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Direct Search for Leptophilic Dark Matter with the DarkSide Program

By

DAVID-MICHAEL POEHLMANN
DISSERTATION

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Abstract

The DarkSide-50 experiment uses an argon two-phase time projection chamber to directly search for dark matter interactions. While DarkSide-50 is optimized to detect interactions of GeV/c^2 to TeV/c^2 -scale dark matter particles with nuclei, it is also sensitive to dark matter interactions with electrons. This dissertation presents the results of a search for leptophilic dark matter candidates, specifically light dark matter, dark photons, and axion-like particles, using data collected by the DarkSide-50 experiment. The inclusion of S2-only events in the dataset lowered the detector energy threshold, resulting in a total exposure of 12 306 kg d. This work produced world-leading constraints on the light dark matter-electron coupling ($\bar{\sigma}_e$). New parameter space has also been excluded for the dark photon kinetic mixing parameter κ , as well as the axioelectric coupling g_{ae} .

The DarkSide-20k experiment will continue the search for dark matter using a 49.7 t argon target. Efforts presented here were directed towards developing event simulation and data reconstruction algorithms, including the proposal of an event data model and a study of energy reconstruction for S1 and S2 signals. The sensitivity of DarkSide-20k to dark matter interactions with electron final states was also studied. DarkSide-20k is expected to improve upon the physics reach of DarkSide-50 for leptophilic dark matter interactions by up to two orders of magnitude.

To better understand and model low-energy electronic recoils for experiments like DarkSide-20k, the ARIS-ER experiment at UC Davis will use the Compton coincidence technique to measure the response of liquid argon. Simulations optimized the experimental design and established baseline requirements such as the γ source activity. Also contained in this dissertation is the development of the ARIS-ER data acquisition system.

*To my family, my partner, and my friends,
who have all supported me through every step of this journey.*

Contents

List of Figures	vii
List of Tables	x
1 Introduction	1
1.1 Evidence for dark matter	1
1.2 Dark matter candidates	3
1.3 Detection techniques	8
1.4 Interaction rates	11
2 The DarkSide program	14
2.1 Dual-phase TPC	14
2.2 Liquid argon	17
2.3 The DarkSide program	20
2.4 DarkSide-50	21
2.5 DarkSide-20k	24
3 Search for leptophilic dark matter with DarkSide-50	29
3.1 LDM-electron interactions	29
3.2 Dark photon interactions	41
3.3 Axion-like particle interactions	43
3.4 Electronic recoil ionization yield	44
3.5 DarkSide-50 dataset	47
3.6 Background model	51

3.7	Response model	54
3.8	Profile likelihood analysis	58
4	Reconstruction for DarkSide-20k	73
4.1	Data processing overview	73
4.2	Photoelectronics and DAQ emulation	78
4.3	Hit finder performance	85
4.4	Energy reconstruction	86
4.5	Event data model	88
5	DarkSide-20k low-mass sensitivity projections	92
5.1	Software tool	92
5.2	Background model	95
5.3	Response model	98
5.4	Nuisance parameters	99
5.5	Background-only fit	99
5.6	Sensitivity projections	101
6	The ARIS-ER experiment	107
6.1	Existing measurements	107
6.2	Experiment design	108
6.3	Simulations	112
6.4	Data acquisition system	115
7	Conclusions & outlook	120
A	Acronyms	123
B	Nomenclature	128
C	DarkSide-50 low-mass analysis cuts	130
C.1	Run selection cuts	130
C.2	Basic quality cuts	132

C.3 Physics cuts	132
Acknowledgements	136
Bibliography	137

List of Figures

1.1	Rotation curve of the M33 galaxy	2
1.2	<i>Chandra</i> x-ray image of the merging cluster 1E 0657-558	4
1.3	Allowed mass range of dark matter candidates, with familiar objects for reference	4
1.4	Dark matter detection technique diagrams	9
1.5	Landscape of direct detection experiments probing WIMP-like dark matter candidates using noble element targets	10
1.6	Standard Halo Model dark matter speed distribution in the lab frame	12
2.1	Diagram of a dual-phase argon time projection chamber	15
2.2	Example of an S2 waveform with an $S2_{\text{echo}}$ pulse	16
2.3	Timeline of the DarkSide program detectors	21
2.4	The DarkSide-50 experiment	22
2.5	DarkSide-20k detector	25
2.7	Renderings of the DarkSide-20k TPC anode and cathode	25
2.8	The DarkSide-20k optical plane	26
3.1	Diagram of an LDM particle scattering off an electron bound to an argon atom, resulting in ionization	30
3.2	Mean inverse speed of DM (η) as a function of the minimum velocity in the lab frame (v_{min})	32
3.3	Bound electron wavefunction in position space	35
3.4	Squared bound electron wavefunction in momentum space	35
3.5	Real part of the outgoing electron wavefunction in position space	35

3.6	Convergence of the continuum hydrogenic and plane wave approximations for computation of the ionization form factor	37
3.7	Squared ionization form factor for relevant argon shells	38
3.8	Differential ionization rate of LDM-electron scattering for various argon electron orbitals	40
3.9	Differential ionization rate of LDM-electron scattering for an argon target	40
3.10	Measured photoelectric cross section tables for argon and xenon	42
3.11	Ionization rate of dark photon absorption for an argon target	43
3.12	Ionization rate of galactic ALP absorption for an argon target	43
3.13	Calibrated ER energy scale	45
3.14	DarkSide-50 S2 maximum channel correction map	48
3.15	DarkSide-50 S2-only dataset at different steps of the data selection process	49
3.16	β -decay energy spectra of ^{39}Ar and ^{85}Kr	51
3.17	DarkSide-50 S2 radial correction map applied to simulated data	56
3.18	Energy-dependent combined acceptance of the CXS2PeakTime and CXS2Gate cuts	56
3.19	DarkSide-50 ionization spectra of backgrounds and signals	57
3.20	Post-fit DarkSide-50 ionization spectra (<i>top</i>) for the background-only fit along with the data pulls (<i>bottom</i>)	60
3.21	Distribution of the data pulls for the background-only fit	61
3.22	Nuisance parameter pulls (<i>left</i>) and correlation matrix (<i>right</i>) from the background-only fit . . .	61
3.23	The 90% confidence levels on leptophilic DM couplings set using DarkSide-50 data	65
3.24	Best-fit nuisance parameter pulls as a function of DM mass	67
3.25	The 90% confidence levels on leptophilic DM couplings set using DarkSide-50 data, plotted alongside constraints from other experiments	69
4.1	Steps in the DarkSide-20k online and offline processing workflows	74
4.2	Time Slice scheme	74
4.3	Simulated DS-20k PDM signal for a single PE alongside the input signal template	79
4.4	Discrete Fourier power spectrum for a prototype PDM	79
4.5	ZLE algorithm flowchart	81
4.6	ZLE algorithm performance on simulated PDM waveforms	83

4.7	Hit finding algorithm procedure	83
4.8	Projected resolution of DarkSide-20k to single photoelectrons using either hit prominence or ZLE integral	84
4.9	Hit finder efficiency in reconstructing two photoelectrons as a function of the delay between them	84
4.10	Simulated energy reconstruction linearity of DarkSide-20k	87
4.11	Projected TPC data rate for DarkSide-20k from a full simulation of background events	91
5.1	Workflow of limit production for the pyds <code>light</code> package	93
5.2	Diagram of the DarkSide-20k TPC and IV, highlighting notable background sources	95
5.3	Energy and position distributions of simulated DarkSide-20k background single-scatter events in the low-mass energy ROI	97
5.4	Pre-fit DarkSide-20k background ionization spectra	100
5.5	Nuisance parameter pulls (<i>left</i>) and correlation matrix (<i>right</i>) from the background-only fit to Asimov data	100
5.6	The projected DarkSide-20k 90% confidence levels on leptophilic DM couplings	102
5.7	Effect of different assumptions on projected DarkSide-20k exclusion limits for LDM-electron scattering assuming a heavy mediator	105
6.1	The ARIS-ER experimental setup	109
6.2	Canberra BE2020 BEGe detector	110
6.3	Scionix 38A38/2M-E1-BAF-X-NEG BaF ₂ detector	110
6.4	The TPC used in the ARIS experiment	112
6.5	Simulated energy deposits in the BEGe detector (E_{BEGe}) and the TPC (E_{er})	113
6.6	Simulated TPC energy spectra for various BEGe detector energy ROIs at $\theta = 0^\circ$	114
6.7	Wiring diagram for the DAQ system	116
C.1	DarkSide-50 runs and their rates	131
C.2	DarkSide-50 top PMT array diagram	134

List of Tables

3.1	Argon binding energies	30
3.2	RHF coefficients for argon	34
3.3	DarkSide-50 background contributions	53
3.4	Nuisance parameters, their sources, and impacted model components included in the binned profile likelihood for the DarkSide-50 low-mass analysis	59
4.1	Simulation chain for producing fake data, followed by the data reconstruction chain	77
4.2	Electronics and DAQ simulation parameters used in dsreco	78
4.3	Proposed data structure of a Time Slice	89
5.1	DarkSide-20k projected background contributions	96
5.2	Nuisance parameters, their sources, and impacted model components included in the binned profile likelihood for the DarkSide-20k low-mass analysis	99
6.1	CAEN V2495 port description for the custom firmware	118

Chapter 1

Introduction

Dark matter is one of the largest outstanding mysteries in physics. The existence of dark matter (DM) is inferred from astronomical observations. However, DM has not been directly observed, and its composition remains unknown. Many candidates have been proposed, including light dark matter, dark photons, and axion-like particles. Experimentalists have developed a wide variety of techniques to test these models and search for DM interactions.

I begin this chapter with an overview of the evidence for DM in Section 1.1 extracted from astronomical observations. I then discuss several well-motivated DM candidates in Section 1.2 and the techniques used to detect them in Section 1.3. These include direct WIMP searches. I finish by describing the Standard Halo Model used to describe the local dark matter distribution to which direct detection experiments are sensitive.

1.1 Evidence for dark matter

Observational evidence for dark matter comes from measurements of both the small and large-scale properties of the universe. At the largest scale, DM is inferred from the motion of stars in galaxies. At the smallest scale, measurements of the cosmic microwave background require the existence of DM to explain the dynamics of the early universe.

1.1.1 Galaxy rotation curves

In the 1970s, Vera Rubin and others studied the motion of stars in the M31 (Andromeda) galaxy [2, 3]. They found that the velocity of stars in the outer regions of the galaxy was higher than expected based on the visible

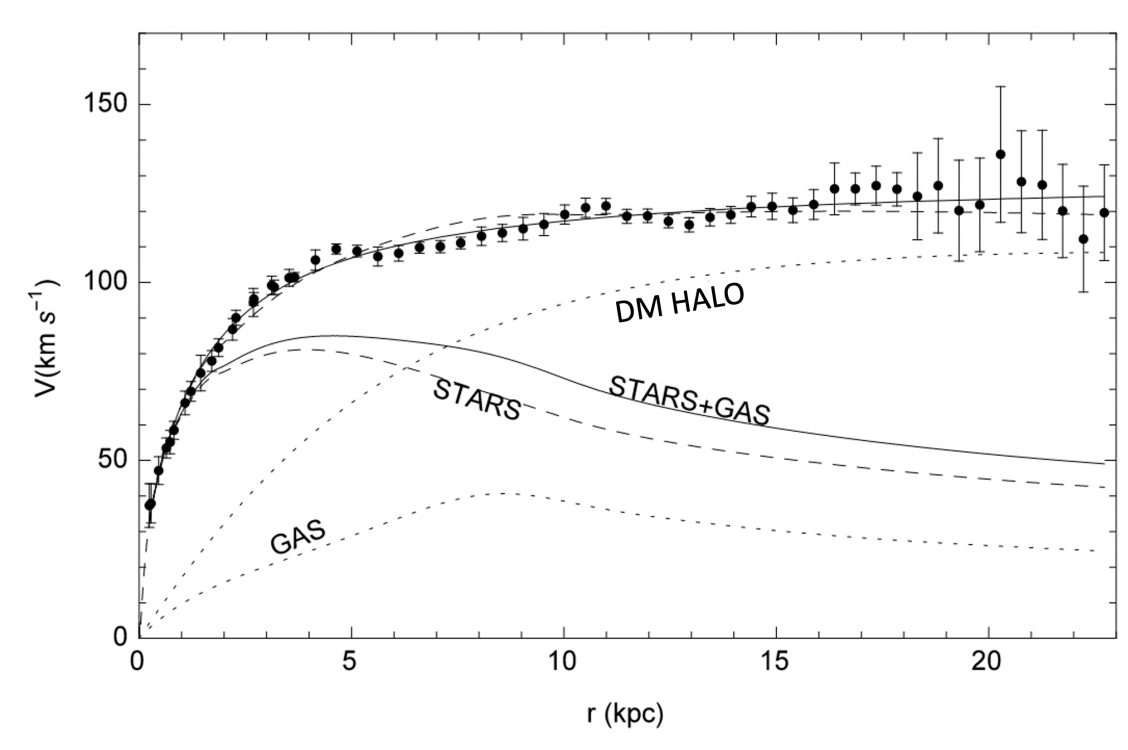


Figure 1.1: Rotation curve of the M33 galaxy. *Black dots with error bars* show the measured values, with the analytical best fit shown by the continuous line. The dark matter component is labeled “DM halo.” Figure reproduced from Ref. [1].

mass of the galaxy, which suggested the existence of additional mass that is not visible.

Stars in a galaxy are collisionless, so their motion can be described solely by Newtonian gravity. The circular velocity (v_c) can be calculated as a function of distance from the galactic center:

$$v_c(R) = \frac{G M(R)}{R} \quad (1.1)$$

where M is the mass enclosed within a radius R . Shown in Figure 1.1 is a recent study of the M33 galaxy [1]. For objects near the edges of a galaxy, where M is approximately constant, it is expected that $v_c(R) \propto R^{-1/2}$ as shown by the line labeled “stars and gas.” However, this is incompatible with the observational data that shows v_c is roughly flat in this regime. This profile requires $M(R) \propto R$, which implies the existence of a spherically symmetric halo of additional mass that is not visible. In Figure 1.1, this the “DM halo” component.

1.1.2 Cosmic microwave background

The cosmic microwave background (CMB) is radiation at a temperature of 2.728 K that originates from photon decoupling in the early Universe. Anisotropies on the order of $10\mu\text{K}$ possess a structure containing information about the universe’s physical properties at that time. CMB temperature power spectrum mea-

measurements by the *WMAP* probe [4] and *Planck* satellite [5] were fitted with high significance to the Λ CDM model, which includes six parameters describing the Universe’s baryonic matter, DM, and dark energy contents. The fit results demonstrated that the DM density is approximately five times greater than the baryonic matter density.

1.1.3 Gravitational lensing

Gravitational lensing is a phenomenon in which the path of light is bent by the presence of a massive object, as predicted by general relativity. The effect is measurable when the light from a distant source passes by a massive object along multiple paths due to perturbation of the spacetime metric. Strong lensing occurs when deflections are sufficiently large to produce multiple images of the source, while weak lensing refers to smaller deflections that distort the image. The distortion can be used to infer the mass distribution of the lensing object. Using gravitational lensing, a large number of observations have measured the DM mass to be 10 to 20 times larger than the mass of visible matter in galaxies and a factor of 100 to 300 larger in galaxy clusters [6].

1.1.4 Galaxy cluster collisions

The 1E 0657-558 “bullet cluster” is a system of two colliding galaxy clusters located at a redshift of $z = 0.296$ [7]. This is shown in Figure 1.2. Weak-lensing measurements reveal that the gravitational potential (*green* contours) does not align with the baryonic mass distribution. The offset between the two can be explained by DM halos that pass through each other during the collision, unlike the gas clouds that interact. Upper limits on the self-interaction cross section for DM can be set from these collisions [8].

1.2 Dark matter candidates

A range of DM candidates have been proposed. Some of these hypothesize that DM is a single particle while others model DM as a collection of particles referred to as the “dark sector.” To be compatible with the previously described measurements, a DM candidate, in general, must be:

- electrically neutral, otherwise DM would couple to photons and produce visible signals.
- non-baryonic, otherwise CMB measurements would not match theoretical models.

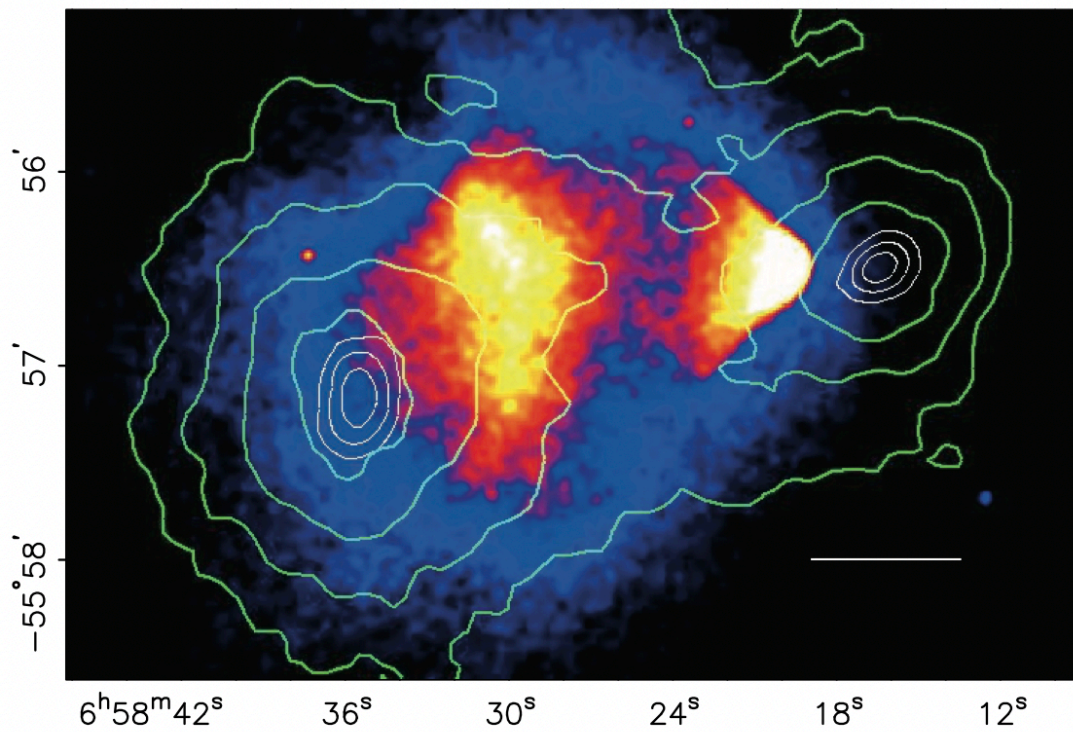


Figure 1.2: *Chandra* x-ray image of the merging cluster 1E 0657-558. The x-ray emission from the visible matter is shown by the color map. The mass contours in *green* are reconstructed from weak-lensing measurements. Figure reproduced from Ref. [7].

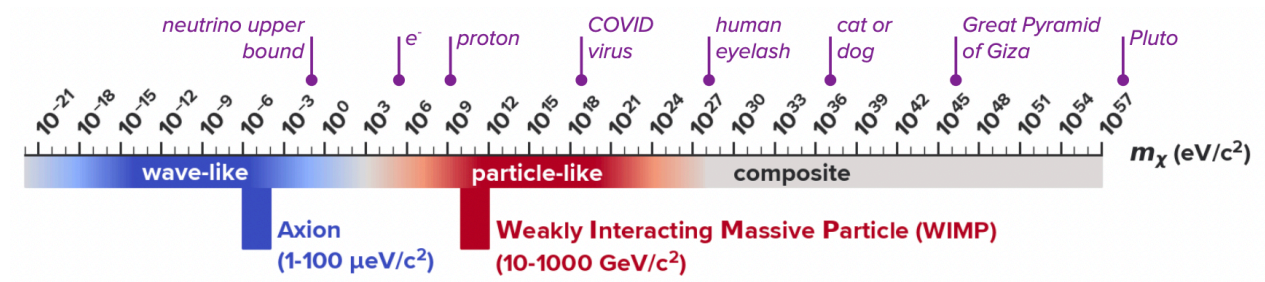


Figure 1.3: Allowed mass range of dark matter candidates, with familiar objects for reference. The lower bound (10^{-22} eV) is set by arguments necessitating sufficient localization of DM particles while the upper bound is set by microlensing observations [9]. This work.

- non-relativistic, otherwise structures in the early universe would not be present.
- long-lived with a lifetime longer than the age of the universe, otherwise structures would be observed to decay over time.
- feebly self-interacting, to match observations of colliding galaxies.
- feebly-interacting with Standard Model (SM) particles, otherwise interactions would have been previously observed.

While a multitude of experiments have set upper limits on non-gravitational couplings between DM and SM particles, no measurement has set a lower bound. However, many DM theories require a non-gravitational interaction to explain the observed relic abundance of DM in the universe [10].

Figure 1.3 shows the allowed mass range of DM particles, along with familiar objects for orientation. The lower bound is set by calculating the de Broglie wavelength for such a particle. For the typical rotational velocity of DM in a galaxy halo, the de Broglie wavelength for a particle with mass 10^{-22} eV is on the order of a dwarf galaxy, meaning that DM with smaller masses would not be sufficiently localized to create the observed structure. At the other end, the dark matter mass upper bound is set by microlensing observations, which do not observe a sufficient number of objects to account for dark matter [9].

1.2.1 WIMPs

One of the leading candidates for DM has been the Weakly Interacting Massive Particle (WIMP) [6, 11]. This is a hypothetical particle with a mass in the range of $10 \text{ GeV}/c^2$ to TeV/c^2 that is thermally produced in the early universe. Through model-specific interactions, WIMPs can self-annihilate into SM fermions and can, in turn, be produced by SM particle annihilation [12]. Models predict that WIMPs were in thermal equilibrium with SM particles in the early Universe, such that the number of DM particles was constant. This condition was broken after the Universe cooled and SM particles had insufficient center-of-mass energy to produce WIMPs. For a period of time, WIMPs could still annihilate into SM particles, reducing the total amount of DM. After the Universe’s expansion rate exceeded the WIMP annihilation rate, the number of WIMPs then became constant; this is known as a process called “freeze-out.” It turns out that weak-scale cross sections between WIMPs and SM particles naturally lead to the currently observed DM density. Numerous extensions to the SM contain particles matching this description, including supersymmetry [11].

Over the past few decades, many searches for WIMPs have been conducted [13–17]. While there have been some tantalizing hints, no conclusive evidence has been found. Furthermore, the lack of non-SM particles in LHC data has eroded the motivation for many WIMP models [18]. In response, new and more exotic theories have been proposed that build upon the original WIMP paradigm and predict DM cross sections with SM particles in as-yet unexplored regions of parameter space. One such theory actively being tested by direct detection experiments like DarkSide-20k is an 11-parameter phenomenological minimal supersymmetric extension of the Standard Model (pMSSM11), which predicts a DM-nuclear cross section on the order of 10^{-48} cm^2 for WIMP masses around 0.1 to 1 TeV/ c^2 [19, 20]. In some WIMP-derivative models such as Super-WIMPs, the DM cross section is so small that observable signatures can only be seen in early Universe cosmological measurements like the CMB [21, 22].

1.2.2 Light dark matter

Given the lack of evidence for WIMP dark matter, there has been a growing interest in probing a wider range of DM masses. Light dark matter (LDM) refers a broad class of DM candidates with masses in the MeV/ c^2 to GeV/ c^2 range, similar to but distinct from WIMPs. The lighter masses of LDM as compared to WIMPs means a different interaction between DM and SM is needed to achieve the observed DM relic abundance. In this work, we will only discuss a benchmark model for LDM in which relic DM is composed entirely of a single fermionic particle χ with mass m_χ and is charged under a new force mediated by a vector boson V with mass m_V , called the dark photon (DP) [18, 23]. For this interaction, the DP is charged under the $U(1)_D$ gauge group and kinetically mixes with the SM photon, which leads to a feeble coupling at low energies between LDM and electrically charged SM particles, providing a portal to the dark sector. The interaction term is

$$\mathcal{L} \supset \frac{\kappa}{2 \cos \theta_W} F_Y^{\mu\nu} F_{\mu\nu}^D \quad (1.2)$$

where κ is the kinetic mixing parameter, θ_W is the weak mixing angle, $F_Y^{\mu\nu}$ is the SM hypercharge field strength tensor, and $F_D^{\mu\nu}$ is the $U(1)_D$ field strength tensor. While interactions with electrons and nuclei are possible, direct detection experiments are more sensitive to the electron scattering channel due to the smallness of the electron mass compared to the LDM mass.

For this LDM-electron scattering interaction, the reference cross section ($\bar{\sigma}_e$) is computed for a momen-

tum transfer q fixed to $\alpha m_e c$ [18]:

$$\bar{\sigma}_e = \frac{\mu_{\chi e}^2 \overline{|\mathcal{M}_{\chi e}(q = \alpha m_e c)|^2}}{16\pi m_\chi^2 m_e^2} = \frac{16\pi \mu_{\chi e}^2 \alpha \kappa^2 \alpha_D}{(m_V^2 + \alpha^2 m_e^2)^2} \quad (1.3)$$

where m_e is the electron mass, $\mu_{\chi e} = m_\chi m_e / (m_\chi + m_e)$ is the reduced mass of the LDM and electron, α is the fine structure constant, c is the speed of light, and $\alpha_D = g_D^2 / 4\pi$ with g_D being the $U(1)_D$ gauge coupling. $\overline{|\mathcal{M}_{\chi e}(q = \alpha m_e c)|^2}$ is the squared matrix element for LDM-electron scattering averaged over the initial particle spins and summed over the final particle spins for the specified momentum transfer of $\alpha m_e c$. For this interaction, the matrix element for an arbitrary momentum transfer q can be written as a function of the reference matrix element [23]:

$$\overline{|\mathcal{M}_{\chi e}(q)|^2} = \overline{|\mathcal{M}_{\chi e}(q = \alpha m_e c)|^2} \times F_\chi(q) \quad (1.4)$$

where F_χ is the LDM form factor. This is a unitless quantity that contains the interaction's momentum transfer dependence. For this interaction, F_χ takes the form of

$$F_\chi(q) = \frac{m_V^2 + \alpha^2 m_e^2}{m_V^2 + (q/c)^2} = \begin{cases} 1, & m_V \gg \alpha m_e \\ \left(\frac{\alpha m_e c}{q}\right)^2, & m_V \ll \alpha m_e \end{cases} \quad (1.5)$$

where α is the fine-structure constant and m_e is the electron mass. Two limiting cases for the mediator mass are a heavy mediator ($m_V \gg \alpha m_e = 3.7 \text{ keV}/c^2$) and a light mediator ($m_V \ll \alpha m_e$). As shown in Equation (1.5), the DM form factor is constant for a heavy mediator and proportional to $1/q^2$ for a light mediator. Due to this momentum suppression, direct detection experiments can probe more parameter space for the heavy mediator case than for a light mediator.

Production mechanisms For a heavy mediator, LDM is produced through the freeze-out mechanism described in Section 1.2.1. If the mediator is very light, namely $m_V \ll \alpha m_e$, LDM is produced through the “freeze-in” scenario in which SM particles annihilate into DM particles.

1.2.3 Dark photons

Another compelling DM candidate is the dark photon (DP). Note that this particle is the same as the mediator in the LDM model described above, namely a vector boson of the gauge group $U(1)_D$. The DP lifetime can be longer than the age of the universe if the DP kinetic mixing parameter (κ) is sufficiently small and the DP

mass m_ν is less than twice the electron mass, so that decay into electron-positron pairs is suppressed [24, 25]. In this case, the DP can constitute all of the relic DM. Theories that predict the DP as a DM candidate do not require additional dark sector particles but often include them, with the DP acting as a portal to the SM. Direct detection experiments can probe DP models through the absorption process, which is analogous to the photoelectric absorption of SM photons. This process arises from the same kinetic mixing term as the LDM model described above.

1.2.4 Axion-like particles

The final DM candidate we will discuss is the axion-like particle. First, we will introduce the QCD axion and then discuss the generalization to axion-like particles. The QCD axion is a pseudoscalar boson originally proposed to solve the strong CP problem [26–28]. If the axion has a low enough mass, namely from about 1 to $100 \mu\text{eV}/c^2$ as shown in Figure 1.3, it is also a viable DM candidate and can constitute all of the relic DM. The connection between the axion mass and coupling strength is fixed by the requirement that the axion solves the strong CP problem. A more general DM candidate is the axion-like particle (ALP) [25, 29, 30], which results from the same mechanism as the axion, namely a spontaneously broken global symmetry. However, the ALP is not associated with solving the strong CP problem; thus, its mass and coupling strength are independent. ALPs appear in many extensions to the SM, including string theories [31].

Both axions and ALPs possess an effective coupling to electrons that can result in observable interaction signals. This process is called the axioelectric effect and is analogous to the photoelectric effect; an ALP is absorbed by a bound electron in an atom, producing a liberated electron. The axioelectric coupling constant g_{ae} characterizes the axioelectric effect. Direct detection experiments optimized for detecting WIMP interactions, such as those with noble liquid targets, are not sensitive to axions due to their low mass. However, ALPs with keV/c^2 -scale masses can be detected by such experiments. As such, we will focus on ALPs in this work.

1.3 Detection techniques

The lack of direct evidence for non-gravitational DM interactions has motivated the physics community’s current approach to DM searches: to “delve deep, search wide, aim high” [32]. Current and future searches are designed to search for a wide range of high-priority DM candidates, including WIMPs, while also expanding

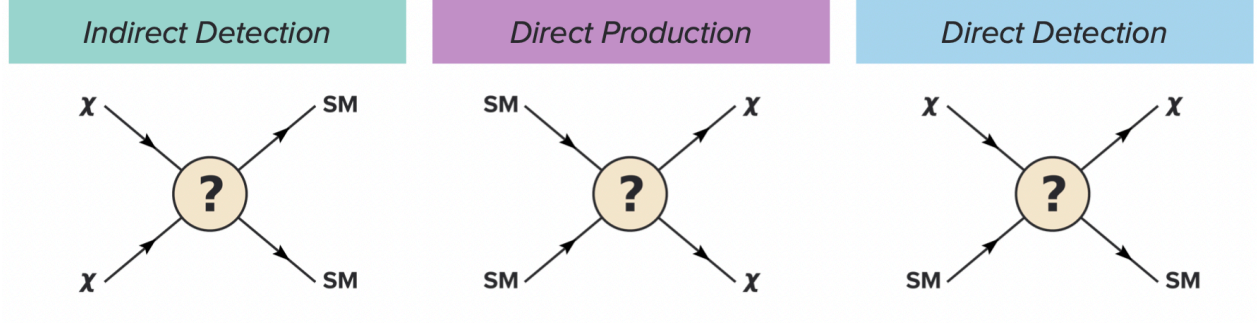


Figure 1.4: Dark matter detection technique diagrams. See the text for details. This work.

the search to probe as much motivated DM parameter space as possible. Dark matter interaction can be detected in several ways, as shown by the toy Feynmann diagrams in Figure 1.4. These include indirect detection, direct production using colliders, and direct detection.

1.3.1 Indirect detection

Indirect searches look for SM particles of astronomical origin that are hypothesized to be DM annihilation or decay products [33]. This is shown in the left panel of Figure 1.4. Favorable targets for indirect searches are relatively nearby, have high dark matter densities, and have low backgrounds; dwarf galaxies and galaxy clusters are prime examples. Observable final state particles must be stable and able to traverse the vast distance from the source to Earth, namely photons, charged cosmic rays, and neutrinos. Detectors can either be space-based or ground-based.

A space-based experiment is advantageous because it is not limited by the atmosphere, which absorbs many of the SM particles. One such detector is the Large Area Telescope (LAT), the main instrument of the *Fermi* Gamma-ray Space Telescope. The LAT is a pair-conversion detector, where incident γ -rays produce electron-positron pairs in a tungsten layer. This is followed by several tracking layers and ultimately a CsI(Tl) calorimeter. Known standard astrophysical processes do not produce monoenergetic γ -rays, so the observation of a γ -ray line would be a strong indication of DM or other new physics. In 2017, *Fermi*-LAT published findings that showed no statistically significant γ -ray excesses [34].

Ground-based experiments are advantageous for the deployment of large target masses. The IceCube experiment is a neutrino observatory in Antarctica that detects Cherenkov light from interactions in the ice using photomultiplier tubes (PMTs) on strings [35]. The fiducial volume of the detector is a cylinder with a 125 m radius and 350 m height, which can detect annihilation products of GeV/c^2 -scale DM particles [36].

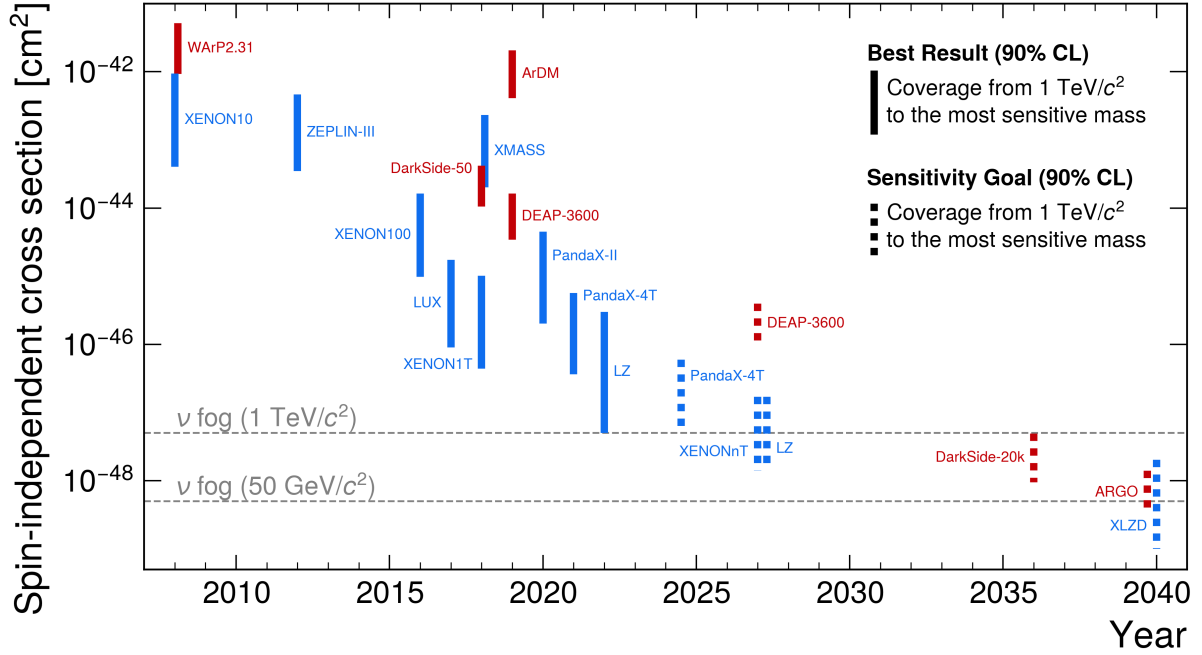


Figure 1.5: Landscape of direct detection experiments probing WIMP-like dark matter candidates using noble element targets. Experiments using argon are shown in *red*, and those using xenon are *blue*. Solid lines show the 90% CL upper limits on the spin-independent DM-nucleon cross section [13, 16, 17, 41–51], while dotted lines show the projected sensitivity of future experiments [20, 52–55]. The line’s extent indicates the range cross sections probed, with the uppermost point located at the 90% CL for a 1 TeV/ c^2 DM particle and the lowermost point at the experiment’s most sensitive mass. This work.

1.3.2 Collider production

Another technique is to look for DM production in collider experiments. The collision of SM particles can result in a final state containing DM particles if DM couples to SM particles, as shown in the center panel of Figure 1.4. The observed final state would have a significant fraction of missing momentum. This can be done using collider experiments, such as those at the Large Hadron Collider (LHC) [37–39], or fixed-target experiments like Light Dark Matter eXperiment (LDMX) [40]. LDMX is a prospective experiment that will use an electron beam to search for DM production in a thin tungsten target through a “dark bremsstrahlung” process. Downstream electromagnetic and hadronic calorimeters will measure the energy of SM particles. Missing final state energy would indicate the presence of DM particles.

1.3.3 Direct detection

Interactions of DM particles with SM particles can be detected by observing the recoil of a SM particle; this is called direct detection, visualized in the right panel of Figure 1.4. Direct detection experiments employ a wide range of detector technology to target specific mass and cross section ranges. Laboratory direct detection

searches targeted at $\text{sub-GeV}/c^2$ to TeV/c^2 DM particles primarily use semiconductors (germanium, silicon), noble liquids (argon, xenon), crystals (NaI, CaWO_4 , etc.), or superheated fluids (C_3F_8).

Semiconductor targets are advantageous for LDM searches due to the low achievable thresholds, as the energy required to make an electron-hole pair is just 3.6 eV for silicon and 2.9 eV for germanium [56]. The SuperCDMS collaboration uses cryogenically-cooled silicon and germanium crystals [57–59]. The SENSEI [60] and DAMIC-M [61] experiments employ charge-coupled devices to detect ionization over an array of pixel.

Noble liquids detectors can be straightforwardly scaled into the multi-tonne regime. The surface-to-volume ratio can be better controlled for noble liquid detectors than for semiconductor detectors, which is important for controlling background levels when scaling to large masses. This makes noble liquids attractive for higher mass DM searches for candidates such as WIMPs. The landscape of noble liquid DM searches is shown in Figure 1.5. One can see the improvement in probing WIMP-nuclear scattering parameter space over the last two decades. The Global Argon Dark Matter Collaboration (GADMC) uses a series of argon dual-phase time projection chamber (TPC) detectors to search for GeV/c^2 to TeV/c^2 DM. These include the DarkSide-50 experiment [16, 62], DEAP-3600 [63], and the upcoming DarkSide-20k experiment [20]. Current xenon-based dual-phase TPC experiments include XENONnT [64], LZ [65], and PandaX-4t [51].

Neutrino fog A major challenge and opportunity of future direct searches for GeV/c^2 to TeV/c^2 DM is coherent elastic neutrino-nucleus scattering (CEvNS) of astrophysical neutrinos [66–68]. Without directional information, the CEvNS signal from these neutrino sources is indistinguishable from DM-nuclear scatters on an event-by-event basis. To further complicate matters, the neutrino energy spectra are similar to that of DM-nuclear scatters. As a result, the sensitivity of next-generation DM experiments to DM-nuclear interactions will be limited by this irreducible background, referred to as the “neutrino fog.” For argon targets, sensitivity to DM-nuclear cross sections below $2 \times 10^{-48} \text{ cm}^2$ at $1 \text{ TeV}/c^2$ will be affected [66].

1.4 Interaction rates

A detector located on Earth is sensitive to DM particles that compose the Milky Way DM halo and pass through the detector. A non-relativistic interaction rate $\mathcal{R}$ can be derived for the detection of DM particles that compose the galactic halo. This is the product of the dark matter flux (Φ_χ) and the interaction cross section

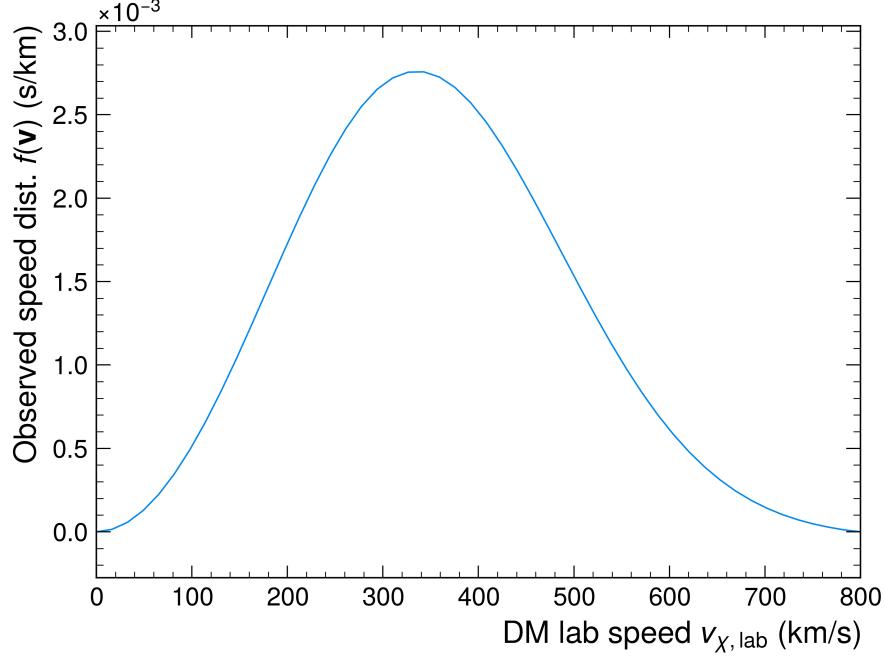


Figure 1.6: Standard Halo Model dark matter speed distribution in the lab frame, evaluated at $t = \text{March 9, 2022}$. This work.

(σ) with a single atom, scaled by the number of target atoms (N_T) in the detector:

$$\mathcal{R} = N_T \Phi_\chi \sigma . \quad (1.6)$$

The flux of DM particles passing through the detector (Φ_χ) is

$$\Phi_\chi = \frac{\rho_\chi}{m_\chi} v_\chi \quad (1.7)$$

where ρ_χ is the local DM mass density, m_χ is the DM mass, and v_χ is the velocity of the DM particles. Throughout this work, we assume the local DM density to be $0.3 \text{ GeV}/(c^2 \text{ cm}^3)$ per the recommendations of Ref. [69].

Standard halo model The distribution of DM velocities that the detector can observe depends on (a) the velocity distribution of the DM particles in the galactic halo, (b) the solar system's orbit around the center of the Milky Way, and (c) the Earth's orbit around the Sun. The Standard Halo Model (SHM) models the DM galactic halo as an isotropic Maxwellian velocity distribution [70]:

$$f_{\text{gal}}(\mathbf{v}_{\text{gal}}) = \frac{1}{N_{\text{esc}}} \left(\frac{1}{\pi^{3/2} |\mathbf{v}_{\text{LSR}}|^3} \right) e^{-|\mathbf{v}_{\text{gal}}|^2/|\mathbf{v}_{\text{LSR}}|^2} \Theta(v_{\text{esc}} - |\mathbf{v}_{\text{gal}}|) \quad (1.8)$$

where $\mathbf{v}_{\text{gal}}$ is the galactic-frame DM velocity and $\mathbf{v}_{\text{LSR}}$ is the local standard of rest (LSR) velocity, more specifically, the velocity of a circular orbit at the Solar radius from the galactic center with a value

of $\begin{bmatrix} 0 & 238 & 0 \end{bmatrix}$ km/s [69], where the vector is given as $\begin{bmatrix} v_r & v_\phi & v_\theta \end{bmatrix}$, r points radially inward, and ϕ is in the direction of the Milky Way's rotation. The distribution is truncated at the galactic escape velocity ($v_{\text{esc}} = 544$ km/s), which requires that DM is gravitationally bound in the galaxy. The normalization factor N_{esc} is defined as

$$N_{\text{esc}} = \text{erf}(z) - \frac{2}{\sqrt{\pi}} z e^{-z^2}, \quad z \equiv v_{\text{esc}}/v_0 \quad (1.9)$$

The SHM distribution in the lab frame (f) is related to the galactic-frame distribution by a Galilean boost:

$$\mathbf{v}_{\text{E}}(t) = \mathbf{v}_{\text{LSR}} + \mathbf{v}_{\text{pec}} + \mathbf{u}_{\text{E}}(t) \quad (1.10)$$

$$f(\mathbf{v}, t) = f_{\text{gal}}(\mathbf{v} + \mathbf{v}_{\text{E}}(t)) \quad (1.11)$$

The peculiar velocity of the Sun ($\mathbf{v}_{\text{pec}}$) with respect to the LSR is $\begin{bmatrix} 11.1 & 12.2 & 7.3 \end{bmatrix}$ km/s, while the velocity of the Earth around the Sun ($\mathbf{u}_{\text{E}}$) is

$$\mathbf{u}_{\text{E}}(t) = (29.8 \text{ km/s}) \times \begin{bmatrix} 0.9941 \cos(\omega \Delta t) - 0.0504 \sin(\omega \Delta t) \\ 0.1088 \cos(\omega \Delta t) + 0.4946 \sin(\omega \Delta t) \\ 0.0042 \cos(\omega \Delta t) - 0.8677 \sin(\omega \Delta t) \end{bmatrix} \quad (1.12)$$

where $\omega = 0.0172/\text{d}$ and Δt is the number of days since the arbitrarily chosen reference data of March 22, 2018. The SHM is evaluated in this work at $t = \text{March 9, 2022}$, as recommended by Ref. [69]. Using these parameters, Equation (1.11) is evaluated and shown in Figure 1.6. The maximum observable DM speed in the lab frame is around 800 km/s, while the distribution is peaked near 340 km/s.

Chapter 2

The DarkSide program

The DarkSide program, operated by the Global Argon Dark Matter Collaboration, primarily seeks to directly detect dark matter using dual-phase argon time projection chambers. Other broader goals include neutrino physics, namely the detection of solar neutrinos and supernova neutrino bursts. Particle interactions can be reconstructed precisely as dual-phase time projection chambers enable precise measurements of energy and position. These detectors are designed and constructed to be highly radiopure and optimized for the detection of rare events. The liquid argon target enables further background rejection through the use of pulse shape discrimination. Auxiliary detectors surrounding the TPC can reject backgrounds from neutrons and muons.

This chapter gives an overview of the detector technology employed by the Global Argon Dark Matter Collaboration to detect DM, starting with a description of dual-phase TPCs Section 2.1. This is followed by details and modeling of the liquid argon target in Section 2.2. This chapter contains detailed descriptions of the previous stage of the program, DarkSide-50, in Section 2.4 and the current stage, DarkSide-20k, in Section 2.5.

2.1 Dual-phase TPC

A dual-phase (liquid-gas) time projection chamber (TPC) is a calorimeter detector that enables timing and three-dimensional position reconstruction of particle interactions. A noble element is used as the target material as they are excellent scintillators and do not chemically react with other elements. Argon and xenon are predominantly used as they have sufficiently large atomic numbers to probe DM interactions with nuclei. While krypton is a scintillator, it is not used as a target in DM searches due to an intrinsic background of long-

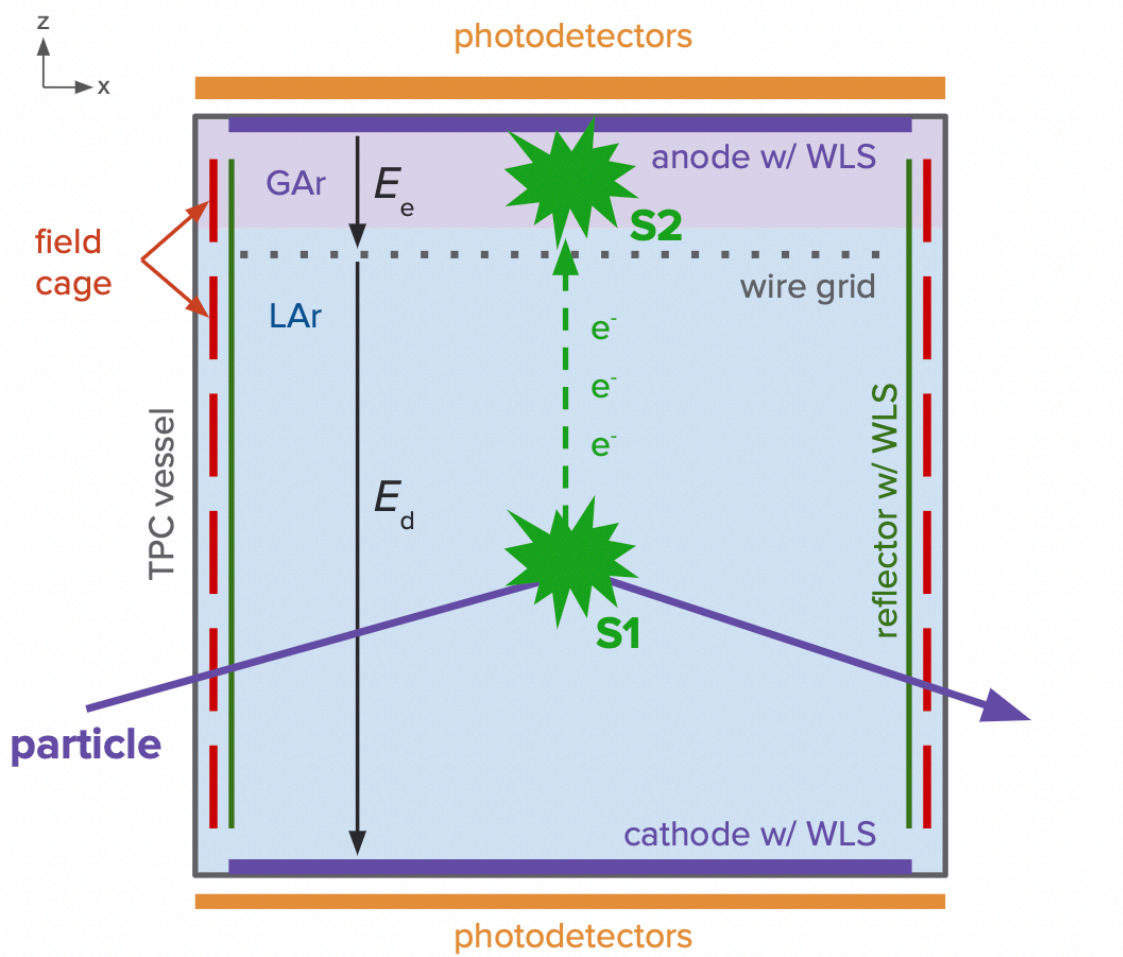


Figure 2.1: Diagram of a dual-phase argon time projection chamber. See the text for a full description. This work.

lived radioactive isotopes such as ^{85}Kr [56]. This, coupled with the stability of the naturally most abundant isotopes, means argon and xenon can be purified easily and can achieve low intrinsic background interaction rates. Dual-phase TPCs are ideal for probing the nuclear scattering of DM candidates with masses in the sub- GeV/c^2 to TeV/c^2 range due to their scalability into the multi-tonne regime.

Figure 2.1 shows a diagram of a dual-phase argon TPC. The liquid phase (*light blue*) is the active target for particle interactions, which produce scintillation light and ionization electrons. The primary scintillation photons detected by the top or bottom photodetector arrays (*orange*) are referred to as the S1 signal, which is measured in units of photoelectrons (PE). Above the liquid phase is a thin gaseous phase (*light purple*). An electric field $\vec{E}_d$ is applied across the active volume to drift the ionization electrons (*green*) towards the liquid-gas interface. Upon reaching the interface, a much stronger electric field $\vec{E}_e$ extracts the electrons through the gas pocket, where they produce electroluminescent scintillation through interactions with gaseous atoms.

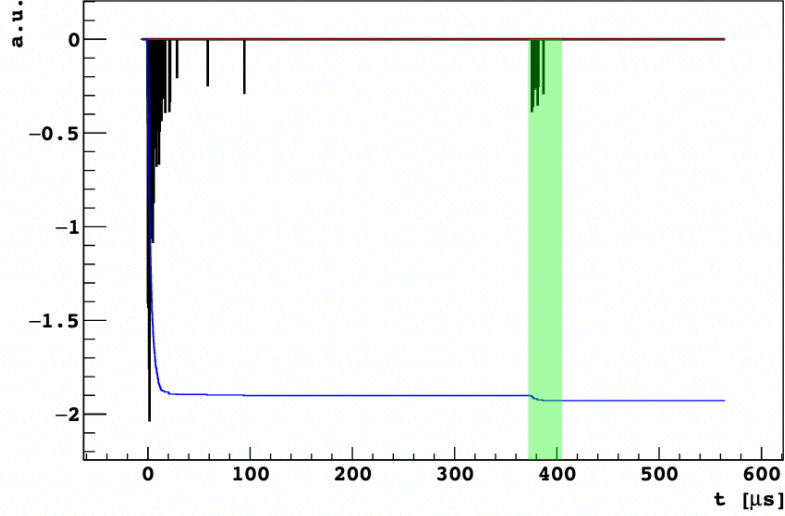


Figure 2.2: Example of an S2 waveform with an $S2_{\text{echo}}$ pulse, highlighted in *green*. Figure reproduced from Ref. [71].

This light forms the S2 signal, or ionization signal, which is usually quoted in units of extracted electrons (N_e). The S2 signal is generally larger than S1, with the exact gain mainly determined by the gas pocket thickness and drift field; this is described in more detail in Section 2.2.2.

All surfaces facing the active volume are typically coated with a wavelength shifter (WLS) to shift the vacuum ultraviolet (VUV) scintillation light into the visible regime where photodetector sensitivities are generally optimized. Further, TPC lateral surfaces typically contain highly reflective materials (*dark green*) behind the WLS to increase the number of detected photons. A drift field is created by applying a voltage difference between the cathode (*purple*) and the wire grid (*gray*), which is a mesh that stretches across the TPC. Field cage rings (*red*) surround the TPC to shape the electric field, limiting non-uniformity to less than 0.5% in the active volume [20]. Uniformity is important to prevent cause charge-up issues and to ensure uniform S1 and S2 signal measurements, as the partitioning of quanta between the two signals is affected by the field strength (see Section 2.2). The extraction field ($\vec{E}_e$) is created by a potential difference between the wire grid and anode (*purple*). Nonuniformities in this field directly affect the S2 yield and reconstructed (x, y) position. Both the cathode and anode are optically transparent to enable light collection.

Echo pulses In a dual-phase TPC, photons from either S1 or S2 pulses can induce photoionization in any of the detector’s inner surfaces. Liberated electrons can be extracted, producing spurious S2 signals correlated in time with S1 or S2. In the case of photoionization of the cathode, the electrons drift the entire length of the TPC and can be identified by looking for single or few-electron S2 pulses around the full TPC drift time

after a given pulse. This specific type of pulse, resulting from cathode photoionization, is called an $S1_{\text{echo}}$ or $S2_{\text{echo}}$ [72]. An example of this is shown in Figure 2.2, with the $S2_{\text{echo}}$ pulse shaded green.

2.2 Liquid argon

Liquid argon (LAr) is an attractive target for usage in multi-tonne TPCs due to its large natural abundance and outstanding pulse shape discrimination capabilities. This section describes the scintillation process in LAr and the mechanism that enables pulse shape discrimination. Also described is the scintillation model used to convert between the deposited energy and the S1 and S2 signals.

An interaction in LAr predominantly results in a track of excited and ionized atoms, which is on the order of a mm in length for DM recoil energies. Within several ps, the excited argon atoms (Ar^*) form weakly-bound excited dimers called excitons (Ar_2^*) with ground-state argon atoms [73, 74]. The excitons then deexcite through radiative emission, producing VUV scintillation photons (γ)



Exciton can be in either singlet or triplet states, which deexcite with very different decay times. The singlet state has a decay time constant of 7 ns while that of the triplet state is 1300 ns [75]. The scintillation light is narrowly peaked at 128 nm [76, 77], to which argon is transparent [78]. This light is one of two contributions to the S1 signal.

A portion of the ionized atoms (Ar^+) form molecular ions (Ar_2^+), which recombine with electrons:



The Ar^* excitons resulting from ion recombination produce scintillation light via the process in Equation (2.1); this is the second contribution to the S1 signal. The TPC's drift field extracts electrons that do not recombine, which form the S2 signal as described in Section 2.1. A portion of the energy is lost to non-radiative processes such as atomic motion (heat).

The fraction of energy observed in each of the channels described above (scintillation, ionization, heat) depends on the incident particle. A track from an electron, produced by processes such as a β -decay or an argon shell electron ionized by a Compton scatter, is called an electronic recoil (ER). For ERs, nearly

all energy is deposited through the excitation and ionization channels. The deposited energy is typically measured in units of electron recoil equivalent energy (e.g. keV_{er}). The track from a recoiling argon nucleus is called a nuclear recoil (NR); this can be produced by a neutron scatter or WIMP scatter. For NRs, a significant fraction of the energy is deposited in channels other than excitation and ionization, namely heat. This quenching results in a scintillation yield of about 0.25 as compared to ERs [79, 80]. Consequently, the deposited energy for NRs is measured in different units, namely nuclear recoil equivalent energy (e.g. keV_{nr}). In a fraction of NR cases, ionization of inner shell electrons can be followed by x-ray or Auger electron emission, a process known as the Migdal effect [81].

Another difference between ERs and NRs is the probability of forming a singlet state in Equation (2.1). The singlet probability is the fraction of excitons that form singlet states; this is about 0.25 for ERs and 0.72 for NRs [75]. Consequently, we can distinguish ERs from NRs by analyzing the S1 time profile; this is called pulse shape discrimination (PSD). The fraction of prompt component (f_p) of a pulse $S(t)$ can be calculated using

$$f_p = \frac{\int_0^{t_p} S(t) dt}{\int_0^{\infty} S(t) dt} \quad (2.3)$$

where the numerator is the pulse area in the prompt window defined up to a time t_p and the denominator is the total pulse area. The prompt window is optimized for a specific detector geometry to maximize the separation between ERs and NRs. For DS-50, t_p was optimized to be 90 ns [82].

The single-phase DEAP-3600 experiment recently achieved ER background rejection better than 10^{-7} using PSD with S1 pulses [63]. This is four orders of magnitude beyond that achieved with liquid xenon, which primarily relies on the ratio of S2 to S1 as its singlet and triplet decay time constants are too similar [17]. Argon's PSD capability will enable a large underground detector to distinguish solar neutrinos ER backgrounds from dark matter interactions.

2.2.1 Underground argon

While atmospheric argon (AAr) is readily available and inexpensive, it contains ^{39}Ar , which undergoes β -decay with a half-life of 269 yr. As the activity of ^{39}Ar in AAr is 1.01 Bq/kg [83], these backgrounds are overwhelming for DM searches. Several underground sources of argon (UAr) were discovered in the last two decades, including the Kinder Morgan Doe Canyon CO_2 wells in Cortez, CO [84]. Layers of rock shield UAr from the cosmic ray flux, severely reducing the production of ^{39}Ar via (n,2n)-reactions on ^{40}Ar . While ^{39}Ar

can still be produced in UAr by neutron capture on ^{39}K , its concentration is reduced by nearly three orders of magnitude. This can be further reduced via isotopic separation using a cryogenic distillation column [85].

2.2.2 Scintillation model

The DarkSide Collaboration developed a custom semi-empirical model for the response of LAr to ERs and NRs called the Precision Argon Response Ionization and Scintillation (PARIS) model [86]. The energy deposited in an interaction (E_{dep}) is quenched to account for energy lost as heat. The quenching factor ($\mathcal{L}_{\text{eff}}^k$) scales the deposited energy for a recoil type k , giving the quenched energy:

$$E_{\text{q}} = \mathcal{L}_{\text{eff}}^k E_{\text{dep}} \quad (2.4)$$

The quenching factor is defined with respect to the ER light yield at null field at 122 keV, so $\mathcal{L}_{\text{eff}}^{\text{ER}}$ is assumed to be 1 and has negligible energy dependence. For NRs, several experiments have measured the energy dependence of $\mathcal{L}_{\text{eff}}^{\text{NR}}$ for LAr, including the ARIS experiment [87].

The quenched energy is divided into excitation and ionization:

$$E_{\text{q}} = w_{\text{ex}} N_{\text{ex}} + w_{\text{ion}} N_{\text{ion}} \quad (2.5)$$

with w_{ex} and w_{ion} being the excitation and ionization mean energies required to produce a corresponding quantum N_{ex} or N_{ion} . An effective work function w , the average energy required to produce an exciton or ion-electron pair, is introduced for simplicity and defined as

$$w = \frac{w_{\text{ex}} N_{\text{ex}} + w_{\text{ion}} N_{\text{ion}}}{N_{\text{ex}} + N_{\text{ion}}} \quad (2.6)$$

We define the excitation-to-ionization ratio as $\alpha_k = N_{\text{ex}}/N_{\text{ion}}$ with k being the type of interaction: α_{ER} is 0.21 and α_{NR} is 1 [88]. The number of excitons and ion-electron pairs can now be expressed as

$$N_{\text{ex}} = \frac{\mathcal{L}_{\text{eff}}^k E_{\text{dep}}}{w} \frac{\alpha_k}{1 + \alpha_k} \quad (2.7)$$

$$N_{\text{ion}} = \frac{\mathcal{L}_{\text{eff}}^k E_{\text{dep}}}{w} \frac{1}{1 + \alpha_k} \quad (2.8)$$

For LAr, the value of w is measured to be $(19.5 \pm 1.0) \text{ eV}$ [89].

As described above, the S1 signal has two sources: the excitons produced by the original track and those produced by recombining ion-electron pairs.

$$\text{S1} = g_1 \times \left(N_{\text{ex}} + r_k(E_{\text{dep}}) N_{\text{ion}} \right) \quad (2.9)$$

where g_1 is the number of photoelectrons detected per primary scintillation photon and r_k is the recombination probability for a given recoil type k as a function of energy. The recombination probability also depends on the drift field strength. The S2 signal can now be calculated as

$$S2 = g_2 \times \left(1 - r_k(E_{\text{dep}})\right) N_{\text{ion}} \quad (2.10)$$

where g_2 is the number of photoelectrons detected per ion-electron pair, including the electroluminescence yield and photon detection efficiency.

2.3 The DarkSide program

The primary objective of the DarkSide program is to directly detect dark matter interactions with argon atoms using dual-phase argon TPCs. Figure 2.3 shows a timeline of the DarkSide program detectors. The DarkSide-10 detector was the first functional prototype in the program, with an active mass of 10 kg. This detector demonstrated the feasibility of dual-phase argon TPC technology for DM searches [91].

The first physics detector of the program, DarkSide-50 (DS-50), began operating in 2013 at the Laboratori Nazionali del Gran Sasso (LNGS) with an active mass of (46.4 ± 0.7) kg. Data from this detector was used to set world-leading constraints on DM-nucleon interactions [16, 92–95] and leptophilic DM interactions [96, 97]. DS-50 achieved the reduction of LAr intrinsic backgrounds by a factor of more than a thousand using UAr as compared to AAr [16].

Following the success of DS-50, more than 400 scientists from the ArDM, DS-50, DEAP-3600, and MiniCLEAN collaborations formed the GADMC to pursue a sequence of future experiments with multi-tonne target masses. Two prototype experiments are used as testbeds for novel technology developed for such detectors. The DarkSide-Proto0 experiment had an active mass of 10 kg and was operated with the primary goal of characterizing prototype silicon photomultipliers (SiPMs). The DarkSide-Proto1 experiment is a scaled-down mockup of the next-generation DarkSide-20k TPC, designed to test the TPC mechanical design.

The current stage of the program is DarkSide-20k (DS-20k), a 49.7 t active mass dual-phase argon TPC to be deployed at LNGS. In addition to further probing cross sections for DM masses in the GeV/c^2 to TeV/c^2 range, the collaboration will also use DS-20k data to pursue a broad program of physics measurements, including the detection of solar neutrinos and supernova bursts [20].

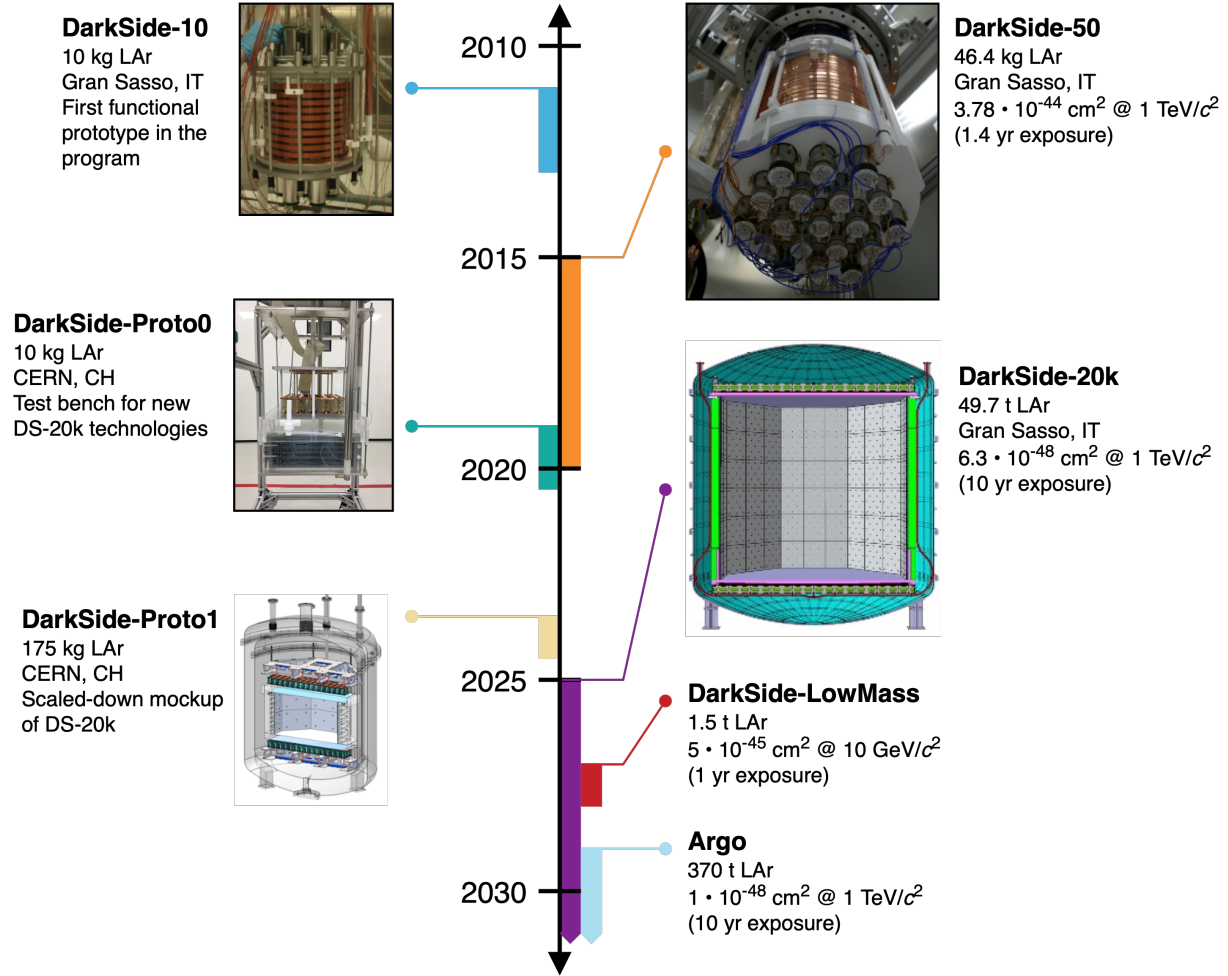
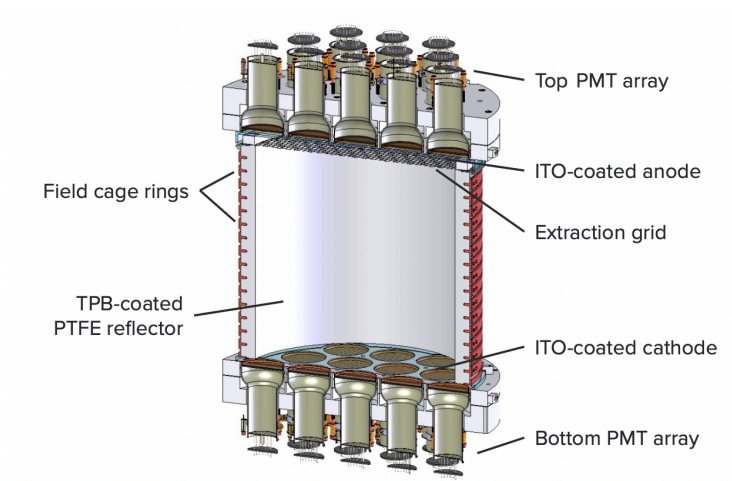


Figure 2.3: Timeline of the DarkSide program detectors. The right side shows the program’s physics detectors [16, 20, 90] while the left contains prototype detectors. For the physics detectors, the observed or projected 90% CLs on the spin-independent cross section of DM on nucleons are listed. This work.

The GADMC is studying several conceptual designs of experiments to continue the search for DM. The Argo experiment aims to push further into the high-mass dark matter parameter space and perform neutrino measurements with an active mass of 300 t [20, 98]. The DarkSide-LowMass experiment is optimized to probe LDM parameter space [90].

2.4 DarkSide-50

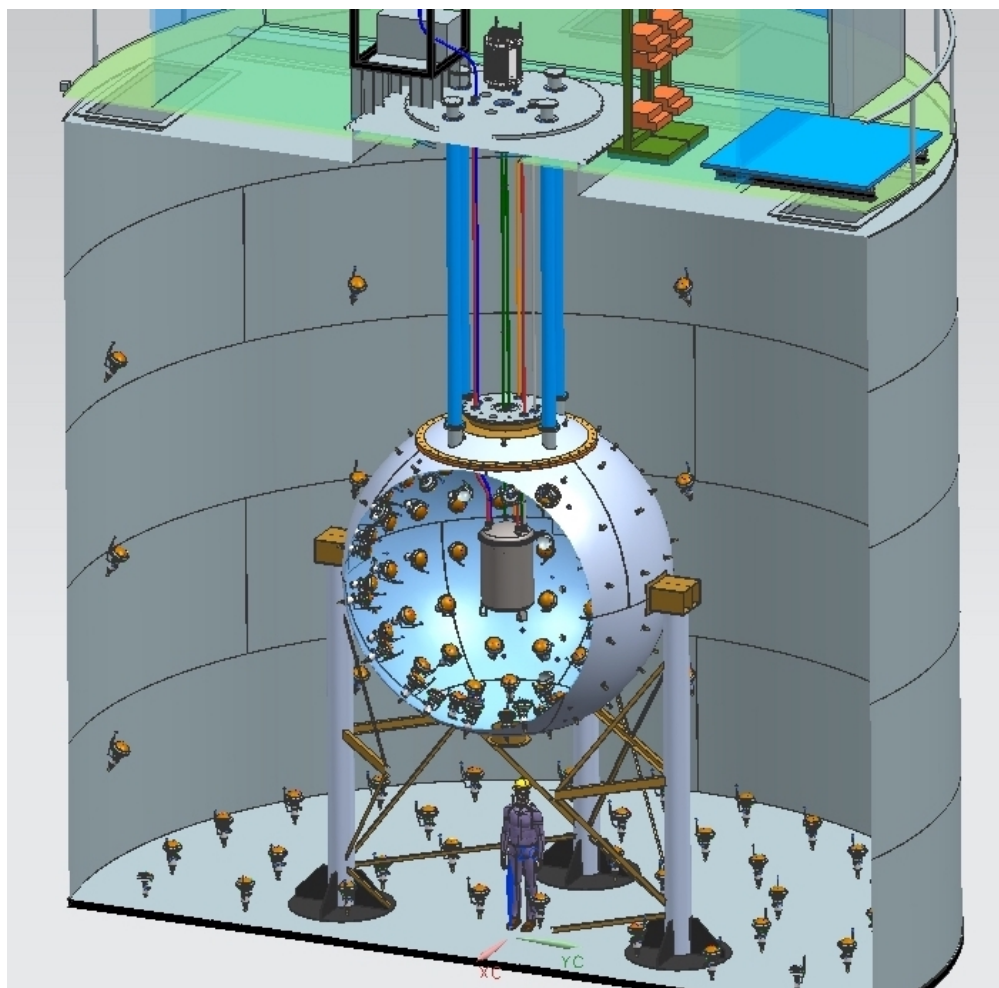
The DarkSide-50 experiment consists of three nested detectors: (*listed from innermost to outermost*) the dual-phase argon TPC, which is the target for DM interactions, the Liquid Scintillator Veto (LSV) which provides



(a) Diagram of the TPC.



(b) Image of the TPC.



(c) Overall schematic.

Figure 2.4: The DarkSide-50 experiment.

shielding and actively vetoes radiogenic and cosmogenic neutrons, and the Water Cherenkov Detector (WCD) which provides shielding and actively vetoes cosmic muons [62]. The experiment was operated from 2013 to 2020 at LNGS in Italy at a depth of 3800 m.w.e. where the flux of cosmogenic neutrons produced by muon spallation reactions is highly reduced.

2.4.1 TPC

The TPC is housed within a double-walled stainless steel cryostat, which hangs at the center of the LSV, supported by leveling rods. The TPC vessel is a polytetrafluoroethylene (PTFE) cylinder with a 2.54 cm-thick wall containing a 36 cm-diameter, 36 cm-tall active volume that holds (46.4 ± 0.7) kg of LAr when cold. The cylinder is capped by fused-silica windows plated with a 15 nm-thick layer of indium tin oxide (ITO), a transparent conductor that forms the anode and cathode surfaces. A 1 cm gas layer at the top of the TPC is contained in a “diving bell.” The gaseous argon (GAr) layer is formed by boiling LAr with a heating element.

All TPC inner surfaces, including the windows, are coated with tetraphenyl butadine (TPB) to convert the argon scintillation light (peaked at 128 nm) to wavelengths detectable by the photodetectors (~ 420 nm). The PTFE vessel on which the TPB is deposited acts as a VUV diffuse reflector, increasing the light collection efficiency.

Photodetectors A total of 38 Hamamatsu R11065 3'' PMTs view the TPC, split evenly into top and bottom arrays. The collaboration chose these specific PMTs due to their low radioactivity, high quantum efficiency, and ability to operate at LAr cryogenic temperatures. The fast response time of the PMTs enables ns-level timing resolution of single photons. The PMT are held in place by two PTFE structures, directly facing the active volume.

Field cage About 5 mm below the liquid-gas interface lies a 50 μm -thick stainless steel grid with hexagonal mesh. The drift field, nominally operated at 200 V/cm, is produced by applying a -12.7 kV potential to the ITO cathode and -5.6 kV to the grid. Copper rings encircling the TPC vessel are held at graded potentials to maintain drift field uniformity throughout the active volume. The anode is held at ground, producing an extraction field of 2.8 kV/cm giving an extraction field of 2.8 kV/cm in the LAr region above the grid and an electroluminescence field of 4.2 kV/cm in the GAr region.

2.4.2 Liquid Scintillator Veto

The Liquid Scintillator Veto (LSV) surrounds the TPC to veto neutron interactions actively. A 4 m-diameter stainless steel sphere houses 30 t of borated liquid scintillator. This mixture consists of the primary scintillator pseudocumene (PC) at 95 wt%, trimethyl borate (TMB) at 5 wt% which has a high neutron capture cross section, and 2,5-diphenyloxazole (PPO) at a concentration of 2.5 g/L to shift the scintillation light to the visible regime where the PMT is most sensitive. On the inside surface of the sphere, 110 Hamamatsu R5912 LRI 8'' PMTs are positioned to detect scintillation photons. A reflective foil lining enhances the light collection efficiency.

2.4.3 Water Cherenkov Detector

Surrounding the LSV is the Water Cherenkov Detector (WCD), which tags cosmic muons and provides passive shielding from environmental backgrounds. The WCD target is high-purity water contained within a cylindrical tank with a diameter of 11 m and a height of 10 m. Cherenkov light produced by muons and other relativistic particles is detected by 80 ETL 9351 8'' PMTs mounted on the side and bottom of the tank.

2.5 DarkSide-20k

This section contains the baseline design for the DarkSide-20k experiment, detailed in technical design report [20]. The detector design has been optimized for a 10 yr run with the primary objective of searching for high-mass WIMP-like particles. Like DS-50, DS-20k is also composed of a set of nested detectors. As shown in Figure 2.5, the TPC is located at the center of the detector, filled with 51.1 t of UAr. This is surrounded by the Inner Veto (IV) that contains 32 t of UAr. The TPC and IV are sealed within a stainless steel vessel. The “inner vessel” is, in turn, surrounded by the Outer Veto (OV), housed within a membrane cryostat.

2.5.1 TPC

The DS-20k TPC is a right octagonal prism, with an inscribed circle diameter of 350 cm and a height of 350 cm. The active target within the TPC is 49.7 t of UAr. The nominal fiducial cuts will give a fiducial mass of 20.2 t. A gas region with a thickness of 7 mm will be located above the liquid phase. Figure 2.7 shows detailed renderings of the TPC anode and cathode regions. These windows are formed from pure polymethylmethacrylate (PMMA), chosen because of its radiopurity and optical transparency. Both the anode and

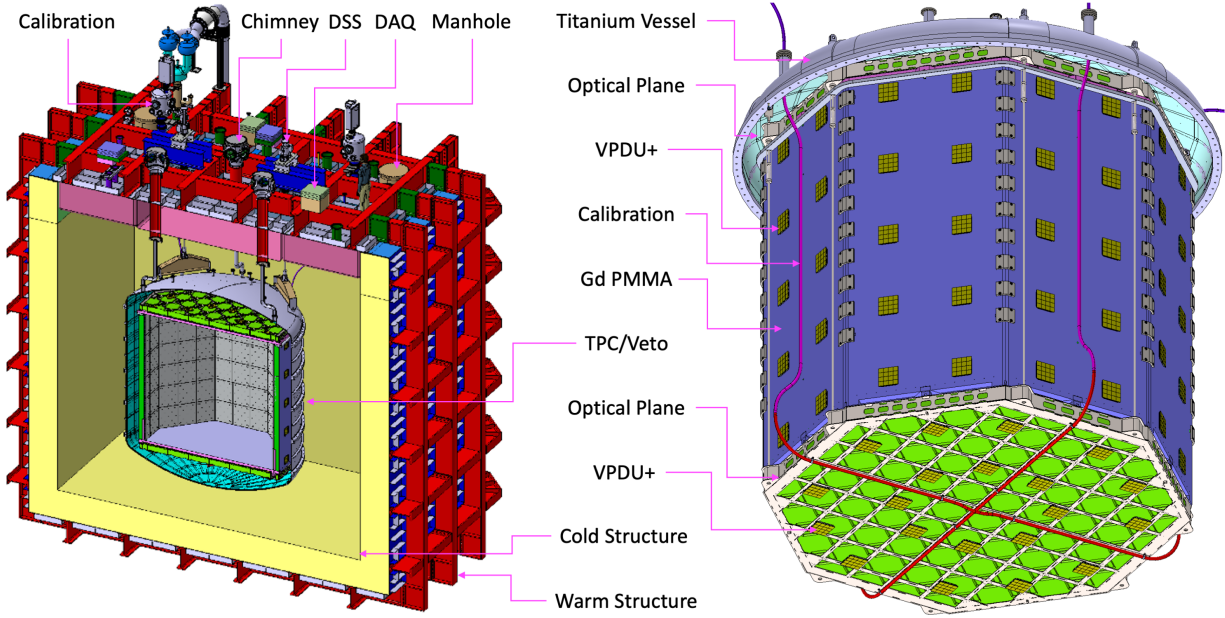


Figure 2.5: DarkSide-20k detector. (Left) Detector cross section with the outer cryostat shown in red and yellow, the inner cryostat in gray, and the Gd-PMMA in green. (Right) External rendering of the TPC and IV. Figure reproduced from Ref. [20].

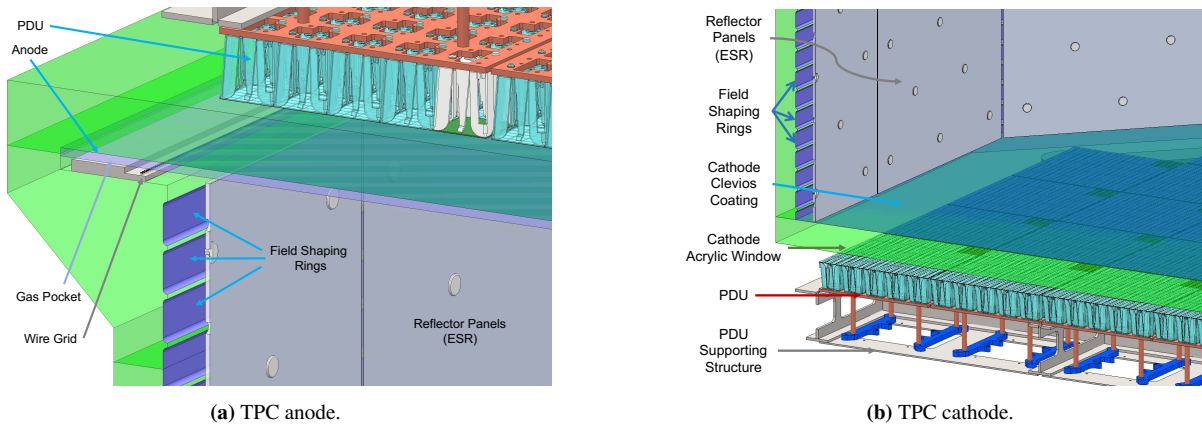


Figure 2.7: Renderings of the DarkSide-20k TPC anode and cathode. Figures reproduced from Ref. [20].

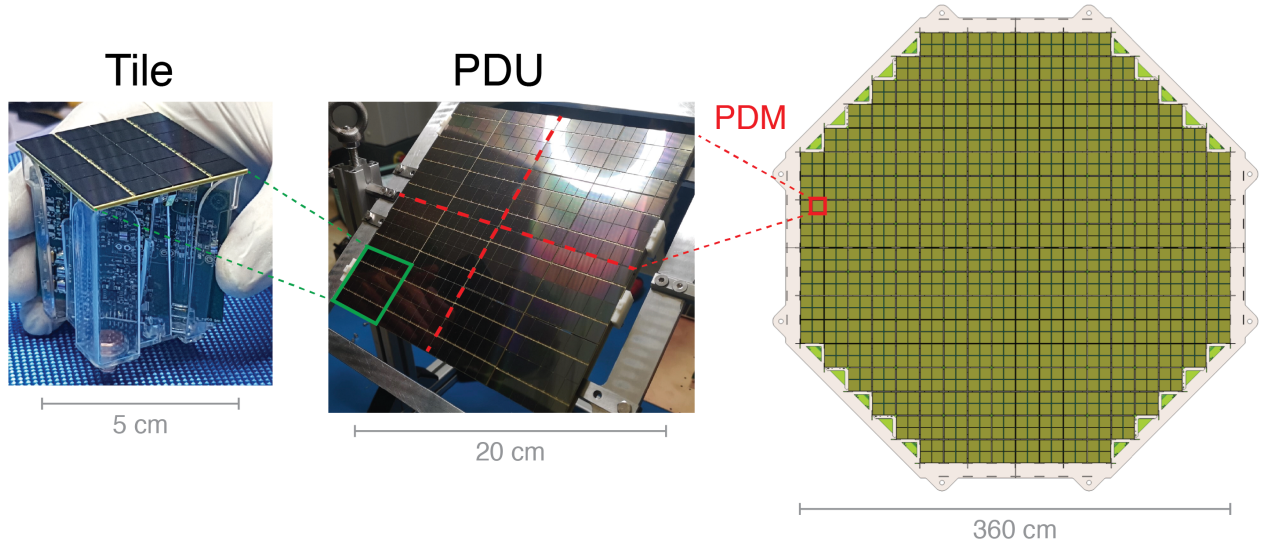


Figure 2.8: The DarkSide-20k optical plane. *Left:* A prototype tile. *Center:* A prototype PDU containing four PDMs (red), with a tile outlined in green. *Right:* Drawing of the optical plane, with a single PDM outlined in red. Figures adapted from Ref. [20].

cathode interiors are coated with Clevios, a transparent conducting polymer. On top of the Clevios coating lies a 3 μm -thick layer of TPB, which converts the VUV scintillation light into the visible spectrum.

TPC walls are formed from gadolinium-doped PMMA (Gd-PMMA) panels, discussed in more detail in Section 2.5.2. On the interior walls are mounted reflector panels composed of an enhanced specular reflector (ESR) foil coated with TPB, designed to enhance the light yield.

Photodetectors As an improvement over DS-50, DS-20k will use SiPMs instead of PMTs to detect the scintillation light. SiPMs have numerous advantages over PMTs, including:

- Lower intrinsic radioactivity
- Higher photon detection efficiency
- Lower operating bias voltage
- Higher active area

However, there are a few disadvantages, such as a higher rate of dark counts and correlated noises as well as more electronic noise. Custom low-radioactivity, low-noise, high-efficiency SiPMs have been developed specifically for DS-20k [99].

The DS-20k SiPMs are organized into optical planes, shown in Figure 2.8, with one at the top and one at the bottom of the TPC. There are a total of 2090 TPC readout channels called photodetector modules (PDMs).

Each PDM is $10 \times 10 \text{ cm}^2$ and consists of four summed tiles, where a tile is an array of 24 SiPMs and each SiPM is $1.17 \times 0.79 \text{ cm}^2$. Four PDMs are mounted on a single motherboard, referred to as a photodetector unit (PDU), which distributes power to the PDMs, contains the PDM amplifiers, and transmits signals to the cryostat feedthroughs.

Field cage The TPC drift field is formed by applying -73.38 kV to the cathode and -3.78 kV to a stainless steel wire grid sitting just below the liquid surface. A series of rings are machined into the interior of the Gd-PMMA walls and painted with Clevios; these are colored *blue* in Figure 2.7. The rings shape the electric field, maintaining a uniform drift field of 200 V/cm across the full 350 cm drift length. A resistor chain connects the field cage rings. The anode is grounded, giving an extraction field of 2.8 kV/cm and an electroluminescence field of 4.2 kV/cm .

2.5.2 Inner Veto

The Inner Veto (IV) surrounds the TPC and is designed to tag and reject neutron scatters that would otherwise mimic a DM signal. As gadolinium has a high neutron capture cross section, Gd-PMMA panels doped with 1 wt% gadolinium are used to detect radiogenic and cosmogenic neutrons. The high hydrogen content of the Gd-PMMA acts as a neutron moderator, increasing the probability of a neutron capture.

The Gd-PMMA panels are colored *green* in Figure 2.5. To optimize space and cost, the panels are the TPC lateral walls. IV end cap panels, also composed of Gd-PMMA, are located above the top TPC optical plane and below the bottom one. The region between the Gd-PMMA panels and inner vessel is filled 32 t of liquid UAr. All Gd-PMMA panel outer surfaces, as well as the inner surface of the inner vessel, are covered with a reflective foil and TPB. Arrays of SiPMs are mounted on the exterior of Gd-PMMA panels to detect the scintillation light produced by neutron captures. Thus, the IV acts as a single-phase detector.

The IV and TPC LAr volumes will detect the γ -rays produced by a neutron capture on gadolinium. DM-like background events will be identified and rejected if a TPC signal is accompanied by a subsequent neutron capture signal in the TPC and IV.

2.5.3 Outer Veto

The volume inside the membrane cryostat, surrounding the inner vessel, contains 700 t liquid AAr. This volume, the Outer Veto (OV), actively vetoes cosmogenic backgrounds, particularly muons and muon shower

products. As the energy regime for cosmogenic backgrounds is about 50 MeV, the increased rate of ^{39}Ar decays in AAr is not a concern. The OV is a single-phase detector instrumented with photosensors to detect the AAr scintillation light. Surfaces are covered with a reflective foil and wavelength shifter to increase the light collection efficiency.

Chapter 3

Search for leptophilic dark matter with DarkSide-50

While the DarkSide-50 experiment was optimized to detect nuclear interactions of dark matter, it is also sensitive to dark matter interactions with electron final states. This enables us to search for interactions between argon electrons and several DM candidates, including light dark matter-electron scattering, dark photon absorption, and axion-like particle absorption. Leptophilic DM interactions are primarily below the DS-50 S1 threshold, so the dataset for this search includes S2-only events.

Initial results from the DS-50 search for DM-electron scattering were published in 2018 [92, 96]. We have made many improvements since these publications, including improved background and signal modeling, a more accurate detector calibration, refined data selection criteria, and an extended dataset. The work presented in this chapter was published in Refs. [93, 97] and has also been used in several other publications [94, 95]. I worked on the numerical evaluation of the DM signal spectra, an improvement of the ER energy scale calibration, a review of the data selection criteria and response model, the development of the likelihood computational framework, the statistical analysis of the dataset, and the calculation of the DM exclusion limits.

3.1 LDM-electron interactions

As described in Section 1.2.2, a light dark matter (LDM) particle with mass m_χ can elastically scatter off of electrons. A diagram of this interaction is shown in Figure 3.1, where the initial LDM momentum is labeled

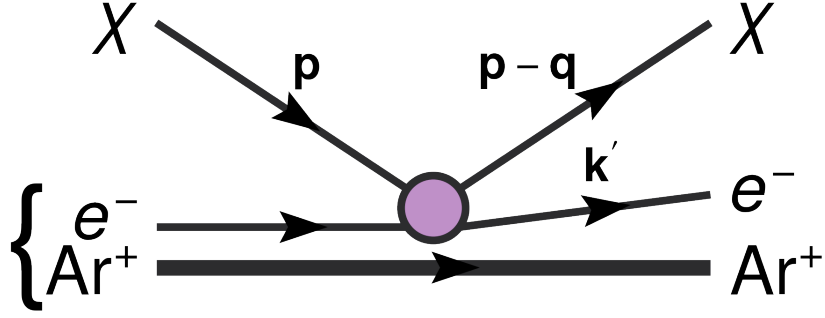


Figure 3.1: Diagram of an LDM particle scattering off an electron bound to an argon atom, resulting in ionization. See the text for details. Figure inspired by Ref. [100].

Shell	Binding energy $E_b^{n\ell}$ (eV)
3p	-16.0823
3s	-34.7585
2p	-260.4528
2s	-335.3028
1s	-3227.5520

Table 3.1: Argon binding energies. Data reproduced from Ref. [101].

p . A momentum transfer q , corresponding to an energy deposit (E_d) of

$$E_d = \frac{p^2}{2m_\chi} - \frac{(p-q)^2}{2m_\chi} = \frac{p \cdot q}{m_\chi} - \frac{q^2}{2m_\chi} \quad (3.1)$$

ionizes an electron in an initial bound state with principal quantum number n and angular momentum quantum number l [18, 23]. As the momentum of the bound state is not definite, the electron can escape with an arbitrary momentum labeled k' . As the recoil energy of the nucleus is negligible, the change in the electron's energy (ΔE_e) is the sum of the initial state binding energy ($E_b^{n\ell}$) and the final state energy:

$$\Delta E_e = |E_b^{n\ell}| + E_{er} \quad (3.2)$$

where $E_{er} = k'^2/(2m_e)$ is the electron recoil energy, with $k' = |\mathbf{k}'|$. Binding energies for argon shells are shown in Table 3.1. Assuming the energy transferred to the nucleus is negligible, E_d is equal to ΔE_e :

$$\frac{p \cdot q}{m_\chi} - \frac{q^2}{2m_\chi} = |E_b^{n\ell}| + E_{er} \quad (3.3)$$

$$p \cdot q = m_\chi(|E_b^{n\ell}| + E_{er}) + \frac{q^2}{2} \quad (3.4)$$

The minimum LDM velocity ($v_{\min}$) required to produce a momentum transfer $\mathbf{q}$ and recoil energy E_{er} can be found when $\mathbf{p}$ is collinear with $\mathbf{q}$,

$$m_{\chi} v_{\min} q = m_{\chi} (|E_{\text{b}}^{n\ell}| + E_{\text{er}}) + \frac{q^2}{2} \quad (3.5)$$

$$v_{\min}(q, E_{\text{er}}) = \frac{|E_{\text{b}}^{n\ell}| + E_{\text{er}}}{q} + \frac{q}{2m_{\chi}} \quad (3.6)$$

This provides a lower bound for detectable LDM velocities, which competes with the maximum velocities for LDM particles in the galactic halo.

As of yet, we have not specified an effective field theory (EFT) for the LDM-electron interaction, represented by a *purple* circle in Figure 3.1. This is to derive an interaction cross section that allows for multiple models to be tested within the same theoretical framework. Instead, the interaction is parameterized using a reference cross section ($\bar{\sigma}_e$) and a dark matter form factor (F_{χ}), which encodes the underlying interaction's momentum dependence (see Section 1.2.2). With this approach, Ref. [23] derived the thermally averaged ionization cross section $\langle \sigma_{\text{ion}}^{n\ell} v \rangle$ for LDM scattering off a bound electron with quantum numbers (n, ℓ) :

$$\frac{d\langle \sigma_{\text{ion}}^{n\ell} v \rangle}{d \ln E_{\text{er}}} = \frac{\bar{\sigma}_e}{8\mu_{\chi e}^2} \int |f_{\text{ion}}^{n\ell}(k', q)|^2 |F_{\chi}(q)|^2 \eta(v_{\min}) q dq, \quad (3.7)$$

where $\mu_{\chi e} = m_{\chi} m_e / (m_{\chi} + m_e)$ is the reduced mass of electron and LDM particle. The mean inverse speed (η) encodes the DM velocity profile in the lab frame (see Section 3.1.1), while the ionization form factor $f_{\text{ion}}^{n\ell}$ encapsulates the effects of the electron's initial and final states (discussed in Section 3.1.2).

3.1.1 Mean inverse speed

The mean inverse speed function η accounts for the DM velocity distribution in our galaxy. It is obtained by integrating the lab-frame SHM velocity distribution f , defined in Equation (1.11), above $v_{\min}$:

$$\eta(v_{\min}) = \int \frac{f(\mathbf{v}, t)}{|\mathbf{v}|} \Theta(|\mathbf{v}| - v_{\min}) d^3 \mathbf{v} \quad (3.8)$$

where t is the time at which the distribution is evaluated, $v_{\min}$ is defined in Equation (3.6), and Θ is the Heaviside step function [18]. Equation (3.8) is plotted in Figure 3.2. Note that the mean inverse speed function is truncated at v_{esc} , which restricts observable recoil energies from above. This, coupled with the detector's energy threshold, governs the range of LDM masses that DS-50 can probe.

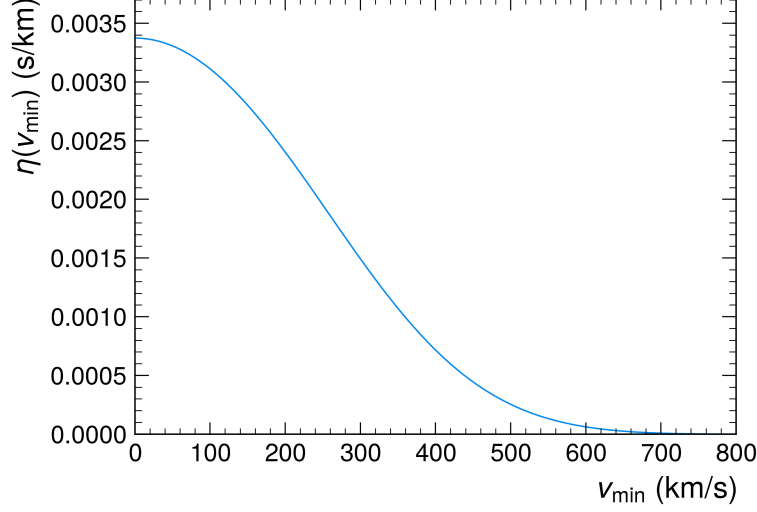


Figure 3.2: Mean inverse speed of DM (η) as a function of the minimum velocity in the lab frame ($v_{\min}$). This is Equation (3.8). This work.

3.1.2 Ionization form factor

The electron's transition from a bound state to a free state is described by the ionization form factor. We first define the initial-state position-space wavefunction as $\psi_1(\mathbf{x})$ for a bound state with quantum numbers (n, ℓ) and the final state as $\tilde{\psi}_{k'\ell'm'}(\mathbf{x})$, where ℓ' and m' are angular and magnetic quantum numbers of the unbound electron and, as above, k' is the free electron momentum far from the nucleus. Using $\tilde{\psi}_{k'\ell'm'}^*(\mathbf{x}) \psi_1(\mathbf{x})$ as the density distribution, the ionization form factor for a given initial state (n, ℓ) can be generically formulated as [23, 102]

$$|f_{\text{ion}}^{n\ell}(\mathbf{k}', \mathbf{q})|^2 = \frac{2|\mathbf{k}'|^3}{(2\pi)^3 \hbar^3} \sum_{\ell' m'} \left| \int \tilde{\psi}_{k'\ell'm'}^*(\mathbf{x}) \psi_1(\mathbf{x}) e^{i\mathbf{q} \cdot \mathbf{x} / \hbar} d^3 \mathbf{x} \right|^2 \quad (3.9)$$

where the sum is over the final angular momentum variables.

The initial-state wavefunction ψ_1 is split into angular and radial parts. The radial part ($R_{n\ell}$) is modeled using Roothaan-Hartree-Fock (RHF) wavefunctions to balance a sufficiently detailed approach with computational limitations [101]. The RHF wavefunctions are approximations of the nonrelativistic Schrödinger's equation for stationary states and consist of linear combinations of Slater-type orbitals ($S_{j\ell}$):

$$R_{n\ell}(r) = a_0^{-3/2} \sum_j S_{j\ell}(r) C_{j\ell n} \quad (3.10)$$

$$S_{j\ell}(r) = \frac{(2Z_{j\ell})^{n'_{j\ell} + \frac{1}{2}}}{\sqrt{(2n'_{j\ell})!}} \left(\frac{r}{a_0} \right)^{n'_{j\ell} - 1} e^{-Z_{j\ell} r / a_0} \quad (3.11)$$

where $n_{j\ell}$ is the principal quantum number, $Z_{j\ell}$ is the orbital exponent, $C_{j\ell n}$ is the expansion coefficient

for a given Slater-type orbital, and a_0 is the Bohr radius (0.0529 nm). These RHF coefficients are tabulated in Table 3.2 for argon. The constant in front of the sum in Equation (3.10) comes from the wavefunction's normalization

$$\int_0^\infty |R_{n\ell}(r)|^2 r^2 dr = 1, \quad (3.12)$$

which gives $R_{n\ell}$ dimensions of $[\text{Length}]^{-3/2}$. The behavior of Equation (3.11) is plotted in Figure 3.3. One can see that for s shells, there is a non-zero probability of finding the electron inside the nucleus ($r = 0$), while for p shells, the probability is zero. This reflects the nature of the shells, which are spherical harmonics. Another feature to note is that the majority of the probability distributions are concentrated within a few a_0 of the nucleus. Shells with lower principal quantum numbers have their probability distributions concentrated closer to the origin, as they experience less electric charge screening.

Plane wave approximation In this work, we consider two treatments of the final-state wavefunction. The first approach approximates the final state as a free plane wave $\tilde{\psi}_{k'}(\mathbf{x}) = e^{ik' \cdot \mathbf{x}/\hbar}$ corrected by a Fermi factor, which accounts for the screened Coulomb potential of the ionized atom [23]. The potential distorts the outgoing plane wave and enhances the probability of finding the final-state electron near the nucleus, particularly for smaller electron recoil energies. The Fermi factor (F) is often used when modeling β -decays and is given by

$$F(k', Z_{\text{eff}}^{n\ell}) = \frac{2\pi x}{1 - e^{-2\pi x}}, \quad x = \frac{Z_{\text{eff}}^{n\ell} \hbar}{k' a_0} \quad (3.13)$$

where $Z_{\text{eff}}^{n\ell}$ is the effective nuclear charge, which can be estimated using the initial bound-state energy:

$$13.6 \text{ eV} \times \frac{(Z_{\text{eff}}^{n\ell})^2}{n^2} = |E_b^{n\ell}| \quad (3.14)$$

After inserting the plane wave definition for the final-state electron and performing a Fourier transform on Equation (3.9), the ionization form factor becomes

$$|f_{\text{ion}}^{n\ell}(k', q)|^2 = F(k', Z_{\text{eff}}^{n\ell}) \frac{(2\ell + 1) k'^2}{4\pi^3 q} \int_{|k'-q|}^{k'+q} |\chi_{n\ell}(k)|^2 k dk \quad (3.15)$$

where $\chi_{n\ell}$ is the radial part of the initial-state wavefunction ψ_1 in momentum space. This is given by

$$\chi_{n\ell}(k) = \frac{4\pi i^\ell}{\hbar^{-3/2}} \int_0^\infty R_{n\ell}(r) j_\ell(kr/\hbar) r^2 dr \quad (3.16)$$

j	n'_{j0}	Z_{j0}	C_{j01}	C_{j02}	C_{j03}
0	1	25.5708	0.316405	0.079148	0.035512
1	1	15.6262	0.542760	-0.507823	-0.181267
2	2	22.3994	0.167691	0.059900	0.02650
3	2	10.5300	0.000408	-0.026389	0.006280
4	2	7.0534	0.002431	0.832638	0.111836
5	2	5.4120	-0.000861	0.295522	0.385604
6	3	46.7052	-0.000422	0.000217	0.000070
7	3	3.7982	0.000066	0.002203	-0.376901
8	3	2.5495	-0.000061	0.001423	-0.593561
9	3	1.7965	0.000009	0.000186	-0.229971

(a) s shell coefficients ($\ell = 0$)

j	n'_{j1}	Z_{j1}	C_{j12}	C_{j13}
0	2	26.6358	0.002436	0.001854
1	2	12.7337	-0.114774	-0.042064
2	2	7.3041	-0.503175	-0.095603
3	2	5.3353	-0.427033	-0.194233
4	3	20.7765	0.009669	0.005891
5	3	3.3171	-0.004825	0.366141
6	3	2.0947	0.000231	0.526490
7	3	1.3780	-0.000098	0.249866

(b) p shell coefficients ($\ell = 1$)

Table 3.2: RHF coefficients $C_{j\ell n}$, $Z_{j\ell}$, and $n'_{j\ell}$ for argon. Data reproduced from Ref. [101].

where j_ℓ is a spherical Bessel function of order ℓ and $R_{n\ell}$ is defined in Equation (3.10). See Ref. [100] for a derivation of Equation (3.16), along with a simplified expression. The behavior of the bound momentum-space wavefunction is plotted in Figure 3.4. The momentum-space bound wavefunctions are concentrated at momenta on the order of $\hbar/a_0 = 3.73 \text{ keV}/c$. The $2p$ shell's average momentum is larger than that of the $3s$ and $3p$ shells as it experiences less electric charge screening, so χ_{2p} is shown in the figure's inset.

Continuum hydrogenic approximation The second approach calculates the outgoing electron's wavefunction by solving the Schrödinger equation with potential $-Z_{\text{eff}}^{n\ell}/r$ [96, 100, 103]. The solutions ($\tilde{\psi}_{k'\ell'm'}$) are called “continuum states” and provide a more accurate description of the outgoing electron than the plane

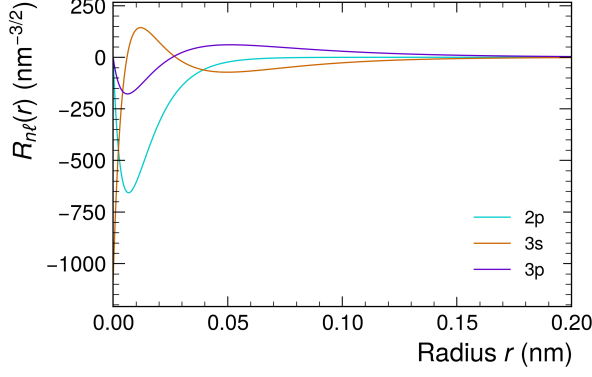


Figure 3.3: Bound electron wavefunction $R_{n\ell}$ in position space. This work.

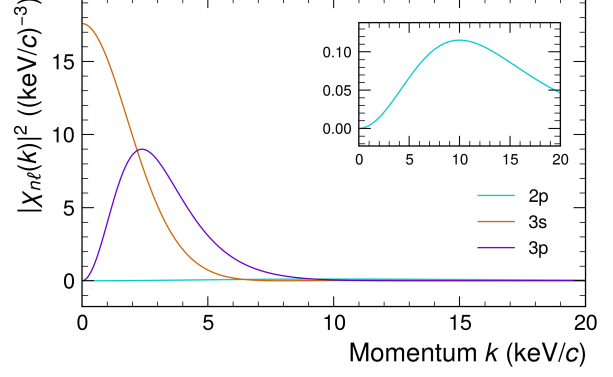
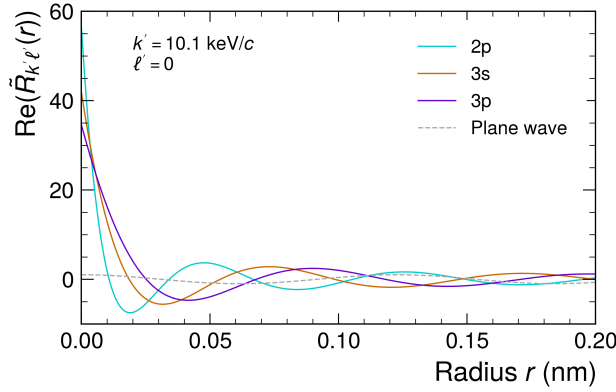
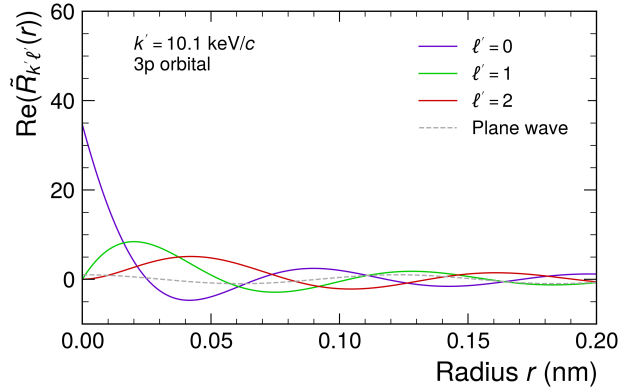


Figure 3.4: Squared bound electron wavefunction $|X_{n\ell}|^2$ in momentum space. The inset shows a zoomed version of the plot for the $2p$ shell. This work.



(a) $\tilde{R}_{k'\ell'}$ for relevant argon shells, evaluated for $\ell' = 0$.



(b) $\tilde{R}_{k'\ell'}$ for various values of ℓ' , for the argon $3p$ orbital.

Figure 3.5: Real part of the outgoing electron wavefunction $\tilde{R}_{k'\ell'}$ in position space. Wavefunctions are plotted for a recoil energy of $E_{\text{er}} = 0.1 \text{ keV}_{\text{er}}$, corresponding to $k' = 10.1 \text{ keV}/c$. This work.

wave approximation, particularly near the nucleus. The radial part of $\tilde{\psi}_{k'\ell'm'}$ is given by

$$\tilde{R}_{k'\ell'}(r) = (2\pi)^{3/2} \left(\frac{2k'r}{\hbar} \right)^{\ell'} \times \frac{\sqrt{\frac{2}{\pi}} \left| \Gamma(\ell' + 1 - \frac{iZ_{\text{eff}}\hbar}{k'a_0}) \right|}{(2\ell' + 1)!} e^{\pi Z_{\text{eff}}\hbar/(2k'a_0)} \times e^{-ik'r/\hbar} {}_1F_1(\ell' + 1 + \frac{iZ_{\text{eff}}\hbar}{k'a_0}, 2\ell' + 2, 2ik'r/\hbar) \quad (3.17)$$

which is indexed by the final-state electron's momentum k' and angular momentum ℓ' [100]. Γ is the gamma function and ${}_1F_1(a, b, x)$ is the confluent hypergeometric function of the first kind. The final-state radial wavefunctions are normalized to

$$\int_0^\infty \tilde{R}_{k_1\ell_1}^*(r) \tilde{R}_{k_2\ell_2}(r) r^2 dr = \frac{(2\pi)^3 \hbar^3}{k^2} \delta_{\ell_1\ell_2} \delta(k_1 - k_2) \quad (3.18)$$

making $\tilde{R}_{k'\ell'}$ unitless. The real part of $\tilde{R}_{k'\ell'}$ is plotted in Figure 3.5 for various argon orbitals and several values of ℓ' to visualize its behavior as the input parameters change. We can see the oscillatory behavior of

the wavefunction with a frequency of $k'/\hbar$, which tapers in amplitude as the radius increases and approaches the simple plane wave solution at large radii. The wavefunction's average position is smaller for inner electron shells. Similarly, wavefunctions are concentrated closer to the nucleus for smaller final-state angular momenta ℓ' . While not shown, increasing the final-state momentum k' increases the oscillatory period and the average position.

Under this approach, the ionization form factor is

$$|f_{\text{ion}}^{n\ell}(k', q)|^2 = \frac{4k'^3}{(2\pi)^3 \hbar^3} \sum_{\ell'=0}^{\infty} \sum_{L=|\ell'-\ell|}^{\ell'+\ell} (2\ell+1)(2\ell'+1)(2L+1) \times \left[\begin{matrix} \ell & \ell' & L \\ 0 & 0 & 0 \end{matrix} \right]^2 \left| \int_0^{\infty} \tilde{R}_{k'\ell'}(r) R_{n\ell}(r) j_L(qr/\hbar) r^2 dr \right|^2 \quad (3.19)$$

The term in brackets is the Wigner-3j symbol evaluated at $m_1 = m_2 = m_3 = 0$ and j_L is the spherical Bessel function of order L . While the sum in Equation (3.19) is over all final-state angular momenta (ℓ'), in practice, it can be truncated when it converges below a desired tolerance. We found that summing up to $\ell' = 5$ ensured convergence to a relative tolerance of $<1\%$ for the range of electron recoil energies considered in this work and for momentum transfers below $400 \text{ keV}/c$.

Numerical evaluation of Equation (3.19) is computationally challenging, particularly for large transfer momenta, due to the highly oscillatory nature of the integrand. While dedicated numerical integration methods exist for such functions, we used the `scipy.integrate.quad` function for simplicity, which uses an adaptive algorithm to evaluate the integral. As shown in Figure 3.3 and Figure 3.5, the wavefunctions are concentrated within a few a_0 of the nucleus, so the numerical integration range was truncated at $100 a_0$ with a maximum of 5000 subintervals used by the adaptive algorithm. Real and imaginary parts of the integral in Equation (3.19) were evaluated to a relative error tolerance of $<0.01\%$. The contribution of the imaginary component was found to be negligible compared to that of the real component.

Comparison of approaches To illustrate the differences between the continuum and plane approximations, we compare the computed ionization form factor as a function of transfer momentum for the argon $3p$ shell in Figure 3.6 for a recoil energy of 5 eV_{er} . The continuum hydrogenic approximation provides a more accurate description of the outgoing electron than the plane wave approximation, so usage of the former is preferred. The more detailed approach is particularly important for outer atomic shells, where the overlap between the initial- and final-state electron wavefunctions is maximized away from the origin. Another relevant case is

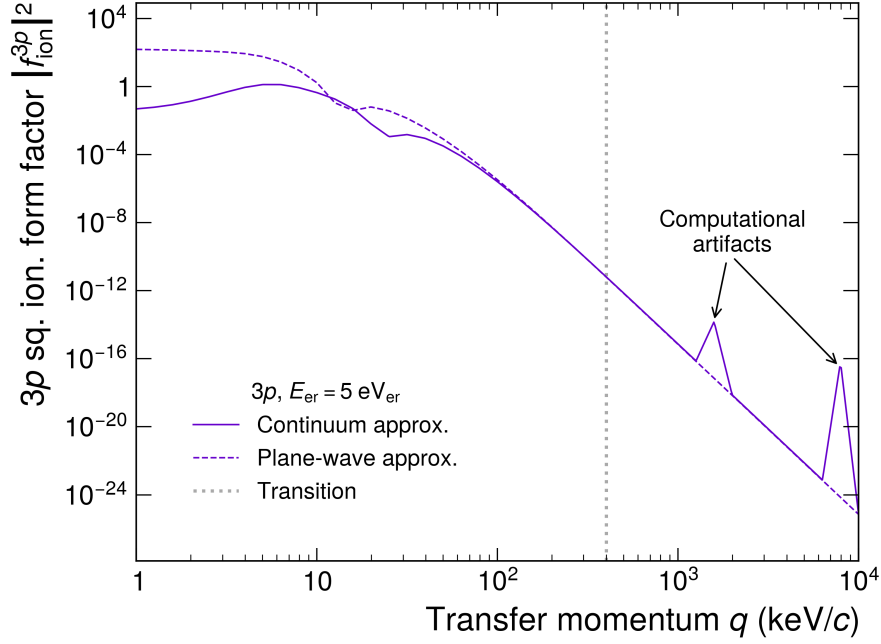
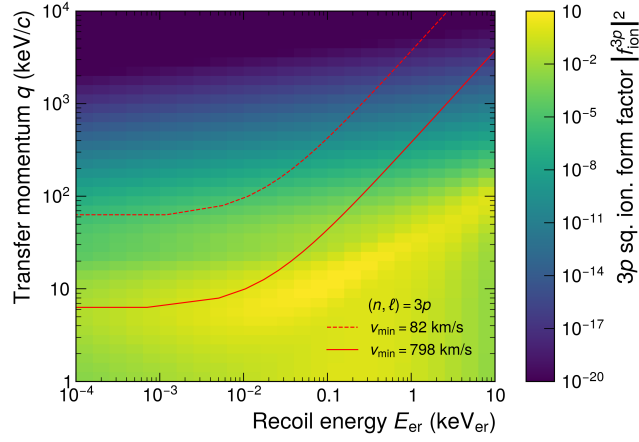


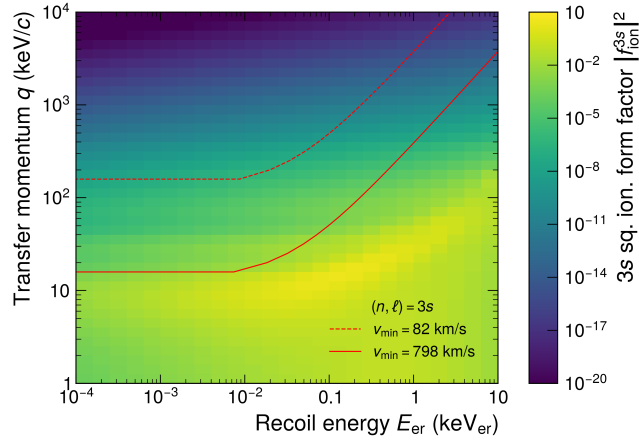
Figure 3.6: Convergence of the continuum hydrogenic (solid) and plane wave (dashed) approximations for computation of the ionization form factor. This is shown for the argon $3p$ electron orbital for a recoil energy of 5 eV_{er} . The transfer momentum at which we choose to transition from using the continuum hydrogenic (below) to the plane wave approximation (above) is $400 \text{ keV}/c$, shown by the gray dotted line. This work.

that of small transfer momenta q , where the final-state wavefunction has a higher probability near the origin, as shown in Figure 3.5a. This can be understood conceptually as the electron spending more time near the nucleus for smaller transfer momenta, so the detailed atomic structure has a more pronounced impact on the outgoing electron wavefunction. We see this discrepancy in Figure 3.6 below $100 \text{ keV}/c$, where the plane wave approximation overestimates the ionization form factor by up to several orders of magnitude compared to the continuum hydrogenic approach. A slight shift in the form factor shape is also observed for the plane wave approximation around $10 \text{ keV}/c$.

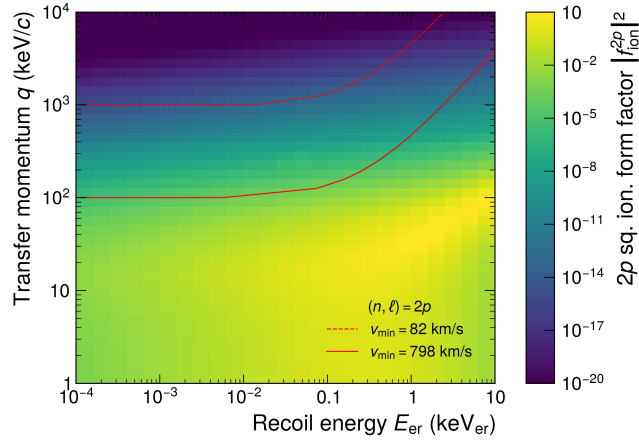
At large transfer momenta, $q > 100 \text{ keV}/c$, the two approaches converge. In this regime, the plane wave model is a good approximation as the electron spends very little time near the nucleus, so the atomic structure is less relevant. However, numerical evaluation of the continuum hydrogenic approach becomes computationally challenging at large transfer momenta, as discussed earlier. This can be seen in Figure 3.6 by the peaks around $1.5 \text{ MeV}/c$ and $8 \text{ MeV}/c$ where the numerical integration algorithm fails to converge to the desired tolerance. Furthermore, the required computation time increases notably with q . As such, we chose to use the plane wave approximation defined in Equation (3.15) for $q > 400 \text{ keV}/c$, above where the two approaches converge and before computational artifacts appear in the continuum hydrogenic approach.



(a) 3p shell table



(b) 3s shell table



(c) 2p shell table

Figure 3.7: Squared ionization form factor $|f_{\text{ion}}^{n\ell}|^2$ for relevant argon shells. The plane wave approximation of Equation (3.15) is used for $q > 400 \text{ keV}/c$ while the continuum hydrogenic approximation of Equation (3.19) is used otherwise. The region between the *red* lines contains the primary contribution of a given shell to the LDM-electron scattering rate. See the text for more details. This work.

Below this value, the continuum hydrogenic approximation is used.

I propagated the discrepancy between the two ionization form factor models to LDM-electron scattering rates. As shown in Equation (3.7), we are integrating over a large region of recoil energy and transfer momentum parameter space, weighted by the DM velocity pdf and DM form factor. The plane wave approach was found to overestimate the LDM-electron scattering rates by $\mathcal{O}(30\%)$ compared to the continuum hydrogenic approach. Consequently, using only the plane wave approximation would lead to overly aggressive exclusion limits on LDM parameter space, motivating the use of the more detailed approach.

Calculated ionization form factor tables for the argon $3p$, $3s$, and $2p$ shells are shown in Figure 3.7. The ionization form factors sharply decrease with transfer momentum but do not necessarily fall monotonically due to the structure of the electron's initial- and final-state wavefunctions and their overlap. As a result, the shape of the differential scattering cross section in Equation (3.7) is also not strictly monotonic. Favored transfer momenta and final-state momenta for which the ionization form factor is maximized are not necessarily kinematically accessible for a given LDM mass due to the incident dark matter velocity distribution. This is visualized by the red lines in Figure 3.7. Parameter space below the solid *red* line is kinematically inaccessible for any LDM mass as $v_{\min}(q, E_{\text{er}})$ is greater than the maximum observable LDM velocity of 798 km/s. The dotted *red* line is drawn for $v_{\min} = 82$ km/s, at which $\eta(v_{\min})$ includes about 99% of the LDM velocity distribution. Thus, the primary contribution of a given shell's ionization form factor to the LDM-electron scattering rate comes from the region between the *red* lines. When m_χ is considered, q becomes kinematically bounded from above, particularly for smaller LDM masses. This severely restricts accessible parameter space, leading to a sharp drop in the differential scattering cross section as m_χ decreases.

3.1.3 Predicted energy spectra

Using Equation (3.7) with Equation (1.6), the differential ionization rate for LDM-electron scattering ($\mathcal{R}_\chi$) as a function of electron recoil energy (E_{er}) is

$$\frac{d\mathcal{R}_\chi}{d \ln E_{\text{er}}} = N_{\text{T}} \frac{\rho_\chi}{m_\chi} \times \sum_{n\ell} \frac{d\langle \sigma_{\text{ion}}^{n\ell} v \rangle}{d \ln E_{\text{er}}} \quad (3.20)$$

The contributions of full shells (n, ℓ) are summed over. The orbital contributions are shown in Figure 3.8 for an example mass of $1 \text{ GeV}/c^2$, assuming a heavy mediator. For an argon target, only the $3p$, $3s$, and $2p$ shells were found to be relevant via numerical evaluation. The figure shows that the $3p$ orbital contribution is dominant for recoil energies below $0.2 \text{ keV}_{\text{er}}$ due to its smaller binding energy, which increases the range

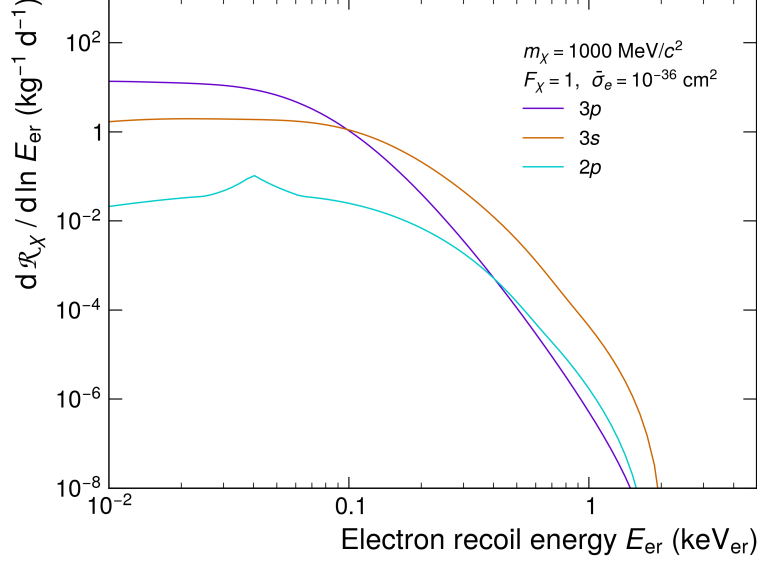


Figure 3.8: Differential ionization rate of LDM-electron scattering for various argon electron orbitals. The sum of the orbital contributions in this plot is shown in Figure 3.9 by the *solid green line*. This work.

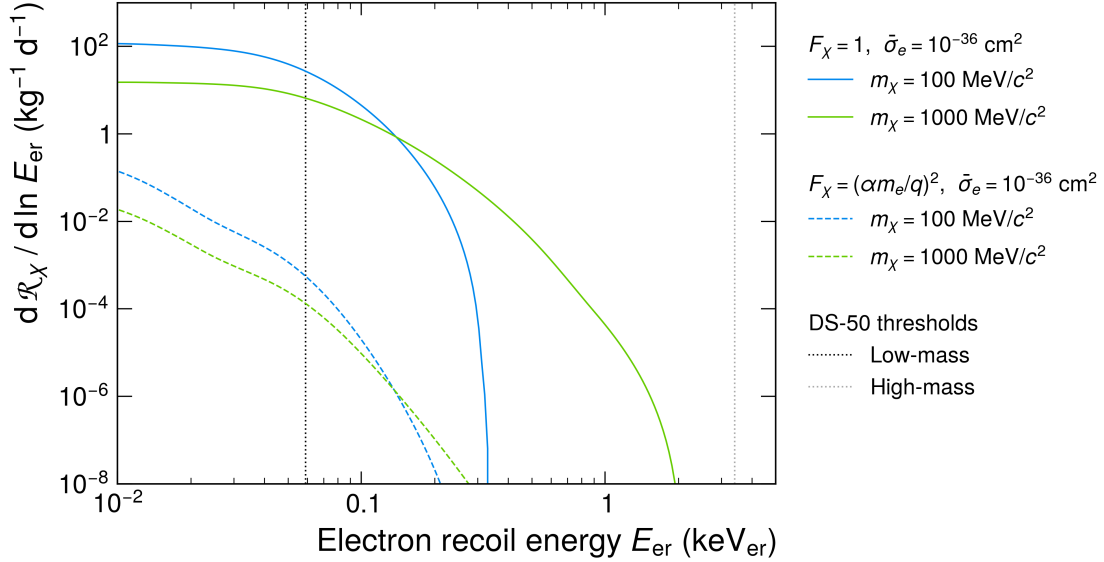


Figure 3.9: Differential ionization rate of LDM-electron scattering for an argon target. See the text for more details. This work.

of allowed transfer momenta. Across the recoil energy range considered here, the $2p$ shell has a non-leading order contribution. When computing Equation (3.7), the ionization form factor tables in Figure 3.7 were interpolated on logarithmic scales to considerably reduce computation time. The mean inverse speed distribution shown in Figure 3.2 was also interpolated to avoid repeated numerical integration for Equation (3.8).

Using the components described above, we can evaluate the predicted LDM-electron scattering rates in Equation (3.20) for various model parameter values. These are shown in Figure 3.9 for an argon target.

For larger LDM masses (*green*), the predicted ionization signals extend to higher energies, where detector backgrounds are better understood and the ionization response calibration is more precise. However, this competes with lower scattering rates for higher LDM masses because the local dark matter energy density is fixed, not the number of particles. Due to the inverse momentum dependence of the LDM form factor for a light mediator (*dotted* lines), the predicted ionization signals are suppressed compared to those assuming a heavy mediator (*solid* lines).

3.2 Dark photon interactions

As discussed in Section 1.2.3, the DP couples feebly to the electron via kinetic mixing with the SM photon. Experiments measuring ionization signals like DS-50 are sensitive to dark photon (DP) absorption through this interaction [24, 25]. The process is analogous to the photoelectric effect, where a photon is absorbed by a bound electron, resulting in the ejection of the electron from the atom. Like the photoelectric effect, the predicted DP absorption signal is approximately mono-energetic at the DP rest mass (m_V). The DP absorption cross section is related to the SM photoelectric absorption cross section (σ_{pe}) by

$$\sigma_V(E_V) = \frac{\kappa^2}{\beta_V} \sigma_{\text{pe}}(E_V) \quad (3.21)$$

where κ is the kinetic mixing between the photon and dark photon, $E_V = m_V c^2$ is the DP rest energy, and $\beta_V = v_V/c$ is the dark photon's relativistic beta factor. Combining this with Equation (1.6), the predicted event rate reduces to

$$\mathcal{R}_V = N_T \frac{\rho_\chi}{m_V} \times \kappa^2 \sigma_{\text{pe}}(m_V c^2) c \quad (3.22)$$

Note that the velocity dependence of the DP flux in Equation (1.7) cancels precisely with that of the DP cross section. Ref. [58] has noted that this rate is derived assuming the DM Compton wavelength is much larger than the size of the atom and requires corrections above $100 \text{ keV}/c^2$. However, we use the rate in Equation (3.22) for the entire mass range due to a lack of available calculations and for consistency with previously published DP constraints.

3.2.1 Photoelectric cross section

As the DP absorption cross section is proportional to the SM photoelectric cross section, we must first understand the latter. The photoelectric cross section $\sigma_{\text{pe}}(E_\gamma)$ is the probability of an electron being ejected from a

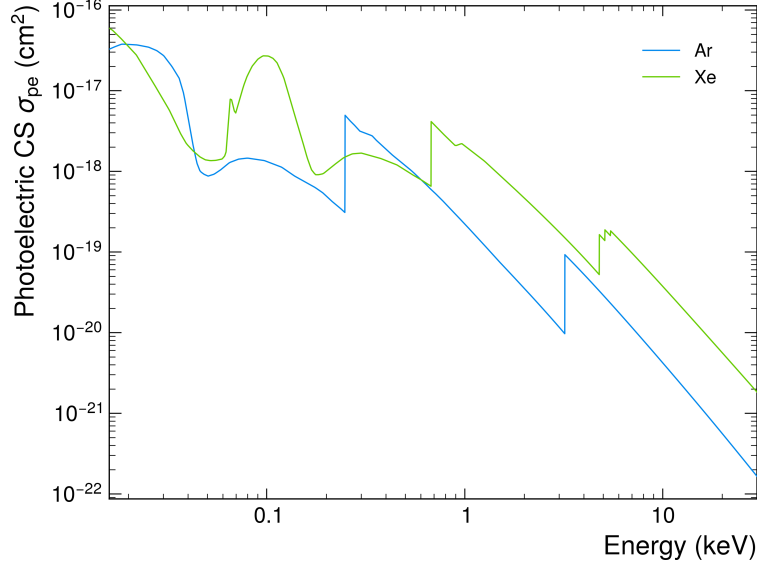


Figure 3.10: Measured photoelectric cross section σ_{pe} tables for argon (*blue*) and xenon (*green*) as a function of photon energy (E_γ). Data reproduced from Ref. [104].

target atom by a photon with energy E_γ . A combination of experimentally measured values and theoretical calculations tabulated in Ref. [104] are shown in Figure 3.10 for both argon and xenon. An overall decrease of the photoelectric cross section with energy can be seen, with sharp discontinuities at the atom’s electron shell binding energies. Specifically for argon, the peaks at 0.26 keV and 3.2 keV coincide respectively with the $2p$ and $1s$ electron shell binding energies, listed in Table 3.1. A less notable peak at 0.335 keV, corresponding to the $2s$ shell, is less prominent due to the comparatively larger number of electrons in the $2p$ shell. The peaks for the $3s$ and $3p$ shell binding energies are not as sharp as those for inner shells due to the larger number of electrons in the outer shells.

Values for xenon are plotted in Figure 3.10 to compare the relative advantages of various targets in different energy regimes. Overall, a xenon target is advantageous compared to argon due to its larger number of ground-state electron shells. However, near argon’s $2p$ and $3p$ binding energies, its photoelectric cross section is higher than that of xenon. Consequently, we expect the signal for DP rest masses near these energies to be more prominent in argon than in xenon.

3.2.2 Predicted detector energy spectra

By interpolating the photoelectric cross section tables in Figure 3.10 on a log-log scale, the DP absorption rates were calculated for several rest masses and plotted in Figure 3.11. For easier comparison with LDM-electron scattering signals, the DP rates are plotted as a function of the electron recoil energy (E_{er}) rather than

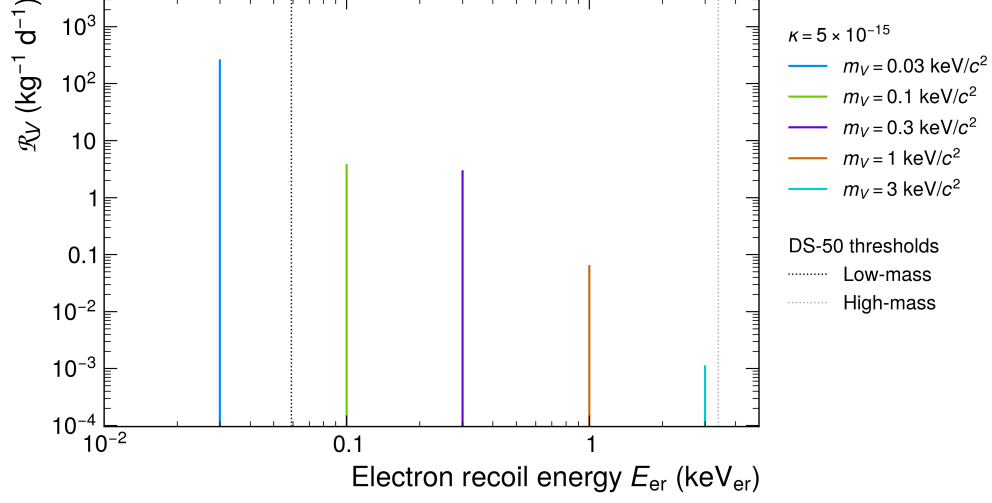


Figure 3.11: Ionization rate of dark photon absorption for an argon target. This work.

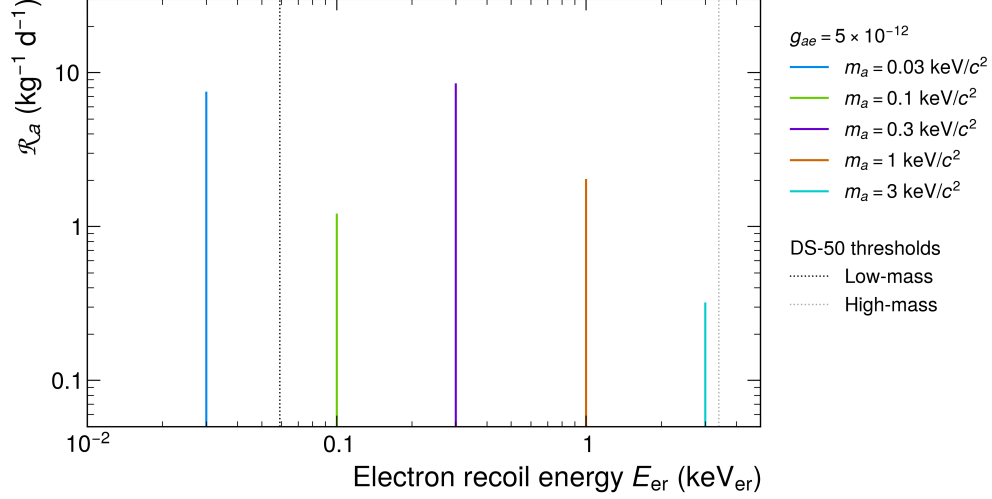


Figure 3.12: Ionization rate of galactic ALP absorption for an argon target. This work.

the DP rest mass, typically shown in other references. One can see that the predicted DP absorption spectra are mono-energetic at the DP rest mass. As $\mathcal{R}_V$ is proportional to $1/m_V$ and σ_{pe} also decreases with energy, DS-50 is more sensitive to DPs with lower rest masses.

3.3 Axion-like particle interactions

ALPs can be absorbed by bound electrons in the detector, a process known as the “axioelectric” effect, as described in Section 1.2.4. The DS-50 experiment is sensitive to the absorption of ALPs produced in the Sun’s core and those that compose galactic DM. Constraints on the solar production of ALPs using DS-50

data can be found in Ref. [105], while in this work, we focus on the detection of galactic ALPs.

As is the case dark photons, the predicted signal for galactic ALP absorption is mono-energetic at the ALP rest mass (m_a) [29, 30, 106]. The process is parameterized by the axioelectric coupling constant (g_{ae}) and can be related to the SM photoelectric effect cross section via

$$\sigma_a(E_a) = \sigma_{\text{pe}}(E_a) \frac{g_{ae}^2}{\beta_a} \frac{3E_a^2}{16\pi\alpha m_e^2 c^4} \left(1 - \frac{\beta_a^{2/3}}{3}\right) \quad (3.23)$$

where σ_a is the cross section for ALP absorption, $E_a = m_a c^2$ is the ALP rest energy, and $\beta_a = v_a/c$ is the ALP's relativistic beta factor. As galactic ALPs are non-relativistic ($\beta_a \ll 1$), the ALP absorption cross section reduces to

$$\sigma_a(E_a) = \sigma_{\text{pe}}(E_a) \frac{3m_a^2 g_{ae}^2}{16\pi\alpha m_e^2 \beta_a} \quad (3.24)$$

Plugging this into Equation (1.6), the ALP absorption rate is thus

$$\mathcal{R}_a = N_T \frac{\rho_\chi}{m_a} \times \frac{3m_a^2 g_{ae}^2}{16\pi\alpha m_e^2} \sigma_{\text{pe}}(m_a c^2) c \quad (3.25)$$

Like for DPs, the ALP rate should be modified for masses above $100 \text{ keV}/c^2$ but is used without such corrections for consistency with previously published constraints.

The calculated galactic ALP rates for an argon target are shown in Figure 3.12. The dependence of ALP rates on velocity and the photoelectric cross section are identical to those for DPs in Section 3.2. However, $\mathcal{R}_a$ is proportional to m_a , which competes with the dependence of σ_{pe} . This results in a more complicated dependency of DS-50 sensitivity on the ALP mass.

3.4 Electronic recoil ionization yield

Calibration measurements are essential to modeling what signal and background energy spectra look like in terms of the detector's observables. The ER energy scale provides a mapping between the measured S2 signal and the energy of the electronic recoil that produced it. For DS-50, this calibration relies on the ^{37}Ar and ^{39}Ar data, fit to a custom semi-empirical model. My work is a refinement of the work published in Ref. [107]. The notable change is the correction of a few bugs in the propagation of uncertainties. This results in fit parameters consistent with Ref. [107], but with slightly larger uncertainties on the model.

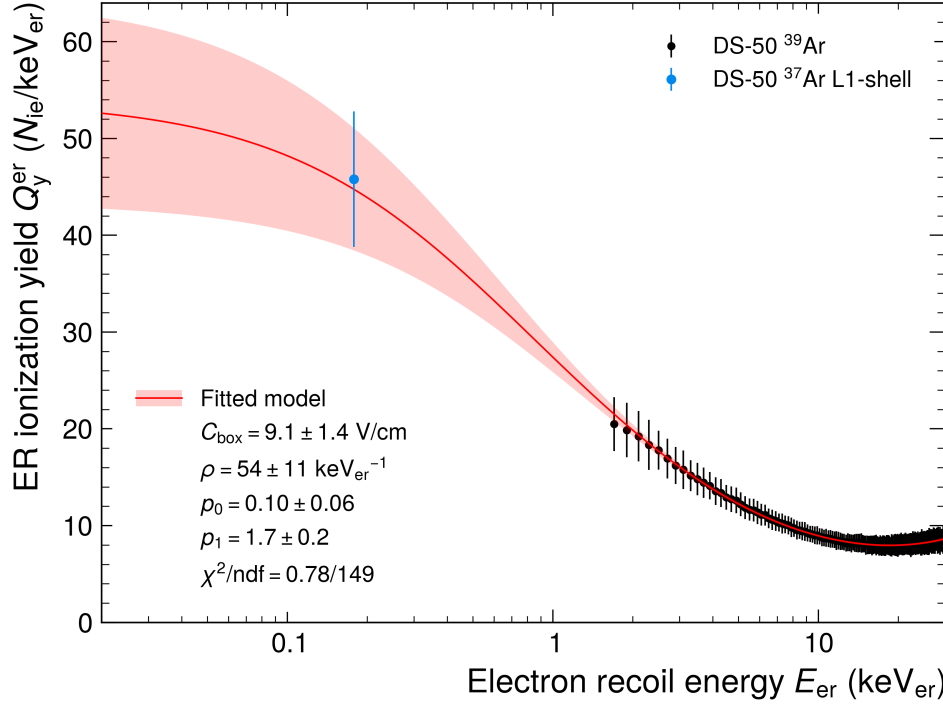


Figure 3.13: Calibrated ER energy scale. Calibration data includes the ^{39}Ar β -decay spectrum (*black*) and ^{37}Ar L1-shell electron capture peak (*blue*). The *red* line shows the best fit to Equation (3.30), with the 1σ uncertainty shaded *red*. This work.

3.4.1 Calibration data

Two sources are used to calibrate the ER energy scale: ^{39}Ar and ^{37}Ar . ^{39}Ar decays via β -decay with a 100% branching ratio and a half-life of (269 ± 3) yr [108]. The Q -value of this decay is 565 keV, leading to the energy spectrum shown in Figure 3.16a, further discussion of which is postponed to Section 3.6.1. From 2013 to 2014, the DS-50 detector was filled with AAr, which has an ^{39}Ar activity of about 1 Bq/kg [62]. Refer to Refs. [105, 107] for a detailed discussion of data selection and correction, some of which overlap with the content of Section 3.5. The energy deposited in the event is reconstructed using the rotated energy variable [71, 107]:

$$E_{\text{er}} = w \left(\frac{S_1}{g_1} + \frac{S_2}{g_2} \right) \quad (3.26)$$

where $w = (19.5 \pm 1.0)$ eV [89] is the average energy required to produce a quantum. As such, this calibration requires both S1 and S2 signals for an event to be selected so that the energy can be reconstructed more precisely, meaning the lowest energy included is $1.6 \text{ keV}_{\text{er}}$ [107]. As the β -decay spectrum is continuous, this dataset was binned into $0.2 \text{ keV}_{\text{er}}$ -wide bins and is shown in Figure 3.13 by the *black* points. Errors on these points come from the 4.3% uncertainty on g_2 . The uppermost energy included in the calibration was $30 \text{ keV}_{\text{er}}$, as this is sufficiently above the low-mass energy region of interest (ROI), for which this calibration

is needed [107].

The ^{37}Ar isotope, produced by cosmogenic interactions in LAr, decays via electron capture with a half-life of $(35.01 \pm 0.02) \text{ d}$ [108]. The dominant ^{37}Ar decay branches are from the electron capture on the K atomic shell (2.83 keV) and L1 (0.277 keV) shell, with branching ratios of 90.4% and 8.4% respectively. Extensive effort by the DS Offline working group modeled the cascades of Auger electrons, x-rays, and UV photons emitted in the decay [107]. While both the K-shell and L1-shell peaks are visible in the ^{39}Ar data, the event topology of the K-shell was too complex to estimate the overall recombination effects and is thus excluded from this analysis. The ^{37}Ar L1-shell peak at $0.179 \text{ keV}_{\text{er}}$ was fit to extract an S2 yield of $(8.2 \pm 1.3) N_e$, which includes both statistical and systematic uncertainties, including that on g_2 [105, 107]. This point is shown in Figure 3.13 by the *blue* point.

3.4.2 Model

Starting from the scintillation model defined in Equation (2.10), we define the number of ionization electrons escaping the recombination process (N_{ie}) as

$$N_{\text{ie}} = (1 - r_{\text{er}}(E_{\text{dep}})) N_{\text{ion}} \quad (3.27)$$

This can then be related to the observed S2 signal by

$$N_e = \frac{\text{S2}}{g_2} = N_{\text{ie}} + N_{\text{fse}} \quad (3.28)$$

where N_e is the number of extracted electrons and the term N_{fse} accounts for final-state electrons produced by an electronic recoil. For interactions like β -decays, Compton scatters, and the DM-electron interactions discussed in Sections 3.1, 3.2, and 3.3, $N_{\text{fse}} = 1$; for electron captures, $N_{\text{fse}} = 0$.

We then define the number of extracted electrons per unit of ER energy as the ER ionization yield, expressed as $Q_y^{\text{er}} = N_{\text{ie}}/E_{\text{er}}$. At low energies (on the order of a keV_{er}), the ER ionization yield is predicted by the Thomas-Imel box model [109]. This approximates Equation (3.27) and describes the recombination of the initial electron-ion pairs contained in a box and immersed in an electric field:

$$Q_y^{\text{er}}(E_{\text{er}}; C_{\text{box}}, \rho) = \frac{1}{\gamma} \frac{\ln(1 + \gamma \rho E_{\text{er}})}{E_{\text{er}}} \quad (3.29)$$

where $\gamma = C_{\text{box}}/F$, C_{box} depends on the mean ionization electron velocity and the size of the ideal box containing the electron-ion cloud, F is the electric field strength (200 V/cm for DS-50), and $\rho = N_{\text{ion}}/E_{\text{er}}$. The

DS Offline working group found that an empirical correction based on the Doke-Birks parameterization [88] allowed the Thomas-Imel model to be extended to higher energies where the recoil tracks are too large [107]:

$$Q_y^{\text{er}}(E_{\text{er}}; C_{\text{box}}, \rho, p_0, p_1) = \left(\frac{1}{\gamma} + p_0(E_{\text{er}}/\text{keV}_{\text{er}})^{p_1} \right) \frac{\ln(1 + \gamma \rho E_{\text{er}})}{E_{\text{er}}} \quad (3.30)$$

where a power function with constant p_0 and exponent p_1 has been included.

3.4.3 Fit results

The model in Equation (3.30) was fit to the DS-50 ^{39}Ar and ^{37}Ar data via χ^2 minimization. The fit results are shown in Figure 3.13. The best-fit parameters are consistent with those published in Ref. [107], with slightly larger uncertainties. The reduced χ^2 is 5.2×10^{-3} , indicating the uncertainties were likely overestimated. Later in this chapter, we will see how the S2-only dataset can further constrain the ER energy scale using a lower energy threshold and a more thorough treatment of systematics.

Using the covariance matrix from the fit, I propagated the uncertainties on the best-fit parameters to the uncertainties on Q_y^{er} . The resulting uncertainties are shown in Figure 3.13 as the *red* shaded region. These also align with the uncertainties published in Ref. [107]. However, I found that the results of this work were incorrectly propagated within the low-mass analysis framework. While this did not affect any existing publications, it was a notable contribution to the work ultimately published in Refs. [93–95, 97].

3.5 DarkSide-50 dataset

This work uses data from DS-50 runs 14433 to 20700, which were taken between December 12, 2015 and February 24, 2018 when the TPC was filled with UAr. The live time of this dataset is 80% larger than the one used in the previous DS-50 low-mass analyses [92, 96], which only included data up to April 2017. A full description of analysis cuts is contained in Appendix C. The run selection cuts (Section C.1) and event quality cuts (Section C.2) were applied to remove runs with possible issues and mis-reconstructed events. These result in a live time of 653.1 live-days.

In this analysis, S2 is used as the energy variable because the majority of the DM signals are below the S1 threshold. The energy ROI is $[4, 170] N_e$, equivalent to $[0.06, 21] \text{ keV}_{\text{er}}$ in the ER energy scale. The ROI is defined up to where the energy scale calibrations have been validated. The ROI lower bound is chosen to avoid the region dominated by spurious electrons, discussed in Section 3.5.2. The S2 trigger efficiency

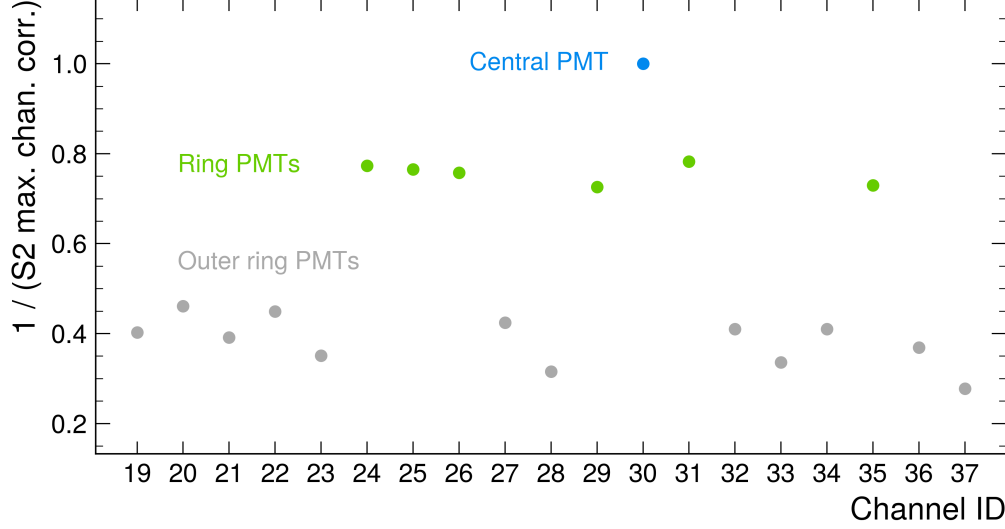


Figure 3.14: DarkSide-50 S2 maximum channel correction map. See Figure C.2 for the correspondence between channel ID and location. The y-axis shows the S2 yield relative to the central PMT, which is the inverse of the factor by which the data is multiplied. Points colored *blue* and *green* indicate core channels used to define the fiducial volume, while outer ring channels (*gray*) are not included in this analysis. Data courtesy of the DS Offline working group.

is estimated to be 100% in the full ROI [92]; such signals (~ 90 PE) are sufficiently large that they are well above the detector’s trigger threshold.

3.5.1 Data corrections

The number of extracted electrons, $N_e = S2/g_2$, is calculated by scaling the number of S2 photoelectrons (PEs) by the S2 gain (g_2). In DS-50, g_2 is measured to be (23 ± 1) PE/ e^- for events reconstructed below the central PMT using S2 echo pulses [92]. As discussed in Ref. [86], a radial dependence on the DS-50 S2 yield was observed in calibration data, with yields differing by up to a factor of four across the channels. This is hypothesized to be due to (a) radial non-uniformities in the electric field in the gaseous region or (b) a layer of condensed LAr on the lower surface of the top window [107]. To uniformize the S2 yield across the TPC, each S2 is corrected relative to the yield at the TPC center (channel 30) using a correction map extracted from $^{83\text{m}}\text{Kr}$ calibration data [92], shown in Figure 3.14. The correction is a function of channel ID as the (x, y) positions are reconstructed as the center position of the S2 maximum channel, meaning it is relatively coarse as the DS-50 PMTs have 3 in diameters. The position dependence of the yield is visible in the figure as the PMT positions are color-coded.

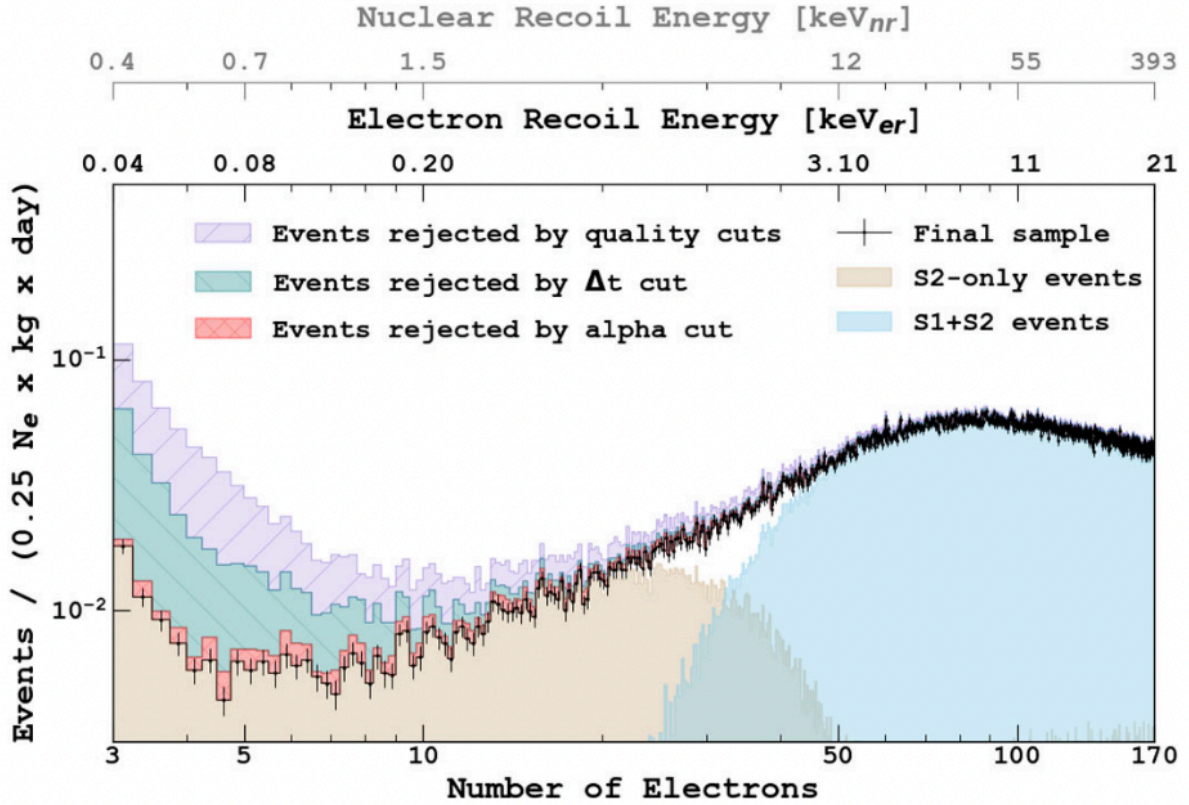


Figure 3.15: DarkSide-50 S2-only dataset at different steps of the data selection process. Figure reproduced from Ref. [93].

3.5.2 Event selection

The physics cuts described in Section C.3 are applied to select signal-like events. The `CXSingleScatter` cut selects event topologies representing a single scatter in the TPC (see Section C.3.1), which are events with two physics pulses (S1 & S2) or one physics pulse (S2-only). The DS-50 reconstruction software classifies pulses using a fixed threshold on the summed waveform (WF) of all channels [62]. A pulse is labeled as an S2 if its f_{90} PSD parameter is <0.1 , as S2 pulses are much slower than S1. Echo pulses are identified by checking if a given pulse has an S2 between $375\text{ }\mu\text{s}$ and $400\text{ }\mu\text{s}$ after it, a window which corresponds to the full TPC drift time.

Fiducialization An inner region called the fiducial volume (FV) is defined to reduce the rate of external background events, which primarily occur near detector edges. As this analysis contains S2-only events for which the z position cannot be precisely reconstructed due to the lack of an associated S1, the FV is constructed only in the (x, y) plane. The DS-50 (x, y) position reconstruction algorithms are inefficient at the

keV scale [93], so this analysis defines the event (x, y) position as the center of the PMT with the highest fraction of S2 light. This (x, y) resolution is on the order of the PMT radius, which is 3.8 cm. Only events with S2 maximum channels belonging to the top core PMTs are selected (see Figure C.2); this is called the CXFiducialXY cut. The FV fraction is estimated to be 41.9% of the active volume using Monte Carlo (MC) simulations and is independent of S2 size [86].

Overlapping pulses The basic S2 identification criteria ($f_{90} < 0.1$) may also select cases consisting of multiple overlapping pulses [93]. Cuts on the S2 pulse length (CXS2Gate) and peak time (CXS2PeakTime) ensure the pulse time profile resembles a single S2 pulse. The CXS2PeakTime cut imposes a maximum S2 peak time of 6 μs and targets events near the cathode with longer S2 signals due to electron longitudinal diffusion. The pulse finder is more likely to accidentally merge these events with nearby interactions. The primary source of these events is multiple scatters of γ -rays from the bottom PMTs.

Interactions within ~ 2 mm of the grid are another source of overlapping pulses. These events have sufficiently short drift times that the pulse finder cannot separate S1 from S2. The CXS1S2Pileup cut exploits the comparatively prompt nature of S1 pulses by requiring a minimum S2 peak time of 0.2 μs . The cut also stipulates a minimum S2 full width at half maximum (FWHM), as the desired event population that lies below 2 mm from the grid will have wider S2 pulses due to electron diffusion.

Spurious electron background Both xenon and argon dual-phase TPCs have observed low-energy S2 signals that are correlated to previous events in both time and space, with delays of up to hundreds of milliseconds [92, 110, 111]. Theories for the sources of these events include trapping by negative ion impurities throughout the TPC and trapping at the liquid-gas interface. A cut labeled CXDeltaT removes events that occur within 20 ms of the previous event, which is an extended version of the 2 ms veto used in the 2018 analysis [92]. This cut introduces a dead time estimated as 3%.

Alpha-induced events A population of events with a large S1 paired with an anomalously small S2 was discovered in the data [93]. The origin was traced to α particles generated at a shallow depth inside the TPC walls. These events have a degraded S1 and no S2, as the ionization electrons are absorbed by the walls. Then, primary scintillation light from this interaction produces an $S1_{\text{echo}}$ pulse due to photoionization of the cathode, which is paired with the α S1. To remove these events, the CXAlpha cut using the ratio of S2 to S1,

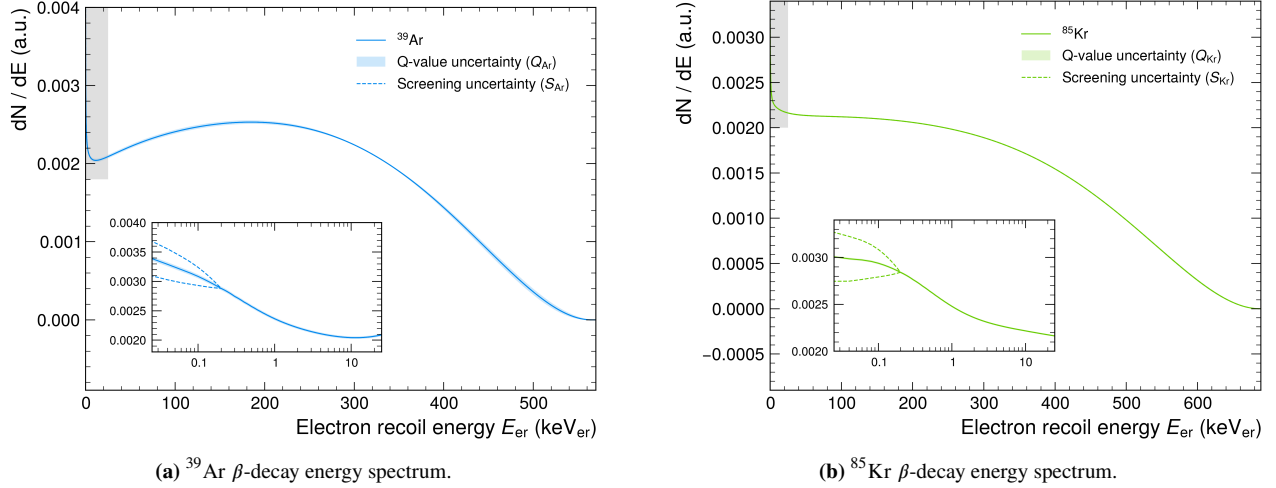


Figure 3.16: β -decay energy spectra of ^{39}Ar (left, blue) and ^{85}Kr (right, green). The y-axis shows the differential number of events depending on the energy. Insets are zoomed-in views of the region shaded gray, namely the low-mass energy ROI, to better show the effects of systematic uncertainties. Data reproduced from Ref. [93].

exploiting the fact that both pulses are proportional to the energy deposited. Using calibration data, a 99% acceptance band for this ratio was determined as a function of S1 [93].

Impact of physics cuts The DS-50 S2 data is shown in Figure 3.15 at different steps of the data selection process. The final sample after all cuts contains about 350,000 events and corresponds to a fiducial volume exposure of 12 306 kg d. While the predicted signals are not present in the region above $50 N_e$, which predominantly contains S1 and S2 events, this data helps to constrain the background model and other nuisance parameters. The event excess below $4 N_e$ is attributed primarily to correlated spurious electrons with longer time delays than the population removed by CXDe1taT and those without a clear time correlation to previous events. As these backgrounds are not fully modeled at this time, we choose the lower bound of the energy ROI to be $4 N_e$.

3.6 Background model

The DS-50 background model describes the expected energy and ionization spectra due to radioactive contaminants in the detector. The model is based on the measured activities of the detector components and MC simulations of the expected energy spectra, a considerable improvement over the 2018 analysis. My specific contributions to this effort included a systematic review of the background model and associated uncertainties, as well as a statistical analysis of the background model (fitting it to data). Presentation of the latter item

is postponed to Section 3.8.3.

The DS-50 background sources considered are listed in Table 3.3. These sources are categorized as being intrinsic to the active UAr target or originate from detector construction materials.

3.6.1 Internal backgrounds

The dominant internal backgrounds are β^- decays of ^{39}Ar and ^{85}Kr . ^{39}Ar is intrinsic to UAr while the presence of ^{85}Kr is likely due to atmospheric leaks or from natural fission underground [112]. The Q -value, which is the energy liberated during a nuclear reaction, is 565 keV for ^{39}Ar and 685 keV for ^{85}Kr [108]. Uncertainties on the Q -values, shown as shaded bands in Figure 3.16, are included as systematics in the background model, labeled Q_{Ar} and Q_{Kr} . These are sufficiently small that they may not be visible to the reader. These have initial values of 1% for ^{39}Ar and 0.4% for ^{85}Kr .

Additionally, the ^{39}Ar and ^{85}Kr β -decay spectra are affected by atomic exchange effects. More precisely, these effects include the weak interaction transition, as well as the atomic and nuclear structures of the initial and final states. The β -decay spectra used in this work have been updated since the 2018 DS-50 low-mass analysis [92, 96] to include these effects, using updated calculations validated down to 0.2 keV_{er} for ^{63}Ni and ^{241}Pu [113, 114]. This is a considerable improvement over the previous work. Shape uncertainty parameters S_{Ar} and S_{Kr} are included on the ^{39}Ar and ^{85}Kr spectra, respectively, to account for uncertainties in the atomic exchange effects below 0.2 keV_{er}. These systematic errors, shown by dotted lines in the insets of Figure 3.16, are linearly interpolated between 25% at 0 keV and 0% at 0.2 keV [93].

To determine the specific activities of ^{39}Ar and ^{85}Kr , S1 spectra from the first 70 d of the DS-50 dataset were fit, giving values of (0.73 ± 0.11) mBq/kg for ^{39}Ar and (1.84 ± 0.12) mBq/kg for ^{85}Kr [107]. These systematics are labeled as A_{Ar} and A_{Kr} respectively. The quoted ^{85}Kr activity is corrected for its decay time and averaged over the dataset live time.

3.6.2 External backgrounds

The main sources of external x-ray and γ -ray backgrounds are the radioactive contaminants in the PMTs and in the stainless steel cryostat. The DS-50 search for LDM in 2018 determined external background activities by extrapolating fits at high energies [92]. To improve upon this, DS-50 collaboration members undertook a material screening campaign to determine the specific activities of individual detector components, shown in the “Activity” column of Table 3.3. The ^{238}U decay chain is split into sections: the upper portion is up to

Location	Source	Activity (Bq)	Event rate (1/s)
LAr	^{39}Ar	0.034 ± 0.005	$(6.5 \pm 0.9) \times 10^{-4}$
	^{85}Kr	0.084 ± 0.004	$(1.7 \pm 0.1) \times 10^{-3}$
Cryostat	^{232}Th	0.19 ± 0.04	$(7.9 \pm 1.7) \times 10^{-5}$
	$^{238}\text{U up}$	1.30 ± 0.20	$(1.5 \pm 0.2) \times 10^{-5}$
	$^{238}\text{U low}$	$0.38^{+0.04}_{-0.19}$	$(5.3^{+0.6}_{-2.6}) \times 10^{-6}$
	^{235}U	$0.045^{+0.01}_{-0.02}$	$(1.5^{+0.3}_{-0.7}) \times 10^{-5}$
	^{60}Co	1.38 ± 0.10	$(4.7 \pm 0.3) \times 10^{-4}$
	^{40}K	$0.16^{+0.02}_{-0.05}$	$(3.4^{+0.4}_{-1.1}) \times 10^{-6}$
PMT stems	^{232}Th	0.16 ± 0.03	$(3.2 \pm 0.6) \times 10^{-4}$
	$^{238}\text{U up}$	1.06 ± 0.22	$(4.9 \pm 1.0) \times 10^{-5}$
	$^{238}\text{U low}$	0.34 ± 0.03	$(3.2 \pm 0.3) \times 10^{-4}$
	^{235}U	0.05 ± 0.01	$(1.2 \pm 0.2) \times 10^{-4}$
	^{40}K	2.39 ± 0.32	$(1.8 \pm 0.2) \times 10^{-4}$
	^{54}Mn	0.05 ± 0.02	$(3.5 \pm 1.4) \times 10^{-5}$
PMT ceramic	^{232}Th	0.07 ± 0.01	$(2.4 \pm 0.3) \times 10^{-4}$
	$^{238}\text{U up}$	4.22 ± 0.88	$(4.2 \pm 0.9) \times 10^{-4}$
	$^{238}\text{U low}$	0.34 ± 0.03	$(5.3 \pm 0.5) \times 10^{-4}$
	^{235}U	0.21 ± 0.03	$(9.8 \pm 1.4) \times 10^{-4}$
	^{40}K	0.61 ± 0.08	$(8.1 \pm 1.1) \times 10^{-5}$
PMT body	^{60}Co	0.17 ± 0.02	$(2.4 \pm 0.3) \times 10^{-4}$

Table 3.3: DarkSide-50 background contributions. Activities are quoted for the decay chain progenitors. The event rates include all single-scatter events in the energy ROI and FV for the full decay chains.

^{226}Ra and the lower portion is from ^{222}Rn to the end. This is done because different techniques are used to measure the activity of the two portions.

Subsequently, the DS Offline working group performed an extensive MC simulation campaign of isotopes in different source locations with G4DS to determine the expected interaction rates and energy spectra. The “Event rate” column in Table 3.3 shows the nominal rates for single-scatter events in the FV and low-mass energy ROI. Event rate uncertainties were propagated from the materials screening measurements.

The cryostat background is largely dominated by ^{60}Co . The energy spectra of all components are very similar as the interactions in the energy ROI ($<21 \text{ keV}_{\text{er}}$) are the low-energy portion of the Compton continuum for γ -rays on the order of 1 MeV. Thus, all cryostat spectra were combined with overall a normalization A_{Cryo} to reduce the number of fit parameters. I confirmed the validity of this approach by comparing the summed spectra while varying the amplitude of each component by 1σ , which showed good agreement.

The DS-50 PMTs were measured as a whole during an initial materials screening campaign before the

construction of the detector. Monte Carlo simulations demonstrated that the modeled distribution of radioactivity within the PMT had a significant impact on the expected interaction rates due to the different distances of PMT components from the active volume [93]. The partitioning of radioactivity between PMT components shown in Table 3.3 was estimated based on detailed assays of similar PMTs, which showed that the stems in the back of the PMT, the ceramic surrounding the dynode chain, and the PMT body made of Kovar are primarily responsible for its radioactivity. Among these, the ceramic material contributes most significantly to the background model. The radioactivity partitioning was shown to have a negligible effect on the spectral shape, so the PMT spectra were combined with an overall normalization A_{PMT} , as was done for the cryostat. As the radioactivity partitioning was measured for PMTs similar to but not the same as those in DS-50, an additional 10% uncertainty, estimated by the simulation campaign, was added to A_{PMT} [93].

3.7 Response model

The detector response is used to convert predicted energy spectra via MC simulations into spectra of observable quantities that resemble observed data. The DS-50 response model steps are summarized as converting the deposited energy to N_e , applying detector effects, and applying selection cuts [107]. The response model was validated by comparing the predicted spectra to calibration data.

3.7.1 Conversion of energy to N_e

An ER in LAr is modeled as a random process that produces a mean number of ionization electrons ($\langle N_e \rangle$):

$$\langle N_e \rangle = E_{\text{er}} \times Q_y^{\text{er}}(E_{\text{er}}) \quad (3.31)$$

where Q_y^{er} is the ionization electron yield per unit of energy for an ER with energy E_{er} , described in Section 3.4. Statistical fluctuations about $\langle N_e \rangle$ are modeled as a Gaussian distribution with mean $\langle N_e \rangle$ and standard deviation $\sqrt{F\langle N_e \rangle}$, which employs a Fano factor F as an empirical correction [115]. A Fano factor value of 0.10 ± 0.03 was used, determined using ^{37}Ar and ^{39}Ar calibration data [107]. Uncertainties on the ER energy scale shown as shaded regions in Figure 3.13 are propagated via MC, meaning the ionization spectra are computed by evaluating Q_y^{er} at its nominal value and $\pm 1\sigma$ in Equation (3.31) to produce three ionization spectra. These are included as shape systematics in the likelihood, discussed in Section 3.8.

3.7.2 Detector effects

Several corrections extracted from calibration data are applied to N_e to model the DS-50 detector response. The dominant effects are a radial correction and the PMT resolution. An electron lifetime correction is also applied, but it is subdominant.

Radial correction A radial correction is needed to model the S2 position dependence observed in DS-50 calibration data [86], as discussed in Section 3.5.1. While the S2 maximum channel-based correction is applied to both real and simulated data, another radial correction must be applied to simulated data to accurately reproduce what is observed in the real data. The goal of the S2 maximum channel correction in Section 3.5.1 is to uniformize the yield, but some structure remains due to coarseness introduced by the large (x, y) position reconstruction resolution in DS-50 (on the order of the PMT radius). To match this structure, a radial correction to MC data was developed by the DS Offline working group using $^{83\text{m}}\text{Kr}$ calibration data [86], shown in Figure 3.17. It is a function of the true event position and normalized so that the average correction across the entire central channel (0 cm to 3.8 cm) is unity, so as to be consistent with the definition of the S2 maximum channel correction. The shoulder-like structure in the radial correction profile is due to the PMT array geometry. Note that both the MC radial correction described in this section and the S2 maximum channel radial correction in Section 3.5.1 are applied to simulated data.

Electron lifetime A fraction of electrons is suppressed according to the electron lifetime, which is the probability that impurities capture an ionization electron as it drifts toward the gas pocket. Thus, the effect depends on an event's drift time (z position). The number of extracted electrons is reduced by sampling an exponential probability distribution, with the DS-50 electron lifetime of 15.8 ms as the scale parameter [107]. While included in the response model, the effect of the electron lifetime correction is relatively small, as electrons from interactions near the cathode have a $\sim 97.5\%$ probability of reaching the gas pocket.

PMT resolution The PMT single electron resolution models the probability that an event recorded by a PMT channel is reconstructed as seeing $N_e^{(f)}$ ionization electrons under the assumption that $N_e^{(i)}$ ionization electrons were in truth extracted. The PMT resolution can be treated as a Gaussian smearing effect similar to the ER Fano fluctuations discussed above. This means sampling a Gaussian probability density function

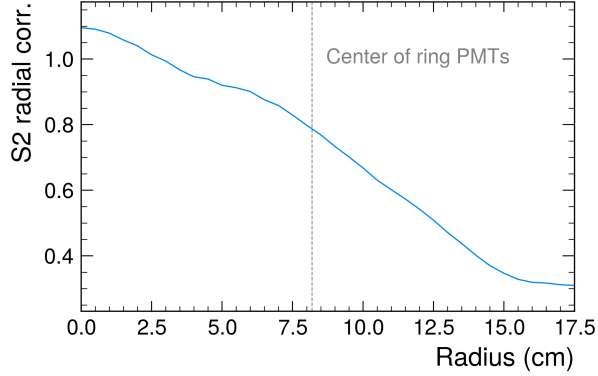


Figure 3.17: DarkSide-50 S2 radial correction map applied to simulated data. Figure based on the data in Ref. [86].

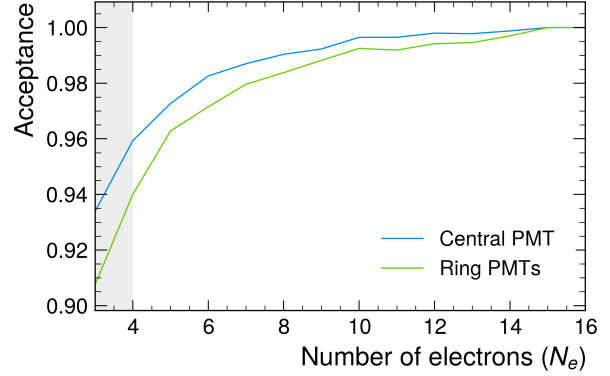


Figure 3.18: Energy-dependent combined acceptance of the CXS2PeakTime and CXS2Gate cuts. Above $15 N_e$, the acceptance is estimated to be $\sim 100\%$. The gray region is outside the energy ROI. Figure content courtesy of the DS Offline working group.

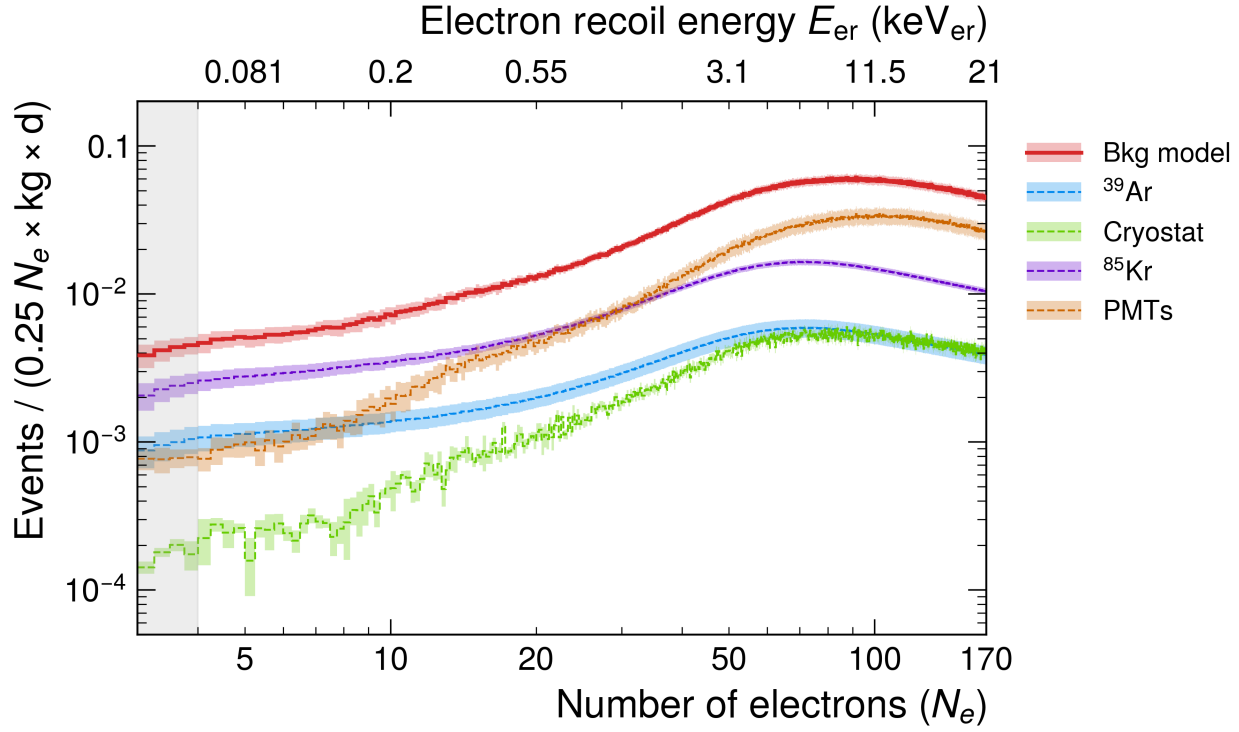
(pdf) with a mean of N_e and a standard deviation of $\sigma_{\text{SPE}} \sqrt{N_e}$, where σ_{SPE} is the single electron resolution determined to be 0.27 using echo pulses [107].

3.7.3 Selection cuts

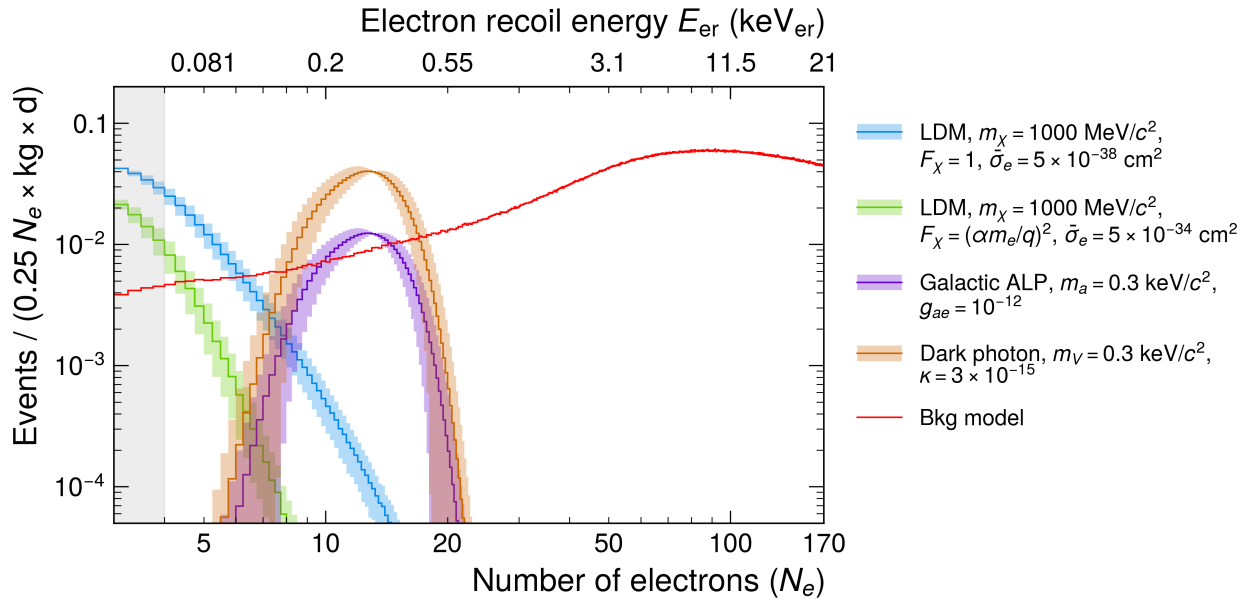
Energy-independent acceptances listed in Appendix C are applied to the final ionization spectra. However, two cuts are applied to the MC samples on an event-by-event basis. Due to the positional nonuniformity of external backgrounds, a toy model reconstructs event (x, y) positions to the nearest top PMT, after which the FV cut is applied. Additionally, the combined acceptance of the CXS2PeakTime and CXS2Gate cuts was found to have an energy dependence, as shown in Figure 3.18. Collaborators assessed this using a toy MC simulation, which emulated S2 waveforms, the DS-50 pulse finding algorithm, and the data reconstruction algorithms. The acceptance is applied to simulated events by randomly sampling a Bernoulli distribution with the acceptance probability interpolated for an event's energy and position.

3.7.4 Ionization spectra

The final samples are binned into ionization spectra, plotted in Figure 3.19. Note that the final values for N_e are not integers, as the fundamental observable is not the number of extracted electrons but rather the number of detected secondary scintillation photons. Binning at $0.25 N_e$ intervals improves the discrimination of component shapes, particularly below $10 N_e$ where LDM-electron scattering signals lie, while minimizing the impact of statistical errors. The dominant errors are due to Q_y^{er} , which affects all signals and backgrounds



(a) Ionization spectra for DarkSide-50 background model components. The *red solid* line shows the sum of all components.



(b) Ionization spectra for several DM candidates, with the DarkSide-50 response model applied.

Figure 3.19: DarkSide-50 ionization spectra of backgrounds and signals. Each *shaded* band shows the combined nominal uncertainty on a signal model, assuming all nuisance parameters to be uncorrelated. Errors due to MC statistics are not drawn. This work.

considered in this work. The ^{39}Ar and ^{85}Kr atomic exchange uncertainties are also notable below $0.2 \text{ keV}_{\text{er}}$, albeit subdominant to Q_y^{er} . While not shown, LDM-electron scattering signals for all masses considered in this work ($5 \text{ MeV}/c^2$ to $1000 \text{ MeV}/c^2$) are located below $10 N_e$ for both the heavy and light mediator cases. Both DP and ALP signals appear as smeared peaks centered on the particle rest mass.

3.8 Profile likelihood analysis

This work tests for the presence of DM signals using a binned profile likelihood [116, 117]. A frequentist significance test quantifies the agreement between the observed DS-50 dataset and a hypothesis, using the likelihood ratio as a test statistic. The hypothesis of the presence of a DM signal (H_{sb}) is compared against the background-only hypothesis (H_{b}) to set constraints on DM model parameters. The formalism described in this section is implemented by the `pydslight` package, described in Section 5.1.

3.8.1 Likelihood function

The observed DS-50 S2 spectrum is labeled $\mathbf{n}$, a histogram with N bins. The model contains one signal component (s) with a normalization factor μ (also called the “signal strength”), as well as several background components ($\mathbf{b}_{\text{Ar}}$, $\mathbf{b}_{\text{Kr}}$, $\mathbf{b}_{\text{PMT}}$, $\mathbf{b}_{\text{Cryo}}$) which are discussed in Section 3.6. Nuisance parameters ($\boldsymbol{\theta}$) account for systematic uncertainties in the model; these are described in Section 3.8.2. The model can be evaluated for a given μ and $\boldsymbol{\theta}$ to obtain a predicted dataset $\mathbf{v}$ (a histogram with N bins):

$$\mathbf{v}(\mu, \boldsymbol{\theta}) = \mu s(\boldsymbol{\theta}) + \sum_k \mathbf{b}_k(\boldsymbol{\theta}) \quad (3.32)$$

where the summation over k is over all background components. The likelihood function $\mathcal{L}$, which is the joint probability of the full experiment, is defined as

$$\mathcal{L}(\mu, \boldsymbol{\theta}) = \prod_{j=1}^N \text{Pois}(n_j | v_j) \times \prod_{\theta \in \boldsymbol{\theta}} \text{Gaus}(\theta | \theta_0, \Delta\theta_0) \times \prod_{j=1}^N \text{Gaus}(1 | \gamma_j, \Delta\gamma_j) \quad (3.33)$$

The first term is the Poisson probability of observing n_j events in bin j given an expected number of events v_j , which depends on μ and $\boldsymbol{\theta}$ as shown in Equation (3.32). The second term contains a set of constraint terms for each nuisance parameter, which reflect that the nuisance parameter has been estimated with a nominal central value θ_0 with uncertainty $\Delta\theta_0$ by an auxiliary measurement. The nuisance parameters are assumed to follow a Gaussian distribution, as is standard [117]. The third term includes additional nuisance parameters that

	Symbol	Description	Affected components
Amplitude	A_{FV}	Uncertainty on the fiducial volume, 1.1% for b_{PMT} and b_{Cryo} , 1.5% for b_{Ar} , b_{Kr} , and s	$b_{\text{Ar}}, b_{\text{Kr}}, b_{\text{PMT}}, b_{\text{Cryo}}, s$
	A_{Ar}	14.0% uncertainty on ^{39}Ar activity	b_{Ar}
	A_{Kr}	4.7% uncertainty on ^{85}Kr activity	b_{Kr}
	A_{PMT}	11.5% uncertainty on activity from PMTs	b_{PMT}
	A_{Cryo}	6.6% uncertainty on activity from the cryostat	b_{Cryo}
Shape	Q_{Ar}	1% uncertainty on the ^{39}Ar decay Q-value	b_{Ar}
	Q_{Kr}	0.4% uncertainty on the ^{85}Kr decay Q-value	b_{Kr}
	S_{Ar}	Uncertainty on atomic exchange and screening effects for ^{39}Ar β -decay	b_{Ar}
	S_{Kr}	Uncertainty on atomic exchange and screening effects for ^{85}Kr β -decay	b_{Kr}
	Q_y^{er}	Uncertainty on ER energy scale	$b_{\text{Ar}}, b_{\text{Kr}}, b_{\text{PMT}}, b_{\text{Cryo}}, s$

Table 3.4: Nuisance parameters, their sources, and impacted model components included in the binned profile likelihood for the DarkSide-50 low-mass analysis.

account for statistical uncertainties in each bin, which treats the MC estimate as an auxiliary measurement. The statistical uncertainty multiplicative modifier for a given bin j is γ_j , and its uncertainty is $\Delta\gamma_j$. For small statistical uncertainties, the distribution is approximately Gaussian [117].

3.8.2 Nuisance parameters

Nuisance parameters (θ) account for systematic uncertainties in the model. Parameters are estimated by auxiliary measurements, giving nominal central values θ_0 and uncertainties $\Delta\theta_0$. For this analysis, the nuisance parameter vector is defined as

$$\theta = \left[A_{\text{FV}} \quad A_{\text{Ar}} \quad A_{\text{Kr}} \quad A_{\text{PMT}} \quad A_{\text{Cryo}} \quad Q_{\text{Ar}} \quad Q_{\text{Kr}} \quad S_{\text{Ar}} \quad S_{\text{Kr}} \quad Q_y^{\text{er}} \right] \quad (3.34)$$

and its components are defined in Table 3.4. Nuisance parameters are classified as “amplitude” or “shape” parameters. Amplitude parameters act on the normalization of model components but not their shape; these can be asymmetric. Shape parameters are systematics that affect the distribution shapes of various samples. These are implemented using a bin-by-bin piecewise exponential interpolation strategy that takes the histogram shapes at the nominal value ($\sigma = 0$), downward variation ($\sigma = -1$), and upward variation ($\sigma = +1$) as inputs [117].

Shrinkage of the PTFE TPC walls and PMT holders introduces uncertainty on the fiducial volume (A_{FV}). This affects the PMT positions, which are used in the (x, y) reconstruction. The uncertainty on the PMT posi-

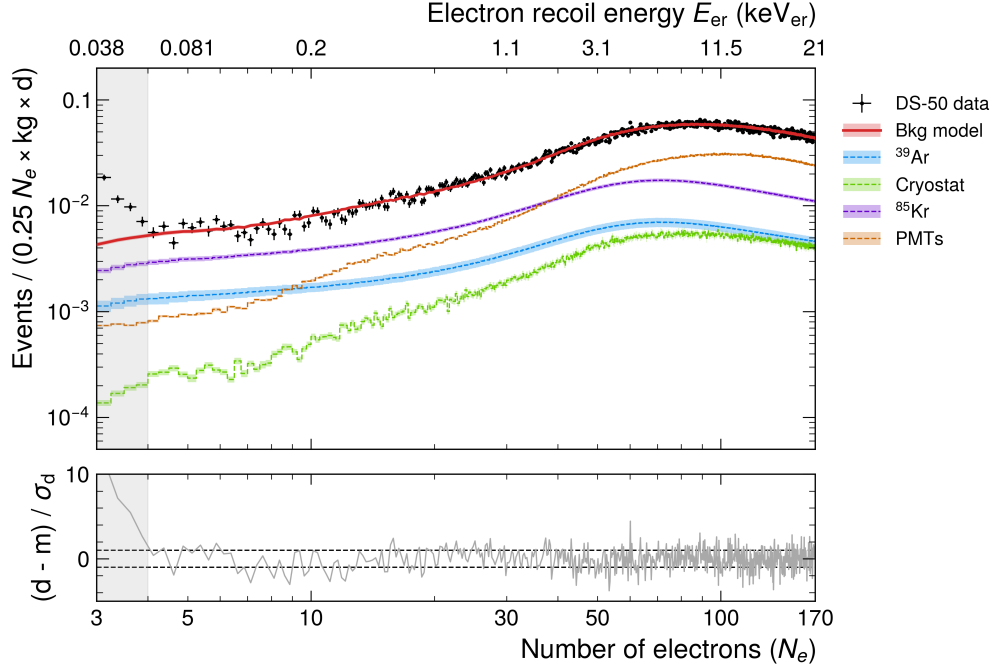


Figure 3.20: Post-fit DarkSide-50 ionization spectra (*top*) for the background-only fit along with the data pulls (*bottom*). See the text for more details. This work.

tions impacts uniformly distributed sources (^{39}Ar β -decays, ^{85}Kr β -decays, and DM signals) differently than external backgrounds (PMT and cryostat γ -rays). For uniform sources, the FV uncertainty (1.5%) directly scales the source's activity. However, external backgrounds are more likely to occur near the detector edges. Hence, a slight change in the FV definition has a non-trivial effect on the fraction of events selected. The FV uncertainties were propagated via MC for external backgrounds, giving a 1.1% error [93].

The dominant shape systematic, particularly at low energy where most of the DM signals are expected, is the ER energy scale calibration, Q_y^{er} , discussed in Section 3.4. As all DM interactions considered here are with electrons and the backgrounds considered in this work are all ERs, Q_y^{er} affects all model components. The single calibration point below 2 keV_{er}, as shown in Figure 3.13, means that the ER energy scale is poorly constrained in this region. This particularly affects the DM signals, as shown in Figure 3.19b.

3.8.3 Background-only fit

The dataset was fit to the background model by maximizing the likelihood of Equation (3.33) while fixing μ to 0, giving fitted nuisance parameters labeled $\hat{\theta}$. This enables model diagnostics and validation of the background model. The fit results are summarized in Figure 3.20, Figure 3.21, and Figure 3.22.

Figure 3.20 shows the post-fit ionization spectra for each model component (dotted lines) alongside the

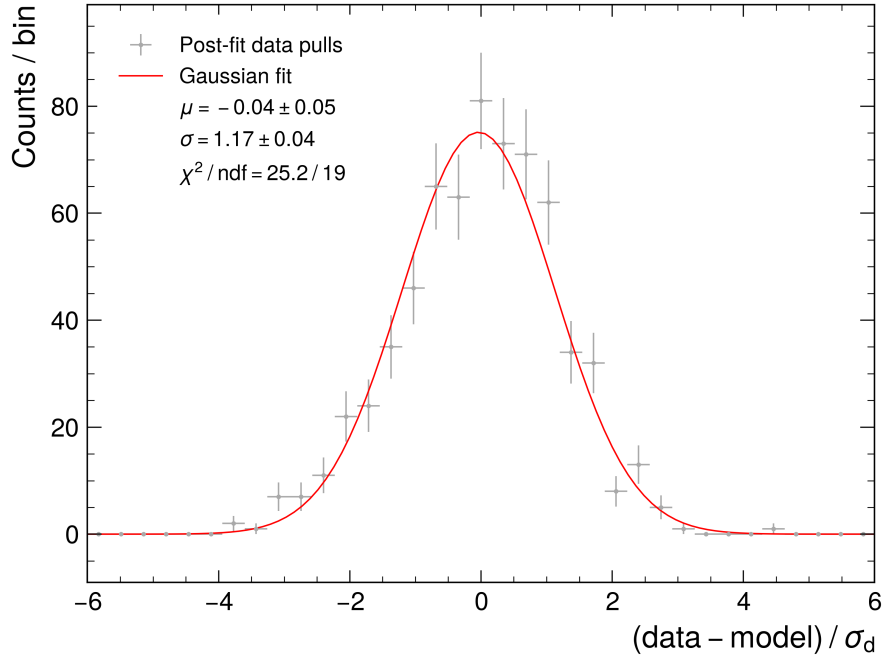


Figure 3.21: Distribution of the data pulls for the background-only fit. These are the values shown in the lower panel of Figure 3.20. The *red* line shows a Gaussian fit for the histogram. See the text for more details. This work.

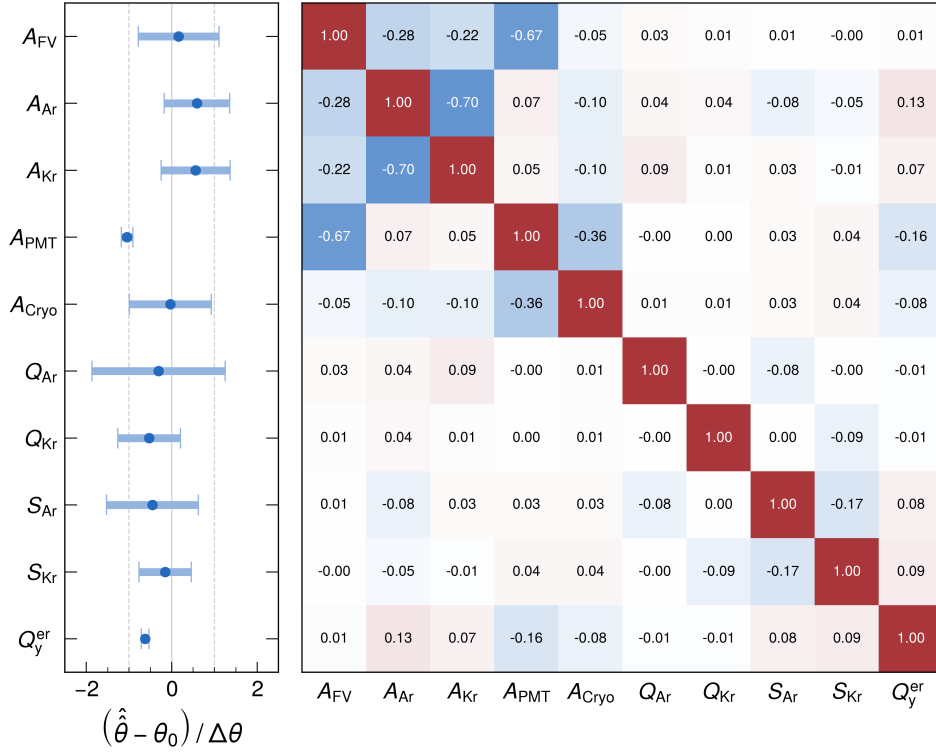


Figure 3.22: Nuisance parameter pulls (*left*) and correlation matrix (*right*) from the background-only fit. See the text for more details. This work.

data to which the model was fitted (black dots). The shaded bands illustrate uncertainties on background model components and factor in the correlation matrix from the fit (see Figure 3.22). As in previous figures, the region shaded *gray* is below the energy threshold and not included in the fit. The fit above $4 N_e$ is compatible with the data, demonstrating the improvements over the 2018 analysis in which there was an event excess above background from $4 N_e$ to $7 N_e$ [92]. There are multiple reasons for this improvement: the more efficient background rejection of quality cuts, the better modeling of ^{39}Ar and ^{85}Kr β -spectra, including atomic exchange and screening effects, particularly important at low energies, and more accurate treatment of systematics.

In the lower panel of Figure 3.20, the *gray* line shows the data pulls, defined as the residuals (difference between the observed and expected events) normalized to the error on the number of observed events (σ_d). Here, σ_d is solely the Poissonian statistical error as this is a counting experiment. The dotted horizontal lines are located at ± 1 for reference. The data pulls for $[4, 170] N_e$ are histogrammed in Figure 3.21 and then fit to a Gaussian distribution. The fit shows that data pulls are normally distributed as expected for a good fit, demonstrating the quality of the background model.

The left panel of Figure 3.22 shows the post-fit nuisance parameter pulls as *blue* dots, where the pull is defined as the difference between the fitted ($\hat{\theta}$) and nominal (θ_0) values, normalized to the nominal uncertainty ($\Delta\theta_0$). The *blue* error bars are located at $\Delta\hat{\theta}/\Delta\theta_0$, which is the post-fit error ($\Delta\hat{\theta}$) normalized to the pre-fit uncertainty. If a post-fit nuisance parameter value is identical to its pre-fit value, the pull would be zero and the error bar would extend from -1 to 1 , illustrated by the vertical *gray* solid and dashed lines, respectively. We see good agreement between the post-fit nuisance parameter values and their pre-fit values. The fit notably reduces the uncertainty on A_{PMT} , which was expected as the pre-fit value included additional error from the PMT radioactivity partitioning. Q_y^{er} is also highly constrained by the fit, reducing its uncertainty by 91%, which improves upon the calibration's lack of data points at low energies.

The right panel of Figure 3.22 shows the post-fit correlation matrix of the nuisance parameters, with *red* indicating full correlation, *white* indicating no correlation, and *blue* indicating full anticorrelation. The anticorrelations between A_{Ar} and A_{Kr} are because their spectral shapes are similar. Likewise, this also occurs for A_{Cryo} and A_{PMT} , but to a lesser extent. The impact of fiducial volume uncertainty, which equally acts on all normalization factors, is larger when relative uncertainties on component amplitudes are higher.

3.8.4 Exclusion limits

To search for DM signals, two hypotheses are compared using the profile likelihood framework: a hypothesis H_{sb} with the presence of a signal with strength μ and a background-only hypothesis H_{b} with $\mu = 0$. For limit setting, H_{b} is used as the null hypothesis and H_{sb} is the alternative hypothesis. The same procedure described below can be used for signal discovery by reversing the roles of the two hypotheses.

Test statistic A test statistic quantifies an entire experiment with a single number, with larger values indicating increasing incompatibility between the data and hypothesis. While there are several standard test statistic definitions [116], this work uses the test statistic $\tilde{q}_\mu$ because we are setting upper limits on DM parameters that are model-constrained to be positive. This is defined as

$$\tilde{q}_\mu = \begin{cases} -2 \ln \tilde{\lambda}(\mu), & \hat{\mu} \leq \mu, \\ 0, & \hat{\mu} > \mu \end{cases} \quad (3.35)$$

where $\tilde{\lambda}$ is the profile likelihood ratio:

$$\tilde{\lambda}(\mu) = \begin{cases} \frac{\mathcal{L}(\mu, \hat{\boldsymbol{\theta}}(\mu))}{\mathcal{L}(0, \hat{\boldsymbol{\theta}}(0))}, & \hat{\mu} < 0, \\ \frac{\mathcal{L}(\mu, \hat{\boldsymbol{\theta}}(\mu))}{\mathcal{L}(\hat{\mu}, \hat{\boldsymbol{\theta}})}, & 0 \leq \hat{\mu} \leq \mu. \end{cases} \quad (3.36)$$

The profile likelihood ratio numerator is the *conditionally maximized likelihood*, with $\hat{\boldsymbol{\theta}}(\mu)$ being the nuisance parameter values that maximize the likelihood for a *fixed* value of μ specified by the hypothesis being tested. This is expressed mathematically as

$$\hat{\boldsymbol{\theta}}(\mu) = \operatorname{argmax}_{\boldsymbol{\theta}} \mathcal{L}(\mu, \boldsymbol{\theta}) \quad (3.37)$$

This process is called *profiling out* the nuisance parameters. The denominator of Equation (3.36) is the *unconditionally maximized likelihood*, which is found at values of $\hat{\mu}$ and $\hat{\boldsymbol{\theta}}$ when leaving both μ and $\boldsymbol{\theta}$ free during the maximization. In the case of $\hat{\mu} < 0$, which is not permitted by the signal model, the *conditionally maximized likelihood* for $\mu = 0$ is used as the denominator. The test statistic $\tilde{q}_\mu$ in Equation (3.35) is called “one-sided” because when testing a value of μ , a value less than the best-fit signal strength ($\hat{\mu}$) should not represent less compatibility with the data obtained and is thus not be included in the rejection region of the test [116].

First, the observed test statistic ($\tilde{q}_{\mu, \text{obs}}$) is calculated. Then, two test statistic pdfs $f(\tilde{q}_{\mu}|\mu)$ are constructed using toy MC experiments, under the assumption of H_{sb} and one under H_{b} . If one has an observed dataset, toy dataset generation uses the nuisance parameter values and uncertainties fitted to the observed dataset, namely $\hat{\theta}(\mu)$ for H_{sb} and $\hat{\theta}(0)$ for H_{b} . Note that the fitted values for $\hat{\theta}(0)$ are shown in the left panel of Figure 3.22. For sensitivity projections, the nominal nuisance parameters and uncertainties are used. For each toy MC, $\tilde{q}_{\mu}$ is calculated using the toy dataset in place of $\mathbf{n}$ in Equation (3.33). Five expected test statistic values ($\tilde{q}_{\mu, \text{exp}}^{\sigma=0, \pm 1, \pm 2}$) are derived by finding the median, 68%, and 95% bands of the pdf generated under the null hypothesis (H_{b} for limit setting).

p-value A significance test is conducted to quantify the level of disagreement between the observed dataset and the alternative hypothesis. This is done by computing a p -value, which is the probability of observing data like that observed or more extreme assuming the hypothesized μ is correct. The p -value (p_{μ}) is calculated by integrating the test statistic pdf generated under the alternative hypothesis (H_{sb} for limit setting) above the observed test statistic ($\tilde{q}_{\mu, \text{obs}}$):

$$p_{\mu} = \int_{\tilde{q}_{\mu, \text{obs}}}^{\infty} f(\tilde{q}_{\mu}|\mu) d\tilde{q}_{\mu} \quad (3.38)$$

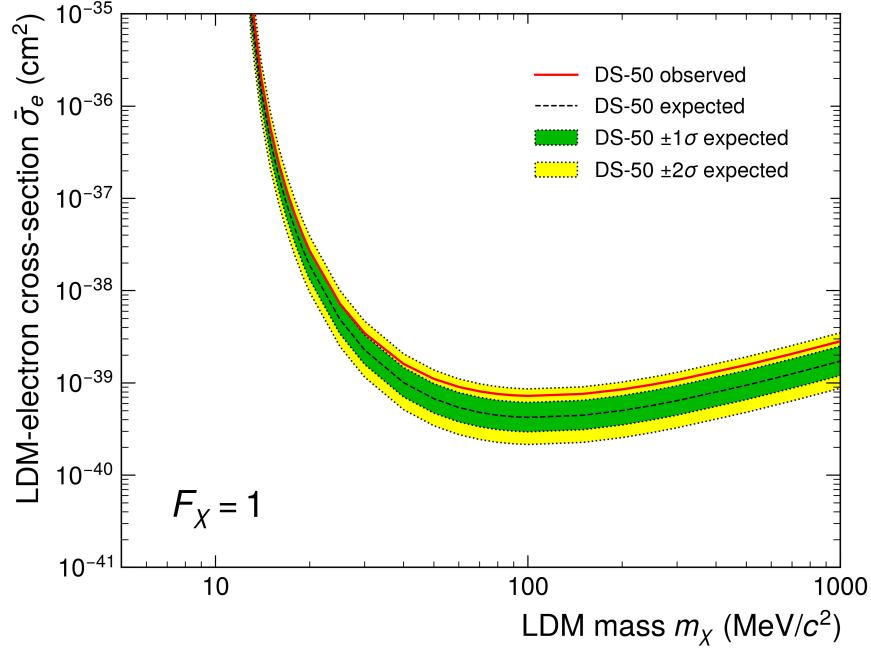
If one finds $p_{\mu} < 0.1$, then the tested value of μ is excluded at 90% confidence level (CL), the typical level quoted for direct DM searches [69]. A scan over μ values is performed to find $\mu_{\text{up, obs}}$, the value of μ that is excluded at the desired CL. We repeat the p -value calculation above to quantify the expected sensitivity of an experiment to a given signal by using the expected test statistic values $\tilde{q}_{\mu, \text{exp}}^{\sigma=0, \pm 1, \pm 2}$ in place of $\tilde{q}_{\mu, \text{obs}}$ in Equation (3.38), giving $\mu_{\text{up, exp}}^{\sigma=0, \pm 1, \pm 2}$. These expected limits form the ‘‘Brazilian bands.’’

To address the issue of exclusion claims resulting from statistical fluctuations, the CL_s method is used [118, 119]. This technique corrects the p -value by the discovery probability, ensuring that the experiment has sufficient sensitivity to the signal:

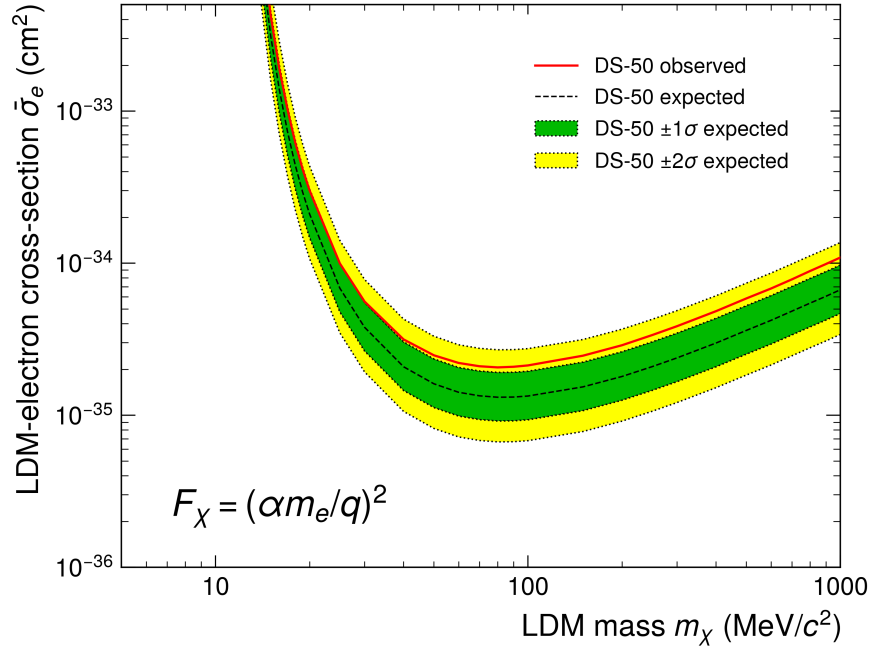
$$\text{CL}_s = \frac{p_{\mu}}{1 - p_0} \quad (3.39)$$

where p_0 is the p -value calculated using the test statistic pdf generated under the background-only hypothesis. This approach is conservative, and generally, the frequentist coverage probability of the CL_s upper limits is larger than the nominal 90% CL.

Results Following the procedure above, the DS-50 90% CLs are calculated and shown in Figure 3.23 as a function of DM mass, alongside the expected limits. The Brazilian bands are shown in green and yellow.

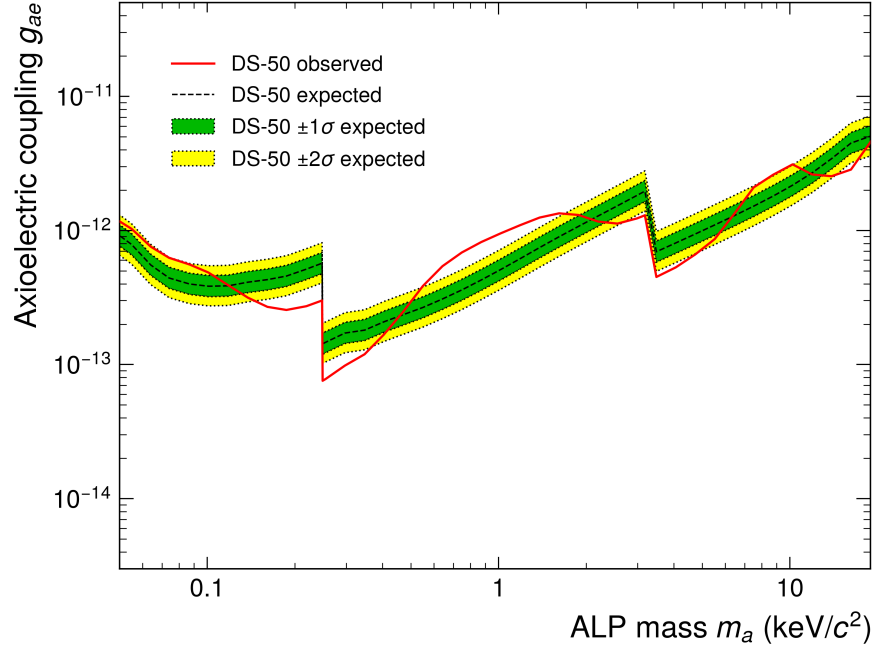


(a) DarkSide-50 90% CL on the LDM-electron scattering cross section, assuming a heavy mediator.

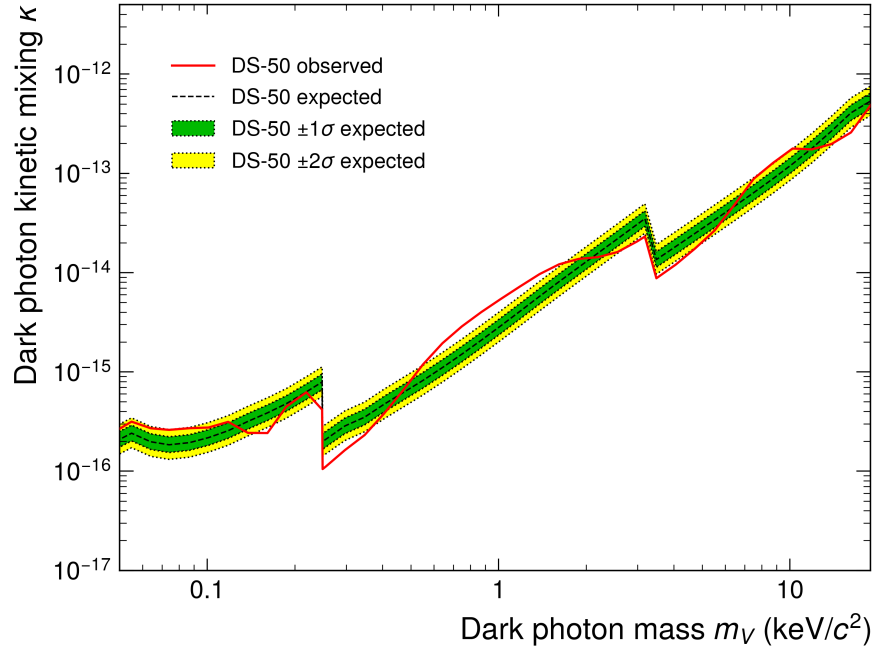


(b) DarkSide-50 90% CL on the LDM-electron scattering cross section, assuming a light mediator.

Figure 3.23: The 90% confidence level on leptophilic DM couplings set using DarkSide-50 data (solid red lines). The dashed black line is the median expected CL while the green and yellow bands are the $\pm 1\sigma$ and $\pm 2\sigma$ expected bands, respectively. The x-axis shows the mass of the candidate, while the y-axis shows the model parameter. This work.

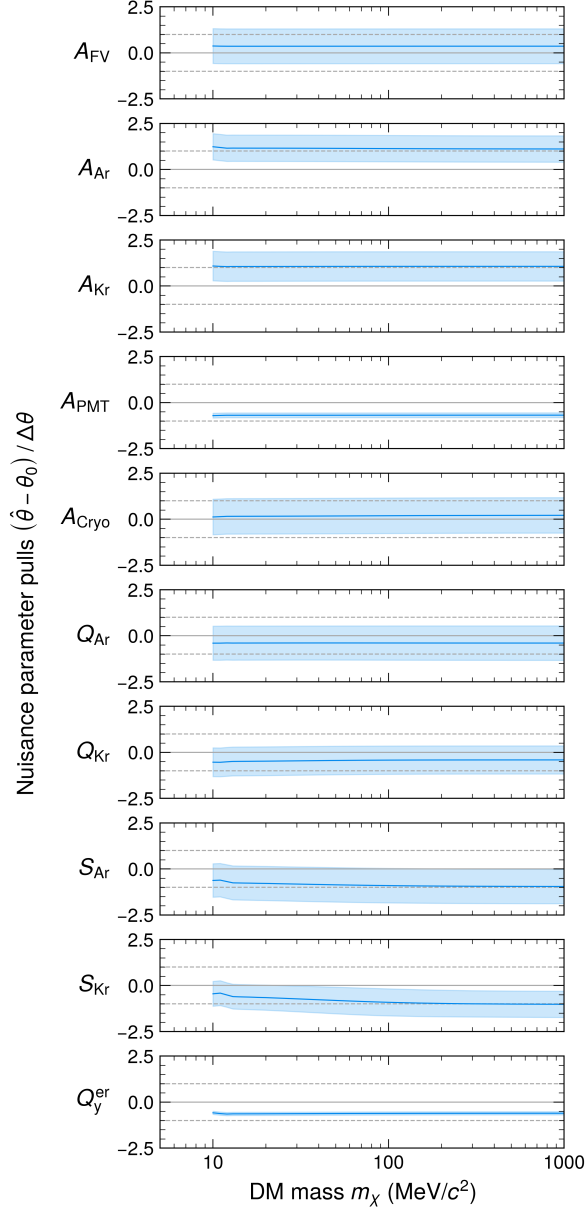


(c) DarkSide-50 90% CL on the galactic axion-like particle axioelectric coupling.

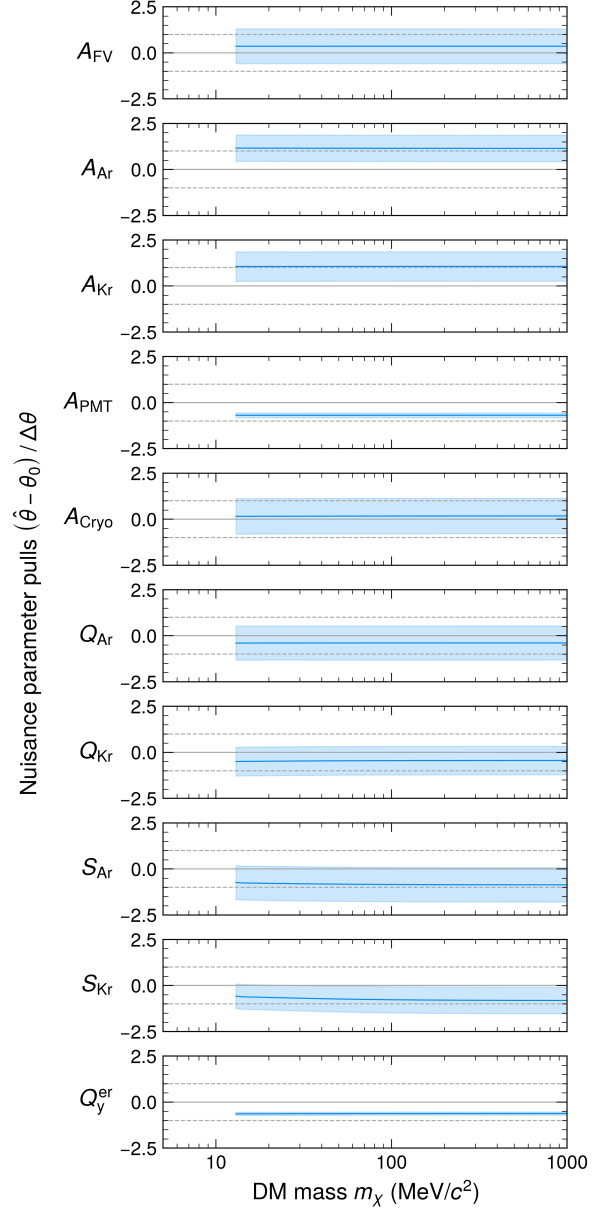


(d) DarkSide-50 90% CL on the dark photon kinetic mixing parameter.

Figure 3.23: The 90% confidence level on leptophilic DM couplings set using DarkSide-50 data (solid *red* lines). The dashed *black* line is the median expected CL while the *green* and *yellow* bands are the $\pm 1\sigma$ and $\pm 2\sigma$ expected bands, respectively. The x -axis shows the mass of the candidate, while the y -axis shows the model parameter. This work.

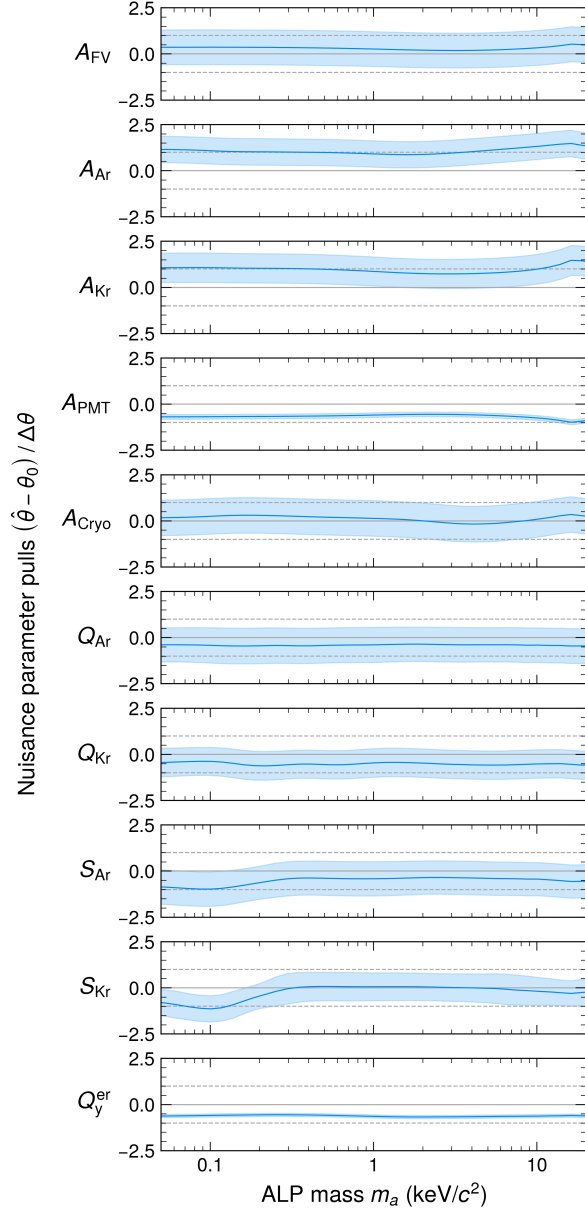


(a) Best-fit parameters for LDM-electron scattering, assuming a heavy mediator.

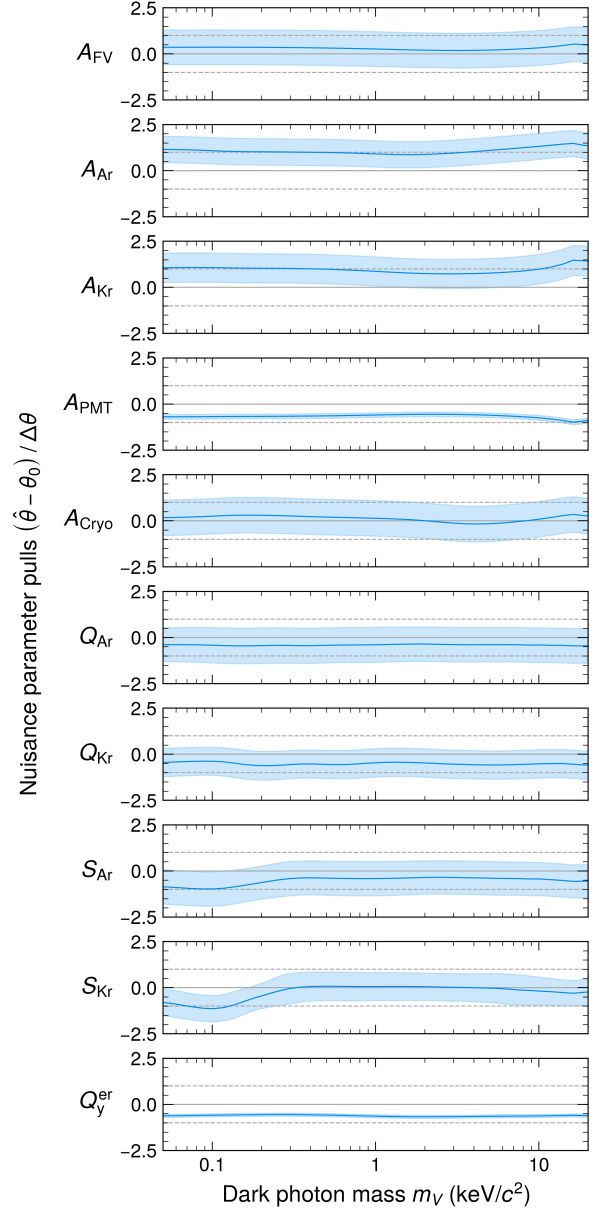


(b) Best-fit parameters for LDM-electron scattering, assuming a light mediator.

Figure 3.24: Best-fit nuisance parameter pulls as a function of DM mass. These values are $\hat{\theta}$, used in the denominator of Equation (3.36). Shaded regions show the post-fit error ($\Delta\hat{\theta}$) normalized to the pre-fit uncertainty ($\Delta\theta_0$). This work.

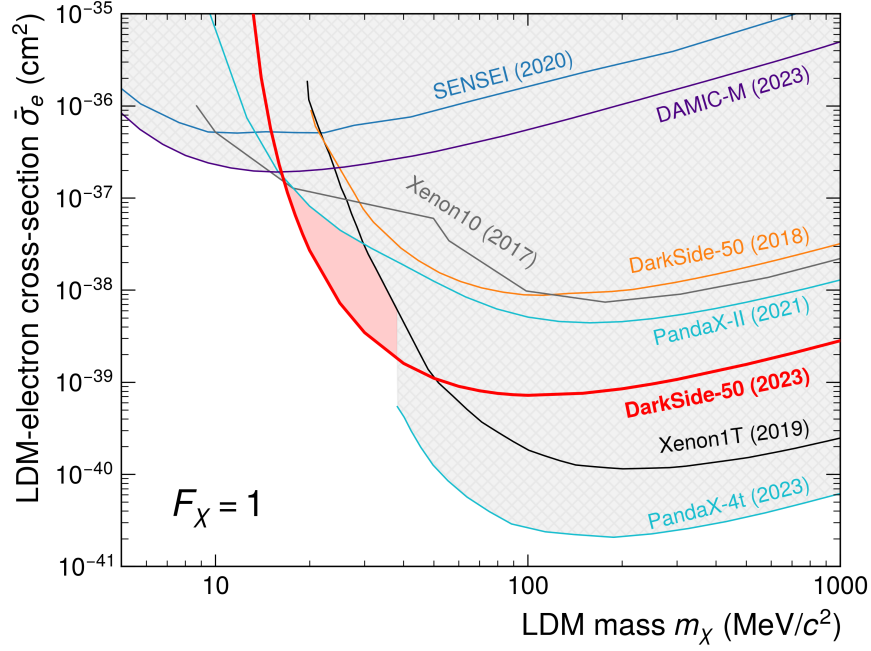


(c) Best-fit parameters for galactic axion-like particle absorption.

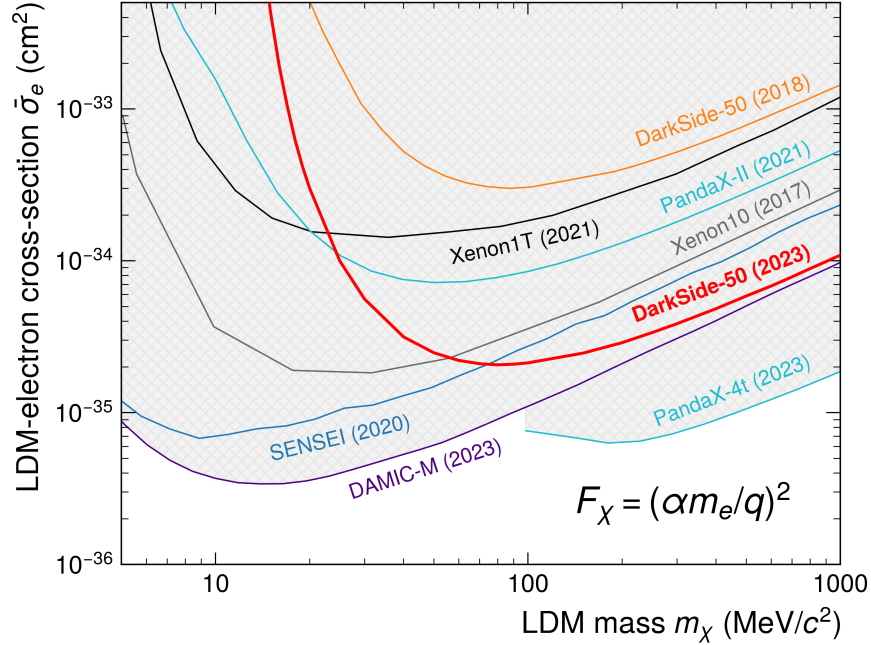


(d) Best-fit parameters for dark photon absorption.

Figure 3.24: (cont.) Best-fit nuisance parameter pulls as a function of DM mass. These values are $\hat{\theta}$, used in the denominator of Equation (3.36). Shaded regions show the post-fit error ($\Delta\hat{\theta}$) normalized to the pre-fit uncertainty ($\Delta\theta_0$). This work.

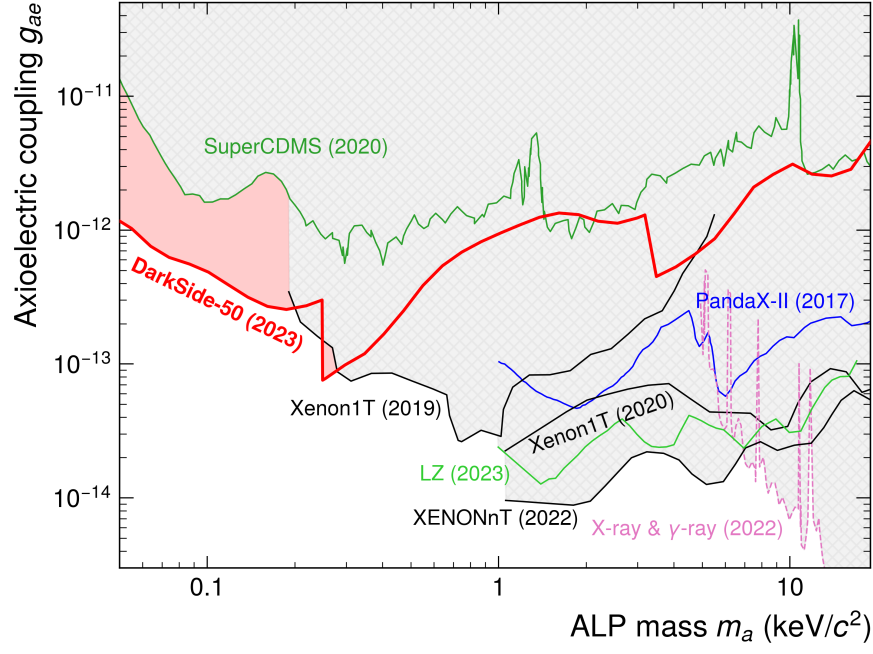


(a) DarkSide-50 90% CL on the LDM-electron scattering cross section, assuming a heavy mediator.

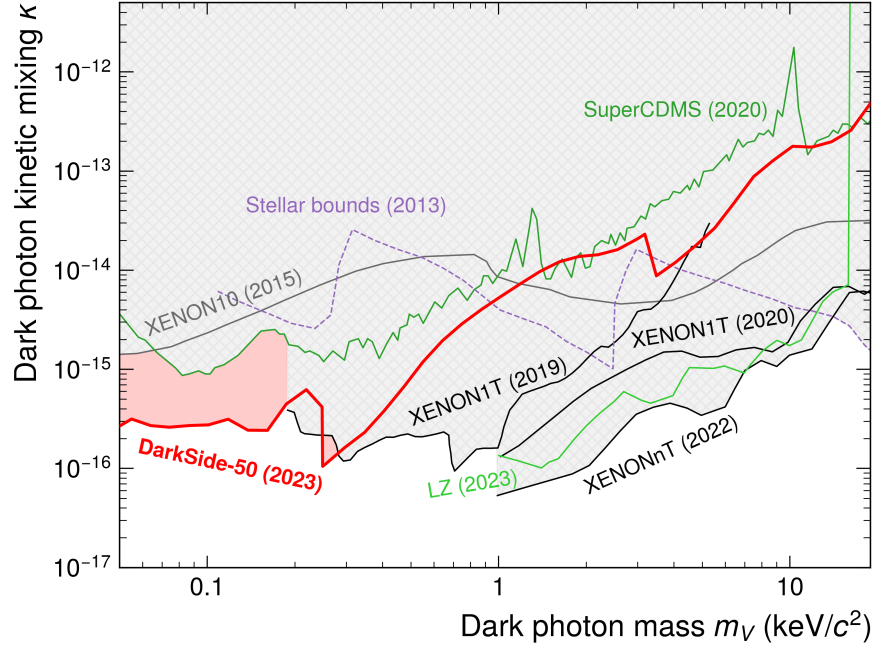


(b) DarkSide-50 90% CL on the LDM-electron scattering cross section, assuming a light mediator.

Figure 3.25: Exclusion limits at 90% CL on leptophilic DM couplings. Limits set by this work using DarkSide-50 data are plotted as *red* lines, with newly excluded parameter space shaded *red*. Selected limits from other laboratory experiments are solid lines, and previously excluded parameter space is shaded gray. These include DAMIC-M [61], DarkSide-50 [96], LZ [120], PandaX-II [106, 121], PandaX-4t [122], SENSEI [60], SuperCDMS Soudan [58], XENON-10 [24, 25, 103], XENON1T [110, 123], and XENONnT [64]. Astrophysical constraints are shown as dashed lines [24, 124]. All limits using the standard halo model are scaled to a local dark matter density ρ_χ of $0.3 \text{ GeV}/(c^2 \text{ cm}^3)$ if a different value was used. This work.



(c) DarkSide-50 90% CL on the galactic axion-like particle axioelectric coupling.



(d) DarkSide-50 90% CL on the dark photon kinetic mixing parameter.

Figure 3.25: (cont.) Exclusion limits at 90% CL on leptophilic DM couplings. Limits set by this work using DarkSide-50 data are plotted as *red* lines, with newly excluded parameter space shaded *red*. Selected limits from other laboratory experiments are solid lines, and previously excluded parameter space is shaded gray. These include DAMIC-M [61], DarkSide-50 [96], LZ [120], PandaX-II [106, 121], PandaX-4t [122], SENSEI [60], SuperCDMS Soudan [58], XENON-10 [24, 25, 103], XENON1T [110, 123], and XENONnT [64]. Astrophysical constraints are shown as dashed lines [24, 124]. All limits using the standard halo model are scaled to a local dark matter density ρ_χ of $0.3 \text{ GeV}/(c^2 \text{ cm}^3)$ if a different value was used. This work.

The observed limit, calculated using the CL_s method, is shown in *red*. Observed limits on the LDM-electron scattering cross section are consistently about 1σ weaker than expected. This results from a slight over-fluctuation of data in bins below $7 N_e$, which is also where the predicted signals are predominantly located. It is hypothesized that the over-fluctuations are due to spurious electrons that the `CXDeltaT` cut fails to remove. While a longer `CXDeltaT` cut could remove more spurious electrons, this would notably increase the dead time, resulting in a net loss of sensitivity.

Sharp discontinuities are present in both the expected and observed limits for galactic ALPs and DPs in Figure 3.23c and Figure 3.23d. These are located at the photoelectric cross section absorption edges, as discussed in Section 3.2.1. Variations in the observed limit about the expected limits are present for these signals, as compared to LDM-electron scattering. As both DP and ALP signals are monoenergetic, their limits are more sensitive to localized statistical fluctuations in the data. An under-fluctuation of data in several bins near the signal energy would lead to stronger constraints, while an over-fluctuation would give weaker limits. The CL_s method prevents exclusion claims in the case of under-fluctuations by ensuring the experiment has sufficient sensitivity to the signal [119]. No visible fluctuations in the observed limits with respect to mass are observed for LDM scattering, as the signals for the mass range considered are concentrated below $10 N_e$. Thus, the statistical fluctuations in data are not as noticeable for LDM limits as for ALPs and DPs, for which signals of different masses span a wide energy range.

The post-fit nuisance parameter pulls of the unconditionally maximized likelihood are shown in Figure 3.24 as a function of DM mass. These are the same quantities plotted in the left panel of Figure 3.22, namely the difference between the fitted ($\hat{\theta}$) and nominal (θ_0) values, normalized to the nominal uncertainty ($\Delta\theta$), except with μ left unconstrained as indicated by the differing symbol. The *blue* shaded regions extend to $\hat{\theta}/\Delta\theta_0$, which is the post-fit error normalized to the pre-fit uncertainty. For LDM-electron scattering, the post-fit values and errors are stable across the entire mass range considered. They are also consistent with the background-only fit results shown in Figure 3.22. Some minor fluctuations are present in the galactic ALPs and DPs best-fit parameters. As these signals are both monoenergetic, the fluctuations are likely due to localized statistical fluctuations in the DS-50 dataset, as mentioned above.

The DS-50 results are shown alongside results from other experiments in Figure 3.25. Notable improvements, specifically a factor of 10, are observed over the 2018 DS-50 results for LDM-electron scattering. This is due to a number of factors, including the improved correlated electron cut, the increased live time, and the improved background model. At the of publication of Ref. [97], world-leading constraints were set

in the range of $16 \text{ MeV}/c^2$ to $56 \text{ MeV}/c^2$ for a heavy mediator and from $80 \text{ MeV}/c^2$ to $1000 \text{ MeV}/c^2$ for a light mediator. In the time since then, results from PandaX-4t [122] and DAMIC-M [61] have further improved the constraints on $\bar{\sigma}_e$. Ref. [122] notes that PandaX-4t results for DM masses lower than $50 \text{ MeV}/c^2$ for the heavy mediator case and $100 \text{ MeV}/c^2$ for the light mediator are not published due to large charge yield uncertainties at low energies. The energy threshold for the DS-50 analysis ($0.03 \text{ keV}_{\text{er}}$) is lower than the PandaX-4t threshold ($0.07 \text{ keV}_{\text{er}}$), which is where a large portion of the LDM signal lies, particularly for the light mediator case.

As published in Ref. [97] and shown in Figure 3.25, world-leading constraints on the ALP axioelectric coupling and the DP kinetic mixing parameter are set from $0.03 \text{ keV}/c^2$ to $0.2 \text{ keV}/c^2$. Above this region, xenon dual-phase TPC experiments hold the strongest constraints [64, 123]. These exclusions of new parameter space demonstrate the strong potential of dual-phase TPC technology, with promising prospects for the future DS-20k detector.

Chapter 4

Reconstruction for DarkSide-20k

Scaling DarkSide-50 technology to DarkSide-20k involves an increase in active target mass by about three orders of magnitude, which poses numerous challenges. The data acquisition system must be able to handle the data rate from 2090 TPC photosensor channels. Offline reconstruction algorithms must deal with the increased data complexity due to the high rate of pile-up events. To enable the study of experiment design choices and their impact on the physics goals of DS-20k, I have led the development of an electronics simulation and data reconstruction framework for the DS-20k experiment. This framework will continue to be developed by the DS Offline Working group within the DS-20k data collection and analysis workflow.

This chapter presents my work developing this software tool called `dsreco`, and subsequently using it to design an event data model and optimize data reconstruction algorithms. I begin with an overview of data workflow in Section 4.1. This is followed by a description of the simulation and reconstruction framework in Section 4.2. Studies using MC data are presented in Section 4.3 and Section 4.4, which feed into the design of the event data model in Section 4.5.

4.1 Data processing overview

This section summarizes the baseline design of the DarkSide-20k data collection and analysis workflow. This is an evolving design; the information presented here may change as more rigorous studies are conducted.

The stages of collecting and processing TPC, IV, and OV photosensor data are broken into two categories: online and offline. These stages and their components are visualized for the TPC photodetectors in Figure 4.1. Online processing refers to the steps taken while the detector actively takes data, which include digitizing

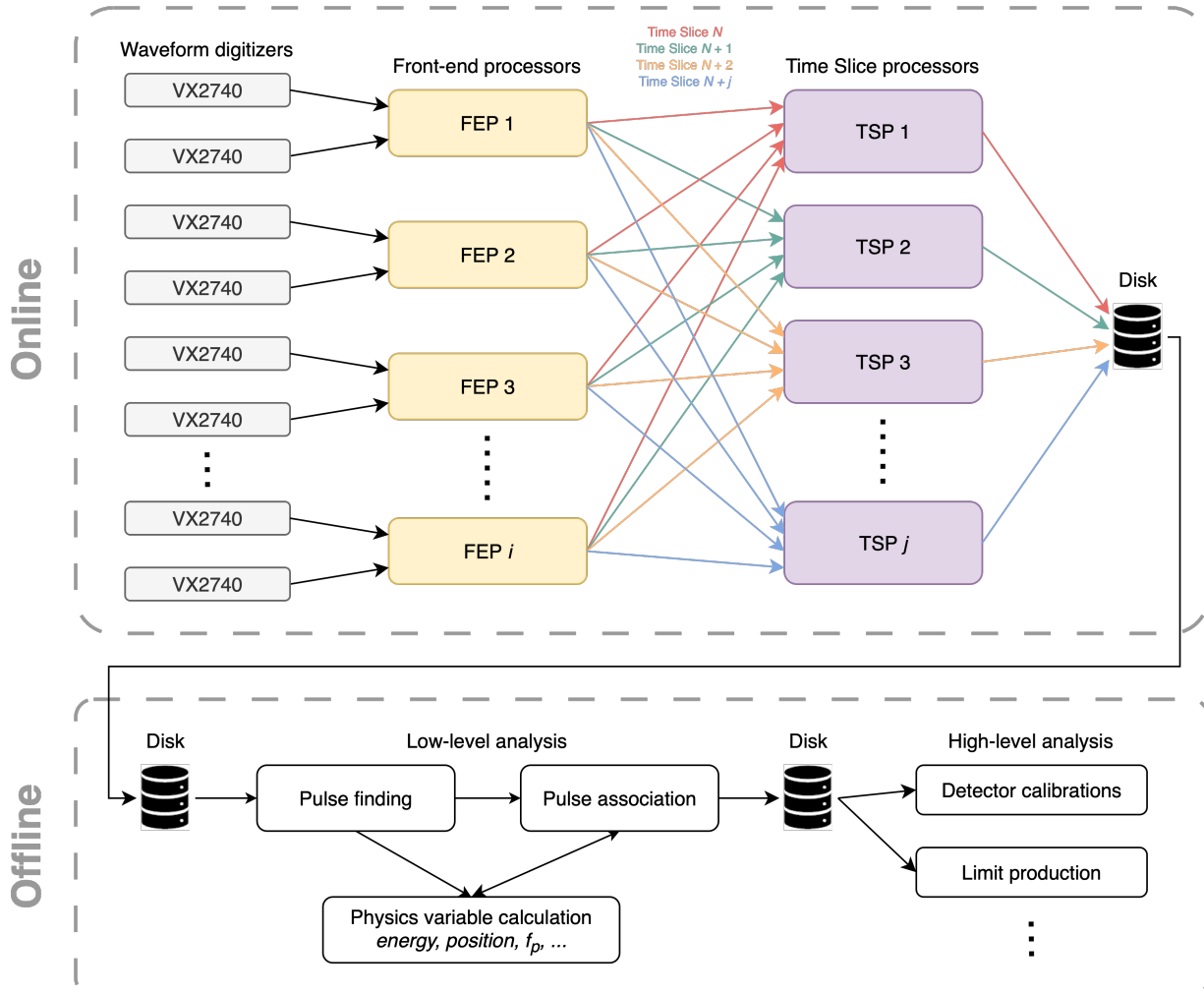


Figure 4.1: Steps in the DarkSide-20k online and offline processing workflows. See the text for more details. This work.

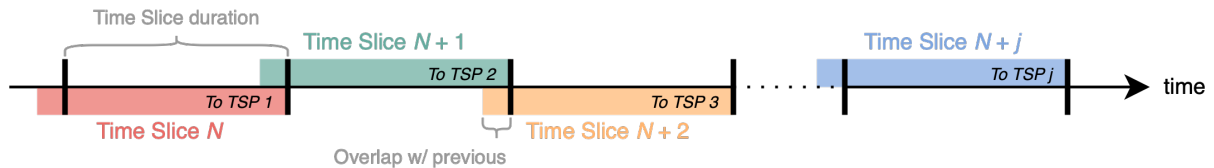


Figure 4.2: Time Slice scheme. Each colored rectangle corresponds to a time segment sent to a TSP. This work.

the WFs, reducing the data, and writing it to disk. Offline processing refers to the steps taken after data collection, such as pulse finding, pulse association, and reconstructing the physics variables of an interaction. The production of DM limits, as in Section 5.1, also falls into this category.

The requirements for online and offline processing are laid out in the DS-20k Technical Design Report [20] and a dedicated design study [125]. For operation in DM search mode, the goal is to limit the rate of data written to disk to 60 MB/s, driven primarily by the cost of disk storage and computing cluster resources. With this data rate, 2 PB/yr of disk storage will be required. The analysis time, defined as the time to go from the data written to disk to computing the ultimate physics results like DM search limits, for one year of data is limited to about 20 days. This is so the full 10 yr dataset can be analyzed within a reasonable time frame, namely six months, which is similar to experiments like XENONnT [54]. This plan will ensure that physics results can be obtained and published promptly.

4.1.1 Online processing

One of the upgrades from DS-50 to DS-20k is the switch from a *triggered* data acquisition (DAQ) mode to a *triggerless* mode. The DS-50 DAQ only recorded data when at least three TPC PMTs were above a 0.6 PE threshold within a 100 ns window [62]. In the triggerless mode of DS-20k, a continuous stream of signals from summed SiPM groups called PDMs are recorded, similar to what is currently used by the XENONnT experiment [126]. This provides a more complete picture of each event and allows for the adjustment of pulse finding and pulse matching algorithms after data collection. The triggerless mode of DAQ is particularly important for DS-20k given the high expected pile-up event rate, discussed in Section 4.5.

The upper panel of Figure 4.1 shows the online processing workflow. The zero length encoding (ZLE) firmware on the CAEN VX2740 digitizer boards produces dynamically-sized acquisition windows of WFs from TPC PDMs; this is described later in Section 4.2.2. These ZLE WF segments form the DS-20k data stream. Front-end processors (FEPs), shaded *yellow*, retrieve the WF segments from the digitizer boards and perform per-waveform operations. As described in Section 4.2.2, these algorithms act to reduce the raw WFs ADC counts for each ZLE segment into summary information, such as the number of hits and the total charge of the segment. The summary information is sorted into 1 s-long sections called Time Slices that are aligned in time across all FEPs [125]. A given Time Slice overlaps with the previous one by 5 ms, slightly longer than the full TPC drift time; this is depicted in Figure 4.2. The FEPs send the Time Slice data to a Time Slice Processor (TSP), shaded *purple*, which assembles the data and ensures that the total data rate to disk

remains within the target value. As mentioned above, the design requirement for the maximum data rate that can be written is 60 MB/s [20]. Data analysis tasks can also be performed in real-time by the TSPs to monitor detector performance and ensure data quality. TSPs run asynchronously with their outputs temporarily stored; the outputs are then combined in chronological order into a raw data file totaling about 10 GB, or 150 s of data, which gets written to disk in the format of the event data model (EDM), discussed in Section 4.5.

4.1.2 Offline processing

The offline processing workflow is developed with the goal of converting observable quantities into the physics variables of particle interactions in the TPC. These include deposited energy, position, and interaction type. The required precision of these variables is driven largely by the DM search energy ROI, the need to distinguish ER events from NR events (Section 4.4), and the definition of the fiducial volume.

To this end, offline processing starts from the reduced data written to disk at the end of the online processing stage, namely the hit and ZLE segment summary information. A visualization can be found in the lower panel of Figure 4.1. Hits must be grouped into pulses and identified as either S1 or S2 pulses based on their time structure. S1 and S2 pulses are then associated with one another to form events, and the physics variables are reconstructed; note that these two steps are interdependent.

4.1.3 dsreco

The `dsreco` Python package provides the tools to perform the offline workflow up to high-level analysis (e.g. DM limit calculation). This work is founded upon code developed for the DS-Proto0 experiment and for initial studies of DS-20k design. Modules within the package also provide tools to simulate the online workflow (`dselec`) so that hit finding and reconstruction algorithms can be tested on simulated data, see Section 4.2. Scalability and modularity are key design features of `dsreco`. The package is designed to have flexible entry points for the user to run the full offline workflow or only parts of it; an emphasis was placed on compatibility with Jupyter notebooks¹ to facilitate interactive data analysis. The package is also designed to be extensible so that trivial modifications can add new algorithms to the workflow.

The steps in the `dsreco` workflow are listed in Table 4.1. While this describes the simulation and analysis of MC data, real data can be fed directly into the “Reconstruction” section. To produce MC data, G4DS simulates particle interactions according to the background model described in Section 5.2. These interactions

¹<https://jupyter.org>

Section	Description	Output variables	Software tool
1. Background production	Particle track simulations	MC energy deposits	G4DS
	Background sources combined randomly	Time Slice of MC energy deposits	event_mixer
2. Scintillation light	Energy deposit clustering	MC energy deposits	event_mixer
	S1 optical simulation	MC PEs	G4DS
	S2 light maps	MC PEs	event_mixer
	Veto light maps	MC PEs	event_mixer
3. Photoelectronics and DAQ	Dark counts and correlated noise	MC PEs	dselec
	WF generation and noise simulation	MC WFs	dselec
	ZLE algorithm	MC WF segments	dselec
	Hit finding	Reconstructed PEs	dselec
4. Reconstruction	Pulse finding	S1 and S2 pulses	dsreco
	Pulse matching	Events, reconstructed energy, reconstructed z coordinate	dsreco
	(x, y) reconstruction	Reconstructed (x, y) coordinates	dsreco

Table 4.1: Simulation chain for producing fake data, followed by the data reconstruction chain.

are then combined according to each component’s activity to energy deposits within a Time Slice. Scintillation is then simulated either (a) optically via the propagation of individual photons or (b) effectively using light maps. Explicit photon propagation is necessary for S1, as PSD is sensitive to minor variations in time structure. The output of this step is MC PEs, which are fed into the photoelectronics simulation, described in the next section. The output of the third portion of Table 4.1 matches the format written to disk at the end of the online processing workflow, namely the EDM. Lastly, `dsreco` contains tools to extract the high-level physics variables from the data written to disk online. These operations can be performed interchangeably on MC and real data. They include the identification of S1 and S2 pulses, the association of pulses to form an event, the reconstruction of the event position, and the measurement of the event energy.

Parameter	Value
PDM rising time scale (τ_R)	83 ns [127]
PDM recovery time scale (τ_L)	300 ns [127]
Single PE amplitude (A_{SPE})	7 mV at 7 VOV [127]
PDM saturation voltage	−1650 mV
PDM dark count rate (DCR)	200/s
Afterpulse (AP) probability	5%
Afterpulse (AP) time scale	1 μ s
Direct crosstalk (DiCT) probability	3%
Digitizer ADC resolution	16 bit
Digitizer sampling frequency	125 MHz
Digitizer dynamic range	2000 mVpp
Digitizer offset	−900 mV

Table 4.2: Electronics and DAQ simulation parameters used in `dsreco`.

4.2 Photoelectronics and DAQ emulation

The `dselec` submodule of `dsreco` contains tools for simulating the PDM and DAQ responses. Relevant input parameters for the simulation are listed in Table 4.2; these are either baseline requirements for DS-20k established in the Technical Design Report [20] or measured values from PDM prototypes. The input to this simulation is MC truth PE hit times and channel numbers for a Time Slice, which can come from optical G4DS simulations or toy simulations that sample light maps. The stages described in this section are the photoelectronics simulation which converts incident photons into simulated PDM waveforms, the ZLE algorithm which locates significant regions in the waveforms, and the hit finder which identifies PEs in the ZLE segments. Given the processing time requirements of detailed electronics simulation, effective descriptions for these stages are also implemented.

4.2.1 Photoelectronics simulation

A DS-20k PDM is an array of SiPMs assembled into a tile and coupled to an amplifier. Each SiPM is a summed array of microcells operated in Geiger mode; a photon absorbed by a microcell creates an avalanche [128]. The photodetection efficiency (PDE) of a SiPM is the combined probability of a photon being absorbed in the active region and the subsequent triggering of an avalanche; this is a function of overvoltage and incident photon wavelength. The PDE measured for the DS-20k SiPMs is implemented in G4DS. In addition to PEs detected from external sources, several sources of noise PEs can be generated. These can be uncorrelated

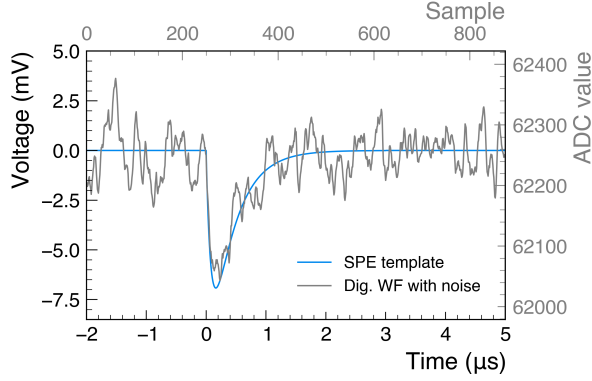


Figure 4.3: Simulated DS-20k PDM signal for a single PE (gray) alongside the input signal template (blue) of Equation (4.1). The simulated signal is shown after the addition of electronic noise and digitization. Input parameters are taken from Table 4.2. This work.

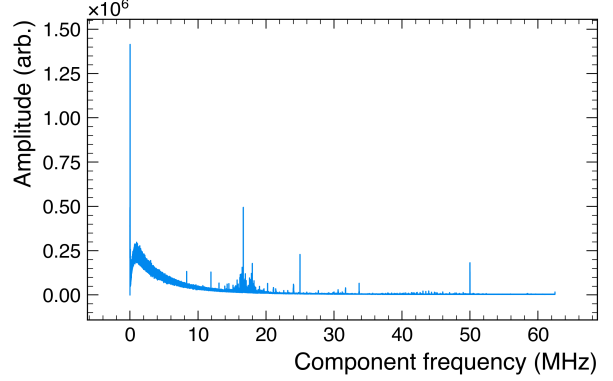


Figure 4.4: Discrete Fourier power spectrum for a prototype PDM. Data provided by the DS Photoelectronics working group.

(dark counts) or correlated (afterpulsing, direct crosstalk).

Dark counts Thermal agitation in SiPM microcells can produce avalanches that mimic the detection of real photons, producing signals known as dark counts. The PDMs developed by the DS-20k collaboration have a DCR of $<0.01 \text{ Hz/mm}^2$ at 7 VOV [20], which meet the baseline requirements set to minimize DCR effects on S1 PSD capabilities and trigger efficiency. In dsreco, DCR generation is simulated by generating PEs randomly across all channels according to the measured DCR.

Afterpulsing Trapping of charge carriers by impurities during the avalanche process can result in delayed avalanches, known as afterpulses. Afterpulses are correlated in time with the primary avalanche, occurring with varying delays. Measurements of the DS-20k SiPM afterpulsing probability and time constants performed by collaborators in Naples, IT [127] are implemented in dsreco to simulate this effect for each PE.

Direct crosstalk Optically-induced afterpulsing can also occur in SiPMs. This process, known as direct crosstalk (DiCT), occurs when a photon emitted during the primary avalanche triggers a simultaneous avalanche in a neighboring microcell the same way an incident photon would. The measured DiCT probabilities are implemented in dsreco to simulate this effect for each PE.

Signal template After simulating correlated noises for all PEs, the PDM signal is constructed by convolving the PDM time response with the PE arrival times. The equivalent circuit for a SiPM is discussed in Ref. [129, 130]. The resulting signal is a linear combination of a slow and fast pulse with a common rising edge.

Members of the DS Photoelectronics working group in Naples, Italy measured the time response of PDM prototypes using low-intensity laser pulses [127]. The measured voltage V as a function of time t is modeled as

$$V(t; t_0, \tau_R, \tau_L) = -A_{\text{SPE}} A_{\text{norm}} \left(e^{-\frac{t-t_0}{\tau_L+\tau_R}} - e^{-\frac{t-t_0}{\tau_R}} \right) \Theta(t - t_0) \quad (4.1)$$

where t_0 is the start time of the discharge, τ_R is the rising time scale, $(\tau_L + \tau_R)$ is the recovery time scale, A_{SPE} is the single PE amplitude, and Θ is the Heaviside step function. The term

$$A_{\text{norm}} = \tau_L^{-1} \tau_R^{-\tau_R/\tau_L} (\tau_L + \tau_R)^{(\tau_L+\tau_R)/\tau_L} \quad (4.2)$$

normalizes the sum of exponentials by amplitude. This template, with the measured values in Table 4.2, is shown by the blue line in Figure 4.3.

Realistic noise Next, electronic noise is added to the PDM signal. The discrete Fourier power spectrum shown in Figure 4.4 was measured for a PDM prototype. For each WF simulated, a random phase is added to each frequency bin in the spectrum and the components are summed, weighted by their amplitudes. The resulting signal is shown in gray in Figure 4.3 after digitization.

4.2.2 Photoelectron identification

To identify PEs in the PDM WFs, regions of interest are identified using a zero length encoding (ZLE) algorithm. As S1-based PSD requires precise reconstruction of PE times, a hit finding algorithm identifies and reconstructs individual PEs. These steps are performed online.

ZLE algorithm The custom zero length encoding (ZLE) algorithm loaded onto each digitizer's FPGA is designed to keep only significant pulses and regions around them [125]. Figure 4.5 shows a flowchart of this algorithm. A pre-trigger threshold, a post-trigger threshold, and a time-over-threshold requirement are used to define the significant regions that contain at least one PE. Pre-trigger and post-trigger windows are defined around each significant region to provide sufficient samples for baseline finding and signal filtering.

The plots in Figure 4.6 show examples of the ZLE algorithm applied to simulated PDM waveforms for several benchmark cases. For these examples, a value of $0.5 \times A_{\text{SPE}}$ was selected for the pre-trigger and post-trigger thresholds, which is ~ 3 times the noise root mean square (RMS). The required time-over-threshold is 144 ns, a third of the FWHM of the single PE template in Equation (4.1). This was chosen by a parameter

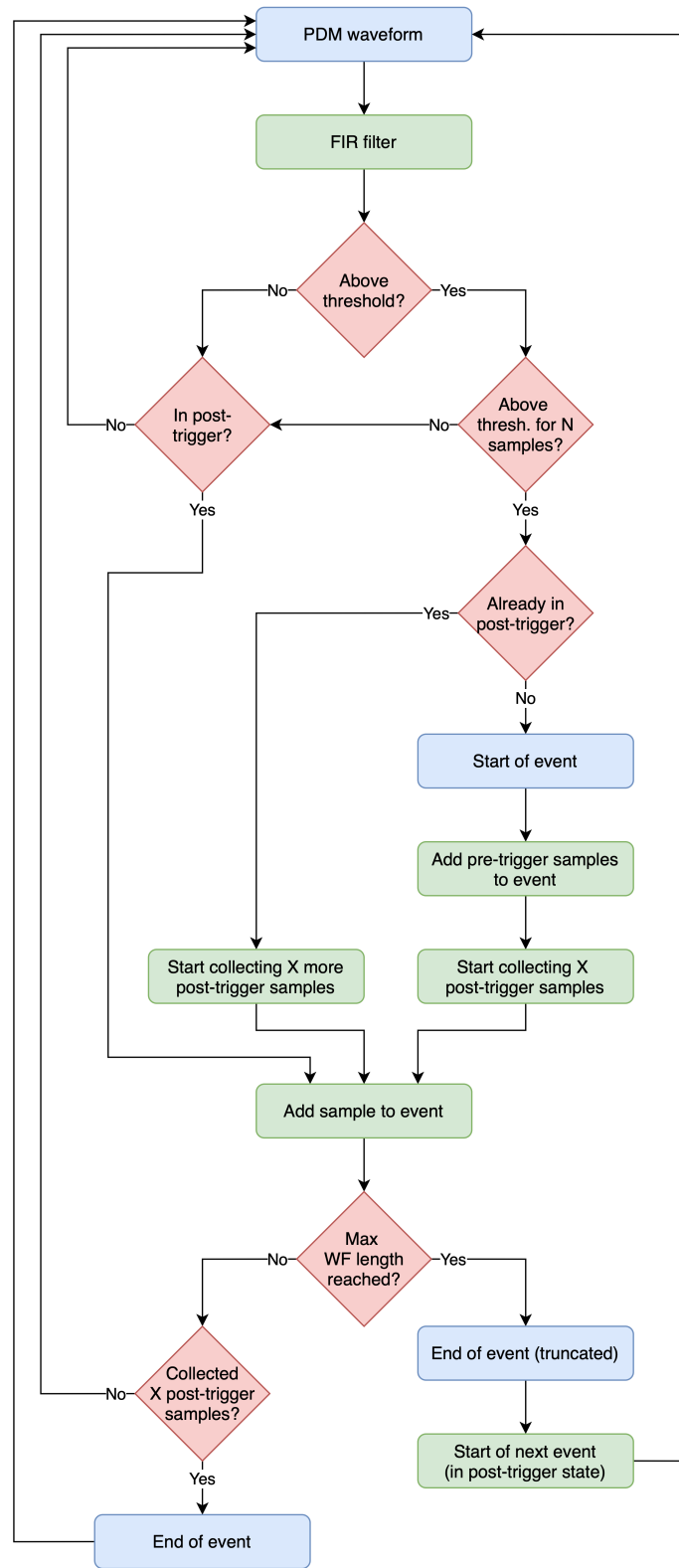


Figure 4.5: ZLE algorithm flowchart. Based on Ref. [125].

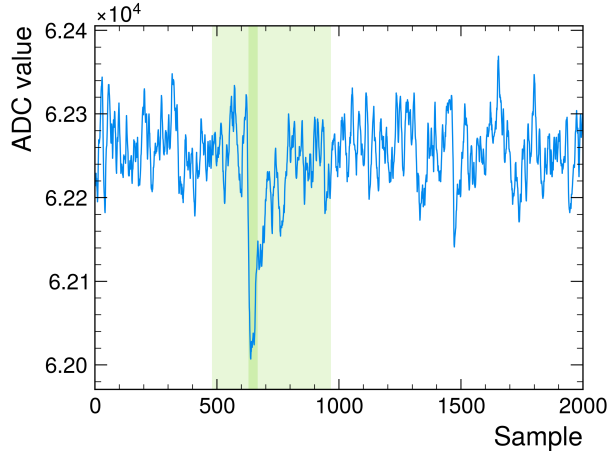
scan that maximized correct hit identification and minimized incorrect hits produced by noise. A pre-trigger window of $1.2\ \mu\text{s}$ and a post-trigger window of $2.4\ \mu\text{s}$ were selected to provide sufficient samples for baseline finding and hit finding.

With these parameters, we see in Figure 4.6a that a single PE, and the region around it, is correctly identified by the ZLE algorithm. In Figure 4.6b, two PEs are identified in separate WF segments, as they occur sufficiently far apart. When two PEs are detected close together, as depicted in Figure 4.6c, the ZLE algorithm identifies a single WF segment that contains both PEs. Finally, Figure 4.6d shows an example where a second PE with amplitude $0.4 \times A_{\text{SPE}}$ is too small to be identified as a significant region and is consequently ignored.

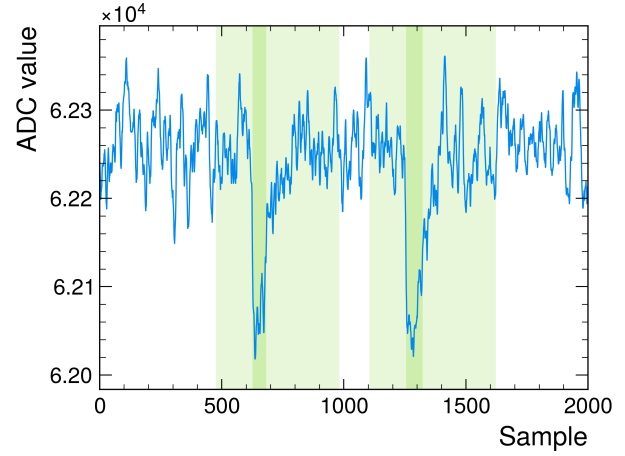
Using simulated waveforms, I studied the PE identification efficiency of the ZLE algorithm. I found that for single isolated PEs, the algorithm correctly identified the WF region more than 99.99% of the time. By simulating long WFs with only electronic noise, the ZLE algorithm produced noise-induced segments at a rate of 2.24×10^{-4} /s per channel.

Hit finding Operations to individual WFs are applied by the FEPs to reduce the amount of data passed to the TSPs and ultimately written to disk. First, the baseline of a WF segment is found by averaging the samples in the pre-trigger window. The baseline is subtracted from the WF segment, and the pulse is inverted to simplify analysis. Summary information, such as the integral of the WF segment, is calculated. A hit-finding algorithm is then applied to each WF segment to identify and reconstruct PEs. The steps are as follows:

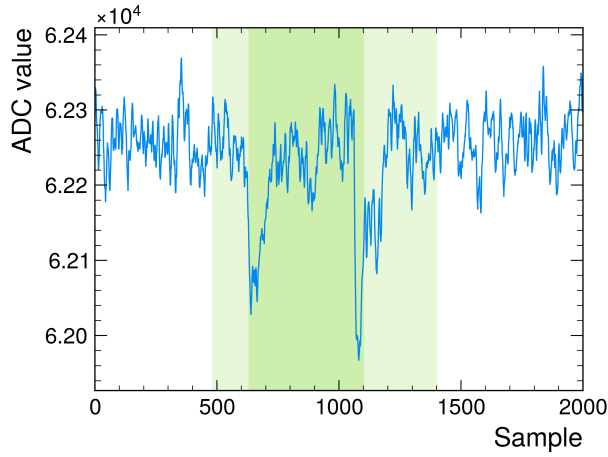
1. The raw WF segment, after baseline subtraction and inversion, is filtered using matched filtering with the PDM single PE template.
2. The moving average (MA) of the filtered WF is calculated to filter electronic noise.
3. The residuals, defined as the MA subtracted from filtered WF, are computed.
4. The RMS of the residuals in the pre-trigger region is calculated.
5. Regions of interest called “hits” are identified where residuals lie above 3 RMS.
6. The maximum (“prominence”) and integral of the residuals for each hit are calculated. The integral-to-prominence ratio is required to be above a given threshold to further reject accidental hits.



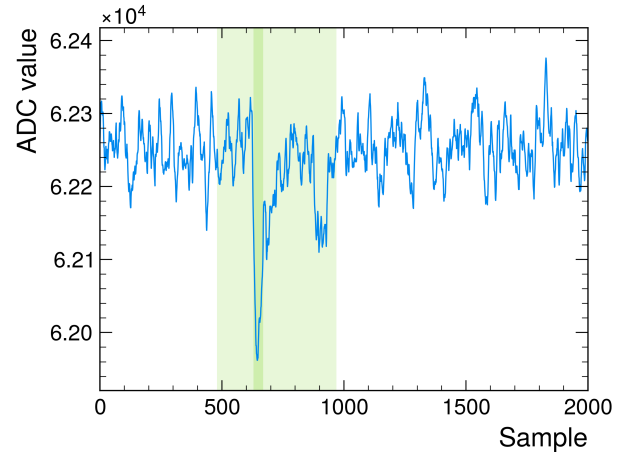
(a) A single PE is identified.



(b) Two PEs are identified in separate ZLE segments.

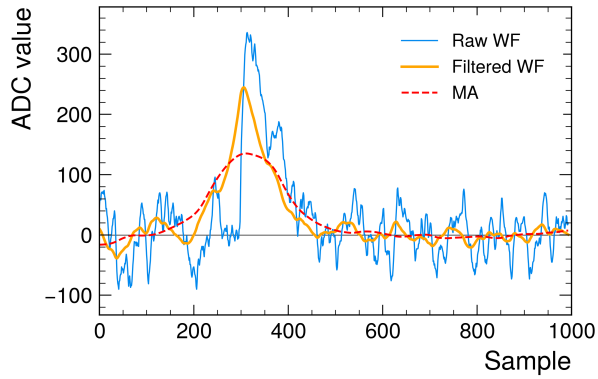


(c) A second PE is identified in the post-trigger region of the first PE, resulting in a single WF segments.

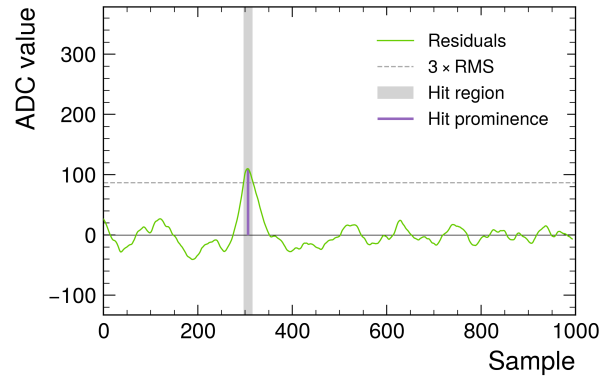


(d) A second PE with amplitude $0.4 \times A_{\text{SPE}}$ in the post-trigger region is too small to be identified as a significant region.

Figure 4.6: ZLE algorithm performance on simulated PDM waveforms. In the lower four plots, the *green* shaded region indicates a WF segment identified by the ZLE algorithm, with *light green* indicating the pre-trigger and post-trigger regions. This work.



(a) Steps 1 and 2 of the hit finding algorithm.



(b) Steps 3-6 of the hit finding algorithm.

Figure 4.7: Hit finding algorithm procedure. This work.

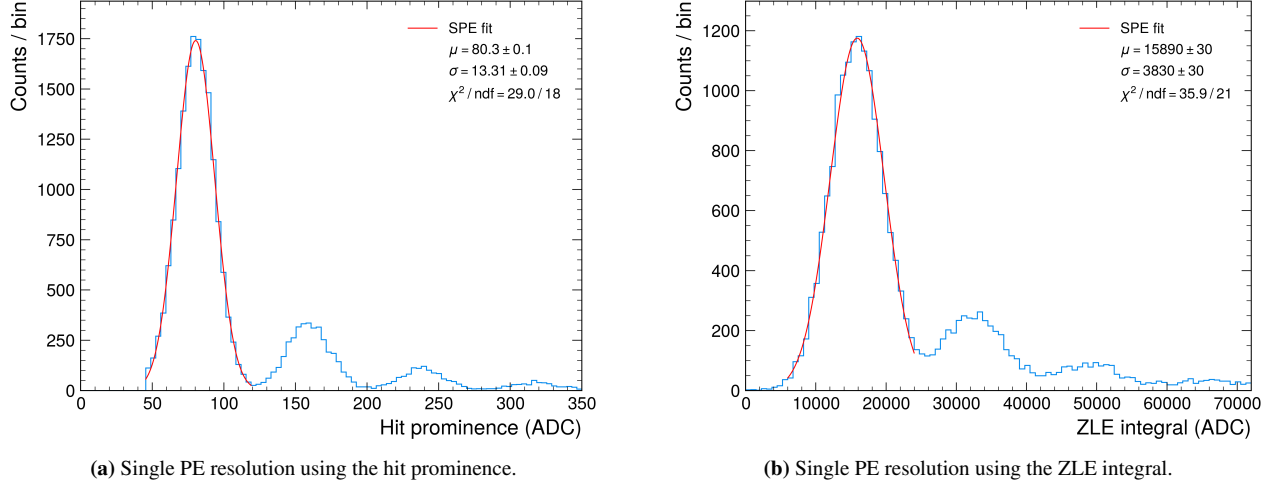


Figure 4.8: Projected resolution of DarkSide-20k to single photoelectrons using either hit prominence or ZLE integral. This work.

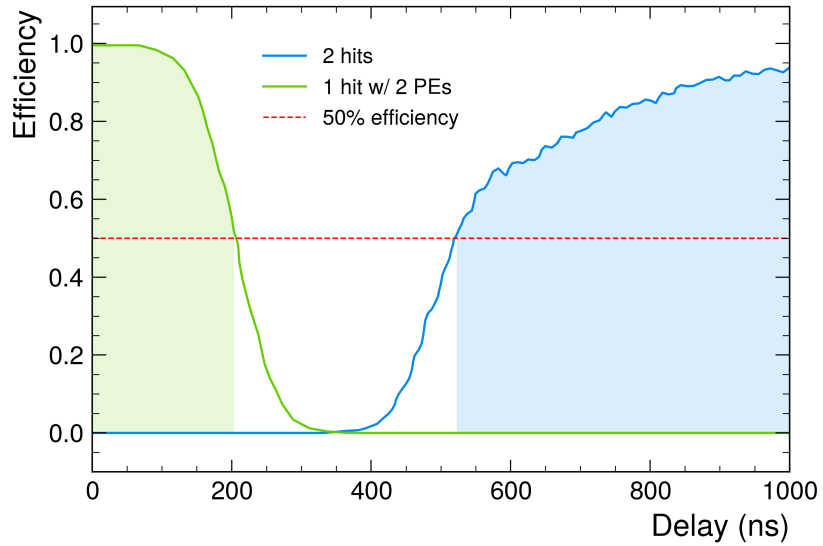


Figure 4.9: Hit finder efficiency in reconstructing two photoelectrons as a function of the delay between them. At low delay, one hit is identified with height and integral corresponding to two PEs (*green*). At a sufficiently large delay, two hits are identified (*blue*). This work.

The hit finding procedure is visualized in Figure 4.7. The free parameters used by this algorithm are the MA gate size, the RMS gate size, and the discrimination threshold. These parameters, as well as the algorithm itself, were optimized using data from the DarkSide-Proto0 (DS-Proto0) experiment, giving a time resolution of 7 ns, an efficiency of 97% for single PEs, and a fake hit rate of 5.5×10^{-4} /s per PDM [105].

4.3 Hit finder performance

The performance of the hit finding algorithm and its scalability from DS-Proto0 to DS-20k were evaluated using simulated PDM waveforms produced by dsreco. While the DS Offline working group has assessed a wide range of metrics [125, 131], this dissertation will highlight the single PE resolution and the reconstruction of multiple PEs in a WF segment.

4.3.1 Single PE resolution

The single PE gain is defined as the voltage or charge measured for the detection of a single PE. The spread about the mean gain is referred to as the single PE resolution. This is driven by properties both intrinsic and extrinsic to the photodetector: intrinsic effects include the charge amplification method, while an extrinsic example is the performance of signal processing algorithms. Precise knowledge of the single PE resolution is important for the calibration of the detector, as it is used to convert the measured charge to the number of PEs detected. In the context of DS-20k, this notably affects PSD and energy measurement.

As alluded to above, the single PE gain can be measured using the amplitude (voltage) or integral (charge) of the SiPM signal. In this dissertation, these two methods are referred to as the hit prominence and ZLE integral, respectively. I evaluated the performance of these two methods using simulated PDM waveforms produced by dsreco. Single primary PEs are generated, to which correlated noise PEs are subsequently added. The electronics simulation described in the previous section is then applied, along with ZLE segment identification. Hit finding is then performed on the ZLE segments to identify the PE hits.

The “finger plots” showing well-separated individual PE peaks are shown in Figure 4.8 for both gain measurement techniques. Each peak is fit to a Gaussian distribution to extract the mean and standard deviation. Fits for the single PE peak are shown in *red*, with the fit information listed in the legend. The hit prominence method is found to measure the single PE gain with a resolution of 16.5%, while the ZLE integral method has a resolution of 24.1%. The resolution of the latter method could be improved by filtering the baseline-subtracted ZLE segments to reduce the effects of electronic noise before performing the integral. Future work by the DarkSide collaboration will include tests of these methods on prototype PDM data.

4.3.2 Multiple PE separation

Another performance criterion of the hit finding algorithm is its ability to reconstruct multiple PEs in a single WF segment. This affects the reconstruction of dense PE clusters expected for S2 signals, particularly in PDMs directly above the interaction. Note that the two PEs occur in different microcells that are summed, not within the same microcell, as activated microcells have a recharge time. To evaluate the hit finding algorithm's ability to reconstruct multiple PEs, PDM waveforms with two PEs separated by a variable delay were simulated.

The results of this study are summarized in Figure 4.9. Two event classes are depicted: events in which the two hits are identified (*blue*) and events in which only one hit is identified (*green*). The plotted quantity, “efficiency”, is the number of events in each class normalized to the total number of events simulated. The maximum efficiency for detecting a single hit with two PEs (99.5%, leftmost point of the *green* line) is slightly higher than that of detecting a single hit with one PE (97%, not pictured). Furthermore, the efficiency for detecting two separate hits (93.8%, rightmost point of the *blue* line) is consistent with the combined probability of detecting two isolated 1 PE hits.

From 200 ns to 520 ns, the hit finder fails to identify the second PE in the WF segment with at least 50% efficiency. The observed output for this region is primarily a single hit with a height and integral corresponding to one PE. Selection cuts can compare the ZLE integral to the hit prominence to identify hits with large discrepancies for S1 signals; this work is under active study. However, even with additional cuts, the hit finder's performance is insufficient for reconstructing S2 signals, necessitating the use of ZLE integral information.

4.4 Energy reconstruction

Both S1 and S2 signals are used for energy reconstruction. They can be used separately, such as S1 in the high-mass analysis [16], S2 in the low-mass analysis in Chapter 3, or as a combined global energy estimator [71]. The required dynamic ranges to precisely measure S1 and S2 are notably different, as S2 pulses can be 10 to 100 times larger than S1 pulses.

Three methods of energy reconstruction for DS-20k are examined in both the S1 and S2 regimes: (1) the number of hits (N_{hits}), (2) the sum of hit prominences, and (3) the sum of ZLE integrals. The N_{hits} method is advantageous as it is unaffected by intrinsic charge or prominence resolutions. Furthermore, this variable is

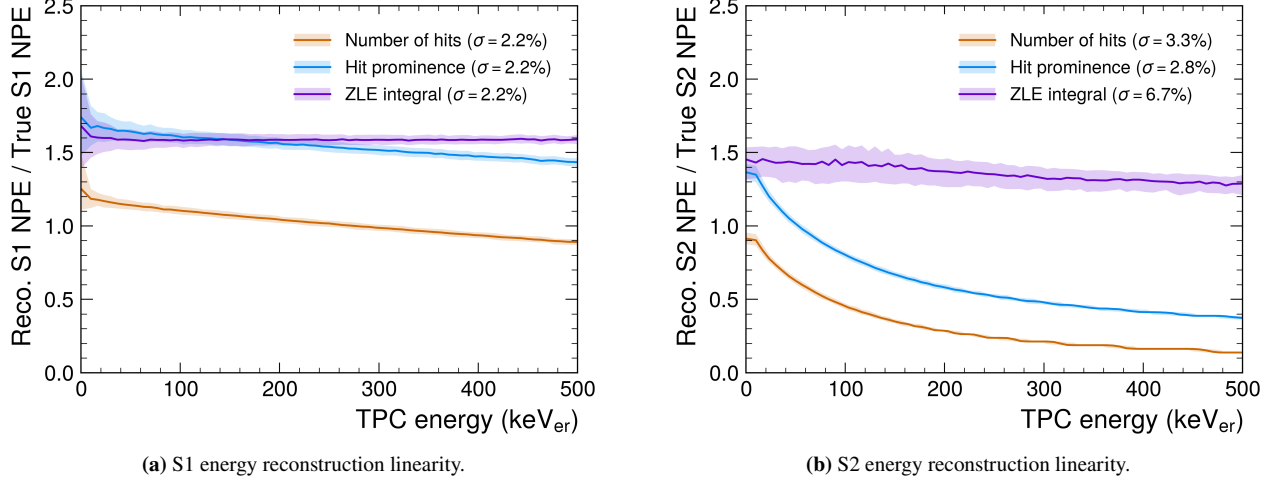


Figure 4.10: Simulated energy reconstruction linearity of DarkSide-20k. Shaded bands show the standard deviation. This work.

insensitive to correlated noise co-occurring with primary avalanches, like DiCT. As such, N_{hits} is promising for PSD by minimizing fluctuations arising from instrumental noise; however, discarding the prominence information may lead to saturation. The gain-corrected sum of hit prominences may be used to mitigate saturation effects of the N_{hits} method, but, as demonstrated in Section 4.3.2, the hit finder is inefficient for PEs occurring sequentially within 200 ns to 520 ns. The ZLE method is highly efficient, as described in Section 4.2.2, but the integral is susceptible to electronic noise and baseline fluctuations.

The performance of these methods is evaluated using simulated ^{39}Ar MC data produced by `dsreco`. This source is chosen as it will be the most frequently observed event in DS-20k and spans a wide range of energies. In particular, the spectrum extends well beyond the high-mass upper energy threshold of 60 keV_{er} , which is selected as it fully contains the signals from 10 TeV/c^2 mass WIMPs [131]. Primaries are generated at the TPC center to isolate the effects of energy reconstruction methods from position-based effects. For this study, all channels are simulated with the same gain: a channel-by-channel gain estimation will be required with real data. The results of this work are shown in Figure 4.10. The rightmost bound of both plots (500 keV_{er}) corresponds to about 10^3 PE for S1 and 10^5 PE for S2. For both pulses, the ratio of reconstructed PEs to the MC truth PEs is consistently larger than unity, as the MC truth PEs are counted before adding the DCR and correlated noise.

The hit prominence and ZLE methods are linear for S1 pulses with equivalent energy resolutions. Notably, the ZLE integral ratio is constant across S1 energies, meaning that the energy conversion is straightforward while an energy-dependent correction is required for prominence. The N_{hits} method is roughly a constant factor difference with respect to the hit prominence and better represents the MC truth PEs due to its insensitivity

to simultaneous correlated noise.

For S2 pulses, the ZLE integral is linear and possesses only a small slope. However, this method has a large standard deviation, indicating poorer energy resolution. The N_{hits} and prominence variables display high degrees of saturation throughout the entire energy range, as indicated by the curvature. Despite this, the energy resolution remains similar to that of S1 pulses of the same energy. In DS-50, S1 saturation was compensated for by using the slow component of the S1 pulse [132]; future work by the DS Online working group will investigate strategies such as this.

4.5 Event data model

The event data model (EDM) describes the data format that is written to disk for each Time Slice when the detector is running in DM search mode. Two constrasting objectives drive the design of the EDM: (1) to retain sensitivity to 1 PE signals and (2) to meet the required 60 MB/s data rate limit. A detailed discussion of the EDM requirements is given in Ref. [20, 131]. The currently proposed format is shown in Table 4.3, which is still under active study by the DS Offline working group [131]. Each Time Slice contains a header, a vector of ZLE segment summary information, vectors of TPC, IV, and OV hits, and vectors of compressed top and bottom TPC summed WFs. While the hits are stored in a flat structure, they can be re-associated with the ZLE segments in which they were found as the hit array is ordered first by ZLE segment index and then by sample within the ZLE segment. The ZLE segments are baseline-subtracted, summed over the top and bottom arrays, downsampled by a factor of 10, and then compressed to remove repeated zeroes in regions without ZLEs.

The hit timing and information is essential for PSD [131, 133]. As demonstrated in Section 4.3 and Section 4.4, the hit finder is inefficient at finding multiple PEs occurring within a short time window, and using hits for energy reconstruction of S2 signals can lead to saturation effects well below the PDM saturation level. As such, the ZLE segment summary information must be included to provide a more complete picture of regions with high PE densities and is important to tasks like S2 energy reconstruction. This approach notably improves the dynamic range of DS-20k. The storage of summed WFs from the top and bottom TPC arrays provides a crucial redundancy for scrutinizing outlier events, the necessity of which was seen in DS-50 for cases such as unresolved overlapping S1 and S2 signals [93].

Section	Variable	Type	Size (B)	Description
HEADER	id	int32	4	Time Slice ID within the run
	time	float32	4	Timestamp of the Time Slice relative to the run start
	n_zles	int32	4	Total number of ZLE segments found in TPC WFs
	n_zhits	int32	4	Total number of hits found across all ZLE segments in TPC WFs
	n_ivhits	int32	4	Total number of hits found in IV WFs
	n_ovhits	int32	4	Total number of hits found in OV WFs
	n_wf_top	int32	4	Length of the WFTOP array
	n_wf_bot	int32	4	Length of the WFBOT array
	mean_baseline	float32	4×2750	Average baseline throughout the Time Slice for each TPC channel
	rms_baseline	float32	4×2750	Baseline standard deviation throughout the Time Slice for each TPC channel
ZLE	channel	int16	$2 \times n_zles$	Channel ID of the ZLE hit
	t_diff	float32	$4 \times n_zles$	Timestamp of the ZLE segment relative to the Time Slice start time
	integral	float32	$4 \times n_zles$	Integral of the ZLE segment after baseline subtraction
	n_samples	int32	$4 \times n_zles$	Length of the ZLE segment in samples
	n_zhits_in_zle	int16	$2 \times n_zles$	Number of hits found in the ZLE segment
ZHIT	sample	int16	$2 \times n_zhits$	Sample index of the ZLE segment at which the hit maximum is found
	prominence	float32	$4 \times n_zhits$	Hit maximum
IVHIT	t_diff	float32	$4 \times n_ivhits$	Timestamp of the hit maximum relative to the Time Slice start
	prominence	float32	$4 \times n_ivhits$	Hit maximum
OVHIT	t_diff	float32	$4 \times n_ovhits$	Timestamp of the hit maximum relative to the Time Slice start
	prominence	float32	$4 \times n_ovhits$	Hit maximum
WFTOP	wf_top	float32	$4 \times n_wf_top$	Compressed sum of all TPC top channel ZLE segments
WFBOT	wf_bot	float32	$4 \times n_wf_bot$	Compressed sum of all TPC bottom channel ZLE segments

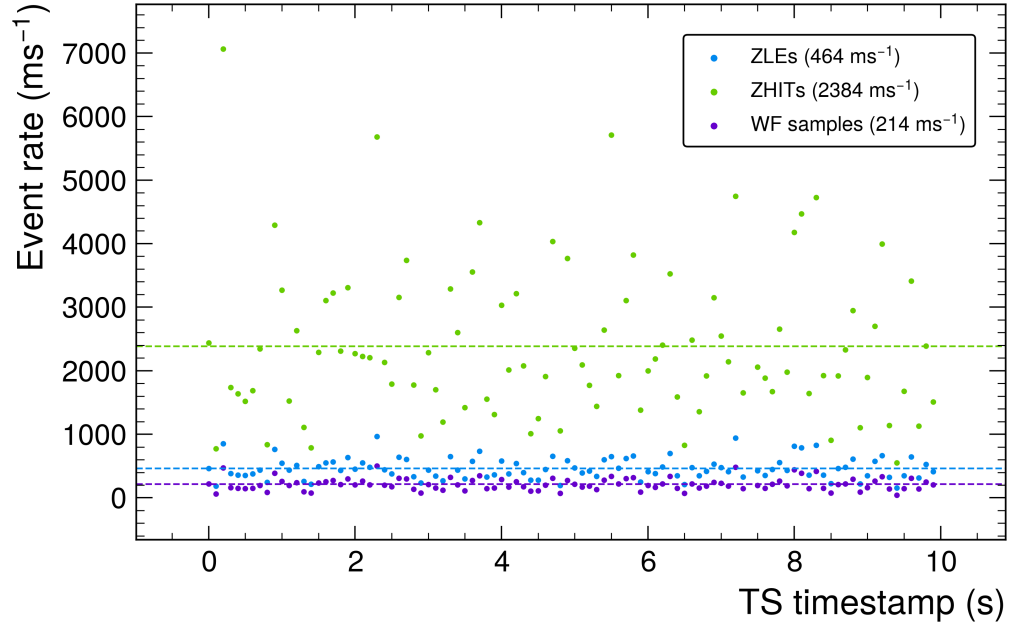
Table 4.3: Proposed data structure of a Time Slice. The precise definition of prominence is given in Section 4.2.2.

4.5.1 Projected data rate

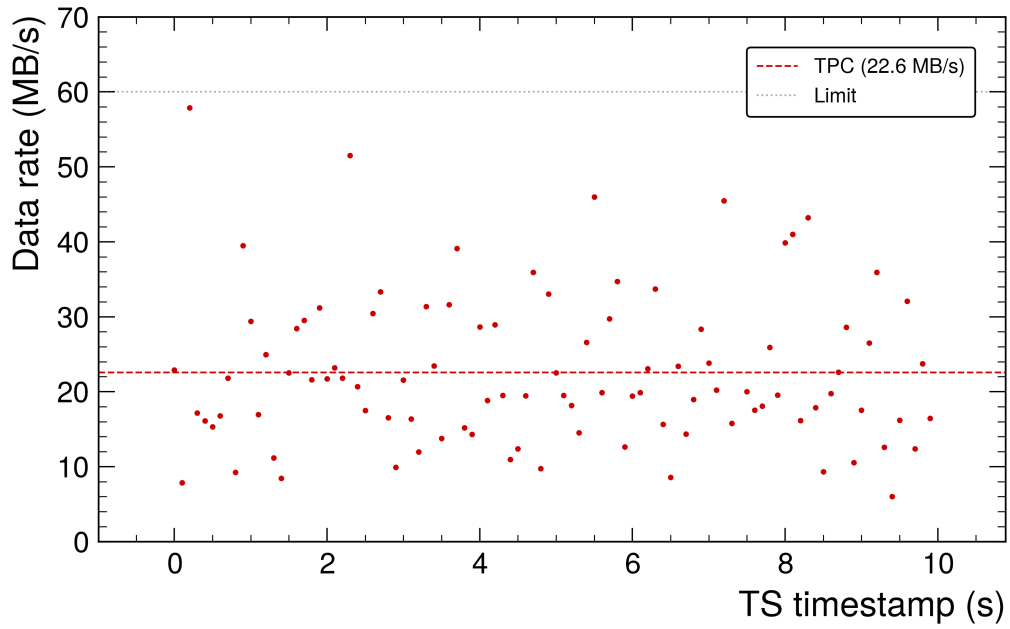
To evaluate the projected data rate for the EDM, I simulated 100 ms-long Time Slices according to the methodology described in Section 4.1.3. This work only examines the TPC contribution, as it is the most important component of the EDM in terms of the experiment’s physics goals; other work is ongoing to evaluate the IV and OV data rates [131].

The rates of each of TPC data structure for a simulated live time of 10 s are shown in Figure 4.11a. The ZHIT rate (*green*) is estimated to be 4.64×10^6 /s, leading to a data rate of 14.3 MB/s. The ZLE rate (*blue*) is much lower than the hits, but the data structure is a factor of five larger, leading to a data rate of 7.4 MB/s. These rate estimates are robust concerning the ZLE the specific ZLE algorithm parameters, as the segment length only affects the summed WF size for the EDM. The summed WFs (*purple*) are the smallest TPC contributor, with a data rate of 0.86 MB/s.

The sum of the TPC data rates is shown in Figure 4.11b by the *red* points, with an average of 22.6 MB/s and standard deviation of 10.1 MB/s. This does not include the 0.22 MB/s of data from the header, which is negligible in comparison. Upper fluctuations in the TPC data rate approach the 60 MB/s limit, but the average rate is well below this limit. A strategy is needed to further compress data for sufficiently large upward fluctuations in data rates, such as during supernova bursts [98]. One option is to omit ZHIT information for S2 pulses above a certain threshold, an approach that requires future study.



(a) Rate of ZLE segments, ZLEs hits, and number of samples in the summed WFs.



(b) TPC data rate.

Figure 4.11: Projected TPC data rate for DarkSide-20k from a full simulation of background events. See the text for more details. This work.

Chapter 5

DarkSide-20k low-mass sensitivity projections

The DarkSide-20k experiment is optimized to search for DM-nuclear interactions for DM masses in the $0.01 \text{ TeV}/c^2$ to $10 \text{ TeV}/c^2$ range. As demonstrated by DarkSide-50, the DarkSide-20k S2-only dataset can be used to search for leptophilic DM interactions. In addition to the large increase in target mass, the reduced background rate per unit fiducial mass over DS-50 will enable DS-20k to logarithmically probe parameter space for such DM candidates.

This chapter contains my work in evaluating the physics reach of DS-20k for leptophilic DM searches, following a similar order as Chapter 3. Section 5.1 describes the software tool used to calculate the detector sensitivity, for which I led the development. This is followed by the current estimates for the DS-20k background model, the response model, nuisance parameter definitions, and a background-only fit to the nominal model expectation values (Asimov dataset). Lastly, Section 5.6 contains the projected sensitivity of DS-20k to DM models that have interactions with final-state electrons.

5.1 Software tool

I led the development of the `pydslight` Python package, which calculates limits and sensitivity projections for the DS-50 and DS-20k low-mass searches. The previous collaboration software tool [105] developed for the original DS-50 low-mass search faced challenges in scalability and flexibility. Considering these challenges, the `pydslight` package has a modular design that enables the straightforward implementation of

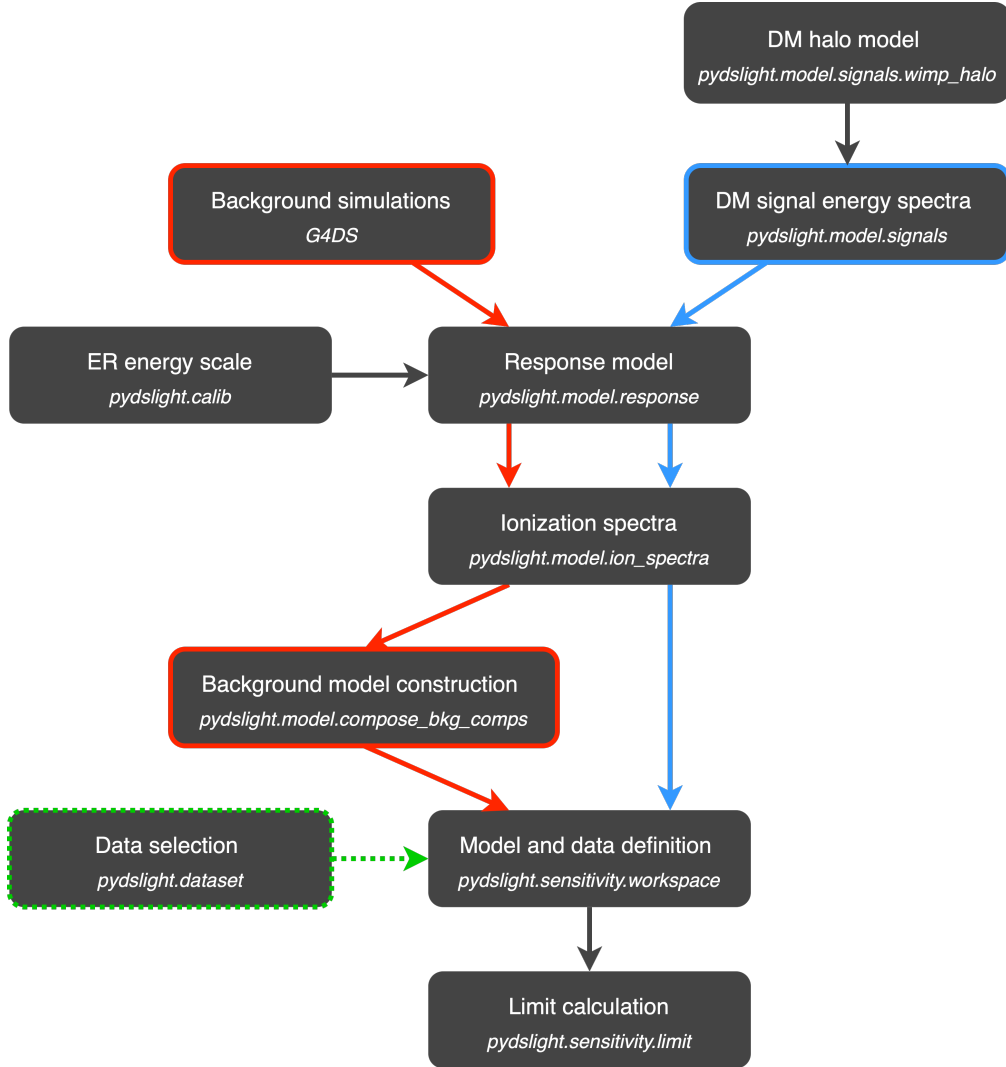


Figure 5.1: Workflow of limit production for the `pydslight` package. Steps in the production of background model ionization spectra are outlined in *red* while those for the DM signals are outlined in *blue*. Steps for the data analysis are outlined in *green*, with dotted lines indicating that it is optional. This work.

detector response models, DM signals, and background components. Some computations, such as the LDM-electron scattering signal computation, are computationally expensive. The Dask package [134] allows for scalable computations and interfaces with the collaboration’s computing grid. The overall workflow of the `pydslight` package is shown in Figure 5.1. While this section describes the workflow concisely, several Jupyter notebooks in the `pydslight` repository contain annotated examples.

Signal spectra Modules to calculate the predicted energy spectra for numerous DM models are implemented in the `pydslight` package, including the candidates detailed in Section 3.1, Section 3.2, and Section 3.3. As the majority of candidates implemented in `pydslight` are theorized to make up the Milky Way’s DM halo, a notable input to these modules is the DM velocity distribution described in Section 1.4. Once the energy spectra are calculated, they are translated to ionization spectra using the DM response model described in Section 5.3. While the response model could be implemented through template morphing, using MC is more straightforward. To cope with the increased statistics needed for DS-20k, MCs are broken into chunks and computed in parallel using Dask.

Background spectra The background model takes as input the DS-20k background screening table, shown in Table 5.1 and discussed in Section 5.2. For each source and location, primaries are generated in G4DS [86], producing a set of energy deposits. The detector response model is then applied on an event-by-event basis, as done for the signal spectra, resulting in ionization spectra normalized to the number of primaries simulated. These histograms are then scaled to the expected activity of each source as listed in Table 5.1 and combined by location.

Limit calculation The calculation of experiment sensitivities to different DM candidates is based on HistFactory [117]. Two different implementations are employed: an interface through PyROOT and a pure Python implementation using the `pyhf` package [135, 136]. The PyROOT implementation provides faster computations and backward compatibility with the previous collaboration software tool, while `pyhf` provides a more user-friendly interface and is more straightforward to extend and debug. Both implementations use the methodology described in Section 3.8 and have been validated against each other and the previous collaboration software tool.

Following the HistFactory convention, a workspace is constructed that contains the signal and background models, with an option to include an observed dataset. Text files are used to define these inputs along with the

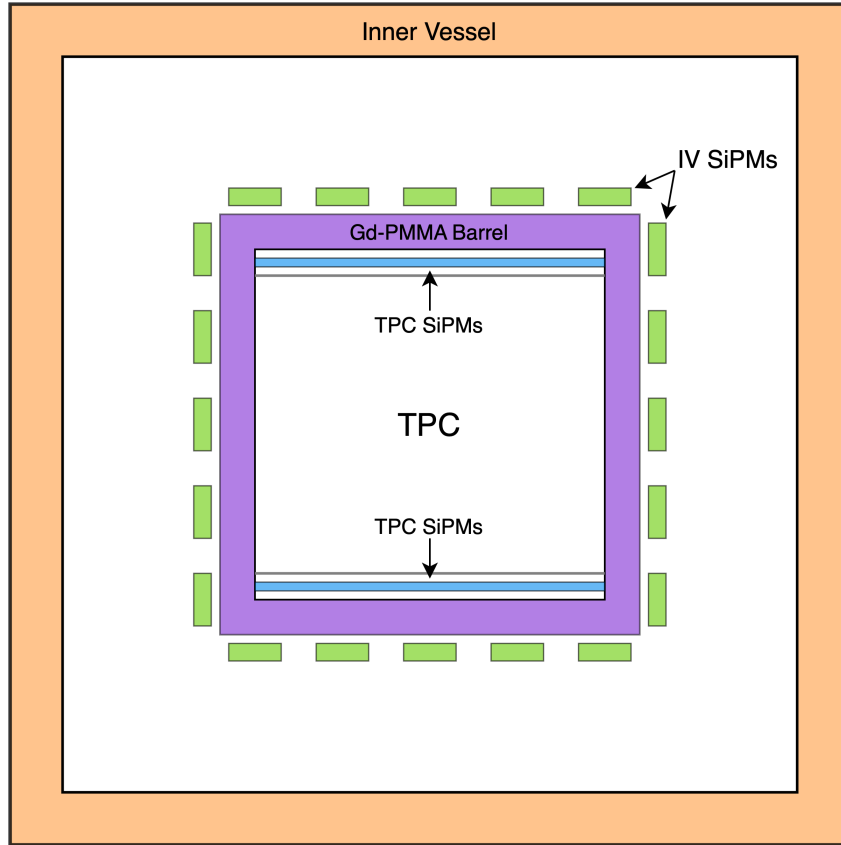


Figure 5.2: Diagram of the DarkSide-20k TPC and IV, highlighting notable background sources. This work.

systematic uncertainties to be included in the model. The user can select between sensitivity calculations to exclusion or discovery in the absence of a dataset or limit calculations for either case if a dataset is specified. Numerous tools for plotting and analyzing the results of the limit calculations are also provided.

5.2 Background model

The current estimates for the DS-20k background model are shown in Table 5.1. These sources and their respective activities are inputs from the DS Materials working group. These backgrounds originate from six locations, as shown in Figure 5.2.

5.2.1 Internal backgrounds

In DS-50, the ^{85}Kr activity was approximately 2.5 times higher than that of ^{39}Ar and was the dominant background below 2 keV_{er} in the low-mass search. For DS-20k, the new Urania plant located at the UAr

Source	TPC SiPMs (Bq)	IV SiPMs (Bq)	Gd-PMMA barrel (Bq)	Inner vessel (Bq)
^{232}Th	13	3.4	3.0	2.3
^{238}U up	48	0.86	3.5	13
^{238}U mid	14	3.7	14	0.74
^{238}U low	330	88	23	130
^{235}U	2.4	0.48	0.16	0.61
^{60}Co	1.1	0.25	2.8	0.16
^{40}K	170	200	57	0.44
^{137}Cs	0.81	0.21	2.9	0.33
^{46}Sc	–	–	–	26
^{176}Lu	–	–	0.26	–

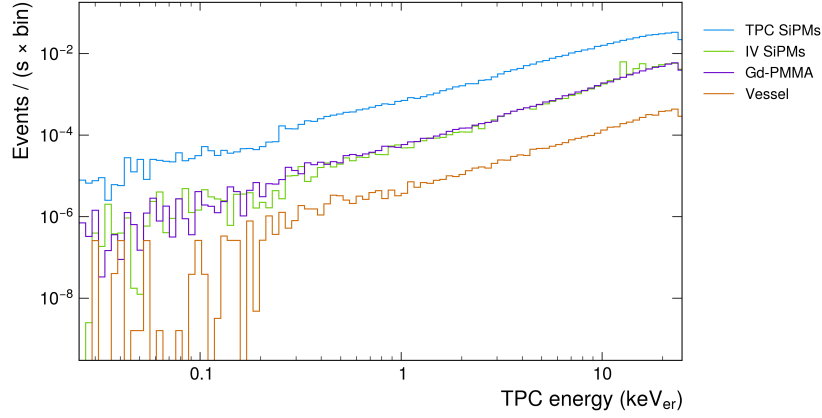
Table 5.1: DarkSide-20k projected background contributions. Activities are quoted for the decay chain progenitors. Data courtesy of the DS Materials working group.

extraction site in Cortez, CO will remove isotopic impurities, including ^{85}Kr , via cryogenic distillation. The output of this facility is 99.99% pure UAr, with a negligible level of ^{85}Kr [20]. Consequently, the ^{85}Kr activity in DS-20k is negligible and not considered in the sensitivity projections.

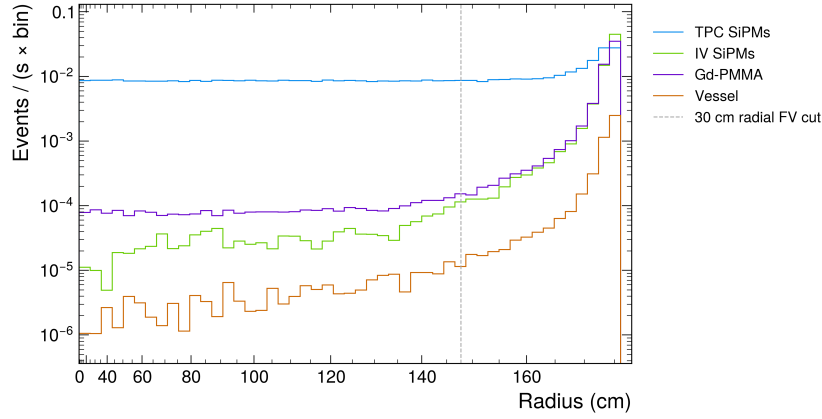
The ^{39}Ar activity in DS-50 was 0.730 mBq/kg, as described in Section 3.6.1. Extrapolating this to DS-20k gives an expected activity of 36.4 Bq, listed in Table 5.1. While this is the baseline requirement for DS-20k, the Aria facility in Sardinia, Italy will use a 350 m cryogenic distillation column to further suppress the ^{39}Ar activity by tenfold [20]. The impact of this reduction on the DS-20k sensitivity is explored later in this chapter.

5.2.2 External backgrounds

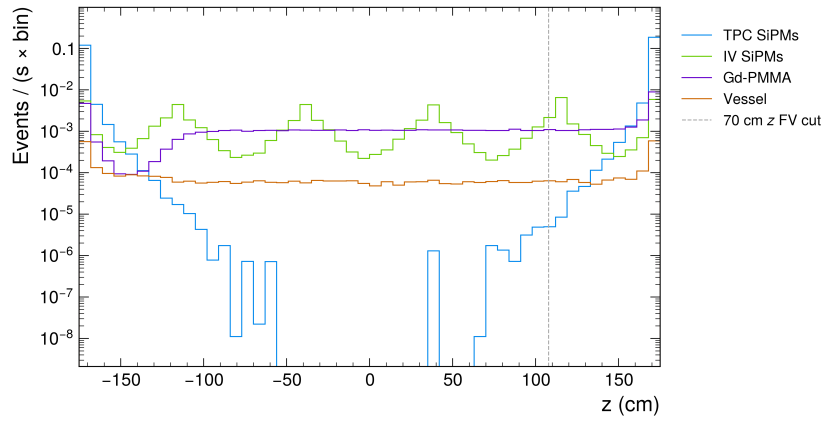
A simulation campaign using G4DS was conducted by the DS Offline working group to produce large-statistics samples (10^8 primaries) for each location and source. Dedicated spatial event generators were implemented in G4DS to generate uniformly distributed radioactive decays within the necessary materials and volumes. The event topologies of the single-scatter events in the TPC are visualized in Figure 5.3. The upper panel shows that the background components share similar energy spectrum shapes, which was also seen in DS-50 (see Section 3.6). This is expected as these interactions are mainly the low-energy region of Compton spectra of MeV-scale γ -rays from similar radioactive decays. Structure in the plot below $0.2 \text{ keV}_{\text{er}}$, particularly for the inner vessel, is due to a lack of MC statistics. Across the energy ROI, the background contribution from the TPC photodetectors (*blue*) is about an order of magnitude higher than IV photodetectors (*green*) and the



(a) Energy distribution.



(b) Position distribution along the radial axis.



(c) Position distribution along the z (drift) axis.

Figure 5.3: Energy and position distributions of simulated DarkSide-20k background single-scatter events in the low-mass energy ROI. Colors match the locations in Figure 5.2. Activities are taken from Table 5.1. The radial axis binning of the position distributions is chosen so that each bin covers an equal area in the (x, y) plane of the TPC. This work.

TPC barrel (*purple*). The inner vessel (*orange*) is another order of magnitude below these.

The radial profile of the external backgrounds in Figure 5.3b and the longitudinal profile in Figure 5.3c show that the majority of external background events occur near the TPC walls, anode, and cathode. In the z profile, the placement of the IV photodetectors on the lateral walls is visible in the structure of the *green* curve. While these backgrounds are already subdominant to ^{39}Ar , they can be further reduced via a fiducial volume (FV) cut. This cut removes events within a certain distance of the TPC edges, which are far more likely to be external backgrounds than signal events. A 30 cm radial FV cut, also used in the DS-20k high-mass analysis [20], removes 52% of single-scatter external background events; this cut location is shown by the dashed *gray* line. As the low-mass analysis includes S2-only events, the z position cannot be reconstructed precisely. However, due to the diffusion of electrons along the drift path, the S2 signal becomes spread out in time. This effect can be used to extract an approximate z position; this was first tested with DS-50 data [137] and is under active study by the collaboration. Sufficiently precise S2-based z position reconstruction would enable a further removal of external background events by 76.2% via a 70 cm longitudinal FV cut from both the anode and cathode.

5.3 Response model

The DS-20k response model is extrapolated from that of DS-50 described in Section 3.7. The DS Offline working group is actively studying the impact of these assumptions on the DS-20k sensitivity [138]. The conversion of energy to N_e is kept the same as DS-50, using the initial uncertainties on the ER energy as calculated in Section 3.4. The electron lifetime was also assumed to be the same. The single electron energy resolution is currently under study by the DS Offline working group. To perform initial assessments of the DS-20k sensitivity, the DS-50 value (27%) is assumed, see Section 3.7.2.

To implement the radial FV cut, MC (x, y) positions are smeared using a Gaussian pdf with a standard deviation of 1 cm, the value set as the DS-20k baseline requirement. While the resolution may depend on position, specifically worsening near detector edges, an assessment of this is left for future work. A 30 cm FV radial cut from the walls is applied, leading to an efficiency of 69%.

I assessed the inefficiency due to pile-up events using the MC dataset produced for the EDM, see Section 4.5. Within the 10 s simulated live time, I counted the fraction of S2 pulses with no other S2 pulse within 3.7 ms (the maximum drift time). This fraction, the efficiency due to pile-up events, was found to be 72%.

	Symbol	Description	Affected components
Amplitude	A_{FV}	Uncertainty on the fiducial volume, 1%	$b_{\text{Ar}}, b_{\text{Kr}}, b_{\text{PE}}, b_{\text{VPE}}, b_{\text{PMMA}}, b_{\text{Ves}}, s$
	A_{Ar}	10% uncertainty on ^{39}Ar activity	b_{Ar}
	A_{PE}	10% uncertainty on activity from the TPC SiPMs	b_{PE}
	A_{VPE}	10% uncertainty on activity from the IV SiPMs	b_{VPE}
	A_{PMMA}	10% uncertainty on activity from the Gd-PMMA	b_{PMMA}
	A_{Ves}	10% uncertainty on activity from the inner vessel	b_{Ves}
Shape	Q_{Ar}	1% uncertainty on the ^{39}Ar decay Q-value	b_{Ar}
	S_{Ar}	Uncertainty on atomic exchange and screening effects for ^{39}Ar β -decay	b_{Ar}
	Q_y^{er}	Uncertainty on ER energy scale	$b_{\text{Ar}}, b_{\text{Kr}}, b_{\text{PE}}, b_{\text{VPE}}, b_{\text{PMMA}}, b_{\text{Ves}}, s$

Table 5.2: Nuisance parameters, their sources, and impacted model components included in the binned profile likelihood for the DarkSide-20k low-mass analysis.

This is a conservative estimate, as it does not account for the ability to associate pulses within pile-up events using metrics like the S1 and S2 energy and S2 pulse width.

5.4 Nuisance parameters

As discussed in Section 3.8.2, nuisance parameters (θ) account for systematic uncertainties in the model; these are defined in Table 5.2 for the DS-20k low-mass analysis. The parameters A_{Ar} , Q_{Ar} , S_{Ar} , and Q_y^{er} are assumed to be the same as the pre-fit values in DS-50. Other nuisance parameters include A_{PE} , A_{VPE} , A_{PMMA} , and A_{Ves} , which are amplitude systematics on the TPC photoelectronics, IV photoelectronics, inner vessel, and Gd-PMMA barrel respectively that account for uncertainty in the radioactivity assay measurements. The fiducial volume uncertainty (A_{FV}) due to the shrinkage of the Gd-PMMA TPC walls is chosen to be similar to the value in DS-50.

5.5 Background-only fit

Well-behaved and stable fitting of the model to data is essential for robust sensitivity calculations and, ultimately, future limit calculations once the observed dataset is available. To assess these qualities, the DS-20k background model was fit to the Asimov dataset. The Asimov dataset, shown as *black* points in Figure 5.4, is defined as the model prediction evaluated at the nominal parameter values [116]. As we are performing a

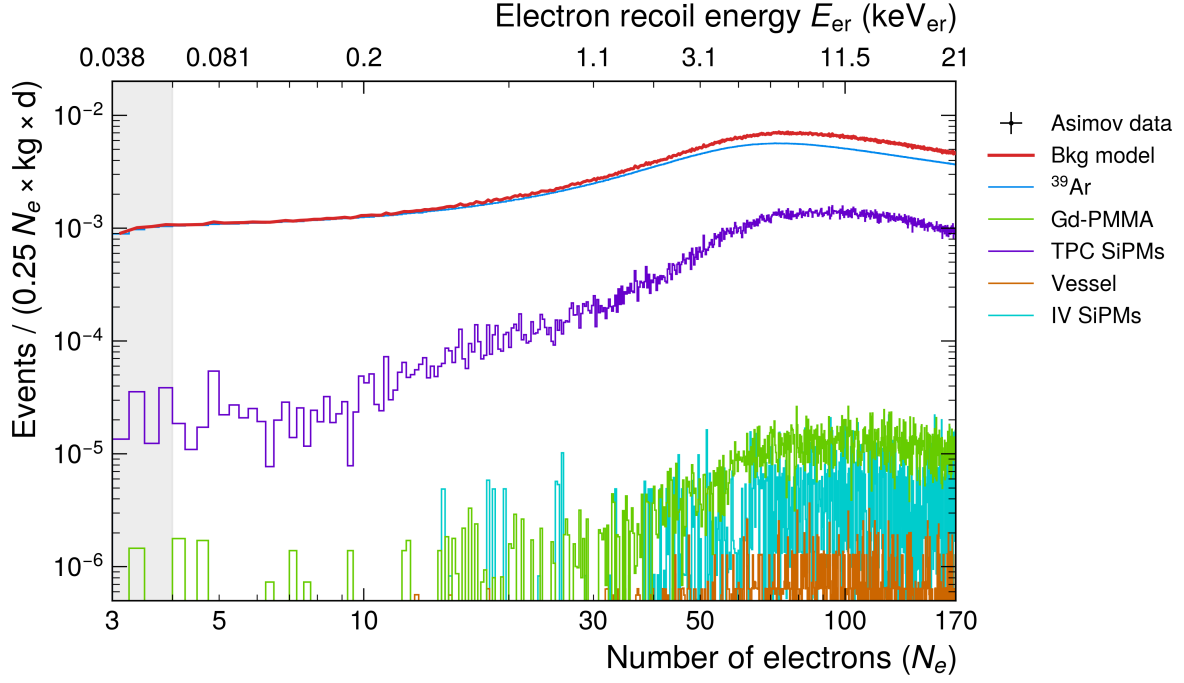


Figure 5.4: Pre-fit DarkSide-20k background ionization spectra, alongside the Asimov dataset. This work.

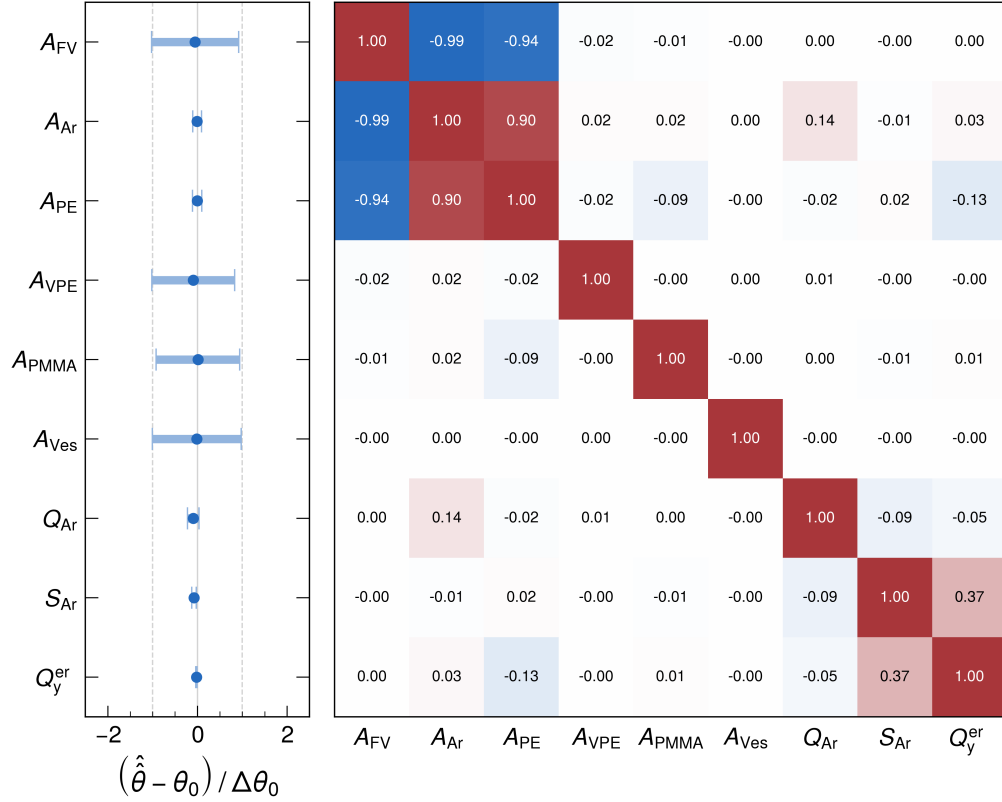


Figure 5.5: Nuisance parameter pulls (*left*) and correlation matrix (*right*) from the background-only fit to Asimov data. See the text for more details. This work.

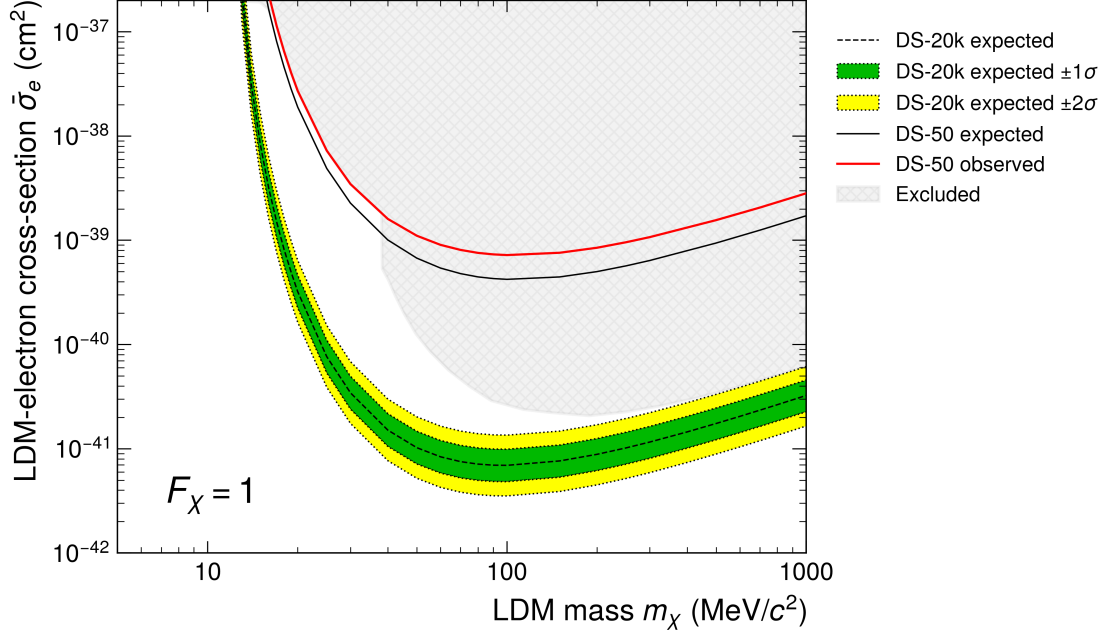
fit to the background model, the Asimov dataset is generated with the signal strength fixed to zero.

The nuisance parameter pulls and correlation matrix for the fit are shown in Figure 5.5. For a detailed description of how to interpret these plots, see Section 3.8.3. As we are fitting to the Asimov dataset, post-fit nuisance parameter values ($\hat{\theta}$) are expected to match the pre-fit values; this matches the observed results. However, the post-fit uncertainties ($\Delta\hat{\theta}$) may differ, showing how the observed dataset will constrain the nuisance parameters. The expected behavior of post-fit parameter values is observed, illustrated by the *blue* dots in the left panel of Figure 5.5, demonstrating the stability of the background model. The post-fit uncertainties, represented by the error bars, show that numerous nuisance parameters will be highly constrained by the observed dataset. These are primarily related to ^{39}Ar , which is quite reasonable given that the ^{39}Ar β -decay spectrum is the dominant background across the full energy ROI. Consequently, this analysis has the potential to provide precise measurements of the ^{39}Ar activity (A_{Ar}), β -decay spectrum shape (Q_{Ar}), and effects due to atomic exchange and screening effects (Q_{Ar}), highly constraining prior model uncertainties. The DS-50 background-only fit in Section 3.8.3 reduced the Q_y^{er} model uncertainty by 91.3%. For the same initial uncertainty, the DS-20k background-only fit to Asimov data shows that DS-20k an uncertainty reduction of 98.5%. However, despite this improvement, the ER energy scale model cannot be adequately tested due to the other systematics affecting the ^{39}Ar β -decay shape. The ARIS-ER experiment, introduced in Chapter 6, will address this issue by providing a cleaner measurement of the LAr response down to and below 1 keV_{er} using the Compton coincidence technique.

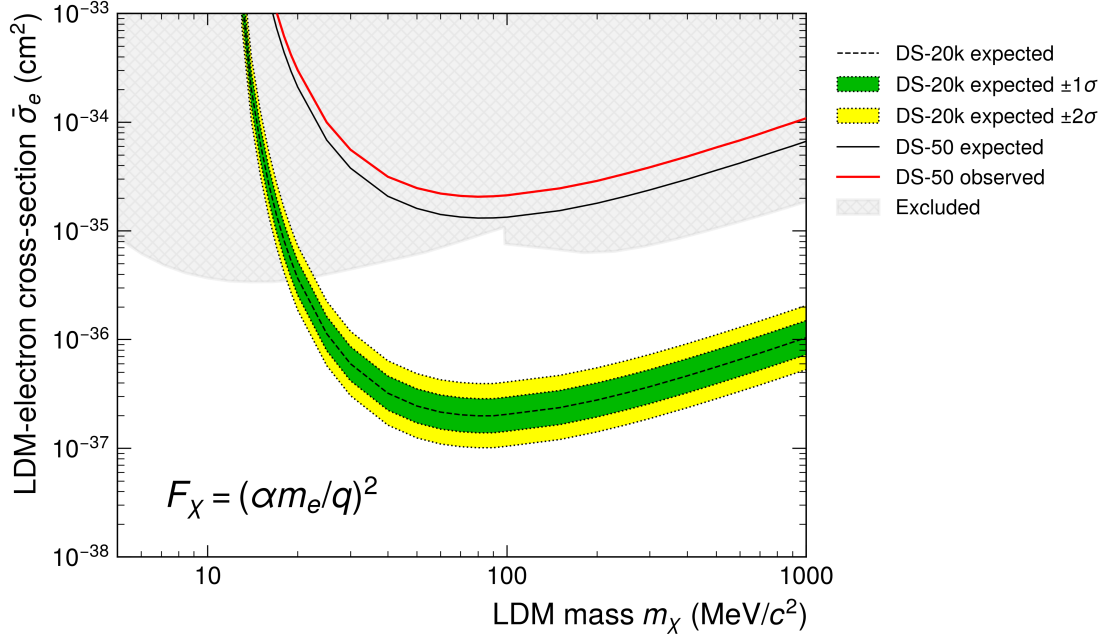
The right panel of Figure 5.5 shows the correlation matrix between the nuisance parameters. As the fiducial volume uncertainty (A_{FV}) is applied to all components, it is highly anti-correlated with the two dominant background component normalizations, A_{Ar} and A_{PE} . A slightly higher anti-correlation of -0.99 is observed for A_{Ar} as opposed to A_{PE} (-0.94) as the TPC SiPM backgrounds only contribute notably above $50 N_e$. One may also notice a strong correlation between Q_y^{er} and Q_{Ar} (0.36) than in DS-50 (-0.01 , see Figure 3.20). It is hypothesized that this is because there are fewer background components with activities equivalent to ^{39}Ar to separately constrain Q_y^{er} .

5.6 Sensitivity projections

The sensitivity of the DS-20k experiment to several leptophilic DM candidates is shown in Figure 5.6, alongside the DS-50 limits derived in Chapter 3 and parameter space currently excluded at $\geq 90\%$ CL. The nominal

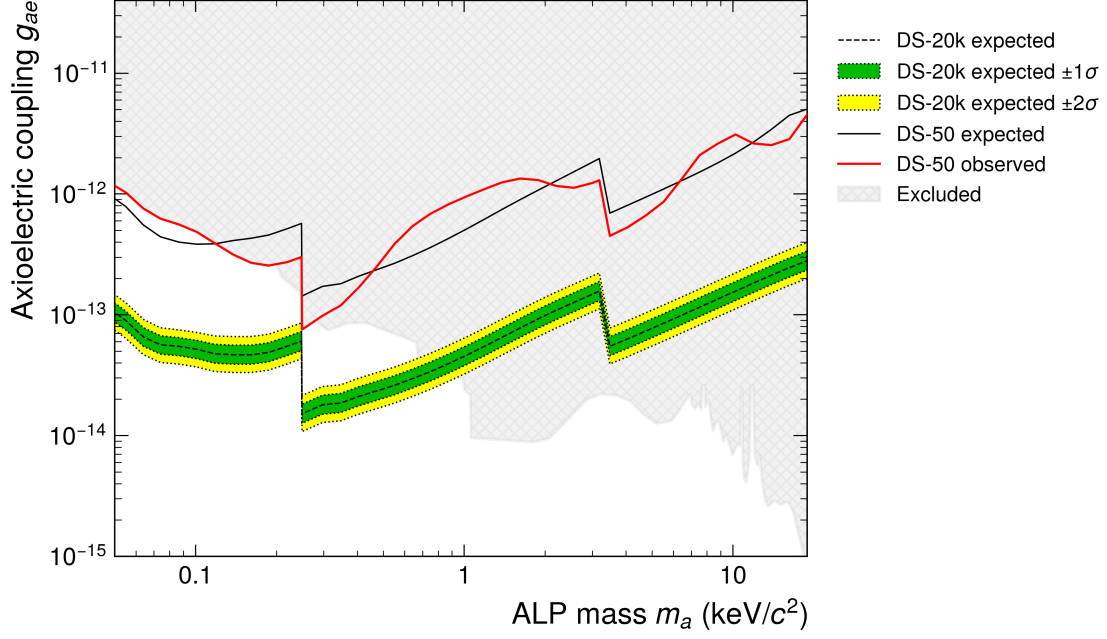


(a) DarkSide-20k projected 90% CL on the LDM-electron scattering cross section, assuming a heavy mediator.

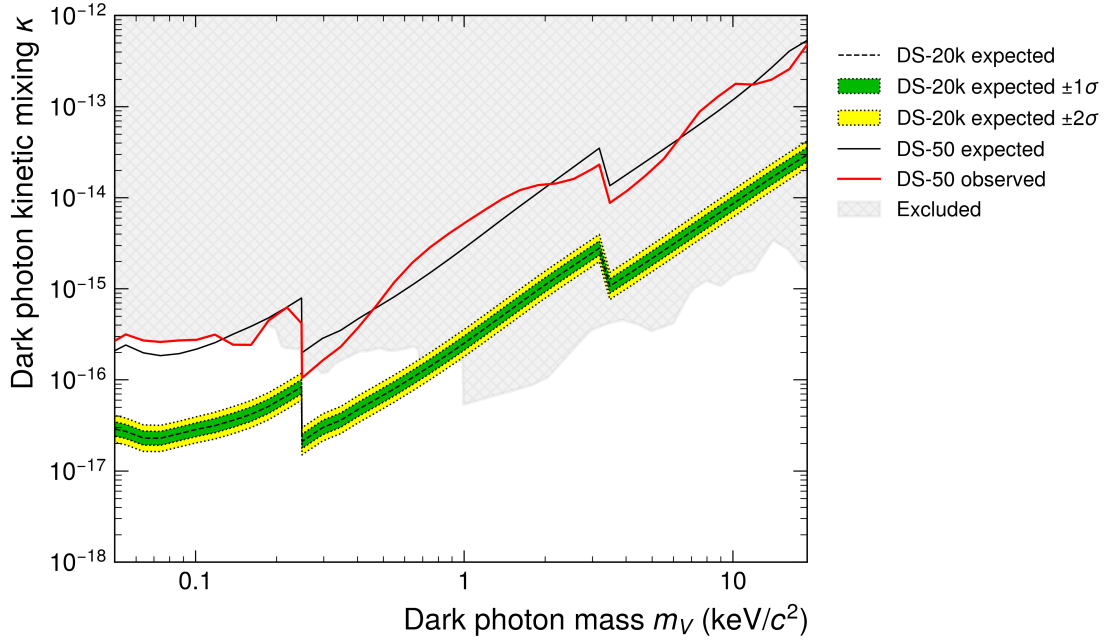


(b) DarkSide-20k projected 90% CL on the LDM-electron scattering cross section, assuming a light mediator.

Figure 5.6: The projected DarkSide-20k 90% confidence level on leptophilic DM couplings. This is shown for the nominal assumptions, namely a 1 yr live time, 30 cm FV cut, and an ^{39}Ar activity of 0.730 mBq/kg. The dashed *black* line is the median expected CL while the *green* and *yellow* bands are the $\pm 1\sigma$ and $\pm 2\sigma$ expected bands, respectively. These are shown alongside the DS-50 expected (solid *black*) and observed (solid *red*) limits from Chapter 3. The *x*-axis shows the mass of the candidate, while the *y*-axis shows the model parameter. This work.



(c) DarkSide-20k projected 90% CL on the galactic axion-like particle axioelectric coupling.



(d) DarkSide-20k projected 90% CL on the dark photon kinetic mixing parameter.

Figure 5.6: (cont.) The projected DarkSide-20k 90% confidence level on leptophilic DM couplings. This is shown for the nominal assumptions, namely a 1 yr live time, 30 cm FV cut, and an ^{39}Ar activity of 0.730 mBq/kg. The dashed *black* line is the median expected CL while the *green* and *yellow* bands are the $\pm 1\sigma$ and $\pm 2\sigma$ expected bands, respectively. These are shown alongside the DS-50 expected (solid *black*) and observed (solid *red*) limits from Chapter 3. The x -axis shows the mass of the candidate, while the y -axis shows the model parameter. This work.

assumptions of a 1 yr live time, 30 cm FV cut, and 0.730 mBq/kg ^{39}Ar activity are used to compute these projections. Combining the cut efficiencies described in Section 5.3, the exposure for the nominal 1 yr live time is 24.7 t yr.

For LDM-electron scattering, the DS-20k expected sensitivity is a factor of more than 60 better than that of DS-50 for both the heavy and light mediator assumptions. This improvement is primarily due to the larger LAr fiducial mass, which is increased by nearly a factor of 900. The reduction of background rate in the signal region, below $1 \text{ keV}_{\text{er}}$, is reduced by a factor of 5, which also contributes to this improvement. This results from the reduction of ^{85}Kr activity to a negligible level. Another contribution, to a lesser degree, is the larger average distance from the TPC photosensor arrays to the LAr FV, which reduces the photodetector backgrounds, showcasing the self-shielding properties of the LAr TPC design.

The potential for DS-20k to probe as yet unexplored LDM parameter space is greater for the case of a light mediator than a heavy mediator, with the DS-20k sensitivity reaching a factor of 36.8 below current exclusion limits at $100 \text{ MeV}/c^2$ as opposed to 3.8 respectively. The best limit for both is currently held by PandaX-4t [122] which, as discussed in Section 3.8.4, uses an energy threshold of $0.07 \text{ keV}_{\text{er}}$. As both DS-50 and DS-20k use a lower energy threshold of $0.03 \text{ keV}_{\text{er}}$ where a large portion of the LDM light mediator signal is expected (more so for a light mediator), DS-20k will be able to make significant improvements over PandaX-4t.

Sensitivity of DS-20k to both galactic ALP and DP models is also shown in Figure 5.6. The factor of 9.4 increase for both models is less than that of LDM, as the interaction rate of galactic ALPs and DPs is proportional to the squared model parameter. In both cases, DS-50 currently holds the world's best limits. DS-20k has excellent prospects to improve upon these significantly.

Let us examine the difference in sensitivity gain between the high-mass and low-mass analyses. For spin-independent DM-nucleon scatter, DS-20k is expected to reach a factor of 600 below DS-50 limits at $1 \text{ TeV}/c^2$ for a 1 yr live time. The high-mass search employs PSD so DM-nucleon interactions can be identified on an event-by-event basis with an expected ER background rate of 0.01 in the 1 yr exposure. Consequently, the sensitivity gain in this case is directly proportional to the LAr mass. Even though the LDM signal rate is directly proportional to the LAr mass like for the case above, the non-negligible background rates in the low-mass search cause sensitivity gains to be diminished considerably.

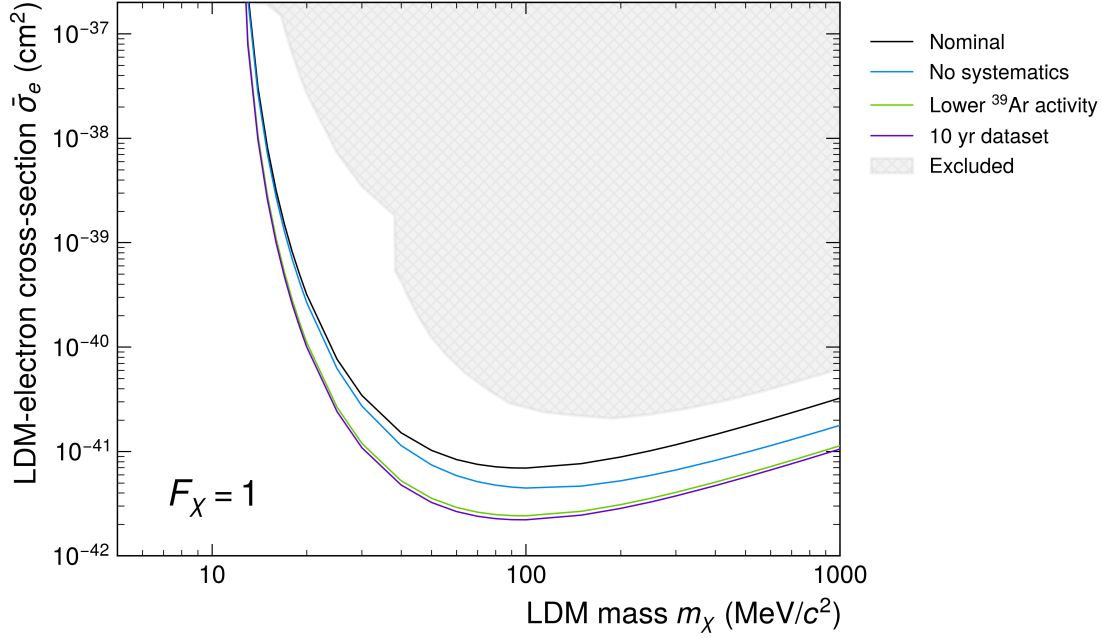


Figure 5.7: Effect of different assumptions on projected DarkSide-20k exclusion limits for LDM-electron scattering assuming a heavy mediator. Each parameter is varied individually. This work.

5.6.1 Effects of assumptions

Here, we examine the effects of several assumptions on the projected DS-20k sensitivity to exclusion. This will help to understand the potential of DS-20k if conservative assumptions are relaxed and to identify the most important factors to consider when designing the experiment. For the sake of simplicity, the LDM-electron scattering model with a heavy mediator is used for this study. The assumptions considered here are the systematic uncertainties, the ^{39}Ar activity, and the live time. Each of these is varied independently, while the others are held constant. The nominal sensitivity, shown in Figure 5.7 by a *black* line, is computed with the systematic uncertainties listed in Table 5.2, a 1 yr dataset, and an ^{39}Ar activity of 0.730 mBq/kg.

By removing all systematic uncertainties, the sensitivity is improved by a factor of 1.5, shown by the *blue* line. Of these, the most notable uncertainties are those that impact the ^{39}Ar background. Improved precision of ^{39}Ar activity measurements and of the ER energy scale (Q_y^{er}) will lead to the largest improvements in low-mass physics reach.

A reduction of the ^{39}Ar activity dramatically impacts the projected limits. The *green* line in Figure 5.7 shows the projected sensitivity for an ^{39}Ar activity of 0.073 mBq/kg, a reduction of a factor of 10. This leads to a factor of 2.9 improvement in sensitivity. As the ^{39}Ar activity becomes comparable to that of the TPC PDMs, the development of cuts to lower the γ -ray backgrounds will enable further improvement. In

particular, the current external background population is predominantly located near the anode and cathode, as seen in Figure 5.3c. An S2-based z position reconstruction algorithm will enable further improvement.

Finally, the last parameter we will consider is the length of the dataset. A factor of 3.1 is gained by increasing the dataset from 1 yr to 10 yr, as shown by the *purple* line, which is the entire planned runtime of DS-20k. Because we are searching for a signal on top of backgrounds, the sensitivity does not scale linearly with live time as in the high-mass search. Proportionality approximate to the square root of the live time is observed. This gain is very similar to that of the ^{39}Ar activity reduction; as these assumptions are independent, a combination of both leads to a projected sensitivity of $7.7 \times 10^{-43} \text{ cm}^2$ at $100 \text{ MeV}/c^2$, nearly an order of magnitude better than the nominal projection.

5.6.2 Comparison with other experiments

For LDM masses above $12 \text{ MeV}/c^2$ for a heavy mediator and $100 \text{ MeV}/c^2$ for a light mediator, LAr or liquid xenon (LXe) TPC experiments using datasets with S2-only signals hold the best limits [97, 122]; this includes the DS-50 results presented in this dissertation. Likewise, the same is true for the galactic ALP and DP mass range considered in this work. While no sensitivity projections have been published, the LZ and XENONnT, which are currently taking data using LXe TPCs, will likely have similar sensitivities to DS-20k [53, 54]. For lower LDM masses, experiments using charge-coupled devices (CCDs) like SENSEI and DAMIC-M will competitively probe parameter space, with the current best limits in this region from DAMIC-M [61]. Ambition plans for future CCD experiments include DAMIC-1K [139], which seeks to deploy a total mass of $\sim 1 \text{ kg}$. Additionally, the SuperCDMS SNOLAB experiment, which will use cryogenically-cooled silicon and germanium crystals, has published sensitivity projections for leptophilic DM candidates [59]. DS-20k has a rich and competitive physics reach for leptophilic dark matter candidates and could become a world-leading experiment.

Chapter 6

The ARIS-ER experiment

The electronic recoil (ER) energy scale models the scintillation and ionization channel occupancy as a function of energy and drift electric field. It is critical to DM searches as it is used in detector calibration, background modeling, and leptophilic DM signal modeling. The Argon Recoil Ionization and Scintillation from Electron Recoils (ARIS-ER) experiment will use the Compton coincidence technique to measure the response of LAr to ERs with two main goals: (1) to characterize the LAr response to ERs down to a keV_{er} and (2) to refine a GEANT4 model describing the fundamental principles governing the ionization and scintillation processes of LAr.

This chapter contains a description of the ARIS-ER experimental design and the detector components. Section 6.3 describes how I optimized of this design using GEANT4 simulations. Lastly, Section 6.4 details my work developing the ARIS-ER DAQ system.

6.1 Existing measurements

In 2018, the Argon Recoil Ionization and Scintillation (ARIS) experiment measured the scintillation and ionization response of LAr to neutrons of known energy [87]. A dual-phase argon TPC with a target mass of 0.5 kg was exposed to a pulsed neutron beam. Using the γ -rays produced by the deexcitation of Li^* in coincidence with the beam pulse, the LAr response to ERs was measured from 40 keV to 511 keV for various drift field strengths. Due to technical difficulties, the ARIS TPC was operated in single-phase mode for this measurement, limiting calibration measurements to only S1.

As discussed in Section 3.4 of this dissertation, I fit a model of the LAr ionization response at low energies

to DS-50 calibration data, specifically the ^{39}Ar β -decay spectrum and an ^{37}Ar electron capture peak. The lowest data point, the ^{37}Ar L1 atomic shell located at $0.179\text{ keV}_{\text{er}}$, was the only sub-keV calibration point. One of the drawbacks of using ^{37}Ar as a calibration source is that the electron capture process has a complex event topology [107], which introduces additional systematic uncertainties.

An additional measurement of the LAr ionization response was measured in this dissertation in Section 3.8.3 using the DS-50 low-mass dataset that included S2-only events. While the background-only fit to DS-50 data reduced the uncertainty on Q_y^{er} by 91%, an independent measurement is still needed to isolate the ER energy scale from other systematics and model components. Furthermore, this calibration was performed solely for the ionization signal. Simultaneous calibration of S1 and S2 is essential for providing a complete picture of the LAr response to ERs.

6.2 Experiment design

The Compton coincidence technique involves exposing a primary detector to high-energy monoenergetic γ -rays and then identifying events in a second detector that occur in prompt coincidence and represent the complete energy deposition of the Compton-scattered γ -rays. Using the energy deposited in the second detector and the initial γ -ray energy, the energy deposited in the primary detector can be calculated. This technique has been used to measure the LXe response to low-energy ERs [140, 141] but has not yet been used with a LAr target.

A diagram of the experimental setup is shown in Figure 6.1. For the ARIS-ER measurement, dual-phase argon TPC is the primary detector. A broad-energy germanium (BEGe) detector is chosen as the secondary detector, depicted as *purple*, due to its excellent energy resolution. The energy of the Compton electron produced in the TPC (E_{er}) can be calculated using

$$E_{\text{er}} = E_{\gamma} - E_{\text{BEGe}} \quad (6.1)$$

where E_{γ} is the energy of the incident γ -ray and E_{BEGe} is the energy deposited in the BEGe detector. This assumes that no scattering occurs in other materials. For a given Compton scattering angle θ , the BEGe detector energy is

$$E_{\text{BEGe}} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_e c^2}(1 - \cos \theta)}, \quad (6.2)$$

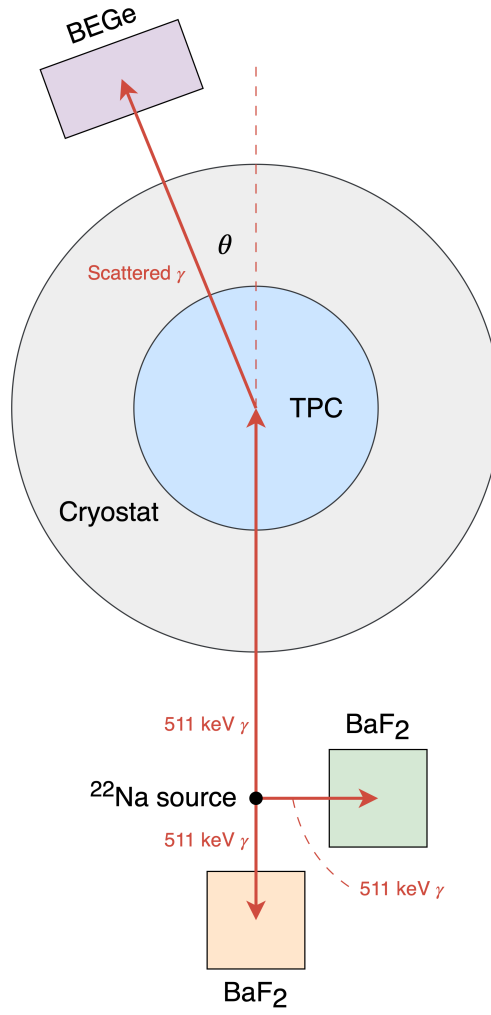


Figure 6.1: The ARIS-ER experimental setup. This work.

meaning the angle of the BEGe detector relative to the incoming γ -ray allows for different recoil energy ranges in the TPC to be probed.

6.2.1 γ -ray source

Ref. [141] measured recoils from 661.7 keV γ -rays from a ^{137}Cs source, triggering on events with an S1 signal coincident with a signal in a germanium detector that measured the energy of the scattered γ -ray. This introduced uncertainties due to the S1 trigger effect and limited the energy range that could be probed.

We seek to improve upon this method by using a ^{22}Na source. The β^+ decay of ^{22}Na produces a positron, which annihilates with an electron in the source's material, resulting in two 511 keV γ -rays. As these are kinematically required to be back-to-back, a detector can tag the γ -ray opposite to the one directed at the TPC.



Figure 6.2: Canberra BE2020 BEGe detector



Figure 6.3: Scionix 38A38/2M-E1-BAF-X-NEG BaF₂ detector. The crystal is contained within the gray aluminum housing.

Combining this trigger with the BEGe detector's trigger, the TPC trigger is no longer needed, meaning lower energies can be probed and TPC trigger efficiency effects are not present. Additionally, the ^{22}Na β^+ decay product $^{22}\text{Ne}^*$ de-excites via the emission of a 1274 keV γ -ray. By using an additional detector to tag this γ -ray, desired events can be further separated from accidental coincidence background events, but at the cost of a lower trigger rate.

6.2.2 γ -ray detectors

The scattered γ -ray will be detected by a Canberra BE2020 broad-energy germanium (BEGe) detector, as it has an excellent energy resolution of 0.6 keV FWHM at 122 keV. The BEGe detector crystal has a diameter of 5.13 cm and thickness of 2.17 cm. The crystal is contained within a 0.1 mm-thick cylindrical aluminum housing and a 0.6 mm-thick carbon composite window in front of the crystal.

The working principle of the Canberra BE2020 detector is summarized as follows. When an incident particle, such as a γ -ray, interacts in the sensitive region of the semiconductor material, electron-hole pairs are produced in proportion to the deposited energy. An electric field applied across the crystal extracts these

charge carriers to electrodes. The Canberra 2002C preamplifier converts the ionization charge to a voltage pulse, namely a step-function with amplitude proportional to the total charge collected, combined with a 50 μ s decay constant.

The ARIS-ER experiment requires precise timing resolution the coincidence trigger. Consequently, a 50 Ω splitter is used to duplicate the preamplifier signal. One signal copy is input into a front-end board for discrimination (see Section 6.2.3) and participates in the experiment's trigger. The other copy is passed through a Canberra 2024 fast spectroscopy amplifier with a 4 μ s Gaussian shaping time constant to improve the energy resolution, which is then recorded by a digitizer.

Barium fluoride (BaF_2) scintillators provide sub-ns timing resolution, far better than required by ARIS-ER. Two Scionix 38A38/2M-E1-BAF-X-NEG BaF_2 detectors were purchased, one to tag the 511 keV γ -ray (shown as *orange* in Figure 6.1) and the other to tag the 1274 keV γ -ray (*green*). Each has a cylindrical crystal with 38 mm diameter and 38 mm height, housed within aluminum shielding. Scintillation light is collected by a PMT, and the signal is passed through a front-end board for discrimination and then recorded by the V1725 digitizer. The discriminator logic signal is combined with the BEGe detector's signal in the trigger logic to form a trigger to indicate the start of an acquisition window.

6.2.3 TPC

The ARIS-ER experiment will use the dual-phase argon TPC developed originally for the ARIS experiment [87], which is based on the DS-50 TPC described in Section 2.4.1. A drawing of this TPC, along with a photo, is shown in Figure 6.4. A PTFE cylinder contains the LAr active volume, which has a 7.6 cm diameter and 7.6 cm height. An ESR film is embedded in the PTFE to improve light reflection. The cylinder is capped by fused-silica windows plated with ITO, like in DS-50. All interior surfaces, including the windows, are coated with TPB to shift the 128 nm LAr scintillation light to the visible spectrum. TPB coating is done with a tabletop evaporation system.

The TPC is viewed from above by seven 1" Hamamatsu R8520 PMTs and from below by one 3" Hamamatsu R11065 PMT (used in DS-50) which collect the wavelength-shifted scintillation light. The segmented top PMT array allows for (x, y) position reconstruction. A drift field, tunable up to 1 kV/cm, is created between the cathode and a hexagonal stainless steel grid placed 8 mm below the anode. Copper field cage rings, connected by resistors in series, are embedded in the PTFE sleeve to maintain field uniformity; these rings are 2.5 mm thick. An extraction field of up to 4 kV/cm is created between the grid and the anode. The gas

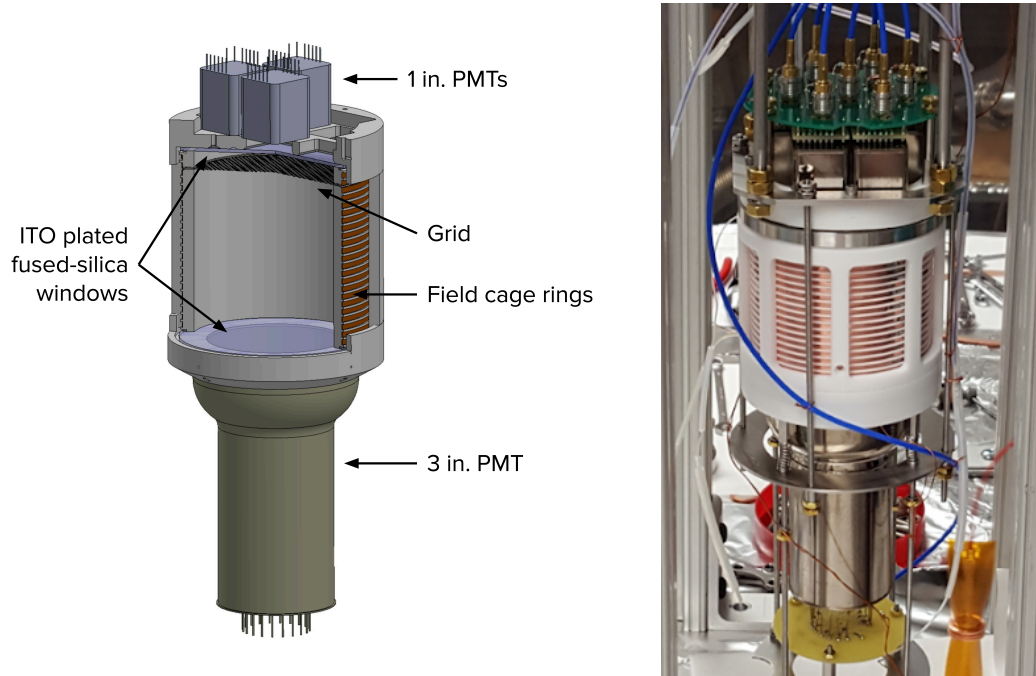


Figure 6.4: The TPC used in the ARIS experiment. Figure reproduced from Ref. [87].

pocket is designed to be 5 mm thick so that the grid lies below the LAr surface. However, the 2018 ARIS measurement [87] could only operate in single-phase mode due to a malfunction in the gas pocket system. Currently, work is underway to repair this.

PMT front-end boards PMT signals are passed through custom front-end boards, based on those used for DS-50. These boards provide signal filtering, amplification, and discrimination. The discriminator logic signals are sent to the V2495 for trigger formation, while the filtered and amplified signals are recorded using the V1725.

6.3 Simulations

I implemented the proposed experimental setup in G4DS. This included detailed descriptions of the cryostat, TPC, PMTs, BaF₂ detectors, BEGe detector, and ²²Na source. Decays from the source were simulated to optimize the experimental geometry and determine the required source activity. Several BEGe detector angles (θ in Figure 6.1) were tested, ranging from 0° to 30°, to examine the effect on the TPC energy spectrum, more specifically the range of deposited energy and event rate. For preliminary simulations, the distance of the BEGe detector to the cryostat was set to 5 cm, the distance of the ²²Na source to the cryostat was 3 cm, and both

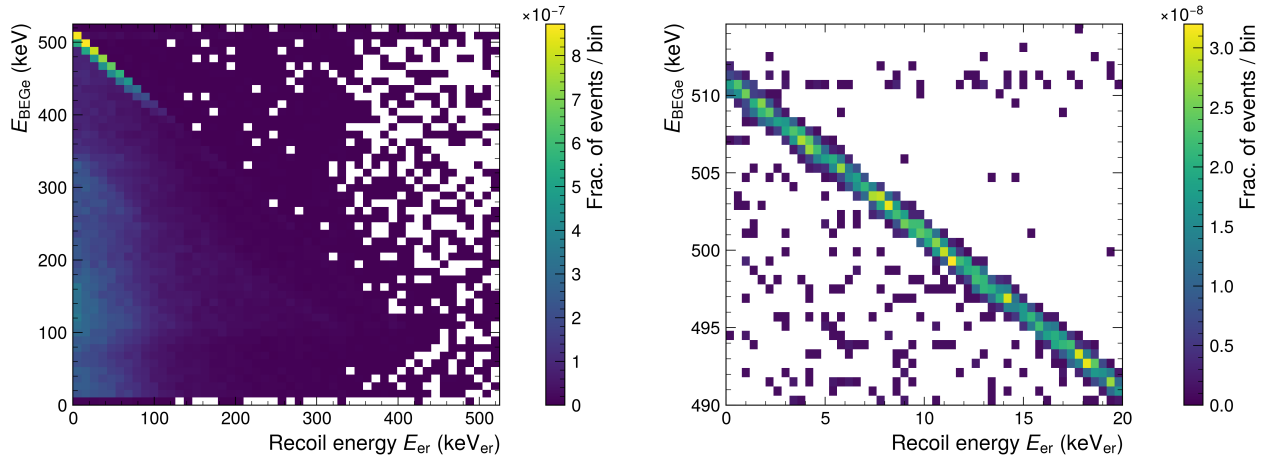


Figure 6.5: Simulated energy deposits in the BEGe detector and the TPC. The BEGe detector is placed at $\theta = 0^\circ$. The energy deposited in the TPC (E_{er}) is shown on the x-axis, with a zoomed version of the energy ROI shown on the right. This work.

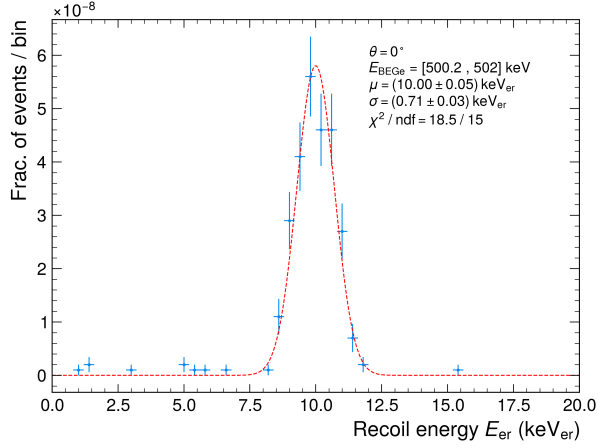
BaF₂ detectors were placed 3 cm from the source. These distances were a starting point for the simulations, chosen for compactness. After energy depositions in the various materials were determined using G4DS, a toy MC simulated the BEGe detector energy resolution σ_{BEGe} , which was modeled as $\sigma_{\text{BEGe}}(E) = \alpha + \beta\sqrt{E}$ as suggested by Ref. [141]. A fit of BEGe detector calibration points to this model yielded values of 0.096 keV for α and $0.016 \sqrt{\text{keV}}$ for β .

Two trigger configurations were examined:

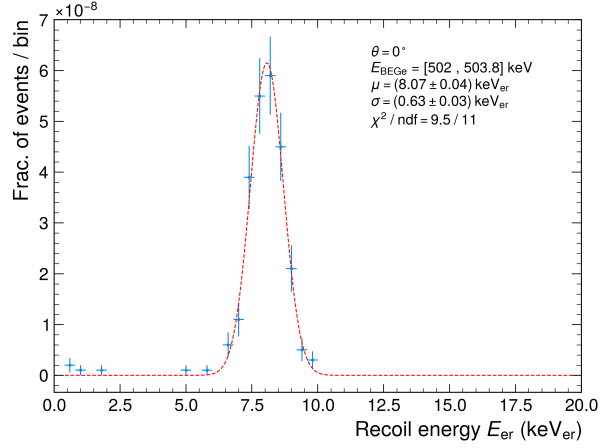
1. Double coincidence: BEGe detector and 511 keV γ BaF₂ detector (*orange* in Figure 6.5).
2. Triple coincidence: BEGe detector, 511 keV γ BaF₂ detector (*orange*), and 1274 keV γ BaF₂ detector (*green*).

The triple coincidence trigger aims to reduce the rate of triggers due to the environmental background by requiring the 1274 keV γ to be detected along with the back-to-back 511 keV γ -rays. This advantage comes at the cost of a lower trigger rate for desired signal events. The double coincidence trigger rate was found to be 32.9/s for a 100 μCi ²²Na source, while that of the triple coincidence trigger was 1.3/s. No environmental background was included in these simulations. To assess the necessity of the triple coincidence trigger, an assessment of the impact of the environmental background on the deposited energy spectra is needed.

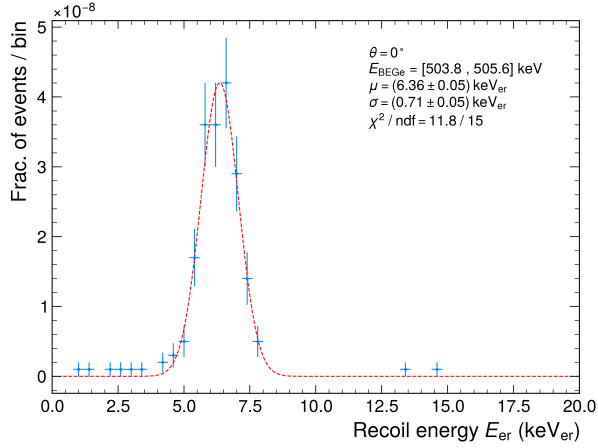
For the simulated dataset, the smeared BEGe detector energy was plotted against the TPC energy in Figure 6.5. This shows events selected with the double coincidence trigger. A very prominent peak can be seen along the line where the BEGe and TPC energies sum to the γ energy, 511 keV. Events above this line, where the total energy is more than 511 keV, are due to scattering of the isotropic 1274 keV γ . Horizontal



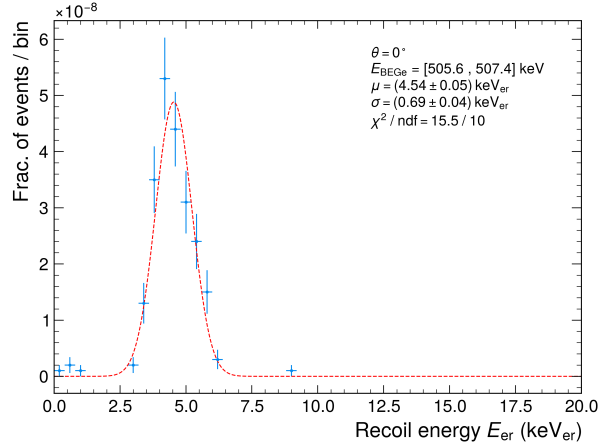
(a) TPC energy spectrum for BEGe detector energy in [500, 502] keV.



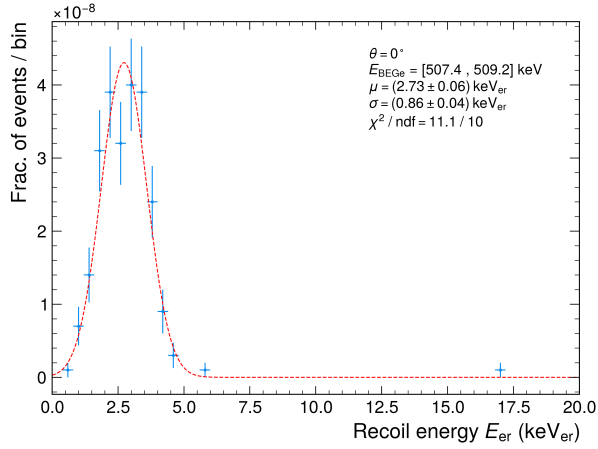
(b) TPC energy spectrum for BEGe detector energy in [502, 504] keV.



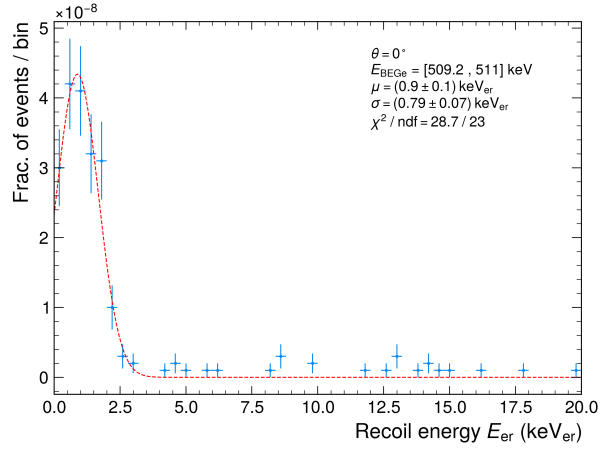
(c) TPC energy spectrum for BEGe detector energy in [504, 506] keV.



(d) TPC energy spectrum for BEGe detector energy in [506, 508] keV.



(e) TPC energy spectrum for BEGe detector energy in [507.4, 509.2] keV.



(f) TPC energy spectrum for BEGe detector energy in [509.2, 511] keV.

Figure 6.6: Simulated TPC energy spectra for various BEGe detector energy ROIs at $\theta = 0^\circ$. Only statistical errors are included. Fits to Gaussian distributions are shown in *red*.

slices of the plot on the right of Figure 6.5, along the BEGe detector energy, were fit to normal distributions to evaluate the systematic uncertainty on the TPC energy spectra due to the BEGe detector energy resolution. These fits are shown in Figure 6.6 for a BEGe detector placement at 0° , targeting recoil energies down to and below $1 \text{ keV}_{\text{er}}$. We can see that the Gaussian fits correctly reconstruct the expected TPC energy. This is demonstrated down to $1 \text{ keV}_{\text{er}}$, demonstrating the ability of this experimental approach to measure low energy recoils. For the actual ARIS-ER experiment, a likelihood fit of the MC energy spectra to data in two dimensions will be performed to calibrate the LAr response to ERs.

I also examined the amount of energy deposited outside of the TPC and BEGe detector active volumes, such as in the cryostat. Events depositing less than $25 \text{ keV}_{\text{er}}$ in the TPC were selected and the energy in the TPC and BEGe detector active volumes (before smearing) was summed. For this population, the average energy deposited outside of the TPC and BEGe active volumes was 52 eV . This corresponds to a systematic error of $\sim 5\%$ for $1 \text{ keV}_{\text{er}}$ events, well below the BEGe energy resolution.

There are several variables that are not explored in this dissertation that can be explored by future work. A lead collimator surrounding the source can be used to reduce the number of pile-up events. If the BEGe detector is placed at an angle to specifically target higher energy Compton scatters, a collimator would result in a larger fraction of such events by geometrically restricting γ -rays that deposit little or no energy in the TPC from reach the BEGe detector. The design of such a collimator is under current study by the ARIS-ER group at UC Davis. While the distance between the TPC and BEGe can be adjusted to more narrowly target a certain energy range, a similar effect can also be achieved via a lead collimator around the BEGe active volume. This is theorized to be particularly useful when looking for sub- keV_{er} recoils with the BEGe detector placed at 0° . Further study of this approach is also underway.

6.4 Data acquisition system

The DAQ system is responsible for collecting data from photosensors and writing it to disk. For ARIS-ER, I developed a DAQ system that supports up to four CAEN V1725 digitizers, a total of 64 readout channels. A CAEN V2495 programmable logic unit synchronizes the digitizers, accepts logic signals from discriminators, and implements numerous trigger logic patterns. The resulting combined trigger logic signal is then used to trigger the digitizers for WF collection.

In Figure 6.7, the wiring diagram of the DAQ system is shown for the maximum supported number of

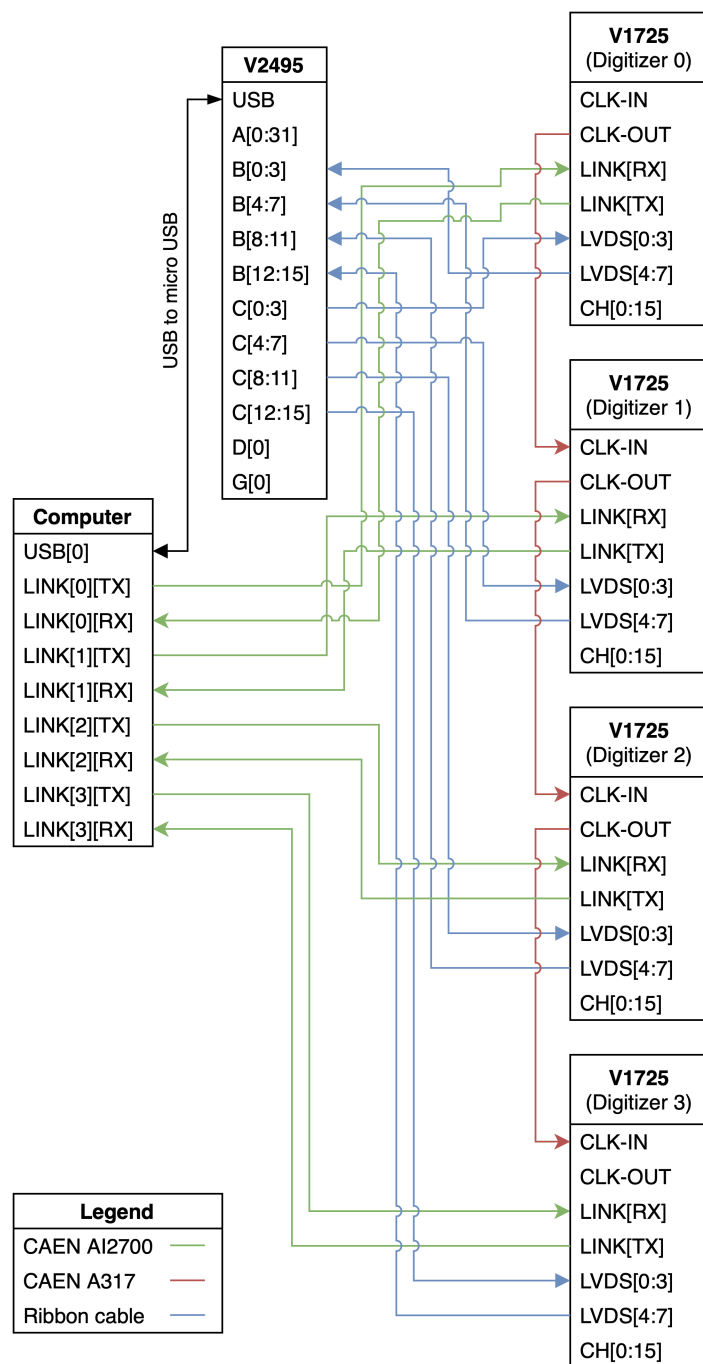


Figure 6.7: Wiring diagram for the DAQ system. This shows the required setup for the maximum number of digitizers supported. See the text for details. This work.

CAEN V1725 digitizers. Communication with the V2495 board is via USB, while communication with the V1725 boards is via optical fibers connected to a CAEN A3818 CONET2 controller. Communication between the V2495 logic unit and the V1725 digitizers is via a low-voltage differential signaling (LVDS) protocol over custom ribbon cables. Further scalability of the DAQ beyond four digitizers is limited by the number of digital input and output channels on the V2495 board.

6.4.1 DAQ software

The DAQ software is based on MIDAS¹, a general purpose DAQ framework which provides application templates for device interfaces. MIDAS also provides a web interface for configuring equipment and monitoring DAQ system parameters. The MIDAS online database (ODB) maintains real-time parameter values and logs information to disk. The interface between MIDAS and the equipment, namely the V1725 and V2495 boards, is handled by a custom C++ DAQ program², based on what was developed for the DS-Proto0 experiment. This program is responsible for numerous tasks: configuring boards with appropriate register values given the current MIDAS database configuration, starting a run such that all digitizer start times are synchronous, optionally sending software triggers to the digitizers and logic unit, board monitoring (including ADC temperatures, trigger rates, and buffer levels), reading data from the digitizers in parallel threads, ensuring trigger timestamps from all boards are aligned, transferring the data internally to MIDAS to be written to disk, and stopping a run.

6.4.2 Logic unit firmware

I developed custom firmware³ for the CAEN V2495 logic unit which uses to synchronize the digitizers and implement various trigger logic patterns. I wrote this using the SCI-Compiler⁴ tool, which compiles block diagrams into firmware code. The firmware interfaces with the DAQ software described above to allow for user configuration and control via MIDAS.

The V2495 has 32 digital inputs to the A mezzanine, 32 digital inputs to the B mezzanine, 32 digital outputs via the C mezzanine, eight LEMO channels in the D mezzanine, and two LEMO channels in the G

¹https://daq00.triumf.ca/MidasWiki/index.php/Main_Page

²https://gitdark.physics.ucdavis.edu/lab9195/daq_frontend

³https://gitdark.physics.ucdavis.edu/lab9195/v2495_firmware

⁴<https://www.caen.it/products/sci-compiler/>

I/O Section	Direction	Description
A[0:31]	In	Discriminator inputs, used in trigger logic
B[0]	In	nBusy input from Digitizer 0
B[1]	In	nVeto input from Digitizer 0, unused
B[2]	In	nTrigger input from Digitizer 0, unused
B[3]	In	nRun input from Digitizer 0, unused
B[4:7]	In	Same as B[0:3] but for Digitizer 1
B[8:11]	In	Same as B[0:3] but for Digitizer 2
B[12:15]	In	Same as B[0:3] but for Digitizer 3
C[0]	Out	nBusy output to Digitizer 0
C[1]	Out	nVeto output to Digitizer 0
C[2]	Out	nTrigger output to Digitizer 0
C[3]	Out	nRun output to Digitizer 0
C[4:7]	Out	Same as C[0:3] but for Digitizer 1
C[8:11]	Out	Same as C[0:3] but for Digitizer 2
C[12:15]	Out	Same as C[0:3] but for Digitizer 3
D[0]	In	External trigger input
G[0]	Out	Trigger output

Table 6.1: CAEN V2495 port description for the custom firmware. A CAEN A395D Mezzanine Board is installed in I/O section D of the V2495 board.

section. The D and G sections can be configured as inputs or outputs. Additionally, eight programmable LEDs can be used as status indicators. Table 6.1 describes how the custom firmware uses each of the ports.

Trigger logic patterns The custom firmware combines input signals in several ways to produce a combined trigger output signal, which is available at the G[0] port. The combined trigger output is the logical OR of all enabled trigger sources, which can be selected through the MIDAS interface. Each implemented trigger source corresponds to a bit of register 0x1008:

- [0]: software trigger
- [1]: external trigger (a logic signal input to D[0])
- [2]: TPC majority trigger (at least N of the eight TPC PMTs are above threshold, where N is configurable via register 0x1020)
- [3]: Compton coincidence trigger (the BEGe detector and both BaF₂ detectors are above threshold)

The external trigger is useful for PMT laser calibration runs and the TPC majority trigger is primarily used for TPC calibration runs. Triggers are indicated by LED[2], but if the trigger signal duration is sufficiently short, the LED light may not be visible.

Digitizer synchronization To synchronize the digitizers in a multi-board system, the digitizer must have the same clock propagated to all boards, the same start times for each run, and aligned trigger timestamps [142]. For ARIS-ER, digitizer clocks are synchronized via a daisy chain, as shown in Figure 6.7. Synchronized clocks are achieved by designating one board as the “Primary” board and the others as “Secondaries.” The internal oscillator installed on the Primary board acts as a reference clock for all Secondary boards and is propagated to each via a daisy chain. The CLK-OUT port of the Primary board is connected to the CLK-IN port of the first Secondary board via a CAEN A317 cable. The CLK-OUT of the first Secondary board is then connected to the CLK-IN of the second Secondary board, and so on, as shown in Figure 6.7. Due to a lag created by the daisy chain, a delay must be added to each Secondary board, which can be done by following the procedure in Ref. [142].

Other synchronization requirements are achieved using the V2495 board, which ensures that run start times are aligned and triggers are propagated synchronously to all boards via LVDS cables. After the digitizers are armed for acquisition, a software run signal is sent from MIDAS to the V2495 board via register 0x1004. The negated value (nRun) is propagated to the digitizers via C[3, 7, 11, 15]. The run status is indicated by LED[3]. The negated combined trigger signal (nTrigger), described below, is output to the digitizers via C[2, 6, 10, 14].

Another concern when synchronizing digitizers is event misalignment, which can occur if a digitizer enters a busy state when a channel buffer is full. To prevent this, the custom firmware aggregates the “not busy” (nBusy) input signals from the digitizers (B[0, 4, 8, 12]) and sends the combined output back to the digitizers (C[0, 4, 8, 12]). Additionally, a software busy signal can also be generated by setting register 0x1018 to 0x1. On the V2495, LED[0] indicates the busy status. A software veto to reject triggers is controlled by register 0x101C. The negated value (nVeto) is output to the digitizers via C[1, 5, 9, 13]. The veto status is indicated by LED[1].

Chapter 7

Conclusions & outlook

The overwhelming evidence for DM comes from a wealth of astronomical observations. Galaxy rotation curves indicate the presence of a DM halo in galaxies to account for the unexpectedly large velocities of astronomical objects at large radii. Measurements of the cosmic microwave background temperature spectrum also provide evidence for DM, where anisotropies fitted to the Λ CDM model give a precise measurement of the DM density in the early universe. No particle in the Standard Model possesses the properties required to explain these observations, leading to the postulation of many new DM particle candidates. Some of these theories suggest that DM is a single particle, while others predict a dark sector of particles interacting with each other and SM particles through new forces.

Uncovering the particle nature of dark matter is, concisely put, one of the most important goals of modern physics. The parameter space of DM models is vast, yet searches have probed many of the most compelling theories, such as Weakly Interacting Massive Particles (WIMPs). The leading technology for probing GeV/c^2 and TeV/c^2 DM candidates, like WIMPs, is the dual phase time projection chamber, which typically uses xenon or argon as the target material due to their excellent scintillation properties.

The DarkSide-50 experiment has been at the forefront of this technology, using a (46.4 ± 0.7) kg liquid argon target to search for DM interactions. The first results of a search for DM-nuclear interactions were published in 2018 [16]. This high-mass search required events to have both S1 and S2 signals so PSD could be used, which limited the detectable recoil energy threshold to $3.4 \text{ keV}_{\text{er}}$. An expanded dataset that included S2-only events, thereby lowering the threshold to $0.06 \text{ keV}_{\text{er}}$, was used to set constraints on light dark matter couplings to electrons and nucleons [92, 96]. After the publication of these world-leading results, the DarkSide-50 experiment took additional data, and the DarkSide low-mass analysis group worked diligently

to improve several parts of the analysis. Chapter 3 presented these efforts, including improved background and signal modeling, a more accurate detector calibration, and refined data selection criteria. In addition to light dark matter, the dataset was also used to set world-leading constraints on axion-like particles and dark photons model parameters. This work was published in Refs. [93, 97] and has also been used in several other publications [94, 95].

Current and future DM experiments will continue to probe well-motivated model parameter space into the neutrino fog, where neutrino interactions are a relevant background. The DarkSide-20k experiment will employ a 49.7 t LAr target, an increase of three orders of magnitude over DarkSide-50. Scaling to this size requires numerous advances, such as detector hardware, data storage and processing methods, and data analysis techniques. To further this objective, Chapter 4 described the development of a simulation and data reconstruction framework for DarkSide-20k. This software tool is used to develop signal processing algorithms, which have been optimized for the new SiPM photodetectors. These algorithms are shown to precisely and accurately reconstruct particle interactions' timing and deposited energy. Machine learning-based algorithms are also developed to determine the (x, y) of particle interactions using the S2 light pattern. The results of these studies have been used to inform the design of DarkSide-20k.

Chapter 5 contained a projection of the DS-20k sensitivity to DM-electron interactions for the candidates considered in Chapter 3. This dissertation demonstrated that DarkSide-20k will be able to improve upon the physics reach of DarkSide-50 for leptophilic DM interactions by up to two orders of magnitude with just one year of data.

Future dark matter searches like DarkSide-20k will require support from a range of research activities, including assays of radioactive detector materials and measurements of LAr properties. An important measurement that affects DarkSide-20k calibrations, background modeling, and the low-mass search is the ER energy scale, which models the response of LAr to ER interactions. The ARIS-ER experiment will use the Compton coincidence technique to measure the LAr ER energy scale at UC Davis, down to and below 1 keV_{er}; this energy region is crucial for detecting LDM interactions. Chapter 6 discussed simulations that demonstrated the feasibility of ARIS-ER. Design parameters, including source activity, detector positioning, and trigger configuration, were optimized to maximize the signal-to-background ratio. The development of the ARIS-ER DAQ system was also described.

Future direct detection experiments will also require support from research activities beyond the scope of this dissertation that span many disciplines of physics [32]. Measurements of the DM density distribution

in galaxies will improve systematic uncertainties on expected DM signal calculations. As direct detection experiments must target a region of parameter space, advances in theory and simulation, as well as in astronomical measurements of DM properties, are required to guide the objectives of future experiments. Indirect detection and collider experiments are also required to provide complementary information about the nature of dark matter. To achieve the scale of experiments required to make groundbreaking discoveries, physicists must work as a global community to discover dark matter. I am proud of my contributions to these efforts, and I fervently hope to see the discovery of dark matter within my lifetime.

Appendix A

Acronyms

AAr atmospheric argon

ADC analog-to-digital converter

ALP axion-like particle

AP afterpulse

ARIS Argon Recoil Ionization and Scintillation

ARIS-ER Argon Recoil Ionization and Scintillation from Electron Recoils

BaF₂ barium fluoride detector

BEGe broad-energy germanium detector

CE ν NS coherent elastic neutrino-nucleus scattering

CL confidence level

CMB cosmic microwave background

DAQ data acquisition

DBSCAN density-based spatial clustering of applications with noise

DCR dark count rate

DiCT direct crosstalk

DM dark matter

DP dark photon

DS-LM DarkSide-LowMass

DS-Proto0 DarkSide-Proto0

DS-Proto1 DarkSide-Proto1

DS-10 DarkSide-10

DS-50 DarkSide-50

DS-20k DarkSide-20k

EDM event data model

EFT effective field theory

ER electronic recoil

ESR enhanced specular reflector

FE front-end

FEP front-end processor

FV fiducial volume

FWHM full width at half maximum

GADMC Global Argon Dark Matter Collaboration

GAr gaseous argon

Gd-PMMA gadolinium-loaded polymethylmethacrylate

HPGe high-precision germanium detector

HV high voltage

ITO indium tin oxide

IV Inner Veto, DS-20k neutron veto detector

LAr liquid argon

LDM light dark matter

LDMX Light Dark Matter eXperiment

LHC Large Hadron Collider

LNGS Laboratori Nazionali del Gran Sasso

LSR local standard of rest

LSV Liquid Scintillator Veto, the neutron veto for the DS-50 experiment

LVDS low-voltage differential signaling

LXe liquid xenon

LZ LUX-ZEPLIN

MA moving average

MC Monte Carlo

ML machine learning

NOA Nuova Officina Assergi

NR nuclear recoil

ODB MIDAS online database

OV Outer Veto, DS-20k muon veto detector

PARIS Precision Argon Response Ionization and Scintillation, an effective model for LAr scintillation

PDE photodetection efficiency

pdf probability density function

PDM photodetector module, a single TPC readout channel of the DS-20k experiment

PDU photodetector unit, a motherboard containing four PDMs

PE photoelectron

PMMA polymethylmethacrylate (acrylic)

PMT photomultiplier tube

PSD pulse shape discrimination

PTFE polytetrafluoroethylene, commonly known as Teflon

QE quantum efficiency

RHF Roothaan-Hartree-Fock

RMS root mean square

ROI region of interest

SER single electron response

SHM Standard Halo Model

SiPM silicon photomultiplier

SM Standard Model

TPB tetraphenyl butadine

TPC time projection chamber

TSP Time Slice Processor

UAr underground argon

VUV vacuum ultraviolet, region of the electromagnetic spectrum with wavelengths below 200 nm

WCD Water Cherenkov Detector, the muon veto for the DS-50 experiment

WF waveform

WIMP Weakly Interacting Massive Particle

WLS wavelength shifter

ZLE zero length encoding

Appendix B

Nomenclature

a_0	Bohr radius
α	fine-structure constant
$E_b^{n\ell}$	electron binding energy of the (n, ℓ) shell
E_{er}	electronic recoil energy
E_{nr}	nuclear recoil energy
F_χ	dark matter form factor
$f_{\text{ion}}^{n\ell}$	ionization form factor
g_{ae}	axioelectric coupling
g_1	number of photoelectrons detected per primary scintillation photon (S1 yield)
g_2	number of photoelectrons detected per extracted ionization electron (S2 yield)
κ	kinetic mixing between the photon and dark photon
m_e	electron mass
m_χ	light dark matter mass
m_V	vector mediator mass in LDM-electron scattering
m_a	axion-like particle mass
m_V	dark photon mass
N_e	number of extracted ionization electrons
Q_y^{er}	ionization yield per unit energy for electronic recoils
ρ_χ	local dark matter density

v_{esc}	dark matter escape velocity (544 km/s)
$\bar{\sigma}_e$	light dark matter-electron reference cross section
σ_{pe}	photoelectric cross section
σ_{xy}	position reconstruction resolution in the x - y plane

Appendix C

DarkSide-50 low-mass analysis cuts

The cuts described in this section are used for the DarkSide-50 low-mass analysis. Cuts are intended to select DM-like events and remove unphysical events while retaining as much exposure as possible. A cut's acceptance is defined as the fraction of signal events that survive the cut. The total acceptance reduces the calculated detector exposure for scaling signal and background model rates.

C.1 Run selection cuts

This set of cuts removes runs with possible issues. Acceptances are not listed as runs failing these cuts are not used in the final exposure calculation.

C.1.1 Live time (CXLivetime)

Definition: The live time of the run, defined as integrated inhibit time subtracted from the integrated live time, must be greater than 0.

Purpose: To remove runs with improperly defined or no live time. This can be caused by DAQ or database errors.

C.1.2 Drift field (CXEDrift)

Definition: The drift electric field must be 200 V/cm, the value used to collect large statistics with UAr for the DS-50 experiment.

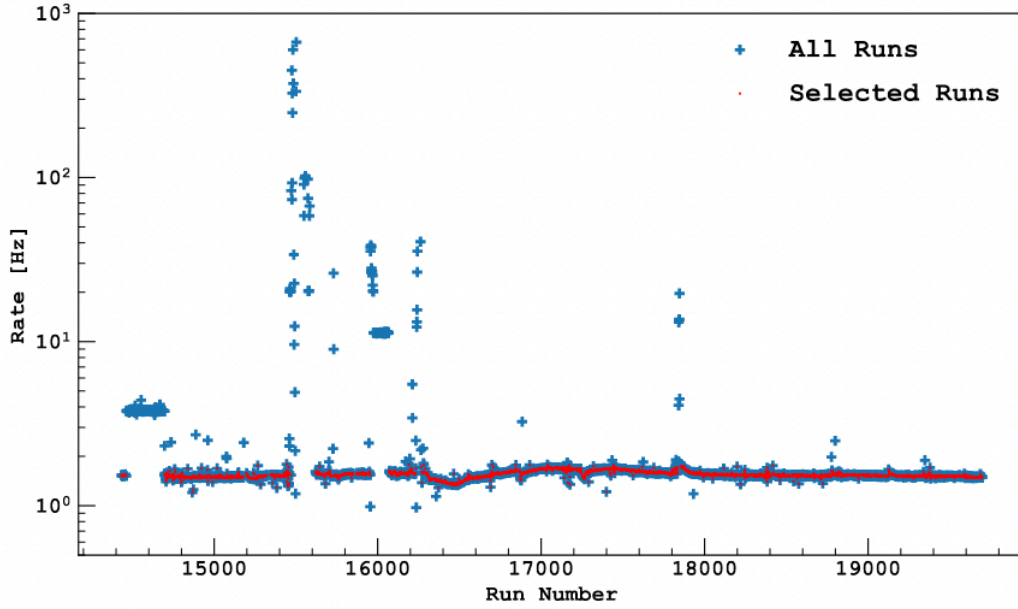


Figure C.1: DarkSide-50 runs and their rates. Runs selected by `CXEventRate` are colored *red*. Runs with higher rates are typically calibration runs, while those with lower rates may result from DAQ or database errors. Figure reproduced from Ref. [143].

Purpose: To remove runs where a different drift field or no drift field was used, as DS-50 took data with multiple field configurations.

C.1.3 Run index (`CXRunIndex`)

Definition: The run index must be greater than or equal to 0.

Purpose: To remove runs where the run index is ill-defined. This can be caused by DAQ or database errors.

C.1.4 Event rate (`CXEventRate`)

Definition: The event rate, defined as the total number of events recorded divided by the live time, is required to be between 1.2/s and 1.8/s.

Purpose: To remove runs taken after calibration campaigns and those with potential issues like DAQ crashes due to high system memory usage. Selected runs are shown in Figure C.1. The average rate of uncorrelated events in the TPC is 1.543/s for the runs selected.

C.2 Basic quality cuts

This set of cuts is designed to prevent the inclusion of mis-reconstructed events.

C.2.1 Number of channels (CXNChannels)

Definition: All 38 channels must be recorded for the event.

Purpose: To guarantee that no information on any events is lost. A channel may not be recorded due to transient problems on one or more PMTs in which one or more of the eight front-end (FE) boards in the DAQ hardware are not working properly.

C.2.2 Baseline found (CXBaseline)

Definition: The baseline is found for each channel composing the WF of the summed channels.

Purpose: To ensure that no mis-reconstructed event is accepted, as all reconstruction steps downstream of the baseline finder are consistent only on the baseline-subtracted WFs.

C.3 Physics cuts

This set of cuts is used to select the specific population of physical events for the low-mass analysis.

C.3.1 Single scatter (CXSingleScatter)

Definition: The number of pulses in the event must be ≤ 4 and match one of the following combinations:

I. Two physics pulses (S1 & S2)

- a) S1, S2
- b) S1, S2, S2_{echo}
- c) S1, S2, S1_{echo}, S2_{echo}

II. One physics pulse (S2-only)

- a) S2
- b) S2, S2_{echo}

Purpose: To remove events that do not represent a DM interaction. Events removed are primarily γ -rays that scatter multiple times in the TPC.

Acceptance: Estimated to be 100%, as the S2 trigger efficiency is estimated to be 100% in the full energy ROI [92].

C.3.2 S2 channel distribution (CXS2ChannelDistribution)

Definition: The fraction of S2 light in the maximum channel must be less than 75%. The S2 top-bottom asymmetry ($S2_{\text{top}}/S2_{\text{bot}}$) must be between 10% and 95%.

Purpose: To remove events where S2 is overly concentrated in a single PMT or in the top or bottom PMT arrays.

Acceptance: Estimated to be 100%.

C.3.3 Fiducial cut in the (x, y) plane (CXFiducialXY)

Definition: The PMT which sees the most S2 light must be one of the seven top core PMTs (channels 24, 25, 26, 29, 30, 31, and 35), as shown in Figure C.2.

Purpose: To remove regions near detector edges where external background event rates are highest. The (x, y) position of each event is set to be at the center of the PMT detecting the largest number of S2 PEs.

Acceptance: The FV fraction is estimated to be 41.9% of the active volume using MC simulations and is independent of S2 size [86].

C.3.4 S2 gate (CXS2Gate)

Definition: The S2 gate, defined as the difference between the S2 end and start times, must be $<100\ \mu\text{s}$.

Purpose: To remove events with overlapping pulses not resolved by the pulse finder algorithm.

Acceptance: The energy-dependent combined acceptance of the CXS2Gate and CXS2PeakTime was estimated using MC simulations, see Figure 3.18.

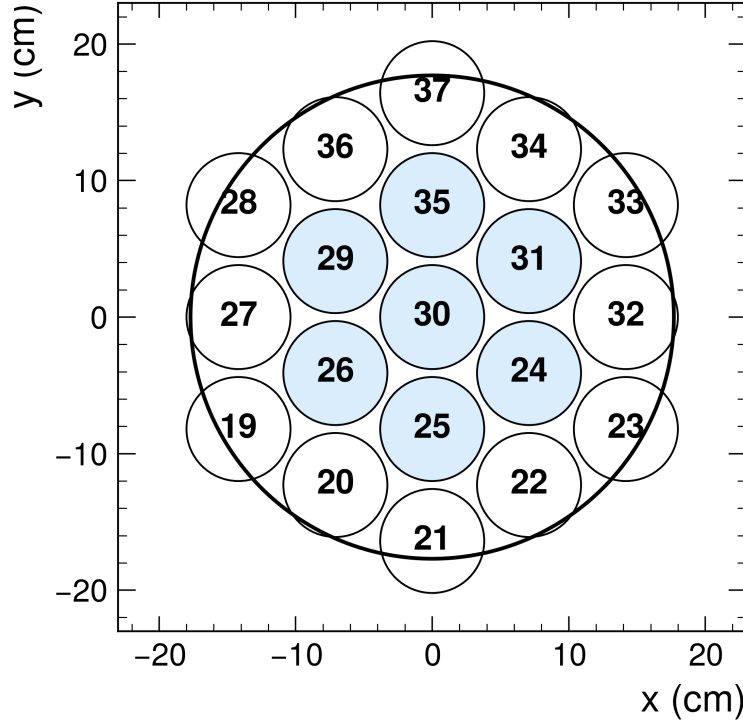


Figure C.2: DarkSide-50 top PMT array diagram. Core channels that define the fiducial volume are shaded *blue*, while outer ring channels are shaded *white*. The core channels contain two types of PMTs: a central PMT (channel 30) and ring PMTs (channels 24, 25, 26, 29, 31, and 35).

C.3.5 S2 peak time (CXS2PeakTime)

Definition: The S2 peak time, defined as the time after the start of the pulse at which the maximum channel saw its greatest amplitude, must be $< 6 \mu\text{s}$.

Purpose: To remove events with overlapping pulses not resolved by the pulse finder algorithm, specifically those including a long S2.

Acceptance: The energy-dependent combined acceptance of the CXS2Gate and CXS2PeakTime was estimated using MC simulations, see Figure 3.18.

C.3.6 S1-S2 pile-up (CXS1S2Pileup)

Definition: The S2 peak time, defined in Section C.3.5, must be $\geq 0.2 \mu\text{s}$. The S2 FWHM, defined using a moving average on the summed waveform with a 64 ns gate, must be $\geq 0.1 \mu\text{s}$.

Purpose: To remove S1-S2 pile-up events occurring within ~ 2 mm of the grid. These are observed because the pulse finder algorithm cannot separate two pulses closer than $2\ \mu\text{s}$.

Acceptance: As this condition occurs approximately within 2 mm of the grid ($\sim 0.5\%$ of the entire volume), the acceptance is rudimentarily estimated to be $(99.75 \pm 0.25)\%$, which ranges from no signal-like events within 2 mm of the grid surviving to all surviving.

C.3.7 Event Δt (CXDeltaT)

Definition: The time with respect to the previous trigger (Δt) must be > 20 ms.

Purpose: To remove correlated events, primarily correlated events.

Acceptance: Introduces deadtime of 3%.

C.3.8 S2 start time (CXS2StartTime)

Definition: The S2 start time must be $< 375\ \mu\text{s}$. This cut is only applied to S2-only events.

Purpose: To select valid S2 triggers. There are two possible ways an S2-only pulse can be recorded. In the first, the DAQ triggers on a small S1 pulse which is ignored by the pulse finder. As the maximum drift time is about $376\ \mu\text{s}$, an S2 start time of at most $375\ \mu\text{s}$ ensures the identified pulse is a physical S2 pulse. In the second case, the DAQ triggers on an S2 pulse. Here, the pulse start time must be in the extended trigger region, namely from $-6.10\ \mu\text{s}$ to $-6.0\ \mu\text{s}$.

Acceptance: Estimated to be 99%.

C.3.9 Alphas (CXAlpha)

Definition: The S2/S1 ratio must be within the 99% acceptance band constructed as a function of S1 using calibration data. This cut is only applied to events with both S1 and S2 pulses.

Purpose: To remove events where an α from the TPC creates an S1-only pulse and an $S1_{\text{echo}}$ pulse, looks like a DM interaction.

Acceptance: Defined to have a 99% acceptance.

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