

# SuperCDMS Soudan High Threshold Analysis Data Release

SuperCDMS Collaboration

September 24, 2018

This document accompanies the public release of the SuperCDMS Soudan High Threshold (HT) Analysis data and gives explanatory material related to the released files themselves and their use in reproducing published upper limit results. The WIMP-search results from these data are found in Ref. [1]. The released data and code have been internally verified to reproduce the official limits and figures presented in this release document. Questions about the data or the limits should be directed to `supercdms_publications@lists.astro.caltech.edu`.

## 1 Description the Data

Three text (`.txt`) files accompany this data release and can be found in the `data_files` directory of the accompanying `.zip` file. The names and descriptions of these files are

- `eventEnergy.txt`: This file contains a single event energy, in units of keV. This 1 event was not excluded by the final HT cut and was used to compute WIMP-search limits.
- `efficiency.txt`: This file contains the WIMP-search efficiency. This curve and its uncertainty are the central-value efficiency and error bars representative of the central 68% uncertainty interval ( $1\sigma$  equivalent). The file consists of four tab-separated columns, with the first column giving bin locations in keV, the second column the total efficiency at that bin location, and the third/fourth column the lower/upper  $1\sigma$  uncertainty at each bin location. The uncertainties are given as the difference from the best-fit. The efficiency is given by the solid purple curve in Fig. 1 while the  $1\sigma$  uncertainties are given by the light purple envelope.
- `limits.txt`: This file contains the spin-independent limit from the published analysis. The file contains two tab-separated columns. The first column contains WIMP-masses in units of  $\text{GeV}/c^2$ . The second column contains limit values in units of  $\text{cm}^2$ . Values of “Inf” in the files indicate that the given limit has no sensitivity at that particular WIMP mass.

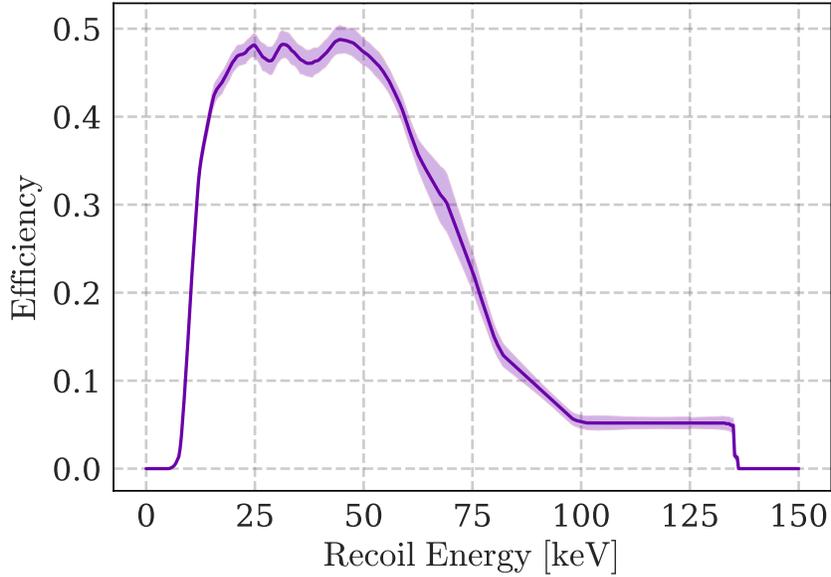


Figure 1: WIMP-search efficiency for the HT analysis is shown (purple line) together with the central 68 % uncertainty interval (light purple envelope).

## 2 Calculating the WIMP-Search Limits

In order to compute WIMP-search limits, four pieces are needed: the observed event energies in keV, the efficiency and exposure, a WIMP-signal model, and a limit-setting technique. This section describes how each of these items are used in the HT analysis in order to allow for reproduction of the WIMP interaction limits given in Ref. [1].

### 2.1 Experimental Inputs

The HT experimental inputs are the observed energy, signal efficiency, and total exposure. These are specified as follows.

**Observed Energy:** The observed energy spectrum is that given in keV in `eventEnergy.txt`.

**Efficiency and Exposure:** The exposure of the HT analysis is 1690 kg d. For the official limit, the curves from `efficiency.txt` are used. It should be noted that the analysis energy range is set by the efficiency curves; they are zero-padded outside of the analysis energy range.

### 2.2 WIMP Signal Model

The published analysis uses the expected WIMP recoil rate in the detector as generally derived in Ref. [2] and summarized here.

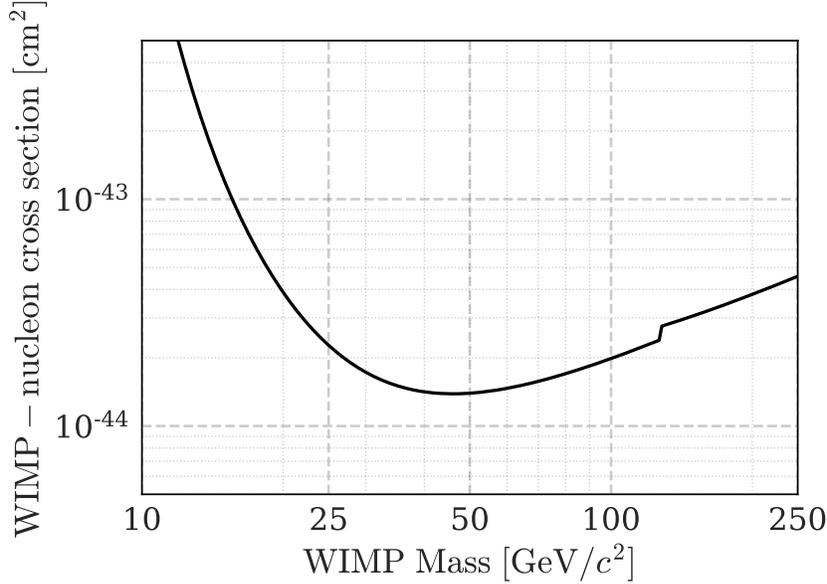


Figure 2: Spin-independent WIMP-nucleon cross section 90% C.L. upper limit from Ref. [1].

**Halo Model:** The WIMP halo is assumed to be an isotropic, isothermal, and non-rotating sphere with a Maxwellian velocity distribution  $f(\mathbf{v}, \mathbf{v}_E)$  of the form

$$f(\mathbf{v}, \mathbf{v}_E) \propto \rho_0 e^{-|\mathbf{v} + \mathbf{v}_E|^2/v_0^2}, \quad (1)$$

where  $\mathbf{v}$  is the WIMP velocity,  $v_0 = 220 \text{ km s}^{-1}$  is the most probable WIMP velocity in the halo, and  $v_E = |\mathbf{v}_E| = 232 \text{ km s}^{-1}$  is the mean circular velocity of the Earth through the halo (ignoring the Earth's orbit around the Sun). The other astrophysical assumptions used are a local dark matter density of  $\rho_0 = 0.3 \text{ GeV c}^{-2} \text{ cm}^{-3}$  and a Galactic escape velocity of  $v_{\text{esc}} = 544 \text{ km s}^{-1}$ . The uncertainties in these astrophysical parameters are considered in [3] and are not discussed here. Note that the integration over the velocity distribution function in Ref. [2] allows for non-physical negative rates for certain velocity combinations. Equation 3.13 of Ref. [2], the differential rate in terms of the target's recoil energy  $E_r$ , is replaced with the more complete result (see e.g. Appendix A of Ref. [4]) of

$$\frac{dR}{dE_r} = \frac{R_0}{E_0 r} \frac{k_0}{k_1} \frac{\sqrt{\pi}}{4y} \begin{cases} \text{erf}(x+y) - \text{erf}(x-y) - \frac{4}{\sqrt{\pi}} y e^{-z^2} & 0 < x < z - y \\ \text{erf}(z) - \text{erf}(x-y) - \frac{2}{\sqrt{\pi}} (y+z-x) e^{-z^2} & z - y < x < z + y \\ 0 & y + z < x, \end{cases} \quad (2)$$

where  $R_0$  and  $r$  are the total rate and kinematic factors defined in Ref. [2],  $k_0$  and  $k_1$  are normalization factors which are also defined in Ref. [2],  $E_0 = (1/2) m_\chi v_0^2$  with  $m_\chi$  as the mass of the WIMP,  $x = v_{\text{min}}/v_0$ ,  $y = v_E/v_0$ , and  $z = v_{\text{esc}}/v_0$ . The minimum velocity for a WIMP to impart  $E_r$  on a target of mass  $m_T$  is  $v_{\text{min}} = \sqrt{m_T E_r / 2\mu_T^2}$ , using the WIMP-target reduced mass of  $\mu_T = m_T m_\chi / (m_T + m_\chi)$ . The value of  $R_0$

uses the atomic mass number  $A = 72.64$  for Ge and  $A = 73$  for the spin-interaction sensitive  $^{73}\text{Ge}$

**Nuclear Form Factor:** In Ref. [2], the WIMP-nucleus cross section is generally taken to be of the form

$$\sigma(q) = \sigma^{\text{SI}}(q) + \sigma^{\text{SD}}(q) = \sigma_0^{\text{SI}} F_{\text{SI}}^2(q) + \sigma_0^{\text{SD}} F_{\text{SD}}^2(q), \quad (3)$$

where  $q$  is the momentum transferred in the collision and the spin-independent (SI) and spin-dependent (SD) contributions are each separated into the total zero-momentum cross section  $\sigma_0^{\text{SI/D}}$  and the nuclear form factor  $F_{\text{SI/D}}$ . The published limit assumes only a spin-independent interaction, and as such we will restrict ourselves to that case below.

**Spin Independent:** The Helm expression is used for the spin-independent nuclear form factor [5]

$$F_{\text{SI}}(q) = 3 \frac{j_1(qr_n)}{qr_n} e^{-\frac{1}{2}(qs)^2}, \quad (4)$$

where  $j_1(qr_n)$  is the spherical Bessel function of the first order and  $q$  is the momentum transferred to the nucleus in the scatter. For the remaining parameters, the parameterization preferred in Ref. [2] is used which gives  $r_n^2 = c^2 + (7/3)\pi^2 a^2 - 5s^2$ ,  $c \simeq 1.23A^{1/3} - 0.6$  fm,  $s \simeq 0.9$  fm, and  $a \simeq 0.52$  fm, with  $A$  as the atomic mass number.

**Normalization:** The HT analysis followed the standard practice of presenting limits on the momentum-independent WIMP-nucleon cross sections. Scaling limits on the WIMP-nucleus cross sections,  $\sigma_0^{\text{SI}}$  in Eq. 3, to a limit on the interaction of a WIMP and a single nucleon was carried out only in the spin-independent interaction case. The standard zero-momentum spin-independent cross section for a WIMP to scatter off any target nucleus can then be written as

$$\sigma_0^{\text{SI}} = \frac{4\mu_T^2}{\pi} A^2 f_p^2. \quad (5)$$

The WIMP-nucleus cross section is then scaled to the WIMP-nucleon cross section as

$$\sigma_0^{\text{SI}} = \left( \frac{\mu_T}{\mu_p} A \right)^2 \sigma_p^{\text{SI}}, \quad (6)$$

where  $\mu_p$  is the reduced mass of the WIMP-nucleon system (the difference between the proton and neutron mass are neglected) and  $\sigma_p^{\text{SI}}$  is the cross section for single-nucleon WIMP interaction. The momentum-dependent cross section is then the combination of Eqs. 4 and 6

$$\sigma^{\text{SI}}(q) = \sigma_0^{\text{SI}} \cdot F_{\text{SI}}^2(q) \quad (7)$$

$$= \left( \frac{\mu_T}{\mu_p} A \right)^2 \sigma_p^{\text{SI}} \cdot \left( 3 \frac{j_1(qr_n)}{qr_n} \right)^2 e^{-(qs)^2}, \quad (8)$$

with the form factor parameters described above.

## 2.3 Limit-Setting Technique

The user is free to use any desired statistical method for computing upper limits. The published analysis uses the high-statistics extension of the Optimum Interval (OI) method, as described in Ref. [6], to set limits on the cross section for WIMP masses from 10-250 GeV/ $c^2$ .

The OI code is publicly available for download from Ref. [7], which includes documentation on the individual-script level. For convenience, a stand-alone implementation of the code for these data is provided in the `OI_code` directory of the release. The OI code is written in FORTRAN with the primary function being in `HT2Upper.f`. The code has been compiled for a Unix operating system, resulting in the `HT2Upper` executable. It can be recompiled on a Unix system using

```
gfortran -frecord-marker=4 -o HT2Upper HT2Upper.f UpperLimNew2.f y_vs_CLf2.f
CMaxinfNew2.f ConfLev2.f ConfLevNew2.f Cinf2.f CERN_Stuff2.f
```

or

```
f77 -o HT2Upper HT2Upper.f UpperLimNew2.f y_vs_CLf2.f CMaxinfNew2.f
ConfLev2.f ConfLevNew2.f Cinf2.f CERN_Stuff2.f
```

The `ULinput` file is the input file read which is hard-coded to be ready by the FORTRAN code. The provided `ULinput` file contains the appropriately formatted spectrum and efficiency information from these data for the spin-independent limit parameters. See the documentation of the public code at Ref. [7] for further details with regards to properly formatting the input. The FORTRAN code produces an output file `ULoutput`, the first two columns of which are the SI WIMP-nucleon cross section limit ( $\text{cm}^2$ ) and WIMP mass ( $\text{GeV}/c^2$ ) respectively. The provided `ULoutput` matches the provided `ULinput`, and gives the SI limit.

## References

- [1] R. Agnese *et al.* (SuperCDMS Collaboration), “Results from the super cryogenic dark matter search experiment at soudan,” *Phys. Rev. Lett.* **120**, 061802 (2018).
- [2] J. Lewin and P. Smith, “Review of mathematics, numerical factors, and corrections for dark matter experiments based on elastic nuclear recoil,” *Astropart. Phys.* **6**, 87–112 (1996).
- [3] R. Agnese *et al.*, “Low-Mass Dark Matter Search with CDMSlite,” *Phys. Rev. D* **97**, 022002 (2018).
- [4] F. Donato, N. Fornengo, and S. Scopel, “Effects of galactic dark halo rotation on WIMP direct detection,” *Astropart. Phys.* **9**, 247–260 (1998).
- [5] R. H. Helm, “Inelastic and Elastic Scattering of 187-Mev Electrons from Selected Even-Even Nuclei,” *Phys. Rev.* **104**, 1466–1475 (1956).
- [6] S. Yellin, “Extending the optimum interval method,” [arXiv:0709.2701](https://arxiv.org/abs/0709.2701) .
- [7] S. Yellin, “<http://titus.stanford.edu/Upperlimit/>,” (2015).