R&D Towards Next Generation Dark Matter Experiment at Boulby

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Abstract

Current dark matter experiments, such as LZ or XENONnT will probe WIMP-nucleon spin-independent cross-section down to about 1.4×10^{-48} cm^2 at 40 GeV/c2. An order of magnitude improvement can be achieved with next-generation dark matter experiments. Research and development has started towards such an experiment. This project is focused, in particular, on some key aspects of the design of an example detector based on a liquid xenon target and located at the Boulby Underground Laboratory. These studies include suitability of the site depth, the size of the cavern needed to accommodate shielding, characterisation of the radiopurity of rock and some detector materials. This poster presents initial simulations of the background from cosmic-ray muons and radioactivity in rock using GEANT4 software.

1. Evidence of Dark Matter

Most of what we are able to observe in the Universe is baryonic matter which only makes up less than 5% [1] of the Universe. The majority is yet to be detected and we call this remainder dark matter and dark energy. There are various pieces of evidence which support this theory. In a spiral galaxy like the M31, the luminous mass distribution falls exponentially outwards from the centre. The orbital velocity, *v*, of the stars would be expected to fall as: $v \propto 1/\sqrt{r}$ where *r* is the galactocentric radius. Observations show, however, a flat rotation curve as seen in figure 1. This is indicative of a large dark matter "halo" surrounding spiral galaxies.

The bullet cluster is the collision of two galaxies. The majority of the cluster's mass is expected to be in where all of the plasma coagulates, as opposed to where collision-less stars and galaxies are. However, the bulk of the mass is actually in these outer regions which points to dark matter (also collision-less) being present.
Gravitational lensing of, for example, the bullet cluster enables physicists to measure the amount of mass between a luminous object and the observer. Presence of dark matter is implied when the measured mass is larger than the visible mass.

Observations of the cosmic microwave background spectrum of density fluctuations and its baryon acoustic oscillations show that the total amount of matter is much greater than that of baryonic mass.

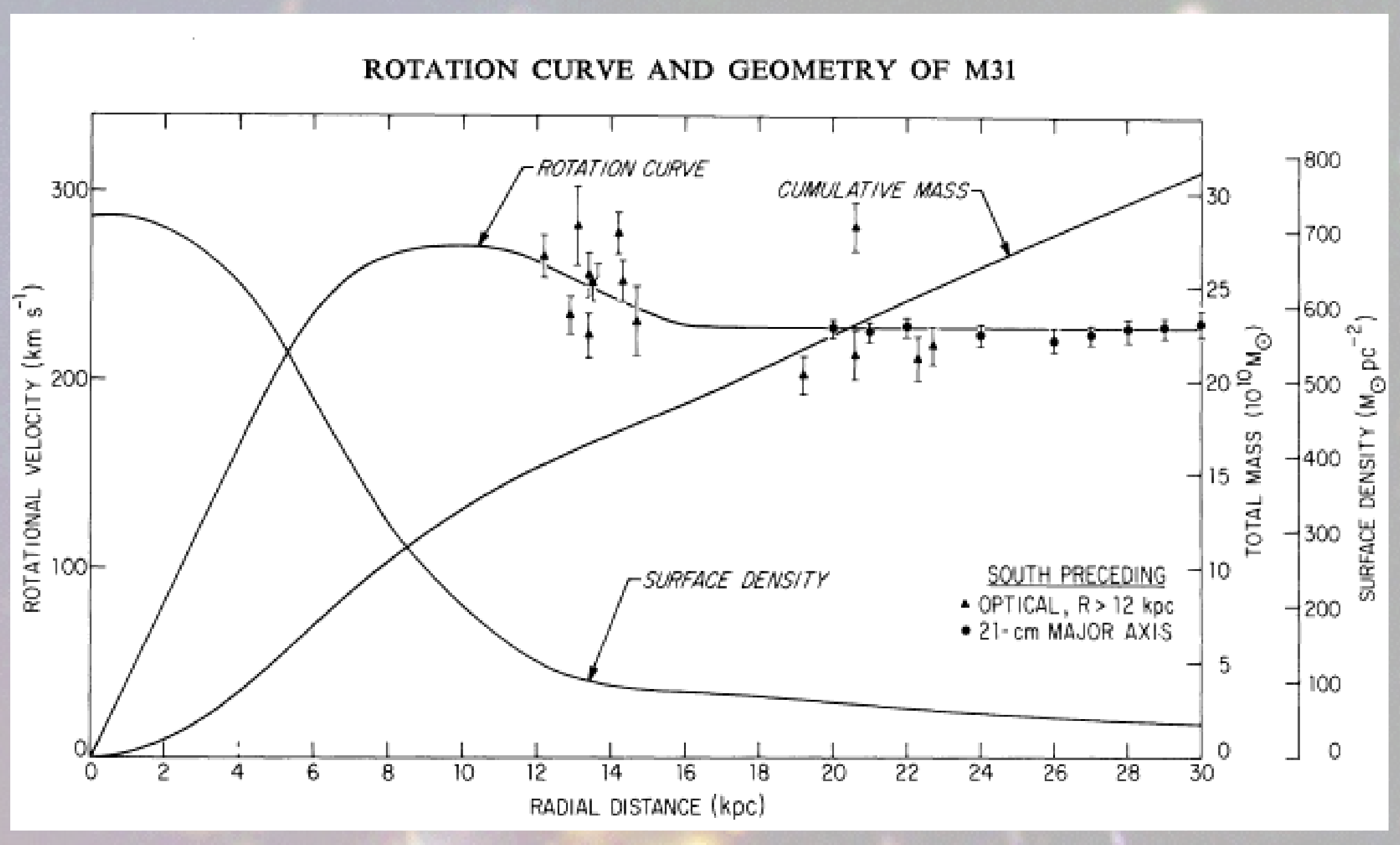

Figure 1. Rotation curve, cumulative mass and surface density of the M31 galaxy. [3].

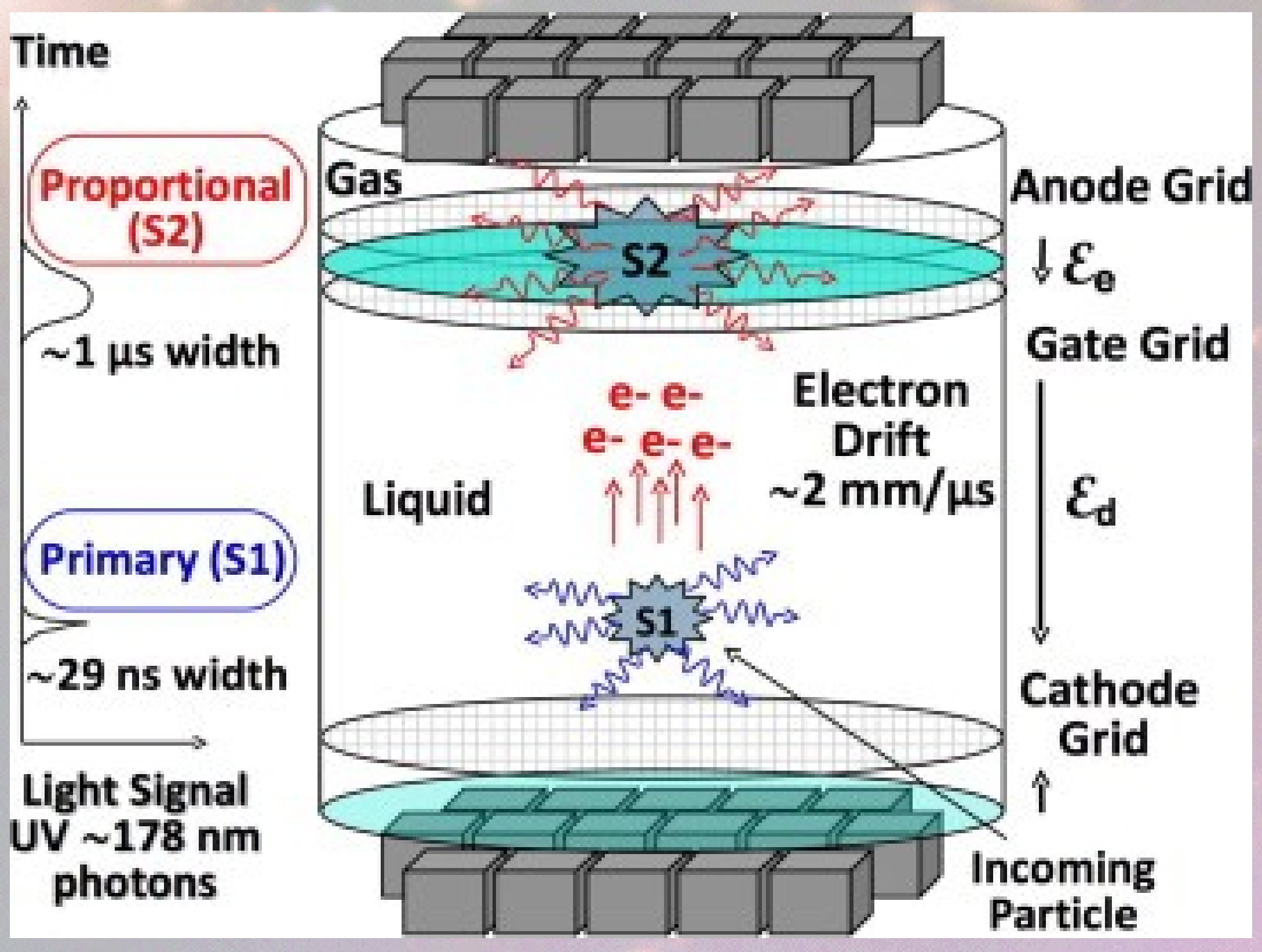

Figure 2. LXe two-phase TPC demonstrating how the primary and secondary scintillation light is produced and then detected by two PMT arrays at the top and bottom of the detector [6].

2. WIMPs and SUSY

A good candidate for cold dark matter (CDM, non-relativistic at the time of decoupling) would be neutral, non-relativistic, non-baryonic, massive, weakly-interacting and stable (or extremely long lived). Popular candidates which satisfy these constraints are weakly interacting massive particles (WIMPs). The most favoured WIMPs are neutralinos from the principle of supersymmetry (SUSY), an extension of the standard model, in particular the lightest neutralino as it is predicted to be stable [4].

3. WIMP interactions

WIMPs are predicted to have a mass in the range 2 GeV to a few TeV [5] and have a small cross-section with baryonic matter. When interacting, due to the large difference in mass, it is usually assumed that the WIMPs will elastically scatter off atomic nuclei giving rise to a nuclear recoil. The observed rate of WIMPs in a detector is the expected rate of scattered WIMPs off a target nucleus factoring in detector efficiency.

One method to directly detect these interactions uses a two-phase liquid noble gas detector with a time projection chamber (TPC), as shown in figure 2, to measure primary and secondary scintillation light. An incoming particle interacts with a liquid noble element (LAr or LXe), this particle scatters off a Xe/Ar atom and produces photons and electrons. Scintillation from this event is measured as the primary S1 signal. The electric field E_d enables electrons to drift upwards and the electric field E_e extracts electrons from the liquid phase and accelerates them through the gas phase, producing the S2 signal.

The time delay between the S1 and S2 signals are proportional to the depth at which the interaction occurred. Using two detection channels, one can discriminate between nuclear recoils and electron recoils that are produced in beta decays and by gammas interacting with the atomic electrons.

4. Boulby Underground Laboratory

Boulby Underground Laboratory, shown on the left of figure 3, is located in the deepest mine in England and one of several locations in the world to house ultra-low background experiments due to its depth and low background radioactivity of the rock. It is considered as a possible site for the next generation dark matter experiment. There are multiple high-purity germanium (HPGe) detectors in the Boulby UnderGround Screening (BUGS) facility which detect low energy gamma-rays with high resolution. BUGS uses these detectors to screen materials for their levels of radiopurity.

Figure 3. Left: CAD image of Boulby Underground Laboratory, image produced by BUL; Right:BUGS facility at Boulby (credit Trevor Palin).

5. Muon Background

There are multiple sources of background when searching for rare events and one of the main sources is cosmic ray muons. In ultra-low background experiments, when interacting in the rock, local shielding or the detector itself, muons cause secondary neutrons to be produced at energies in the WIMP signal range.

The best way to significantly reduce background from muons is to move experiments underground and have as much overburden as possible. The graph in figure 4 shows the dramatic decrease of muon flux as depth increases.

A simulation was created using GEANT4 [8] to assess the suitability of Boulby as a potential location to host the a next generation dark matter detector. Figure 5 shows visualisations of the geometry used to represent the rock, cavern, water shielding and detector being depicted respectively, as red, grey, blue and mixed colours in (a). Image (b) shows the detector's geometry layers in more detail.

Muons were produced in the rock to estimate the rate of background events occurring over in the detector.

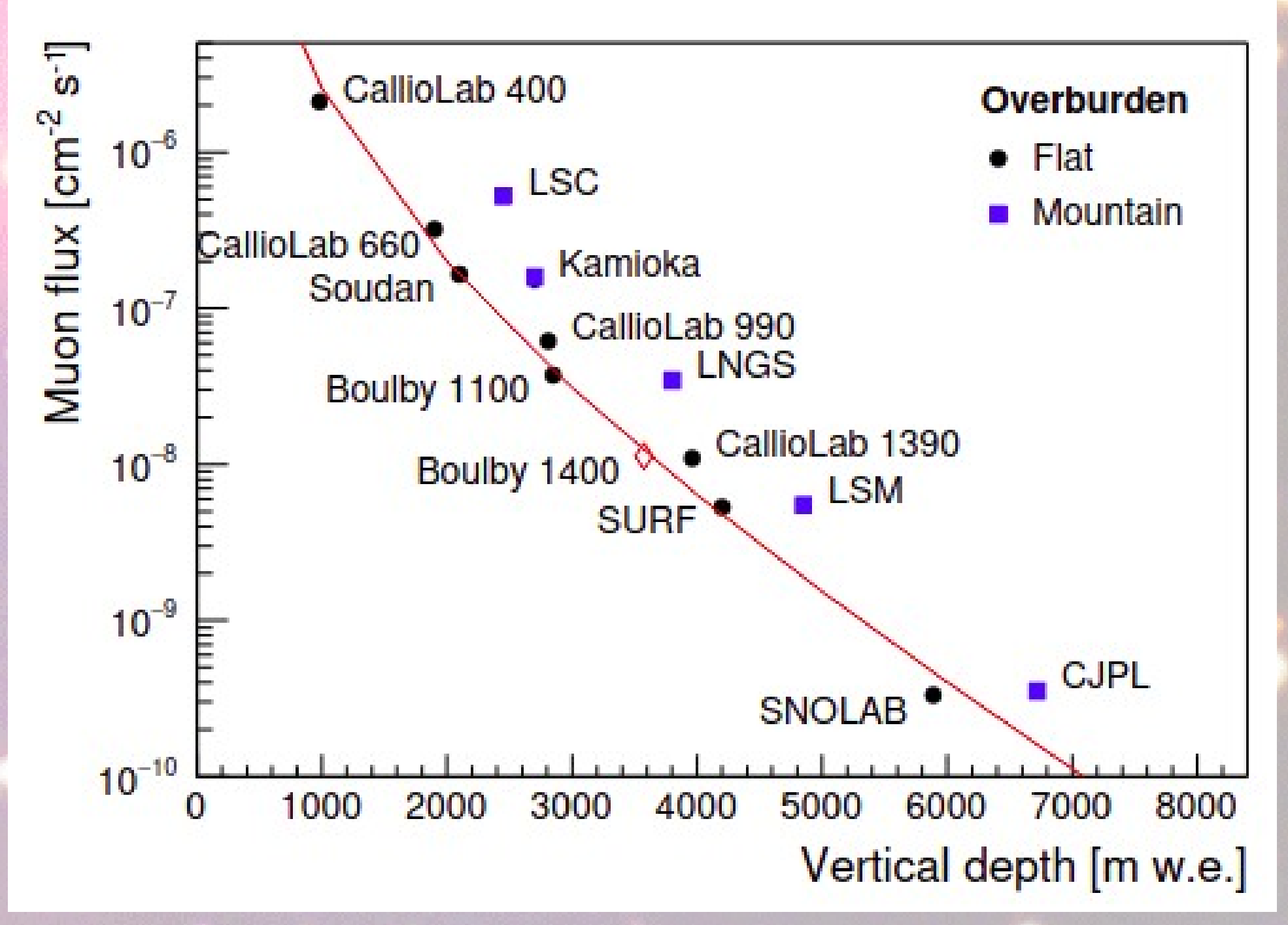

Figure 4. Muon flux as a function of vertical depth for underground laboratories around the world [7].

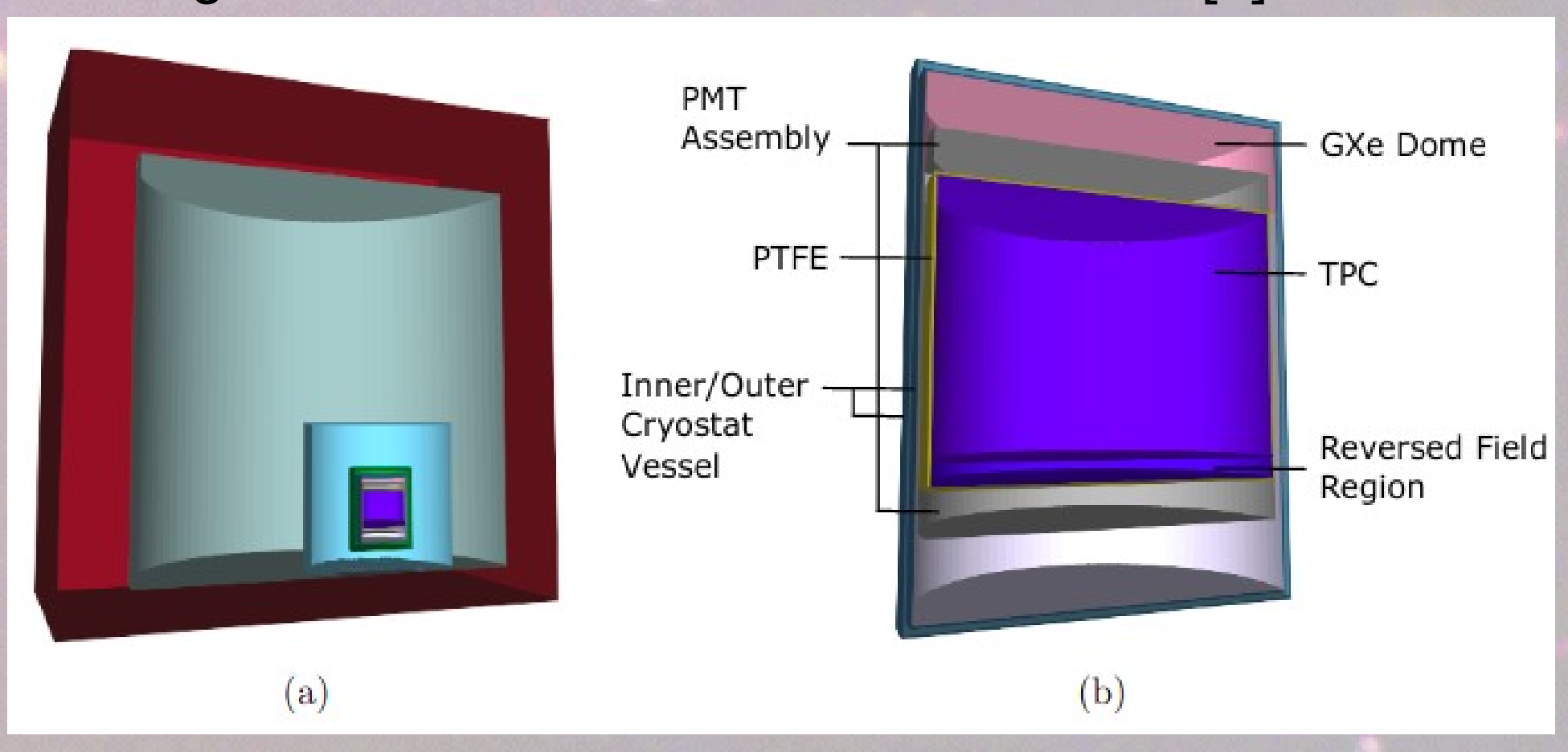

Figure 5. Cross-sectional diagrams of the simplified geometry model used in the simulations [7].

5. Gamma-ray Background From Rock

The goal of this project is to carry out preliminary work towards the design of the facility at Boulby to host a next generation dark matter experiment. LXe has been chosen as a target based on the world-best sensitivities of the current experiments.
Natural radionuclides such as ^{238}U and ^{232}Th are found in rock and trace amounts exist in construction materials. They have decay chains which have daughter isotopes that emit gamma-rays of a broad range of energies. A simulation is underway using GEANT4 to investigate the required thickness of shielding to protect a future, next generation, dark matter experiment from gamma-rays from rock. Similar to the muon simulation, mono-energetic gamma-rays are produced isotropically in the rock with an energy of 2.615 MeV (see figure 6). This value is that of the highest energy gamma that is emitted by ^{208}Tl, an isotope in the ^{232}Th decay chain with a high intensity of 99.754%.

The aim of this project is to assess the attenuation of gamma flux in water to see how big the cavern needs to be and how thick the water shielding should be. The gammas are tracked and stopped using parallel geometries where the statistics of every particle is collected. Trillions of gammas need to be produced for reliable results. Each gamma will be recorded at each surface and propagated to the next surface multiple times to reduce the CPU time needed for simulations.

6. Future work

Studies will be extended to screening of rock samples and other materials for radioactivity at Boulby and will also include propagation of all gammas from ^{238}U and ^{232}Th decay chains and ^{40}K through the shielding. Radon gas from these decay chains can cause additional background events if it enters the detector. Radio-assay techniques will be employed to measure the radon emanation The overall objective is to optimise shielding thickness and investigate into whether Boulby is a suitable location for the next generation dark matter detector.

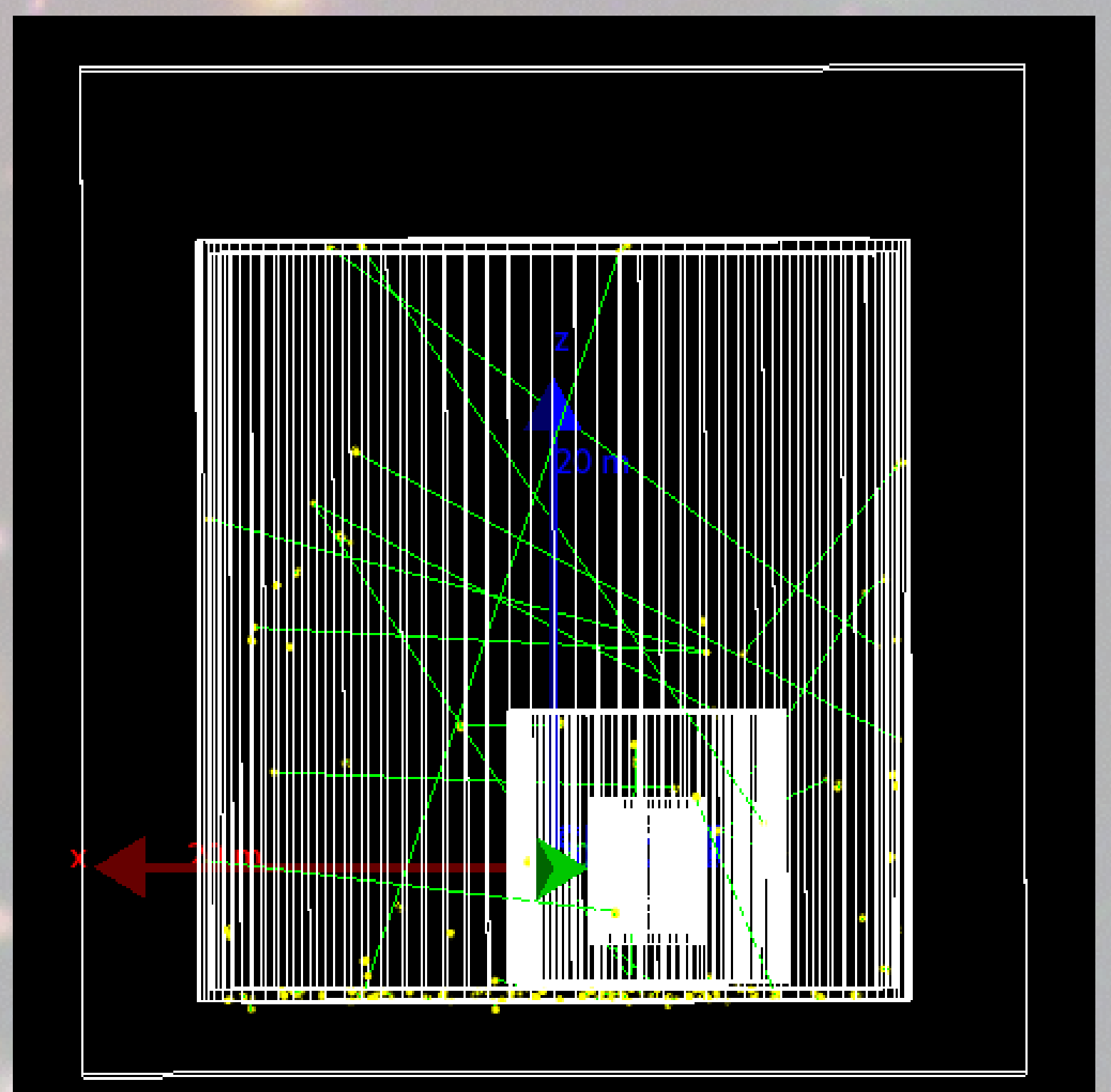

Figure 6. Visualisation of a model of a LXe detector in a rock cavern.

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References
Background image of Bullet Cluster: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.
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