Sensitivity study for DM search in the Low Energy Region of LEGEND 1Ton

Douglas Fields, Michael Gold, M.R. Tousif
(UNM LEGEND Group)

April 27, 2024

1 Introduction

LEGEND 1Ton is an upcoming experiment for a neutrino less double beta decay search. Having the highest level of purity of Germanium in LEGEND with a good energy resolution of the detector and having the ability to identify the backgrounds over signal makes LEGEND a competitive machine to search for other BSM physics like dark matter particle. Dark matter is a big term, there are different types of dark matter. In the next section, first we develop a understanding of the scattering kinematics of WIMP dark matter with Germanium target and we present the physics sensitivity of WIMP dark matter search with LEGEND 1Ton.

2 LEGEND Detector Specifications

The future experiment LEGEND 1ton will carry 92% enriched germanium ^{76}Ge isotope which correspond to $\approx$ 920 kg of pure Germanium as an active volume for the experimental run. The experiment is planned to run for ten years potentially leading to 9200 kg of total exposure throughout it's lifespan. The collaboration is committed to provide the best energy resolution at least better than MAJORANA. Here we use the MAJORANA's resolution.

$$\sigma_{Ge}(E) = \sqrt{a + b^2\,(E/KeV) + c^2\,(E^2/KeV)}\ KeV$$

In our detector for neutrino less double beta decay channel the Q value of can be estimated as $Q_{\beta\beta} = 2039$ KeV. We report detector resolution is going to be $\sigma(Q_{\beta\beta}) \approx 1$ KeV and the full width at half maximum (FWHM) is ≈ 2.35 KeV. At this point we successfully recover the limit of σ and FWHM at LEGEND 1ton. We can use this MAJORANA resolution for now in order to draw the sensitivity, no doubt we will have better resolution than MAJORANA which we can at least use for the LEGEND sensitivity. In low energy region i.e 1-10 KeV we obtain the resolution (0.139-0.15)KeV and FWHM of (0.32-0.35)

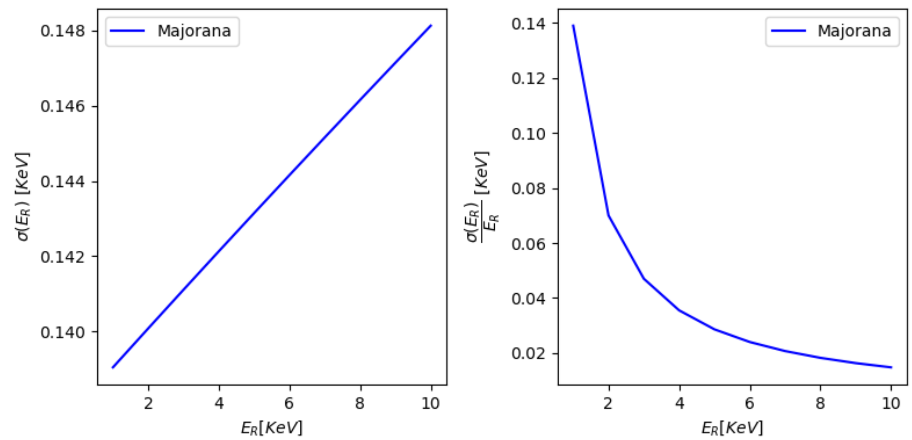

Figure 1: Detector resolution

KeV assuming gaussian peak. For Gaussian peak the detector resolution is related to FWHM as 2.35σ where σ is the resolution in a given energy recoil. The detector efficiency is energy dependent in many of the rare event search experiments including LZ and PANDAX, however in deign of LEGEND 1Ton we expect on an average 0.7 i.e 70% efficiency to record a recoil signal.

3 Scattering inside a Detector

We develop the scattering kinematics in a nonrelativistic regime in which we expect WIMP dark matter will hit the detector's target with a average speed of (200-280) km/s based on Astrophysical uncertainties and we treat spin independent at the lowest order interactions as ^{76}Ge is a even even nuclei with a net spin zero. With this understanding we assume a coherent scattering of WIMP with Germanium since in a non relativistic regime, WIMP will see our detector target as a point particle and 2-2 scattering process works well for the analysis here.

We defined reduced mass of the two body scattering process to simplify our algebra as follows.

$$\mu_T = \frac{mm_T}{m + m_T}$$

here m is the mass of DM and m_T is the mass of Ge target.

$$\mu_p = \frac{mm_p}{m + m_p}$$

here m_p is the mass of nucleon. It could be mass of proton or neutron. Usually proton and neutron mass are almost equal. For spin independent interactions

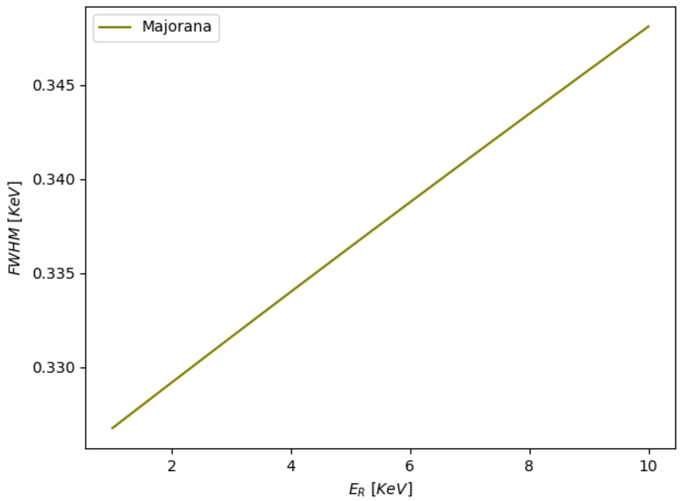

Figure 2: Full width at half maximum of gaussian peak

we use the helm form factor for nucleus given by,

$$F_{Heml}(q^2) = \frac{3j_1(qR)}{qR} e^{\frac{(qs)^2}{2}}$$

$$j_1(qR) = \frac{sin(qR) - qR\,cos(qR)}{(qR)^2}$$

where q is the momentum transfer in the scattering process and R represents the size of the target nuclei and they are related to bessel functions J.

The author will add the details algebra later on . For now we write the scattering rate:

- Rate is defined as $\frac{dR_T}{dE_R}(E_R, t) = R(E_R, t)$

$$\frac{dR_T}{dE_R}(E_R, t) = \sum_T \zeta_T \frac{\rho}{m} \frac{\sigma_p}{2\mu_N^2} \left[Z + (A - Z)\frac{f_n}{f_p} \right]^2 F_{SI}^2(E_R)\, \eta_0\, (v_{min}, t)$$

for the elastic scattering process, we have found that $v_{min}(E_R) = \sqrt{\frac{m_T E_R}{2\mu_T^2}} = \frac{q}{2\mu_T}$ and $\mu_N = \frac{m m_p}{m + m_p}$ is the WIMP-proton reduced mass, $\sigma_0 = \sigma_p \frac{\mu_T^2}{\mu_N^2} \left[Z + (A - Z)\frac{f_n}{f_p} \right]^2$ for the isosinglet condition, we have $f_n = f_p$ and σ_0 becomes

$$\sigma_0 = \sigma_p \frac{\mu_T^2}{\mu_N^2} A^2$$

$$\sigma_p = \sigma_0 \frac{\mu_N^2}{\mu_T^2} \frac{1}{A^2}$$

Here N represents nucleons i.e proton or neutron and σ_0 is total cross section fr Ge nuclei which essentially different than σ_p.

$$\frac{dR_T}{dE_R}(E_R, t) = \sum_T \zeta_T \frac{\rho}{m} \frac{\sigma_0}{2\mu_T^2 A^2} \left[Z + (A - Z)\frac{f_n}{f_p}\right]^2 F_{SI}^2(E_R)\, \eta_0 \left(v_{min}, t\right)$$

For now introducing v_{min} we write, here ζ_T is the target mass fraction and f_n and f_p are the coupling to proton and neutron, in our analysis we take $f_n = f_p$ means WIMP couple to proton or neutron in similar strength.

In th above expression, η_0 is the the velocity integral that carry the information of WIMP velocity distribution .

3.1 Close look to velocity Distribution

$$f(\vec{v}) = \left\{ \frac{1}{N} \left(e^{-v^2/v_0^2} - \beta e^{-v_{esc}^2/v_0^2} \right) \quad v < v_{esc} \right. \tag{1}$$

Here N is the normalization and $v_0 \approx (215-250)$ km/s and $v_{esc} \approx (530-580)$ km/s. The range of this values is account for uncertainties.

$$N = \pi^{3/2} v_0^3 \left[erf(x_{esc}) - \frac{4}{\sqrt{\pi}} e^{-x_{esc}^2} \left(\frac{x_{esc}}{2} + \beta \frac{x_{esc}^3}{3} \right) \right]$$

It is convenient to define $x_{esc} = \frac{v_{esc}}{v_0}$, $x_{min} = \frac{v_{min}}{v_0}$ and $x_e = \frac{v_e}{v_0}$
The analytic form of velocity integral

$$\eta_0(E_R) = \int_{v_{min}}^{\infty} \frac{d^3 v}{v} f(\vec{v} + \vec{v}_e) = \int_{v_{min}}^{\infty} F(v) v^2 dv$$

here β is an anisotropic parameter which is non-zero, latest study suggests $\beta = (0.9 - 1.0)$.

4 LEGEND 1Ton current Backgrounds

In the LEGEND 1ton we are expected to encounter a large backgrounds in the low energy region.It is expected from background model simulation that we have more background events in low energy region of interest i.e 1-100 KeV however the identification of background is robust from the background simulation. Any excess over the background events is an naive techniques to claim the dark matter signature in the detector. A couple of experiments in modern time like Majorana, XENON, LUX, PANDAX and NEXT and LZ are looking for such signatures i.e double beta decay and dark matter in their detectors. Lindard model is used to transform the electron equivalent recoil to nuclear recoil.

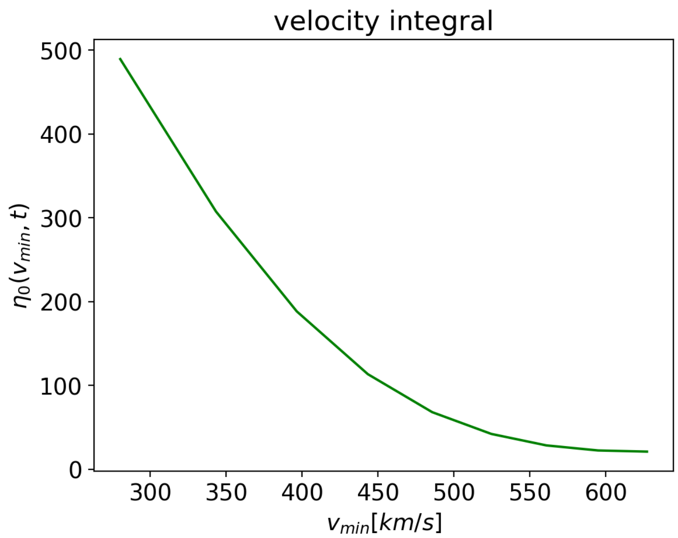

Figure 3: v_{min} is the expected WIMP speed in the recoil 1-5 KeV in our detector.

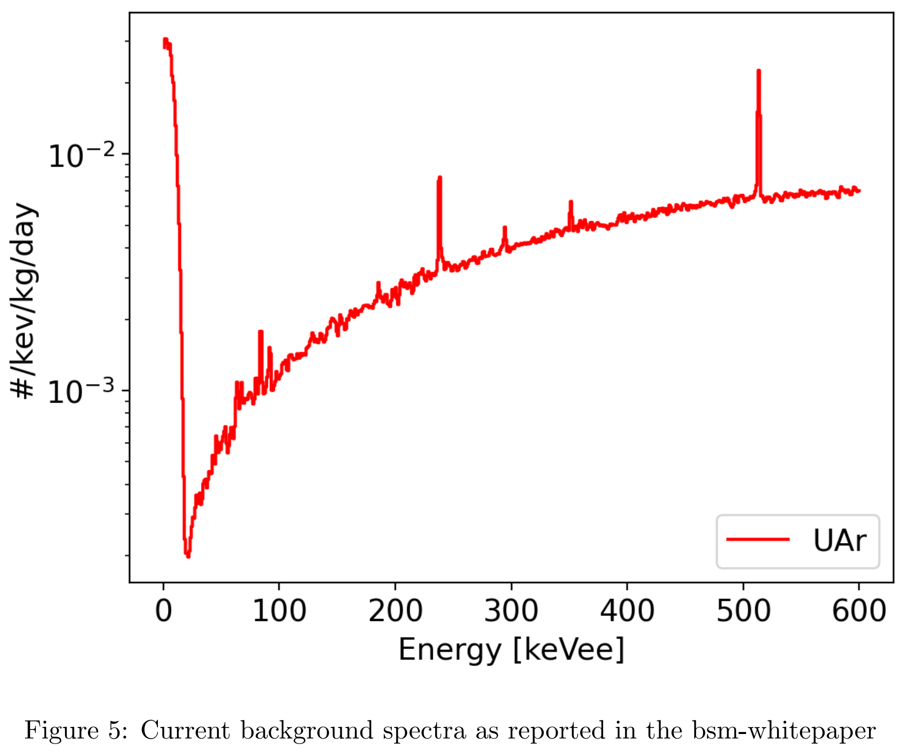

Figure 5: Current background spectra as reported in the bsm-whitepaper

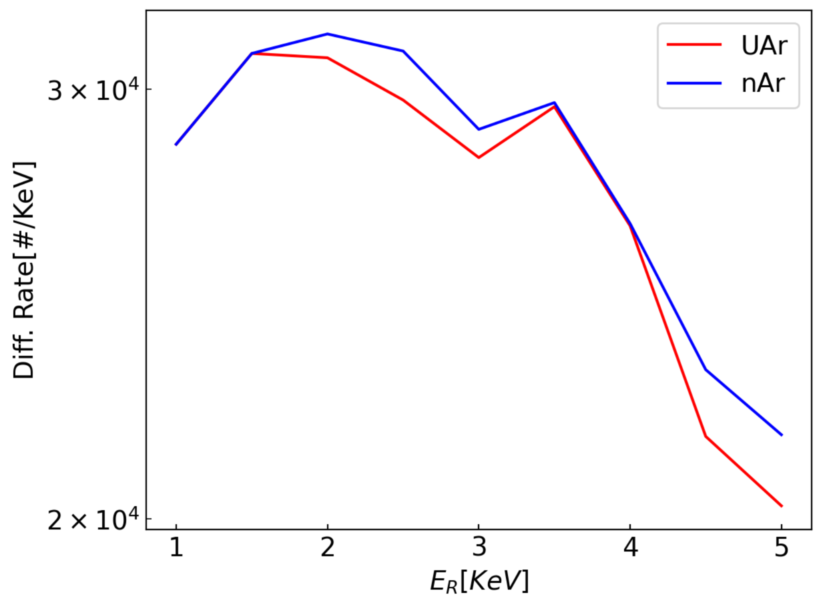

Figure 6: Expected background events in low energy region of interest at LEGEND 1ton as per current background model.

5 Results for WIMP Dark Matter Search

We simulate the total number of events by folding the recoil rate with the detector resolution. In our analysis we used binned method. We estimate counts in each energy bins from nuclear recoil and summed them up bin by bin.

$$\frac{d\tilde{R}}{dE_R}(E_R) = \int_0^{\infty} dE'_R \frac{dR}{dE_R}(E'_R) \frac{1}{\sqrt{2\pi}\sigma(E'_R)} e^{\left(-\frac{(E_R - E'_R)^2}{2\sigma^2(E'_R)}\right)}$$

$$\sigma_{Ge}(E_R) = \sqrt{(0.3)^2 + (0.06)^2 E_R/KeV}\ KeV$$

First we obtain the smeared rate and then we integrate from detection threshold to the upper limit as favor by analysis region of interest and we multily the total events with efficiency since our detector is limited to record events upto some extent and will never achieve 100% efficiency.

$$N(E_1, E_2) = \int_{E_1}^{E_2} dE_R\, \epsilon_{eff} \frac{d\tilde{R}}{dE_R}(E_R)$$

Finally using the poisson statistics we set the exclusion limit (90% C.L)on parameter of interest, here we have only one dependent parameter i.e spin independent WIMP nucleon cross section.

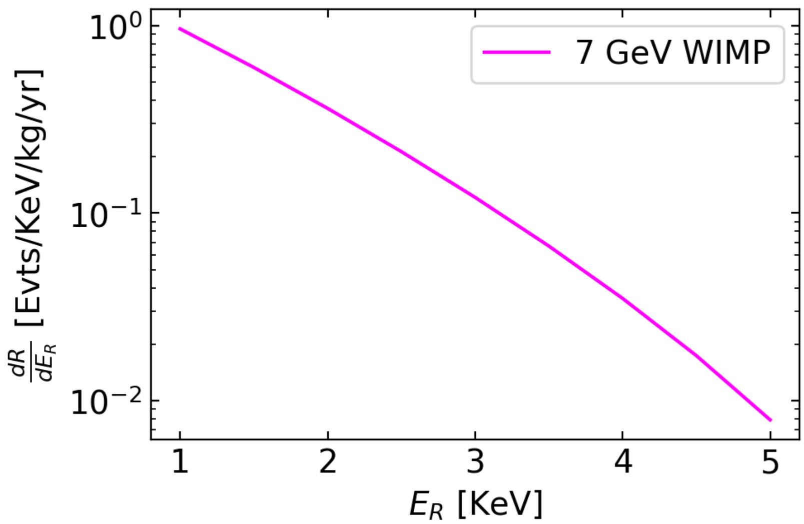

Figure 7: Expected diffrential recoil rate of WIMP at LEGEND 1ton using SHM model without resolution.

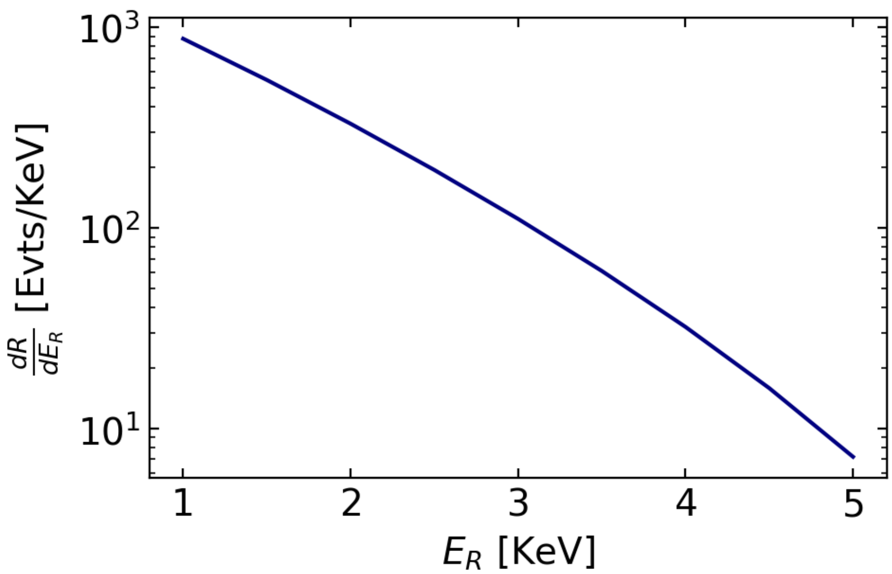

Figure 8: Expected 7 GeV WIMP recoil rate for one year exposure of LEGEND 1ton without detector resoution.

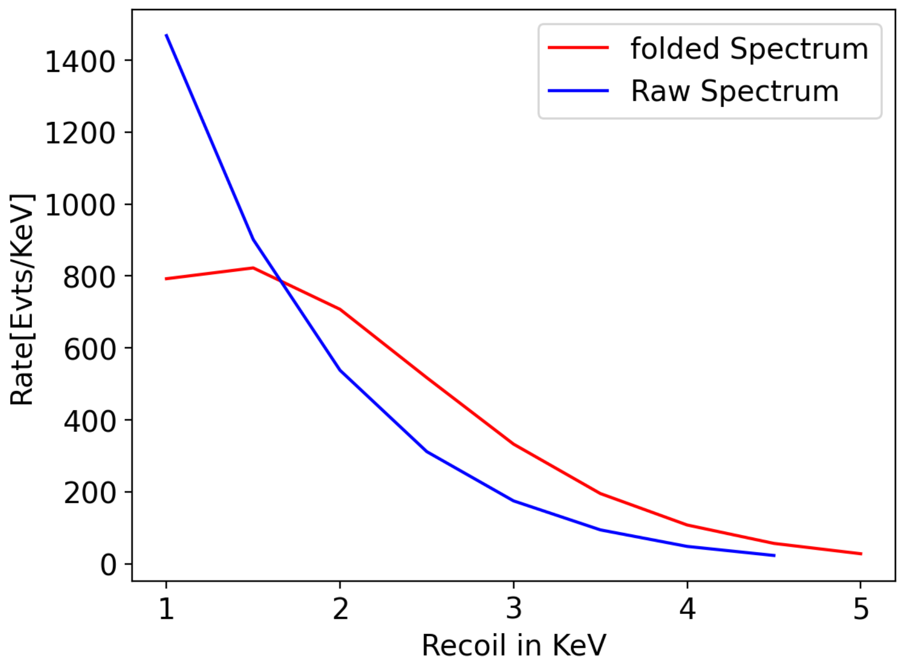

Figure 9: Smeared rate of WIMP DM at LEGEND 1ton for one year exposure using constant resolution of 1 KeV as simulation run

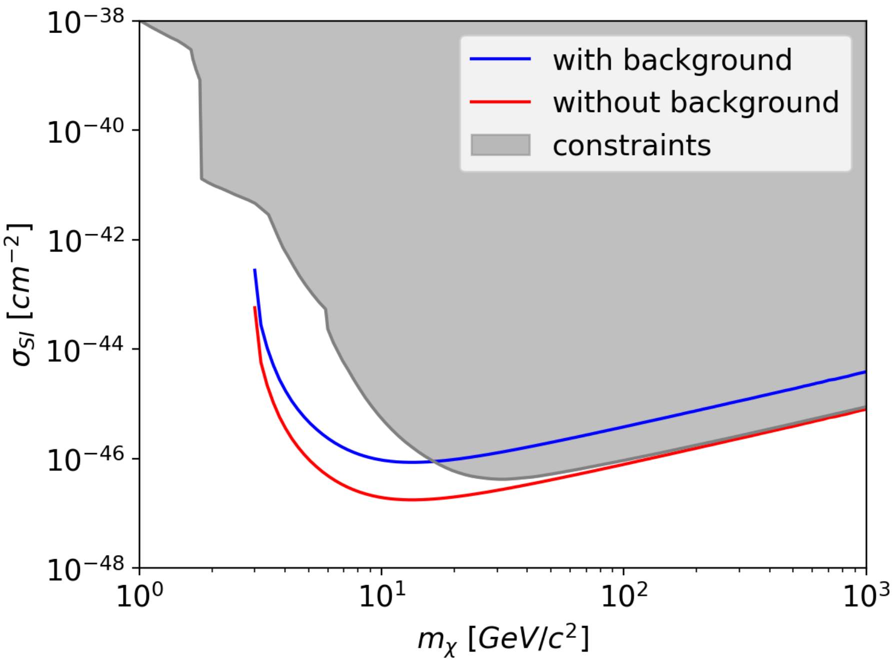

Figure 10: LEGEND 1ton sensitivity to WIMP after one year of simulation run using energy dependent resolution like MAJORANA. In drawing the sensitivity WIMP of GeV mass and interaction cross section of $\sigma_p = 2.489 \cdot 10^{-44}$ is used from XENON1T 2018 limit.