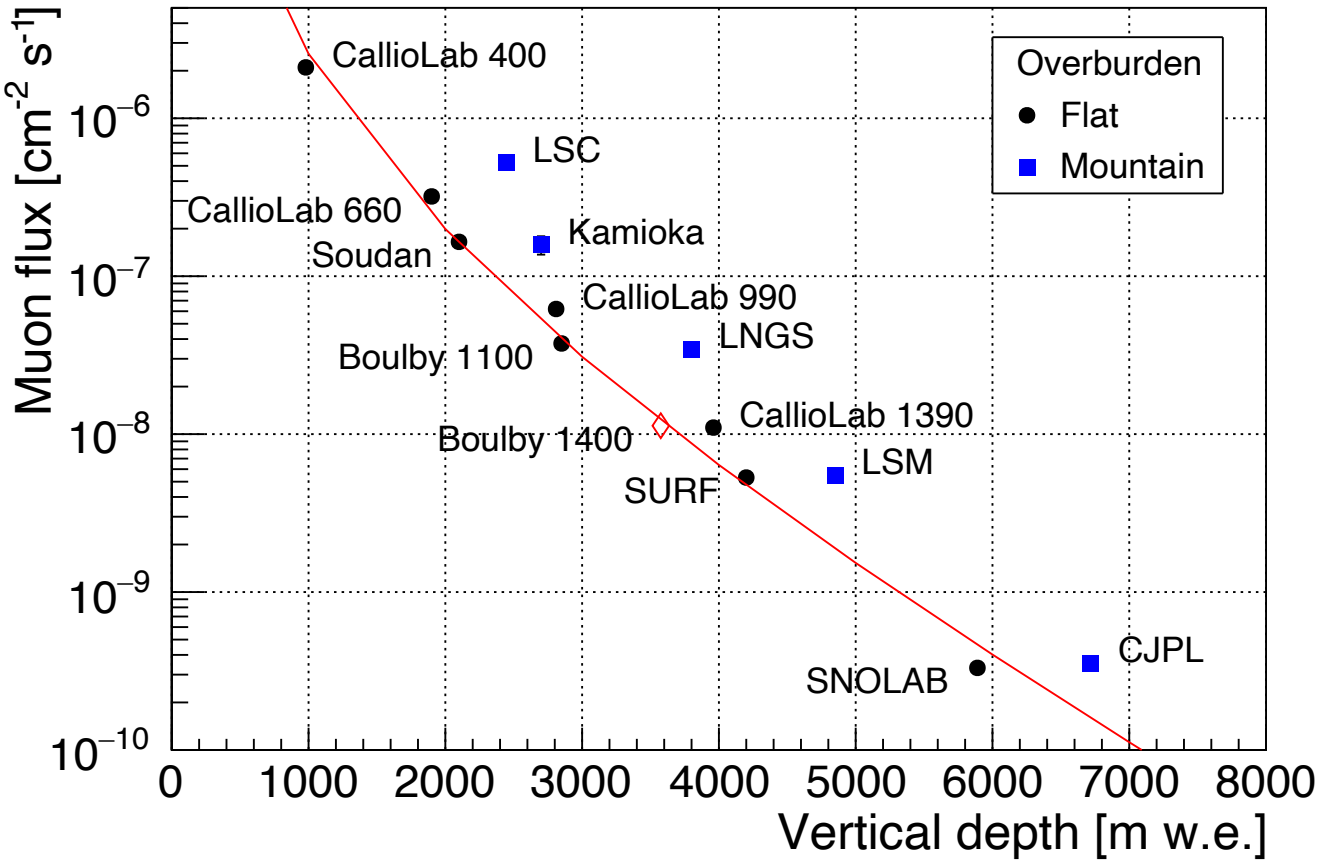
Outline

- Goals.
- Geometry in GEANT4.
- Muon model.
- Simulation runs: summary.
- Event selection.
- Results.
- Example events.
- Summary.
- All results are preliminary.

Goals

- Concern about muon-induced background.
- Determine the requirement on depth for a future G3 DM experiment.
- Work funded by STFC with a link to Boulby: is Boulby mine depth sufficient for the next generation DM experiment?
  - Hence, Boulby depth was chosen as a benchmark.
  - Results are relevant to other sites at a similar depth.
- Focus on LXe TPC.
- Create geometry model with reasonable level of details — use the main materials and approximate layout.
- Use realistic muon flux and energy spectrum.
- Focus on neutron induced Xe recoils — assumed that other energy depositions can be rejected using standard S2 vs S1 discrimination technique (S1/S2 were not produced in these simulations).

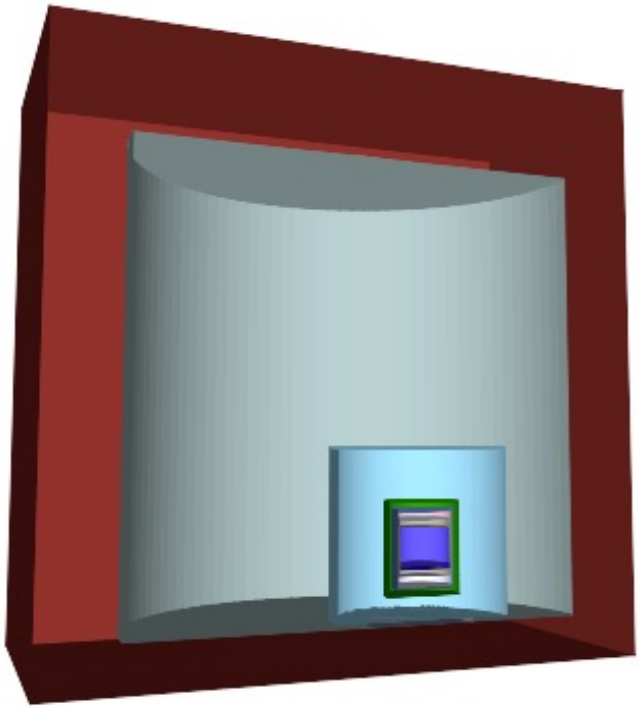
Underground labs



- Similar fluxes at Boulby and LNGS (about 10% difference).
- The curve shows simulations for 'flat' surface and 'standard' rock: $Z = 11$, $A = 22$.

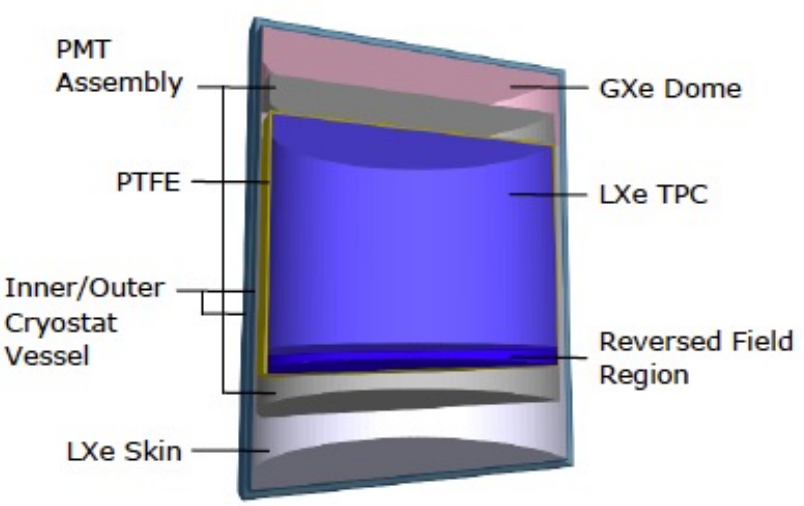
Geometry

- Cavern: cylindrical, 30 m height and 30 m diameter.
- Rock material: NaCl or polyhalite.
- Water tank (WT):
  - 10.9 m height, 11.9 m diameter;
  - water shielding 3.5 m (top), 3.5 m (side), 1.5 m (bottom).
- Steel plate underneath the WT
  - 30 cm (H), 6.9 m (D) – additional shielding.
- Gd-loaded liquid scintillator (LS) – 50 cm around the cryostat.
- Cryostat: 5 m height, 4 m diameter.
- Offset from centre, 5 m between the WT and the cavern wall.



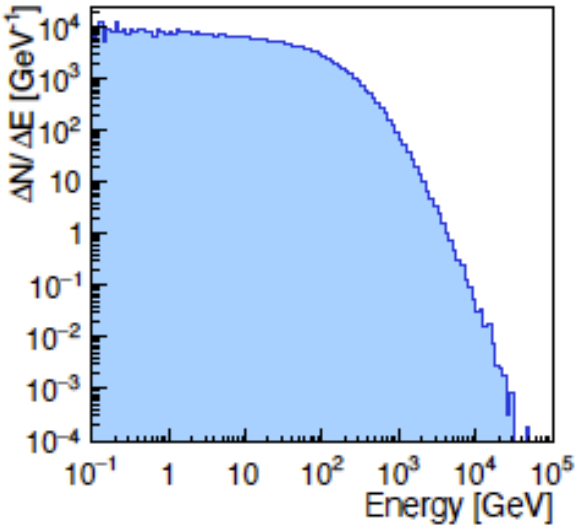
Geometry: TPC

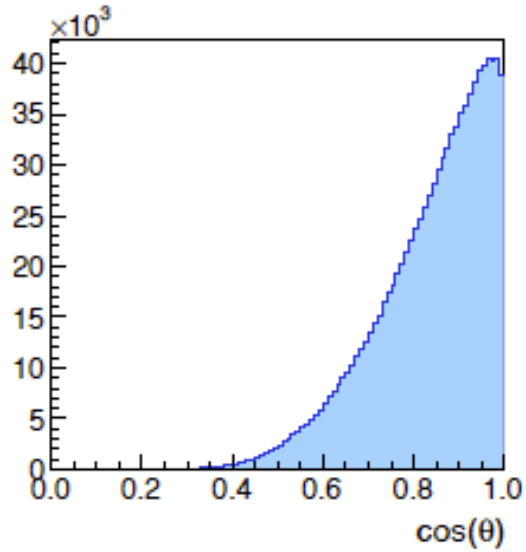
- Simplified main detector, based on the LZ design, scaled up – 71 t LXe in the TPC; about 100 t of LXe in total.
- Cryostat: 5 m height, 4 m diameter.
  - Cylindrical, no dome on top or bottom.
  - Two titanium vessels.
- Simplified PMT array (top and bottom) – steel with 5% of standard density.
- LXe skin – 8 cm thick, 70 cm beneath bottom PMT array; assumed to be instrumented with PMTs.
- TPC wall: PTFE, 3 cm thick.



Muon model

- Flux and energy spectrum calculated using MUSUN at current Boulby lab location (1100 m, 2850 m w. e.).
- Flux (through spherical detector):
  - 3.75×10^{-8} cm^{-2} s^{-1} from ZEPLIN-I/II/III measurements.
  - $\langle E \rangle$ = 261 GeV.
  - $\langle \theta \rangle$ = 30.6º.
- Muons sampled on surface of a box in rock:
  - 7 m from the cavern on top, 5 m on the sides.
- Also potential site at 1400 m, 3575 m w. e.
  - Used same muon distributions.
  - Calculated flux: 1.13×10^{-8} cm^{-2} s^{-1}.

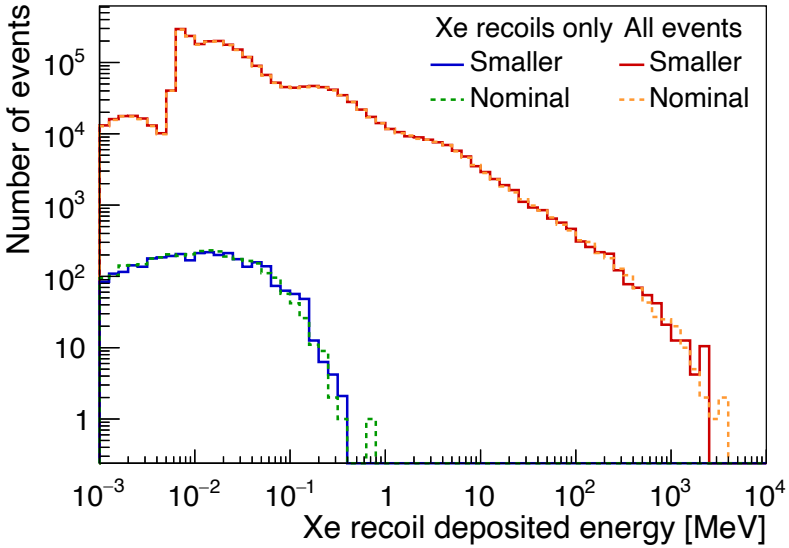


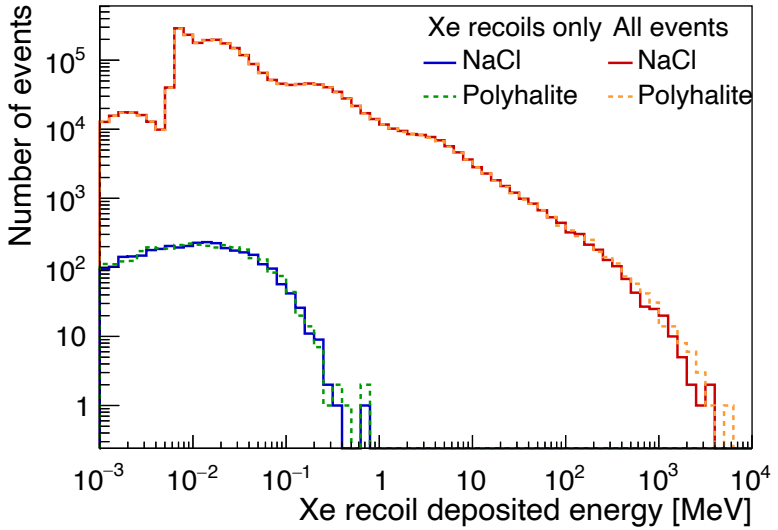


Simulation runs

- GEANT4 v10.5, Shielding physics list.
- Two rock materials: NaCl, polyhalite.
- 800 million simulated muons each.
- 1100 m site in NaCl: detector exposure 29 years.
- 1400 m site in polyhalite: detector exposure 97 years.
- Two tests with smaller statistics:
  - 'Small' versus 'big' cavern – no noticeable difference in Xe recoil spectra (no analysis cuts).
  - NaCl vs $CaCO_3$ as rock – no noticeable difference in Xe recoil spectra (no analysis cuts).
- All results below are for a 'big' cavern as described on slide 5 and two types of rock: NaCl, polyhalite.

Test runs





No noticeable difference between small and big cavern, and between different rock compositions.

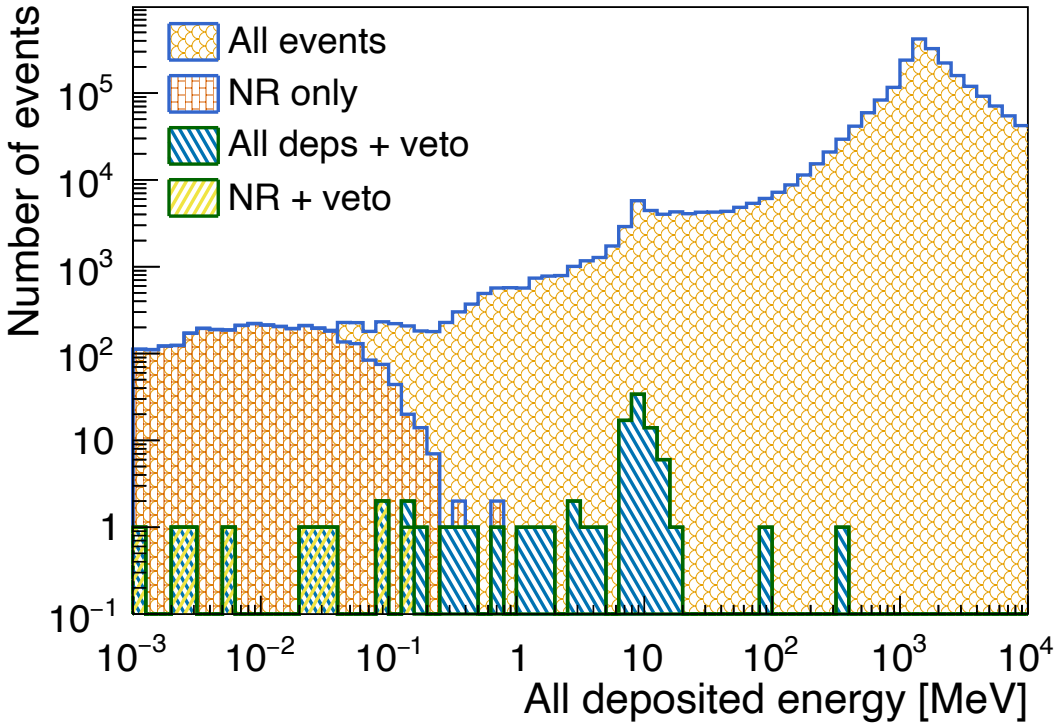
Analysis

- TPC energy depositions:
  - Summed over 1 ms window – mimicking realistic readout times.
  - Recorded by type:
    - Xe recoils,
    - Muon,
    - EM (originated from either a photon or an electron),
    - Other.
- Veto energy depositions:
  - Skin, LS, WT,
  - Summed over 1 μs window – assumed PMT signal shaping time,
  - No distinction by type.
- Event information is stored together with the seed used to simulate this event.
  - Every event can be re-processed to get more detailed info.

Background events

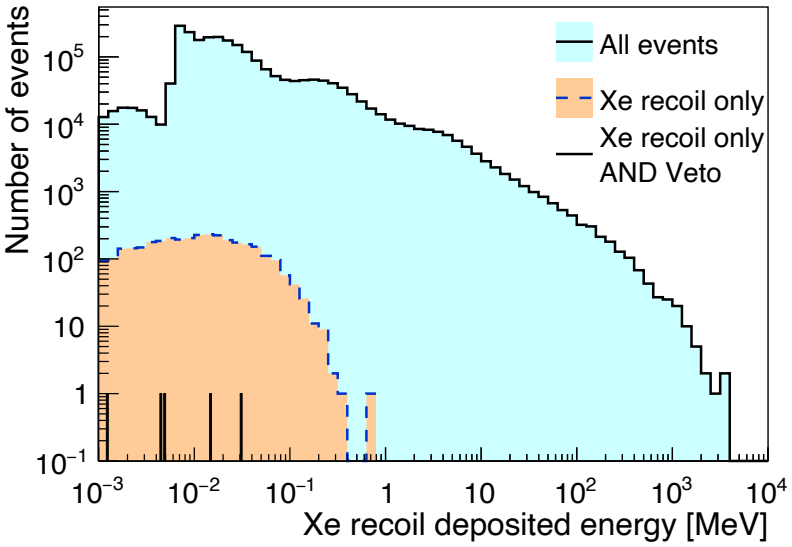
- TPC
  - Total Xe recoil energy >1 keV,
  - Other depositions must be below threshold: (+ EM + Other/10) < 10 keV,
  - Single Xe recoil above 1 keV, no other above 0.5 keV,
  - At least 5 cm from TPC walls.
- Veto
  - Anti-coincidence window: 0.5 ms.
  - Thresholds:
    - Skin: 100 keV,
    - LS: 200 keV,
    - WT: 200 MeV.
  - Scenario without LS
    - Emulated by treating LS and WT as a single volume,
    - Energy depositions in LS and WT summed (used WT threshold of 200 MeV).

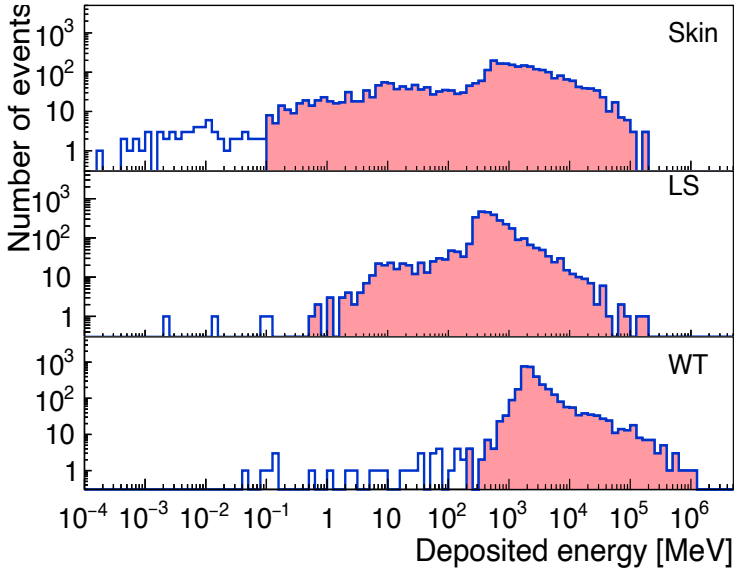
Energy spectra of events in the TPC



- Energy spectra of all events and of NR only, without and with veto cuts - polyhalite.
- All (or almost all) events at low energies are NRs.

Energy spectra in the TPC and other volumes





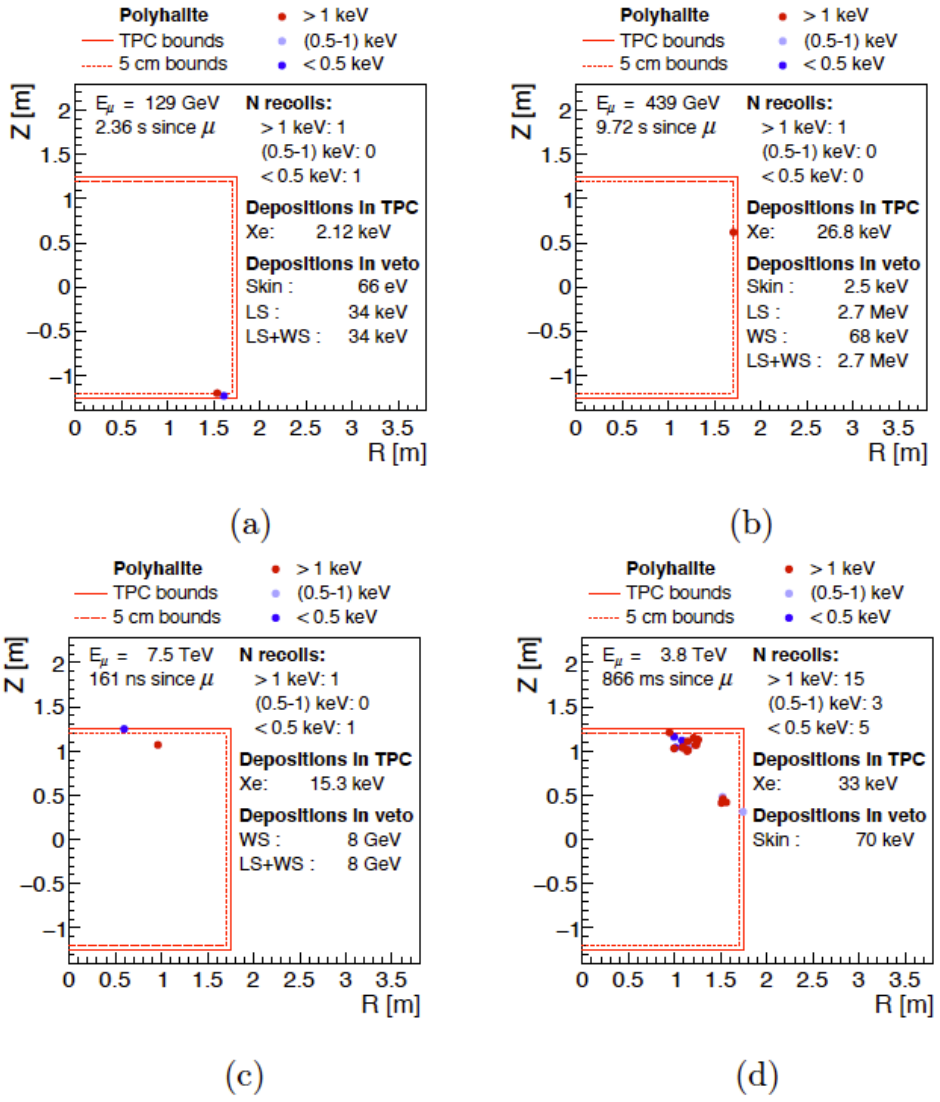
- Left: energy spectra of Xe recoils in the TPC (at 1100 m depth – NaCl).
  - All events – Xe recoils may be accompanied by other energy depositions.
  - Xe recoil only – events where only Xe recoils are present.
- Right: energy spectra of events in the skin, LS, and water tank.
- 5 events pass cuts on energy and veto in NaCl (27 without LS).
- 10 events pass cuts on energy and veto in polyhalite (38 without LS).

Results

Depth/Material	Equivalent exposure [year]	Preselection	Observed events	Rate [per 10 years]	90% CL
		With liquid scintillator veto			
2850 m w. e./NaCl	29	5	0		<0.84
3575 m w. e./polyhalite	97	10	1	0.10	0.01–0.45
		Without liquid scintillator veto			
2850 m w. e./NaCl	29	27	0		<0.84
3575 m w. e./polyhalite	97	38	2	0.21	0.05–0.61

- Limits are based on statistical uncertainties only.
- Systematic uncertainty is about ×2 due to neutron production models.
- Muon flux can be measured and calculated to 10% accuracy for exact lab location if rock composition, density and surface profile are known.
- Increase in neutron production with increasing depth (mean muon energy) is limited to about 7%.

Example events (in polyhalite)



- (a), (b) – single NRs (delayed); 2nd pulse in (a) may be missed.
  - No energy deposition above the threshold in WT if no LS.
  - (a) – will not be identified as a background; potential signal.
  - (b) – Potential signal if no LS.
- (c) – rejected due to veto (WT/LS).
- (d) – a multiple scatter event that will be rejected.
- Most events are from the production of ^{17}N from ^{19}F in PTFE (3 cm thick) followed by a β-n decay to ^{16}O with a half-life of 4.2 s.

Summary and conclusions

- Background event rate for a next generation DM experiment (based on LXe) at about 3 km w. e. is low.
- For both locations the background rate is < 1 event in 10 years of running.
- Main background comes from PTFE activation with an emission of a neutron (a few seconds after a muon).
- Muon rate is expected to be about 200-300 per day in the TPC (at about 3 km w. e.). With 10 s dead time after a muon, we may lose 3-4% of efficiency (not obvious that this is needed).
- Limit PTFE use; currently assumed to be 3 cm wall thickness but could be thinner.
- Paper in preparation.