# Detecting Dark Matter: Exploring WIMP Interactions and Background Noise Mitigation in the LUX-ZEPLIN Experiment

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## Abstract

The LUX-ZEPLIN experiment is a cutting-edge dark matter detector that endeavors to detect weakly interacting massive particles (WIMPs), long-sought as one of the prominent dark matter candidates. Located in the deep underground Sanford Underground Research Facility, it uses the biggest liquid xenon detector yet to capture rare interactions between dark matter particles and xenon atoms. This experiment hopes to differentiate between dark matter signals and background noise by detecting the light and electrons associated with these interactions, as one of the most sensitive experiments in search of dark matter, improvement in the shielding and analysis systems could provide new perspectives on the universe's unseen matter. This paper compares the LUX-ZEPLIN (LZ) dark matter detector with other detection technologies - in particular, solid-state detectors and liquid noble gas detectors. The critical analysis is set in motion by a detailed characterisation of the novel working principles of the LUX-ZEPLIN detector, pointing out the dual-phase xenon time projection chamber as a highly sensitive method for detecting Weakly Interacting Massive Particles, which is one of the leading candidates for dark matter. The paper compares LZ with solid-state detectors and other liquid noble gas systems, underlining the benefits that come with using a liquid xenon target, especially a very large target mass and the capability to distinguish between nuclear and electronic recoil events.

It delves deep into what makes LUX-ZEPLIN sensitive to dark matter interactions, including the sensitivity aspects that arise from background noise that is exceptionally low and placement deep underground at Sanford Underground Research Facility, improving the detection capability. The article details how cross-sections, especially the spin-independent WIMP-nucleon cross-section, are important and how precise measurement of these interactions plays a crucial role in refining dark matter search.

The paper also displays the latest experimental results from LZ, including limits set on interaction rates of WIMP, and prospects for increasing sensitivity and detection limits. These results show that LUX-ZEPLIN is going to be one of the most promising tools for further understanding dark matter, so one may really say it was worth developing.

# Introduction

Dark matter is matter that does not interact with electromagnetic radiation and hence is invisible to telescopes. In this respect, it forms a hidden nature of matter, despite such natures, dark matter is presumed to make up about 27% of total mass-energy in the universe[1] . The large-scale galaxy and cluster structures show the gravitational effects it exerts, holding them together[2]. If dark matter were missing, gravity could not explain the observed speeds of galaxies in rotation. A noticeable shortage of gravitational attraction in galaxies to describe such high rotational speeds has led scientists to believe in the existence of dark matter, whose real nature is a huge mystery in modern astrophysics. The evidence for dark matter primarily comes from rotation curves of galaxies, in which the stars in the outer reaches seem to be moving at speeds that cannot be accounted for by visible matter; gravitational lensing[3] bends light coming from other galaxies as a result of the effect that dark matter has on space; fluctuations in the cosmic microwave background[4] indicate the spread of dark matter; and simulations on cosmic structure formation require dark matter to form larger structures in the cosmos. One of the most interesting theories about dark matter candidates is the WIMPs,[5][6] weakly interacting massive particles. These particles would interact with normal matter only through weak nuclear force and gravity, thus making them elusive entities. One of the leading candidates for dark matter is the Weakly Interacting Massive Particle. These particles would only interact with normal matter through the weak nuclear force and gravity, making them difficult to detect directly. However, detectors such as LUX-ZEPLIN[7] aim to observe rare interactions between WIMPs and ordinary matter by measuring nuclear recoils caused by potential WIMP collisions.

Aside from WIMPs, several other dark matter candidates have been proposed. Axions[8], for instance, are hypothetical light particles that could be detected through their interaction with electromagnetic fields. Sterile neutrinos[9], another candidate, are theorized to be a heavier, non-interacting form of the known neutrinos[10], capable of contributing to dark matter. Macroscopic candidates like primordial black holes[11] could have formed in the early universe and contributed to today's dark matter content.

The LUX experiment that took place from 2013 to 2016 at the Sanford Underground Research Facility is considered a giant leap in detecting dark matter because it utilized an advanced liquid xenon detection system and established strong limits to WIMP-nucleon interactions. The plan was to be extended as the LUX-ZEPLIN (LZ) project in 2017 to improve the sensitivity and capabilities toward the target of finding rare dark matter interactions with the focus on yielding a mass of 10 tons of liquid xenon. [12]Despite many such challenges, such as delays from the COVID-19 pandemic, LZ officially started its data collection in 2022, a new era for properly unraveling mysteries on dark matter and a better understanding of the universe. Liquid xenon detectors have several advantages over other detection methods: solid-state and other noble gas detectors, making them extremely effective in this long search for WIMPs. The detector essentially houses a two-phase liquid xenon[13] time projection chamber, wherein the interaction of dark matter particles with the nuclei of the xenon produces ionization electrons and scintillation light. [14]In the TPC, the ionization electrons drift towards the liquid-gas interface under the influence of a strong electric field of about 100 kV/m and easily transfer into the gas phase from it. This mechanism enhances sensitivity and enables refined measurements of the interaction events. More than 500 photomultiplier tubes surround the TPC (Dual Phase Time Projection Chamber) and detect light from scintillation in the interactions. The light is converted to electrical signals that become important for recording the timing and the intensity of each event. Free-flowing electrons in an electric field will minimize recombination, thereby maximizing the signal detected. The detector is placed inside a huge water tank that absorbs stray radiation and cosmic particles to minimize background interference. In addition, the LZ operates at cryogenic temperatures of around -100 degrees Celsius to retain liquid xenon properties so that sensitivity will be improved. There should also be a xenon purification system where impurities are continuously removed to maintain purity at high levels. Finally, the data acquisition and analysis system are crucial in interpreting the signals captured by the PMTs. Advanced algorithms filter out background noise from any real dark matter interaction. The LZ Detector, through its innovative design and robust components, will unveil the mysteries behind dark matter and significantly advance knowledge of the universe.

This paper is organized as follows, section 1 discusses the comparison between solid-state detectors, such as those using germanium and silicon, and liquid xenon (LXe) detectors like those used in the LUX-ZEPLIN (LZ) experiment. Solid-state detectors are known for their extremely high energy resolution, which makes them effective for detecting low-mass WIMPs due to their ability to observe small energy depositions. However, they are limited by their small target mass, as it is challenging to obtain large, high-purity crystals of germanium or silicon. This limitation reduces the probability of detecting rare WIMP interactions.

Section 2 discusses the comparison between liquid xenon (LXe) detectors and other liquid noble gas detectors, such as liquid argon (LAr) and liquid neon (LNe), which are also used to detect dark matter. One of the key differences among these gases is their atomic mass and number, with xenon having a much higher atomic number (Z=54) compared to argon (Z=18) and neon (Z=10). This makes xenon more sensitive to spin-independent WIMP-nucleon scattering, as the larger nucleus increases the probability of interaction with WIMPs. While LAr and LNe are more sensitive to lower-mass WIMPs, their overall cross-section for WIMP interactions is smaller than that of xenon.

Section 3 examines the working mechanism of the LUX-ZEPLIN (LZ) Detector advanced facility designed to detect dark matter particles through interactions with liquid xenon (LXe). Situated in the Sanford Underground Research Facility in South Dakota, LZ's depth provides strong shielding from cosmic rays and environmental radiation, meaning a huge reduction in background noise. Thus, the odds of spotting dark matter interactions increase. Section 4 We will talk about the sensitivity of the LUX-ZEPLIN experiment for detecting dark matter, especially of the WIMP variety. Important factors that will dictate this sensitivity are the WIMP-nuclei interaction cross-section, the enormous volume of liquid xenon used, and crucially, the elimination of significant background noise through the experiment being located deep underground. We will further analyze the efficiency of the detector in differentiating a true WIMP signal from background noise. A comparison shall be done by a graph which plots LUX-ZEPLIN's predicted sensitivity and limits set by previous experiments such as XENON1T and SuperCDMS. In section 5, We shall, in this section, present some sources of background noise that may interfere with the LUX-ZEPLIN (LZ) experiment, one of the next-generation dark matter direct detection experiments. The sensitivity of LZ will depend on its background signal suppression or mitigation to the rare interactions between WIMPs. We discuss some environmental factors, cosmic rays, neutrons and muons. In section 6, we will examine the current results and limits set by the LUX-ZEPLIN (LZ) experiment in its search for dark matter. Additionally, we will explore how these findings compare with or constrain existing theoretical models of dark matter.

## 1. Comparison with Solid-State Detectors

Germanium[15] and silicon[16], in solid form, have been the most common base for WIMP detectors. Such detectors have extremely high energy resolution (Refers to a detector's ability to accurately measure very small amounts of energy. In dark matter detection, this is important because WIMPs are expected to produce only tiny amounts of energy when interacting with matter); they can observe even very small energy depositions by releasing events, which is particularly important in detecting interactions from low-mass WIMPs. The target mass (The total amount of material in a detector that is available to interact with particles like WIMPs. A larger target mass (refers to the amount of liquid xenon used within the detector that is actively available for interactions with particles, such as Weakly Interacting Massive Particles) increases the chances of detecting rare interactions) of solid-state detectors is generally quite limited. Because germanium and silicon crystals are difficult to obtain in large, high-purity volumes, this limits the overall size of these detectors. Consequently, they provide fewer target nuclei for WIMP interactions, thus lowering the overall detection rate for these rare events.

Liquid xenon detectors, like LZ, can be scaled up much larger. [17]For example, in the LZ experiment, several tonnes of liquid xenon are used; this causes a dramatic increase in the number of possible interaction sites. This is a large mass that not only enhances the sensitivity of the experiment to WIMPs but also more readily detects rarer interactions due to the elusive nature of dark matter[18]. Although solid-state detectors could be highly sensitive to light WIMPs, large volumes of detectors made from xenon make them better suited for probing a wider mass range for WIMPs, especially heavier masses where the WIMP-nucleus interaction cross-section[19] is larger (the WIMP-nucleus interaction cross-section is a larger term refers to the likelihood that a WIMP will collide with and interact with an atomic nucleus. A larger cross-section means a higher probability of interaction, especially with heavier WIMPs).

Another important area is the potential to differentiate between background noise. The surface event problem (In solid-state detectors, particles interacting near the surface can create signals that mimic WIMP interactions. [20]This makes it difficult to distinguish between real and false signals) often trouble solid-state detectors, for background particles interact near the detector's surface and generate signals that can masquerade as the desired WIMP signals. LXe detectors, by contrast, have excellent background rejection. LXe detectors use both liquid and gaseous phases to measure both the scintillation light (Scintillation light is a type of light produced when certain materials, known as scintillators, absorb high-energy particles such as electrons or gamma rays and then re-emit the energy in the form of visible light) as well as the ionization electrons (ionization electrons are electrons knocked off atoms during an interaction) produced by particle interaction. The combination of these two measurements provides an excellent discrimination mechanism between nuclear recoils (Nuclear recoil occurs when a WIMP hits an atomic nucleus), which are potentially induced by WIMPs, and electron recoils (electron recoil happens when background particles hit electrons), which are more likely to be caused by background particles like gamma rays. That kind of discrimination is much more difficult in solid-state detectors, usually relying on single-phase detection and therefore more susceptible to background contamination.

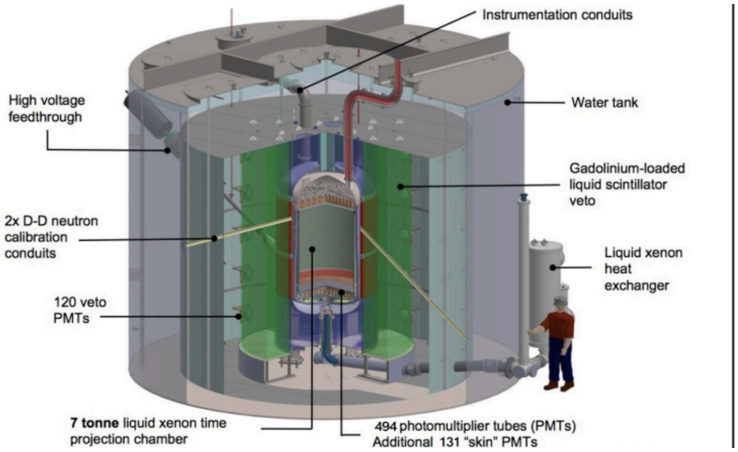
## 2. Comparison with other liquid noble gas detectors

[21]Some other liquid noble gases (these are inert gases that do not easily react with other elements) when in their gaseous form but can be made into liquids) are used to detect dark matter including LAr and LNe. However, they have different merits and demerits relative to Xe. One of the major differences among these gases is in the atomic mass and number. The atomic number of xenon is greater than that of argon and neon (Z=54; compared to the respective Z values for argon and neon, Z=18 and Z=10), so the nucleus is larger. This means the sensitivity of xenon to spin-independent WIMP-nucleon scattering is vastly higher than that of argon or neon because the interaction probability is greater with more massive nuclei. Liquid argon and liquid neon are less dense and are thus more sensitive to lower-mass WIMPs, but their overall cross-section (cross-section refers to the probability of interaction between WIMPs and atomic nuclei) for WIMP interactions is smaller than that of xenon.

**Background suppression:** another set of advantages of using xenon. The biggest problem of any dark matter experiment is the ability to distinguish between real signals and background noise. Liquid-xenon detectors are self-shielding (This means that the dense material of the liquid-xenon detectors can effectively block or absorb external radiation like gamma rays, reducing background noise and making it easier to detect dark matter interactions), meaning that the high density of these detectors allows them to absorb better external radiation, like gamma rays, than do the LAr or liquid neon detectors. This further reduces the number of potential background events possibly taken to be an interaction with dark matter. Additionally, unlike natural argon, xenon does not contain long-lived radioactive isotopes such as 39^ Ar that cause severe background in the LAr detectors. To overcome this problem, argon-based experiments have to put much effort into the use of underground sources of argon depleted of 39^Ar, which complicates the working of this kind of experiment. On the other hand, xenon does not suffer from this problem and it is easier to purify and maintain in the low-background environment.

Liquid xenon also operates at a higher temperature, about 165 K, than argon (87 K) or neon (27 K). On the other hand, the higher boiling point of xenon does not greatly detract from its convenience, either in its handling or in its detectors, again relative to argon, much less so for neon. Since it is easier to operate in large quantities, this is an important advantage of xenon detectors in experiments such as LZ, where many tonnes of the material are used. It will also lower the system complexity and energy costs (System Complexity and Energy Costs refers to how complicated and expensive it is to set up and maintain the cooling systems needed for the experiments. If a detector operates at a higher temperature, it simplifies the process and reduces costs. Liquid xenon detectors are easier to handle in large quantities, which is beneficial for experiments that require a lot of material, like the LZ experiment) of cryogenic cooling (This is a method of cooling substances to very low temperatures, which is necessary for keeping noble gases like xenon in liquid form. The temperature for liquid xenon is about 165 K (which is about -108 °C or -162 °F), while argon and neon are kept at even lower temperatures).

## 3. Working Principle of the LUX-ZEPLIN Detector



This image is taken from the Berkeley Lab website

**Location and Shielding:** The Function of the Underground Facility Located nearly a mile underground in the Sanford Underground Research Facility (SURF) in Lead, South Dakota, the LUX-ZEPLIN detector is placed in a sort of unique location for the success of the experiment: for shielding from cosmic rays that could produce false signals in any particle detectors. Cosmic rays hit Earth constantly; without the natural shielding created by Earth's crust, these interactions would greatly interfere with the detection of such rare dark matter interactions. Apart from the natural shielding of the underground facility, the LZ detector uses multiple layers of artificial shielding. The detector is surrounded by a very large tank of water that will help cut through the environmental radiation background noise. More to this, the water tank is fitted with photomultiplier tubes (PMTs), which can detect and identify any remaining particles that may have an impact on the experiment.[22]

**Dual Phase Time Projection Chamber (TPC):** The main core of the LZ experiment is a dual-phase liquid xenon time projection chamber or TPC. This allows for the detection of the faint signals that occur due to WIMP interactions. The chamber is a device consisting of a liquid xenon-filled device that acts both as the target for WIMP interactions and the detection medium itself. This detector is a dual-phase detector, indicating it runs in two states: liquid and gas.

In the context of WIMP (Weakly Interacting Massive Particles) interactions, the cross-section is a fundamental parameter that quantifies the likelihood of a collision between a WIMP and a xenon nucleus.

It can be thought of as an effective target area that characterizes how likely a WIMP is to interact with the nucleus. In dark matter experiments, there are two important cross-sections to consider:

**Spin-Independent (SI) Cross-Section**: Spin-independent cross section represents those interactions that are un-dependent on the intrinsic spin of the nucleus. In such interactions, the WIMP interacts with the nucleus as a whole, rather than interacting with individual nucleons, namely protons and neutrons. A basic property defining SI is that the cross-section, which gauges the probability of interaction, scales with the atomic mass of the nucleus squared ($A^2$). In this sense, WIMP-SI interactions can be highly probable between such heavy nuclei as, in the case of LUX-ZEPLIN detectors, xenon and WIMPs due to their high number of nucleons. In most experiments, it is the spin-independent cross section that is of interest, as it's easier to have large, heavy nuclei detect SI on those. The majority of experiments set limits on the SI cross section versus the WIMP mass, so that sets limits on a possible WIMP-nucleus interaction**.** [23] The spin-independent (SI) cross-section is given by

$$\sigma_{SI} = \sigma_n \frac{u^2}{u_n^2} \frac{(f_p Z + f_n (A-Z))^2}{f_n^2} = \sigma_n \frac{u^2}{u_n^2} A^2$$

Where:

- $\sigma_{SI}$ represents the spin independent cross section
- $\sigma_n$ is the reference cross-section for dark matter interactions with a single nucleon (neutron or proton).
- $u$ is the relative velocity of the dark matter particle.
- $u_n$ denotes a characteristic velocity scale, often associated with the average velocity of dark matter particles in the local galactic halo.
- $f_n$ and $f_p$Coupling factor to protons.and Coupling factor to neutron
- Z and A: Z is the atomic number of the nucleus, which indicates the number of protons. A is the mass number, representing the total number of nucleons (protons + neutrons) in the nucleus. The term $f_n Z + f_n (A - Z)$ thus calculates the overall effective coupling of the dark matter to the entire nucleus, accounting for both protons and neutrons.
- Here, $A^2$ emphasizes that the detection probability increases with the square of the mass number of the target nucleus, reflecting how larger nuclei (with more nucleons) provide a greater target for dark matter interactions.

**Spin-Dependent (SD) Cross-Section**: On the other hand, spin-dependent cross-section refers to interactions dependent on nuclear spin. For WIMPs to interact in a spin-dependent manner, they must couple specifically to nucleonic spins that are unpaired either as protons or neutrons. Usually, this interaction is weaker compared with the spin-independent interaction since only nuclei sensitive to SD are those with unpaired nucleons which are like specific isotopes. Thus, the number of possible target nuclei is smaller, and the overall rate of interaction is reduced. The spin-dependent interactions do not scale with the mass of the nucleus but depend on the spin configuration of the nucleons. Experiments such as LUX-ZEPLIN, which are primarily designed for SI interactions, can also be used to look for SD interactions, though with sensitivity typically somewhat poorer. Limits on SD cross-sections offer further constraints to theories in which WIMPs were supposed to couple more strongly to nuclear spin than to mass. [24] The spin-dependent WIMP-nucleus cross section can be expressed as

$$\sigma_{SI} = \frac{32 G_F^2 \mu_N^2}{\pi} \frac{(J+1)}{J} \cdot \left(a_p \langle S_p \rangle + a_n \langle S_n \rangle\right)^2$$

- $G_F$ is the Fermi coupling constant
- $\mu_N$ is the WIMP-nucleus reduced mass
- J is the total spin of the nucleus.
- $S_p$ and $S_n$ are the proton and neutron spin expectation values, respectively.
- $a_p$ and $a_n$ are the WIMP couplings to protons and neutrons.

The table below summarizes the cross-section sensitivities that LZ aims to achieve:

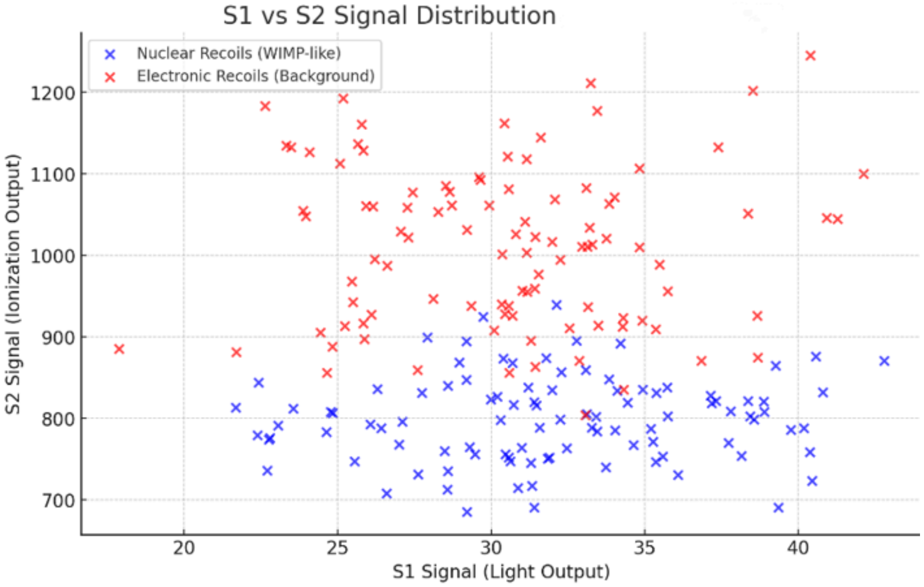
| Type of Interaction | Cross-Section Sensitivity | WIMP Mass Range |
|---|---|---|
| Spin-Independent (SI) | 1.4×10−48cm^2 | 1 GeV/c^2 to several TeV/c^2 |
| Spin-Dependent (SD) | ~10−43cm^2 | 1 GeV/c^2 to several TeV/c^2 |

When energy is transferred to a xenon nucleus during a WIMP collision, it triggers two primary types of signals: scintillation light (S1) and ionization electrons (S2). Together, these signals serve as crucial indicators for dark matter detection. The cross-section plays a crucial role in determining the rate at which these collisions occur, influencing the signals produced in experiments designed to detect dark matter. These two signals, arising from the nuclear recoil, include:

**Scintillation Light (S1):** [25] The excited xenon atoms emit scintillation light as they return to their ground state. Ionization Electrons Furthermore, electrons may be knocked off the xenon atoms, leading to ionization(S2). Scintillation light plays an important role in detection. The first sparks that indicate that there may be an event are the scintillation lights produced when a WIMP interacts. The measurement of both S1 and S2 signals raises the sensitivity of the experiment. Scientists can better distinguish WIMP interactions from background noise through analysis of the ratio of S2 over S1 and thus greatly increase the chances of concluding that a true dark matter signal has been detected. However, the detection of WIMPs is complicated by various sources of noise that can obscure or mimic the signals produced by true interactions. One significant source of noise is background radiation. This includes natural radioactivity from isotopes present in the environment, such as uranium, thorium, and potassium-40. [26]These isotopes can emit gamma rays and beta particles that interact with the xenon atoms, generating both scintillation light and ionization electrons.

## S1 vs. S2 Signals Distribution

The plot below demonstrates the separation of WIMP-like nuclear recoils events and electronic recoils background events:



Now, regarding this plot S1 Signal represents the scintillation (light) signal created when a particle interacts with the liquid xenon. It's on the x-axis, showing how much light (S1) is emitted as a result of the interaction. S2 signal represents the ionization signal, generated by the freed electrons that drift towards a gas region in the detector, creating a secondary light signal. It's on the y-axis, showing the amount of ionization (S2) caused by the interaction. Blue Dots (Nuclear Recoils, WIMP-like) represent nuclear recoils, interactions that could be caused by dark matter particles like WIMPs (Weakly Interacting Massive Particles). The blue dots are generally clustered in the lower region of the graph (lower S2 values) because nuclear recoils typically produce less ionization compared to electronic recoils. Red Dots (Electronic Recoils, Background) represent electronic recoils, which are more likely to be caused by background particles such as gamma rays or beta particles. The red dots are higher up on the y-axis (higher S2 values) because electronic recoils typically produce more ionization than nuclear recoils. The blue dots (WIMP-like events) and the red dots (background events) have some partial overlap, indicating that there could be some difficulty in distinguishing between dark matter signals and background noise.

**Photomultiplier Tubes (PMTs):** In the LUX-ZEPLIN experiment, PMTs are critical in capturing both scintillation and electroluminescence light, thus providing the necessary sensitivity to detect potential WIMP interactions. This includes scintillation light; it occurs due to the excitation of the xenon atoms within the liquid upon being struck by a dark matter particle. [27] The return of the excited xenon atoms to their ground state emitted photons of ultraviolet frequency, typically at 178 nm. The other type of signal is electroluminescence [28], which is caused by the fact that the freed electrons, ionized from the initial interaction, drift in the upward applied electric field to the gaseous xenon layer. This will cause excitation of gas-phase atoms of xenon during collisions with these electrons and, as a consequence of this process, there will be an emission of photons at other wavelengths in the visible spectrum, especially in the range 1,000 nm to 1,300 nm. In characterization, the amount of scintillation and electroluminescence light is also crucial to be found since it contributes to the total signal collected by PMTs.

Such PMTs can differentiate between dark matter signals and background noise using a few sophisticated methods. In one of those methods, known as timing analysis, the time of arrival of light signals at different PMTs is cross-referenced. Dark matter interactions produce correlated signals time-synchronized, while the noise typically caused by background is randomly uncorrelated. Dark matter signals are distinguished from background noise by advanced methodologies involving several PMTs . One such methodology involves timing analysis, wherein the PMT contains multiple photodetectors that measure the light signal at different arrival times and cross-reference them. The characteristics associated with the time synchronization of correlated signals generated due to dark matter interactions and random and uncorrelated background noise distinguish the different features.

However, the type of events can also be distinguished by measuring signal intensity. Dark matter interactions give rise to some level of intensity as determined by the expected energy deposited into potential collisions, whereas most background radiation emits a wide distribution of intensities. A huge amount of data has to be analyzed by the researchers to further improve discrimination with advanced statistical techniques and machine learning algorithms. This is achieved when such algorithms are trained on previously characterized events to make optimizations in identifying a potential dark matter signal.

In addition to that, spatial distribution analysis plays a highly important role. The pattern of light collection across the array of PMTs may be indicative of the location and nature of the interactions, allowing researchers to reconstruct the topology of the event. This multidimensional approach greatly enhances the accuracy of separating between valid dark matter interactions and background signals. The interpretation of the signals coming from PMTs in the LUX-ZEPLIN experiment poses several technical challenges. However, the primary areas of concern include background noise containing cosmic rays, radioactivity, and other source contributions in broad ranges of frequencies. These background noises could overwhelm the weaker signals produced by dark matter interactions as they obscure meaningful data extraction.

Variability of signal characteristics would also imply complicated dark matter event identification. The level of variability involves energy levels by the source, scattering angles, and even interaction types; these make it very hard to distinguish between signals and noise due to immense variability in light emission. Such a massive amount of data throughput from the PMTs poses a significant challenge in terms of processing the data. Sensitive and precise data analysis and acquisition of high volumes of events call for very strenuous systems that can filter and analyze data without losing sensitivity or accuracy. The PMTs must also be calibrated. There is a shift in the performance of detectors based on time due to environmental influences or aging elements, which might alter the sensitivity over a while. [29] Calibration runs are essential at appropriate intervals to ensure that the PMTs are functioning within their optimal ranges of performance to limit the possibility of misinterpretation of a signal.

Finally, there is an intrinsic physical limitation imposed by the technology itself. Although the PMTs are responsive to very small levels of light, there is a lower boundary below which they lose effectiveness in detecting signals; hence, it demands the continued need for technological innovations in the design and materials of PMTs to enhance their sensitivity and overall performance in future experiments.

**Electric Field:** The operation of Photomultiplier Tubes (PMTs) is intricately linked to the application of an electric field, which enhances their sensitivity by facilitating the movement of charge carriers generated from scintillation events. Keeping the created ionized electrons drifting within the liquid xenon by a strong electric field, once the xenon atom collides with the dark matter particle, it creates light and, in addition, ionizes the atom by removing electrons from it. Those freed electrons are then drawn upwards toward the gaseous xenon layer at the top of the chamber by the electric field. The energy of the electrons collides with the gas, thus creating a second flash of light; this is what allows the experiment to measure the total ionization produced. The electric field is controlled in such a way as to allow for the drift of the electrons to be smooth and consistent, which enables the reconstruction of the event and the separation of real dark matter interactions from noise or interference sources. [30] The first requirement is that all materials coming into contact with the liquid xenon be non-conductive and tolerate low temperatures without degrading or expanding/contracting to an extent that might distort the electric field. Therefore, the electrodes are constructed using special materials such as cryogenically stable metals and insulators. Another challenge is the breakdown by the electric field (sparking) in a high-voltage environment. The detector design involves critical electrode spacing and surface finish which will eliminate sharp points and edges that may lead to electrical discharges. Another crucial function is that continuous monitoring systems are capable of picking the performance of the electrical field. Since small fluctuations are easily detectable and correctible, the system uses these feedback systems to ensure a smoother and steadier electric field for ideal measurements. Other interference factors that might impact the electric field inside the LUX-ZEPLIN detector include mechanical vibrations, thermal fluctuations, and electrostatic discharges. These will temporarily disturb or fluctuate the field, affecting the drift of the ionized electrons that may lead to noisy or distorted data. To avoid such interference, the detector is isolated with great care from external sources of vibration or noise. [31] It is kept underground for protection against environmental influences. Also, the temperature of the cryogenic system is held strictly in limits to prevent thermal fluctuations that may move the electrodes and the xenon medium. Another mitigation strategy employs redundant and symmetrical electrode configurations such that, even with a small disruption, the electric field would be uniform. Voltage monitors continuously monitor the stability of the electric field, and feedback systems could adjust the field in real time, which would thus correct small instabilities.

**Water Tank Shielding:** In addition to the electric field's role, effective water tank shielding provides a critical barrier against external radiation, ensuring that the signals detected by PMTs are primarily due to interactions within the xenon**.** [32]The water tank surrounds the LUX-ZEPLIN detector; it serves to shield the experiment from environmental radiation such [33] as neutrons and gamma rays that interfere with the detection of dark matter. Water is highly effective in cooling and neutron capture. Neutrons are among the main sources of background noise. Neutrons could fake signals like those expected from the interactions involving dark matter. In Section 5, we will delve deeper into the implications of neutron backgrounds and their management strategies in the LZ experiment. Thus, their suppression of the detector is important. The energy of the neutrons going to the xenon detector is decreased through Neutron elastic scattering by collision with hydrogen nuclei in the water; this reduces the probability of neutrons reaching the xenon detector. [34] Gamma rays are another source of interference: they are absorbed by Compton scattering in the water. In this manner, the water tank acts as a buffer in such a way that only the deepest penetrating particles—if any—will reach the sensitive xenon volume, which helps give the detector the specificity of true dark matter signals and avoid background events. Water is a good protecting material against some types of radiation but, on the other hand, it is outperformed by several other materials.

Its principal advantage is the possibility of protecting against neutrons because of a high presence of hydrogen, but with gamma-rays, lead has many advantages since its density is much higher than water's, thus, it can more effectively attenuate gamma radiation in a thinner layer. Other materials like polyethene are also good neutron shields but are probably not too handy for such large-scale experiments due to their cost and the problem associated with scaling them to the size they are needed to blanket the entire system. Of course, a disadvantage of water is its bulk-in addition to being quite effective at neutron shielding, one would need a huge tank to get an attenuation that might be impractical in most experimental configurations. Water also cannot be able to protect against all forms of radiation, which include high-energy gamma rays that require additional types of shielding

materials. For LUX-ZEPLIN, the choice of water comes in that balances out the factors of availability, cost effect, and effective shielding for the types of radiation most likely to interfere with the dark matter signal. Keeping the water in the shielding tank pure is of supreme importance because impurities could lead to the presence of new backgrounds coming from naturally occurring radioactive isotopes that might mimic the signals arising from dark matter interactions and dilute the sensitivity of the experiment. Therefore, the water in the tank is purified to an extreme degree. This could involve filtering systems and deionization to remove particulate matter and dissolved ions that may be carrying radioactivity with them. The continuous circulation of water can minimize the entry and presence of contaminants entering the system, provided that the removed contamination is properly degraded. Furthermore, the choice of materials that are to construct the tank itself has taken into account the low levels of radioactivity. In some experiments, the water is also checked for traces of radon, the naturally occurring radioactive gas, and for other isotopes periodically. Radon in particular can dissolve in water and may be a major problem in low-background experiments, therefore any water that enters the system is checked for this gas and treated appropriately. The size of the water tank will directly affect the shielding effectiveness. The water tank must have a width to absorb or scatter neutrons and gamma rays before they have a chance to hit the detector thoroughly. For the width of the LUX-ZEPLIN water tank, a 10m width was used based on the calculations and simulations of the expected radiation levels of its underground and the types of particles that the detector needed to be shielded against. The 10-meter size proved sufficient to absorb most neutrons and reduce gamma rays enough not to interfere with the search for dark matter. The choice of dimensions was derived from balancing the requirement for effective shielding against space and cost constraints in the actual underground facility. If it was too small a tank, then neutrons and gamma rays could go through, again with added background noise but enlarging it would prove to be well within diminishing returns since, by this distance, the gamma radiation was adequately damped out by 10 meters of water.

To date, the water shield is of high efficiency in LUX-ZEPLIN. Future upgrades may include improvements based on newly found features or changes in experimental requirements. The researchers are always in search of better means to improve their sensitivity in dark matter detectors; the background noise remains one of the key areas of focus. Future developments may also be connected to shielding around the water tank like lead layers to block any of the higher energy gamma rays or precision in the purification of water into lower levels of radioactive contamination. Even the monitoring and maintenance technologies of the water tank could also be further improved with live sensors tracking the radiation levels for better time-specified adjustments. Another potential upgrade would be to employ a liquid scintillator instead of pure water, so shielding while allowing any residual background radiation within the shielding to be detected. It could potentially add another layer of sensitivity for the dark matter search by allowing them to reject anything cosmic rays or neutrons happen to penetrate through the shielding. These would depend on the goals of subsequent experiments and the continued development of shielding technologies.

**Cryogenics:** [35] Maintaining the integrity of the detection system further necessitates the implementation of cryogenic techniques, which not only preserve the liquid state of xenon but also minimize thermal noise that could obscure the detection of faint signals**.** The LUX-ZEPLIN experiment uses the cryogenic system, in which mechanical cryocoolers maintain the liquid xenon in temperatures around -100°C. The commonly used technology found here is the pulse-tube refrigerators or the Stirling cycle cryocoolers [36] and is consequently capable of maintaining low temperatures over a relatively long period. These systems are used in handling high quantities of xenon that would be needed for the detector without losing the state of the liquid itself because gaseous xenon would decrease the detector's sensitivity to a drastic level. [37]

[38] The fluctuations in temperature will also have major impacts on the sensitivity of the detector. The xenon needs to remain stable in its liquid state, since temperature variations may lead to phase changes from liquid to gas, which then allow for variations in light signals produced as a consequence of the particle interactions. Even slight elevations in temperature can introduce noise or degrade the ability of the detector to sort actual dark matter signals from noise in the background. With the constant temperature, the signals that come from ionization and scintillation are captured precisely and uniformly, which then makes the data much easier to interpret.

There are natural challenges to long-term storage at temperatures as low as -100°C. The cryogenic system should not break down under any circumstance, so periodic monitoring and maintenance are necessary. External heat leaks into the system from its environment can sometimes create problems. So, insulation of the system is important to exclude any possibility of heating of the working fluid. There is also the question of the power consumption to be used in keeping the xenon cold for months or years of runtime of experiments. Xenon will warm up, become gas, and then fail to detect any signal when the cooling system eventually breaks down. Providing redundancy in the cooling system and having backup systems is therefore critical in order not to have interruptions in the experiment.

Most of the cryogenic system calls for many safety precautions. In case there is contact with the extreme temperature involved, then it can cause frostbite and thus the researchers near the cryogenic system require protective equipment. Liquid xenon when warmed expands tremendously to form a gas; thus, it requires proper venting to avoid pressure buildup. Therefore, the system includes pressurization relief provisions that protect against any form of over-pressurization. A gas vent in a confined room could displace oxygen and thus pose a risk to asphyxiation, hence proper ventilation and oxygen monitoring systems are necessary. Scientists carry out stringent safety standards to ensure that the system is handled with much care and that routine safety inspections are held.

The cryogenic system is designed to fit seamlessly with the photomultiplier tubes (PMTs) and electric field system in the detector. PMTs should naturally continue to operate at low temperatures within the xenon detector, and the design lends itself well to cryogenic temperatures. The electric field system will be used to drift the ionized electrons, and that too needs to be calibrated for a cryogenic environment. The uniformity of the electric field is critical in directing electrons towards the gaseous xenon layer, and temperature fluctuations would be transitive enough to transfer into the electric field, affecting the stability. The cryogenic system ensures that all these components remain within their operational temperature ranges, working together with minimal noise or interference in the detection and analysis of particles interacting.

In addition, the xenon purification system works alongside these cryogenic elements to ensure minimal impurities within the detector. Alongside cryogenic considerations, a robust xenon purification system is essential to eliminate impurities that could affect both the clarity of the scintillation signals and the overall efficacy of the dark matter detection process**.** The most important impurities to remove include electronegative gases such as oxygen, water vapor, and carbon dioxide, along with others like hydrocarbons. These impurities would just attach onto the ionized electrons produced in interaction with dark matter during a direct dark matter interaction, leading to lesser mobility of these and hence reduced signal strengths. Impurities may also produce their scintillation light or ionization signals which could create noise simulating or dominating those that should arise due to dark matter interactions. Xenon purity must reach a high level to isolate the observed signals as dark matter events rather than noise arising from contaminations. [39]

A circulation system is used to circulate liquid xenon in the purification system, thereby maintaining its purity at the highest achievable level. Typically, the system washes xenon dozens of times per day, so that impurities can be eliminated. Impurity removal is commonly done using one of two processes: getter materials or cryogenic distillation. The principle behind cryogenic distillation is that xenon and the impurities boil at different temperatures so that the xenon can be separated from the impurities. Other getter materials, which can chemically bind to specific impurities, can be included in the purification cycle to trap and remove contaminants from the xenon.

The greater difficulty, however, in maintaining its purity is due to the possibility of recontamination by materials contacted by the xenon. Any leak or permeation from the materials used in the detector can reintroduce impurities into the system. This is because these materials tend to degrade over time, meaning their effectiveness over prolonged periods may be affected, necessitating either replacement or regeneration. Their operating environment must also be well-controlled in the sense that the detector will not introduce atmospheric contaminants such as moisture and particulates into the device. Its maintenance and checking of the purification system becomes essential for easy resolution of these challenges.

Xenon's physical properties may be affected by the purification system. For example, the purity of the liquid xenon may alter with impurities being removed. The purification process also maintains controlled pressure to keep the xenon in a state of liquid inside its chamber. It has pressure management systems that measure and regulate the internal pressure within the xenon chamber to compensate for the pressure fluctuation as a result of the purification process. The system is calibrated to sustain an acceptable level of density fluctuations during detection, thus permitting very precise measurements.

Impurities are detected from time to time by sampling and liquid analysis in the purity level of the xenon purification system. It can be possible to use either gas chromatography or mass spectrometry to detect the levels of impurities present in the xenon. This system is also provided with real-time sensors that monitor temperature, pressure, and flow rates so that the purification process is carried out with specified parameters. Any variation in the expected performance is flagged and subjected to further investigation. Schedules for maintaining and inspecting the system are in place to ensure all components of the purification system function correctly to maintain the sensitivity of the detector and overall detector performance.

**Data Acquisition and Analysis System:** The LUX-ZEPLIN Data Acquisition and Analysis System is intended to detect, digitize (The process of converting analogue signals (continuous signals) into digital data discrete values that computers can process), and record the signals that are produced when dark matter candidate particles interact with xenon nuclei. It consists primarily of a photomultiplier tube-based light detector; a digitizer that converts signals into digital form; and a central processing unit controlling data acquisition and storage. The system is designed to provide the highest precision and speed in capturing events and suppressing irrelevant background signals. Hence, if there is a likelihood of a dark matter interaction, ionized xenon atoms emit scintillation light. This signal by the detectors is sent to digitizers that digitize the analogy signals into digital data. The DAQ (Data Acquisition) system from where the event reconstruction is set in a database where data are filtered and processed for further analysis. [41]

The DAQ provides for a multilevel triggering system that allows only those events that exceed some predefined thresholds to be recorded (for instance, energy levels). This means discarding those low-energy events which are probably not dark matter interactions, thus minimizing the data load. The trigger settings can be changed in real time based on observation to optimize the recording of the DAQ. The advanced filtering algorithms will separate the signal from the background noise. Some of the suggested methods include the analysis of shape, energy thresholds, and statistical methods to clarify patterns related to dark matter interaction by boosting the signal-to-noise ratio.

The DAQ system also facilitates real-time data analysis for monitoring key parameters, such as event rates, energy distributions, and background levels. All this enables rapid checks on the performance of detectors and helps in making decisions about possible adjustments in experimental conditions. The DAQ system uses dedicated software for processing data. [42] The core tools are from ROOT (Rapid Object-Oriented Technology is an open-source data analysis framework primarily developed by CERN. It provides powerful tools for handling large datasets, event reconstruction, and statistical analysis, especially in particle physics experiments), which is a custom-built framework of analysis tailored to manage large datasets and realize many algorithms that allow event reconstruction and analysis. Major challenges include managing data volumes and assuring the accuracy of reconstructing events from noisy data.

Collected data is handled in a hierarchical database system (A way of organizing data in a structured format that allows for easy access and retrieval) designed to ensure easy and efficient access and retrieval. Access protocols, therefore, have been devised for researchers to query and analyze data as much as guidelines that ensure data security and integrity are strictly adhered to. Data is also made available to collaborators and the scientific community under specific agreements. It is also closely integrated with the Xenon Purification System and Cryogenics setup that keeps the detector in optimum operating conditions. For example, changes in temperature or pressure of the xenon can affect the detection of the signals; thus, it will monitor for such changes and alter the process accordingly.

Upgrades of the DAQ system may be designed with an eye toward future development, such as bringing upgraded digitizer technology to increase sampling rates, infusing machine learning algorithms for improved classification of events, and scaling up the potential for data storage to handle larger volumes of data resulting from extended running times. These upgrades could provide a means for greater sensitivity as well as detection efficiency in dark matter signals. [43]

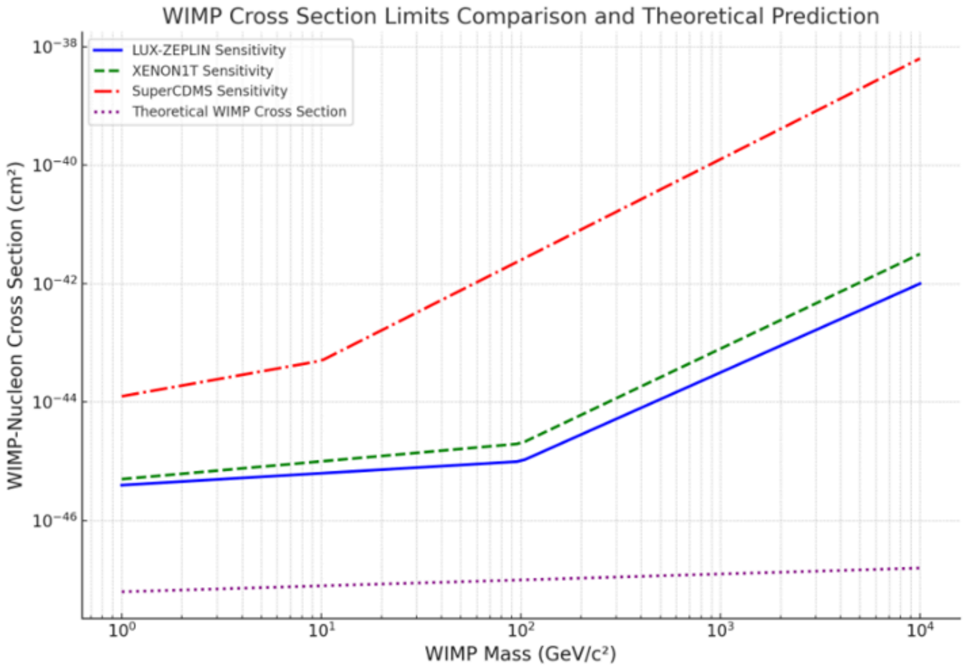
## 4. LUX-ZEPLIN and Sensitivity to Dark Matter

The sensitivity of a dark matter experiment, such as LUX-ZEPLIN, refers to its ability to detect or put limits on dark matter. Sensitivity can be understood in terms of the following:

- **Cross-section** of WIMP interactions with nuclei
- **Detector's size** (LZ has a large volume of liquid xenon, which increases the chance of detecting rare events)
- **Background noise reduction** (the experiment is placed deep underground to minimize interference from cosmic rays and other background sources)

- **Detection efficiency** and the detector's ability to distinguish a real WIMP signal from background noise.

The graph below shows the predicted sensitivity of LUX-ZEPLIN on a blue line relative to the limits set by previous experiments, such as XENON1T with dotted red dashed lines and SuperCDM with a dotted green line. The scales use logarithmic values for the cross-section sensitivity in terms of variations of the WIMP masses. The data incorporated here is purely a theoretical exercise in illustrating possible results resulting from specific assumptions rather than actual experimental results. All values and comparisons should be regarded as hypothetical-only, without reflecting the real results or experimental data from the LUX-ZEPLIN detector. In this case, we will analyze some possible scenarios in terms of WIMP detection and cross-section limits. [44] [45] [46]



The X-axis represents the WIMP mass, measured in GeV/$c^2$, covering a broad spectrum from 1 to $10^4$ GeV/$c^2$. This range captures the potential masses where dark matter particles, specifically WIMPs, might exist. Meanwhile, the Y-axis denotes the WIMP-nucleon cross-section in $cm^2$, which quantifies the likelihood of a WIMP interacting with a nucleon. This axis employs a logarithmic scale to illustrate the exceedingly small interaction probabilities, typically around $10^{-45}$ $cm^2$ or lower.

The plot you see compares how sensitive an experiment (like LUX-ZEPLIN) is to detecting WIMPs at different masses (WIMP masses are shown on the x-axis) and how well it can set an upper limit on the interaction cross section (the y-axis), which measures how likely a WIMP will interact with a nucleon. The plot essentially shows at what level the experiment can detect or exclude WIMP-nucleon interactions, depending on the mass of the WIMP.

A curve isn't linear since WIMPs of different masses interact with the detector differently. Here's how this works out: Low WIMP Masses (left side of the plot) With a light meaning low mass, it does not have much energy to give when it strikes a nucleon in the detector. This makes it harder for the detector to detect these interactions, so the cross-section limit (y-axis) should be higher to exclude possible interactions at those light masses.

Therefore, the curve is large for light WIMPs as the detector is not very sensitive to them. WIMP Mass in the middle of the plot: For intermediate mass values, the WIMP has the right energy to hit the nucleon in the detector. These are easier for the detector to sense since the signals produced by the interaction fall within the optimal range of the detector. Consequently, the sensitivity of the detector is at its best in this mass range and hence, the limit in the cross-section is lower, as even weaker interactions can be detected. This is why the curve dips in the middle detector can detect these interactions more easily, so the experiment sets stronger limits on the cross-section.

High WIMP Masses (right side of the plot): For very heavy WIMPs, they can transfer a great deal of energy when they collide; however, such WIMPs are rarer and slower. It is like searching for a very rare particle that does not interact much. For such heavy WIMPs, therefore, the sensitivity of the detector begins to fall behind, and the cross-section y-axis limit rises again. It can only detect them when they are more frequent or stronger.

*Theoretical Cross Section*: The predicted cross section is much lower than the experimental detection limits. This shows that current detectors might need even more sensitivity to capture true WIMP interactions. The line for the theoretical WIMP cross-section in this plot is an estimate drawn to provide a hypothetical reference. It is important to note that this line does not represent real data—it is simply a visual guide to help illustrate how the WIMP-nucleon cross-section might theoretically vary with mass. No actual detection has been made to support this line, and its precise location and shape remain unknown.

## 5. Background Noise in the LUX-ZEPLIN Experiment

In the search for WIMPs as dark matter candidates, experiments such as LUX-ZEPLIN (LZ) face the daunting task of distinguishing between actual dark matter signals and background noise. Background noise is all signals not due to WIMP interactions and can include cosmic rays, natural radioactivity, electronic noise, and other environmental factors. These two characterisations and reductions of noises are quite critical, and the impact would be boosting the sensitivity and accuracy of detection of dark matter.

One type of background noise source among such is due to the cosmic ray [47] interaction. These cosmic rays are in reality streams of high-energy protons along with atomic nuclei formed in outer space. On coming into contact with the atmospheric molecules at the time of crossing over the Earth, there are produced secondary particles in the form of muons [48] and neutrons. [49] These could penetrate deep underground and therefore reach the detector material where there would be secondary interactions hence producing signals that resemble what WIMPs would. Their high energy makes it possible to produce nuclear recoils in xenon while making it hard to trace the true WIMP event. In addition, through cosmic rays, there arise secondary neutrons which in turn contribute to the overall noise. This can be mitigated by situating the LZ experiment at about 1,500 m underground, which has significantly reduced the flux of cosmic rays due to the overburden of rock. Polyethylene and water are added to further minimize cosmic ray contributions, and the experiment also uses active and passive shielding techniques to monitor the cosmic ray effects and correct them in the data obtained.

There are also radiogenic background noise sources. Radiogenic background noise is from natural radioactivity in materials used to construct the detectors and in the surrounding environment. Common isotopes radon, uranium, and thorium decay and give off a wide variety of particles. These isotopes can provide alpha, beta, and gamma emissions that can create nuclear recoils or scintillation light indistinguishable from those expected from WIMP interactions. For instance, emanation of radon may introduce a substantial background noise if not strictly controlled. The LZ experiment counters this by using ultra-pure materials and judiciously selecting detector components that possess low radioactive contamination. The environment during detector assembly is kept radon-free with techniques of removal of radon to create a clean and controlled atmosphere. Strong shielding made of lead and copper is carried out to reduce gamma and beta radiation contributions from surrounding materials.

Neutrons[50] are another potentially challenging source of background noise. The particles could have origins that are both natural, resulting from the atmospheric interaction with cosmic rays and radioactive decay processes. From the viewpoint of LZ, there will be two problematic sources: slow or thermal neutrons and fast (high energy) neutrons. They may also leave nuclear recoils in a xenon target that gives signals close to what it is supposed to look like for WIMPs. The use of large quantities of hydrogenous materials such as polyethylene near the detector captures neutrons and slows them down, which reduces their energy and subsequently does not induce detectable recoils. The collaboration of the LZ also presents active techniques of neutron detection including counters capable of monitoring and recording levels of neutron background always.

The second type of background noise comes from electronic noise due to the components used for reading out and processing signals produced within the detector. It could be from thermal fluctuations, shot noise, or flicker noise from electronic circuits. Such noise would hide the faint signals generated from the possible WIMP interactions and lead to false negatives in the detection capability. The presence of electronic noise also complicates analysis and the interpretation of results, which is a severe problem with low-energy thresholds. Thus, the advanced signal processing techniques and filtering algorithms through noise in its readout electronics enhance detection of a signal in this experiment. Optimized low-noise electronic circuits will be utilized, and calibration processes will take place to allow for an accurate distinction of real signals from electronic artifacts.

Lastly, there is light and scintillation background that significantly impacts the LZ experiment. The detector uses liquid xenon, which scintillates whenever a particle interacts with it. However, extraneous light sources and other than WIMP interactions will have to produce background signals complicated by true signals. These unwanted scintillation events may be due to radioactive decay or other forms of interactions that mimic the desired outputs from WIMP interaction. For that, the LZ detector was designed with robust light-tight shielding, which helps eliminate ambient light that may interact with the detector. Then, through active collection methods, such as photomultiplier tubes with certain thresholds, scintillation signals that have been identified are relevant to the analysis.

## 6. Current results, limits set and Theoretical Models of Dark Matter in Light of LZ Results.

To the date of 2024, the LZ experiment has accumulated data for 280 days and has established new limits on WIMP-nucleon cross-sections, in particular above 9 GeV/c². This analysis accounts for just about 25% of the total planned data, which has catapulted the sensitivity of this experiment to record levels. [51] LZ has achieved a cross-section sensitivity of about 10^-48 cm^2, proving effective in excluding some dark matter models. Although no WIMPs have been detected, this result is of the utmost importance in helping to hone in our perception of dark matter. Some models that did predict interaction rates much more detectable are now being rejected, hinting that perhaps WIMPs, if they do exist, must either be of lower masses, have weaker interactions, or may in themselves belong to a completely different class of particles than what had previously been anticipated.

This also promises to continue until 2028 and collect 1,000 days of data. So far only about a quarter of the data coming from this experiment have been analyzed. There is still so much more to be discovered in the following years. Another reason why the results are reliable is "salting," which refers to introducing some fake signals to counteract bias when analyzing. The success of LUX-ZEPLIN is an important milestone in the search for dark matter. Because it is still working and collecting data, scientists are quite optimistic that either convincing evidence for dark matter will be uncovered or further constraints on the properties of WIMPs will be obtained to guide future theoretical models and new experiments. [52]

**The WIMP Paradigm: -** WIMPs (Weakly Interacting Massive Particles) have long been one of the main dark matter candidates because of something called the WIMP miracle. The WIMP miracle is an idea that, if WIMPs exist with certain characteristics, they would naturally make up the right amount of dark matter that scientists observe in the universe. This makes WIMPs a convenient solution, as it means they could fit neatly within the current understanding of both cosmology and particle physics. Theories about WIMPs often come from frameworks called beyond-the-standard-model (BSM) theories [53], which suggest particles beyond the usual particles in physics, like electrons and quarks. Some of the best-known BSM theories are supersymmetry (SUSY) [54] and extra-dimensional models: Supersymmetry (SUSY) assumes that every particle has a partner particle, and one of these partner particles, the neutralino [55] , is one of the best WIMP candidates. The extra-dimensional models imply that beyond three spatial dimensions (refers to the different directions or axes along which objects can move or exist in space). and the time dimension, there can be others that make space for new particles with some of the characteristics of dark matter.

These theories predict enormous ranges of WIMP mass (typically from 1 GeV to 10 TeV) and "cross-sections," or chances of interacting with ordinary matter. Experiments like the LUX-ZEPLIN (LZ), built to search for WIMPs based on these theoretical predictions, have seen nothing yet. Simultaneously, discoveries by LZ do reduce the range of possibilities of WIMP as they rule out certain specific characteristics these WIMPs would need to have to possibly be detected. The LUX-ZEPLIN experiment recently set an exclusion limit for WIMPs with a mass of about 40 GeV. This exclusion limit translates to the fact that had WIMPs of that size had interactions stronger than this level, LZ would have probably seen them. Since LZ didn't find any such interactions, the scientists now know that in case WIMPs actually exist, they must interact with regular matter at a much weaker strength than that limit. This eliminates some of the WIMP theories in contention. Theories, where WIMPs interact much more strongly, are now extremely unlikely, and scientists have gone back to the models to determine if WIMPs might still exist, but with even weaker interactions than initially thought. The process of elimination is critical since it allows scientists to narrow down their theories and to be able to narrow in on the most likely explanations.

Supersymmetry (SUSY) is one of the strongest frameworks for WIMP models, especially in forms like the Minimal Supersymmetric Standard Model (MSSM) and pMSSM11 [56]. These models predict several particles that could serve as WIMPs, including Neutralinos, one of the main SUSY particles thought to be a good WIMP candidate. Gravitons [57] , Another SUSY particle, although it’s less common as a primary dark matter candidate. Many SUSY models predicted WIMPs with higher interaction cross-sections, which means they would interact more frequently with ordinary matter. However, LZ’s exclusion limit now rules out many of these higher cross-section WIMP models. As a result, scientists are making adjustments to SUSY models by either: Increasing WIMP mass, which would lower the interaction rate (cross-section). Exploring complex configurations that fit within SUSY but have a weaker interaction with ordinary matter. Each new exclusion limit from experiments like LZ makes simpler SUSY models less likely, which means theorists are often forced to explore more complex parameter spaces to find models that are still viable.

As WIMP theories become more constrained by experimental limits, scientists are increasingly considering other dark matter candidates that don’t follow the traditional WIMP properties. Two promising alternatives are axions [58] and sterile neutrinos [59] . Axions were initially proposed to solve a different problem in particle physics called the strong CP problem [60] in quantum chromodynamics (QCD)[61]. Axions have extremely low mass and interact only very weakly with regular matter, which makes them hard to detect in WIMP-focused detectors like LZ. To find axions, scientists use different detection methods, such as haloscopes and helioscopes **[63]**. Haloscopes detect the electromagnetic effects axions could produce in a strong magnetic field, while helioscopes focus on axions that might come from the Sun. Sterile neutrinos are neutrino-like particles that don’t interact through any of the regular forces in the Standard Model except for gravity, making them very hard to detect directly. Sterile neutrinos could naturally account for the dark matter density observed in the universe. They would likely have been produced in the early universe and would fit well with what we know about dark matter’s effects on cosmic structure. Unlike WIMPs, sterile neutrinos are better detected through indirect methods, such as observing the X-ray emissions from their decay. This makes them attractive candidates as WIMP constraints grow tighter.

**Conclusion: -** The LUX-ZEPLIN experiment has given us insights into the elusive nature of dark matter by using a highly sensitive liquid xenon detector with unmatched precision and exclusion capabilities. The comparisons made between the detectors via comprehensive analysis, reveal that there are advantages with the liquid noble gas detectors over their solid-state counterparts, particularly in noise reduction and maximization of sensitivity to interaction. This comparative basis has firmly cemented LZ's place as one of the leading instruments in the search for Weakly Interacting Massive Particles (WIMPs), which remain the most popular dark matter candidates. This paper details experimental advances that have enhanced sensitivity through the elaboration of working principles and operational mechanics of the LZ detector. Background noise, in this same vein, drives home the rigor of methodologies employed to separate the true signal from environmental and intrinsic noise to improve accuracy and reliability. The combination of the LZ results with the existing exclusion limits would highlight great success in dark matter research. Though full detection of WIMPs is still not attained, the outcome confirms theoretical models that continually refine our comprehension of the possible mass and cross-section range of dark matter particles. Such agreement will mean that indeed, the null discovery of WIMP can equally play a meaningful role in guiding the progress of theoretical models and changing experimental focus. Future experiments will build on the legacy established by LZ, for example with new detection materials or two-phase techniques for sensitivity gain. The LZ experiment is therefore not the end but a step down the ongoing path toward discovering the secrets of dark matter. Improvement in these methods now promises discovery in perhaps the most intriguing question remaining in the universe.

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