Advancements and Challenges in Dark Matter Detection: A Review of the XENONnT Experiment

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Abstract: This study aims to examine the methodology behind the XENON dark matter detector, which utilizes liquid xenon as a medium to detect signals generated from collisions between dark matter and known particles. With the significance of dark matter in galactic orbitals, velocity dispersions, and rotational curves, the potential implications of verifying dark matter through the XENONnT experiment are demonstrated, as well as the similarities and differences with other experiments that sought to directly detect the presence of dark matter in our cosmos. The study further discusses the exact methodology of the experiment, such as the production of photons and energy from the theoretical dark matter-particle collisions and the infrastructure of the XENON detector—namely the photomultiplier tubes and the time-projection chamber utilized for tagging and identifying signals, along with the recovery and storage system RESTOX II—that aids in converting raw signals into interpretable data. Major sources of noise for the detection of dark matter signals–including cosmic rays, radioactive material, and neutron recoil background signals–are explained, alongside the improvements that were made to previous XENON experiments to increase the sensitivity of the detector and to better reconstruct scintillation signals. Particularly, the geographical location of the XENONnT detector, along with the nuclear and muon veto systems are mentioned. Moreover, recent data from the XENONnT experiment regarding enhanced sensitivity and background reduction capability are mentioned, to highlight the implications of these collected pieces of data for future liquid xenon detectors.

Keywords: Xenon; Muon veto; Dark matter; Photomultiplier tubes; Time-projection chamber

1. Introduction

In our current understanding of physics, dark matter has been an undiscovered and rather unidentified substance, mainly due to its peculiarity when interacting with Physical forces and particles. Dark matter, specifically, describes a theoretical, nonluminous, and non-baryonic form of matter permeating galaxies, only confirmed to interact with the gravitational force, among the four fundamental forces of Physics, with certainty. It fails to interact with electromagnetic radiation and the Strong nuclear force nor is there empirical evidence to suggest its definite interaction with the weak nuclear force, contributing to the elusiveness of the substance and the difficulties in direct detection through traditional astrophysical instruments. Dark matter is vital to the composition of the universe, with its impact on the rotation curves of galaxies through the creation of dark matter halos (Sivaram & Reddy, 2007).

WIMPs

A highly plausible candidate of dark matter is proposed to be Weakly Interacting Massive Particles (WIMPs). WIMPs refer to a group of observed and hypothetical particles—including the neutrino—that are predicted to interact with only the gravitational force and the weak nuclear force. WIMPs are one of the most compelling candidates for dark matter in galaxies mainly due to their theoretical abundance, which may accurately compose the density of dark matter predicted to exist (Cerdeno & Green, 2010).

Both the physical characteristics of WIMPs and their capacity to substantiate the quantity of dark matter in the universe places them as a highly plausible explanation for the presence of dark matter, and the detection of such WIMPs would provide an enhanced understanding of the exact identification of dark matter along with its impact on the formation and dispersion of galaxies.

Supersymmetric Implications of Dark Matter

Particularly, the implications of detecting WIMPs lie in the potential extension to the currently established Standard Model of Physics through the concept of Supersymmetry (Bertone, 2010). In essence, the standard model of particle physics is incomplete, and supersymmetry is one hypothesized expansion.

According to the framework of supersymmetry, the particles in the standard model have associated, undiscovered superpartners that are not currently identified in the standard model itself. Regarding the role of dark matter, the standard model alone does not account for the presence of dark matter; however, the superpartners suggested by supersymmetry have conditions that are similar to those of dark matter. Projected superpartners such as neutralinos (superpartners of the Higgs and Gauge bosons), sneutrinos (superpartners of the neutrino), and gravitinos (superpartners of the graviton) could potentially act as viable candidates for dark matter (Garrett & Duda, 2011).

Such a predicted correlation between dark matter and superpartners of currently verified elementary particles, emphasizes the foundational role of dark matter detection in explaining phenomena beyond the Standard Model. The properties of WIMPs—such as weak-scale interactions and stability at a subnuclear level—that have situated them as candidates for dark matter also align with those of certain superpartners like neutralinos. Therefore, with accurate and direct detection of WIMPs and the consequent verification of the presence of dark matter, adjustments would be made to the widely approved Standard model. Such supersymmetric extensions of the model could accommodate the light superpartners for elementary particles (Griest & Kamionkowski, 2000).

2. Direct Detection Through the XENONnT Experiment

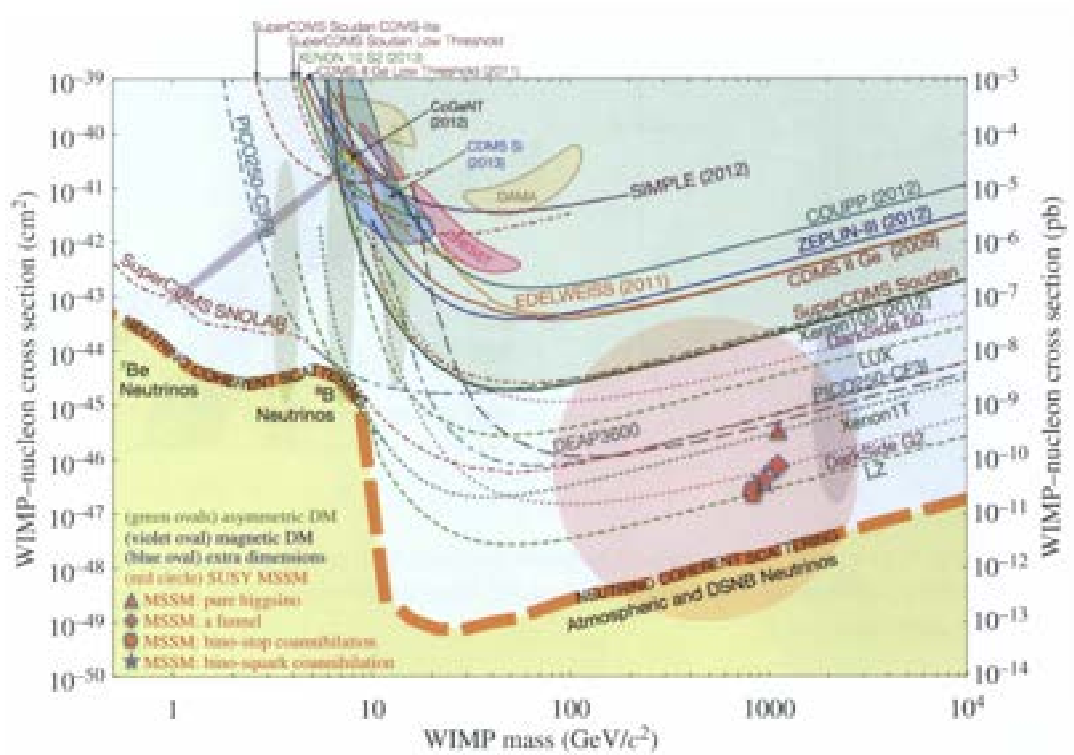

Figure 1. A comprehensive comparison of the sensitivity of different dark matter direct detection experiments. The WIMP-nucleon cross sections, indicators of detectors' abilities to effectively discriminate background signals are graphed with WIMP mass as the independent variable. Floors of Neutrino interactions are also indicated above (Virdee, 2016).

Other Direct Detection Experiments

Two notable direct dark matter detection experiments—other than the XENONnT experiment—were conducted, mainly as attempts to utilize a target material to detect WIMP signals. Primarily, the Super Cryogenic Dark Matter Search experiment (SuperCDMS), utilizes germanium and silicon-based detectors located at the SNOLAB, in Vale Creighton Mine, Sudbury, Canada (National Accelerator Laboratory, 2023). The Cryogenic Dark Matter Search experiment series, with the target material set as germanium and silicon, aims to detect the crystal lattice vibrations along with the ionized signals created from interactions between projected dark matter particles and the target material particles (Albakry et. al, 2022). The experiment collects signals produced by collisions of WIMPs and normal matter nuclei to induce the presence of dark matter.

Another set of experiments, the Large Underground Xenon experiment (LUX), more directly coincides with the XENONnT experiment, due to its appointment of liquid xenon as the target material and its purpose of identifying WIMP collisions. The most recent of the LUX experiments, LUX Zeplin, takes place at the Sanford Underground Research Facility in Lead, South Dakota, USA (Akerib et. al, 2020). The experiment aims to detect nuclear recoil signals that could be caused by WIMP interactions with xenon atomic nuclei (Mount, 2017).

XENONnT

The XENONnT experiment is a part of the XENON project for direct dark matter detection, which—like the LZ—uses concentrated proportions of liquid xenon to detect scintillation signals produced from WIMP collisions with the atomic nuclei of the xenon particles. Located at the INFN Laboratori Nazionali del Gran Sasso, Italy, the XENON detector uses a Time Projection Chamber (TPC) containing ultrasensitive photomultiplier tubes to detect scintillation signals caused by the ionization of xenon atoms through chemical interactions with WIMP particles (Federica, 2017).

The XENON project currently consists of four sub-experiments—XENON10, XENON100, XENON1T, and XENONnT—with improvements to enhance sensitivity and accuracy of both signal detection and removal of background noise made to the detector with the progression of the project (Alfonsi, 2016).

3. Infrastructure and Detection Methodology

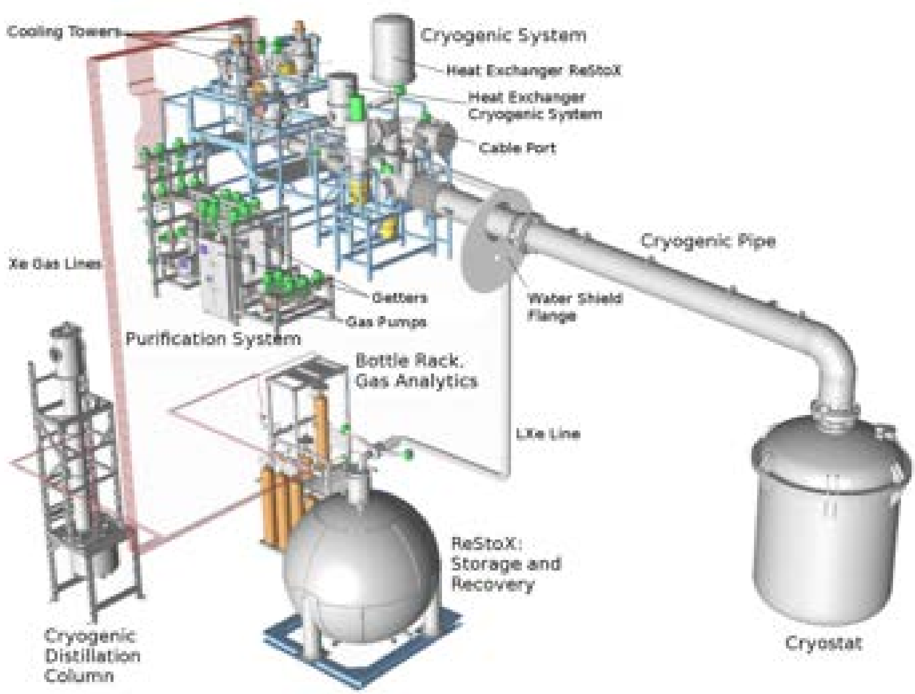

Figure 2. The gas-handling infrastructure of XENONnT is a combination of several key components: the cryogenic system for cooling, the purification system for the continuous removal of electronegative impurities, a cryogenic distillation column for eliminating natural krypton (^{nat}Kr), ReStoX for liquid xenon storage, filling, and recovery, a gas bottle rack for injecting gas into the system, and a gas analytics station for gas chromatography. The cryostat housing the Time Projection Chamber (TPC) is situated within the water shield (Lavina, 2021).

Dual Phase TPC and Installed PMTs

The Dual-phase TPC is a cylindrical implement achieving high reflectivity through its polytetrafluoroethylene (PTFE) frame (Time Projection Chamber, n.d.). Within the TPC, a layer of gaseous xenon is placed on top of the liquid xenon, with PMTs installed on the top and the bottom of the chamber for the prompt detection of produced light. Moreover, surrounding the liquid xenon volume, light reflectors are instated to maximize even the weakest scintillation in the detector (Aalbers, 2022). As evident, the TPC's purpose mainly consists of the identification of particles, capturing scintillation signals created in the ionization process and reconstructing the generated signals to analyze the characteristics of the original WIMP-particle collision through the installed PMTs and the xenon layers.

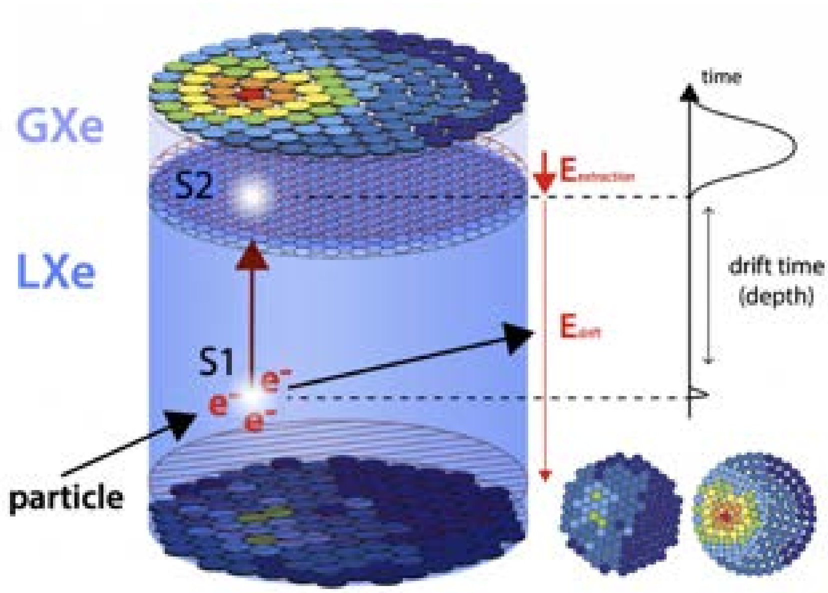

Figure 3. A diagram of the XENONnT TPC. When the scintillation signals captured in both the liquid and gaseous xenon phases of the cylindrical detector are analyzed in terms of time and position to reconstruct the collision activity that occurred (Time Projection Chamber, n.d.).

An important feature of the TPC that allows the accurate capturing of scintillation signals is the ultrasensitive PMTs located at each end of the cylindrical detector. These PMTs are capable of detecting vacuum ultraviolet scintillation produced in the liquid xenon volume, by capturing the individual photons (Polyakov, 2013). Moreover, to refrain from hindering raw signals or from introducing irrelevant background, the PMTs exhibit a high radiological purity (López et. al, 2018).

Recovery and Storage System (ReStoX II)

ReStoX II is an improved recovery and storage system that controls the liquid xenon concentration to be used in the detector. Specifically, the implementation of ReStoX II marks a critical difference between XENON1T and XENONnT, especially from the ReStoX system utilized in XENON1T. With the increased amount of liquid xenon used in XENONnT, a ReStoX II was amplified in size, from the original ReStoX that stored 7.6 tonnes of xenon (Pierre, 2021). The necessity of such a system for liquid and gaseous xenon lies in its ability to not only provide a storage place but also to contribute to the recovery process of used xenon by limiting thermal contact of the xenon concentrations (Lavina, 2018).

Detection Procedure

The detection methodology of the XENONnT detector is grounded upon the generation of photons during WIMP collisions with the atomic nuclei of the target material, liquid xenon, through the PMTs installed in the dual-phase TPC. The theoretical rationale for the experiment is that when a xenon atom undergoes a chemical reaction with the incoming WIMP particle through a direct physical collision, energy and momentum are produced, consequently producing weak scintillation (Time Projection Chamber, n.d.). A total of two scintillation signals are produced and detected by the PMTs in the detection process—s1 and s2—which are then used to determine the time difference between these two signals (Aalbers, 2022).

The prompt scintillation signal (s1) is produced directly when a particle enters the liquid xenon chamber and gives off energy, exciting xenon atoms and emitting photons through nuclear collisions. Generated immediately after the collision takes place, the s1 signal is the first to be captured by the TPC. The secondary scintillation signal (s2) is produced later, as ionized electrons drift through the liquid xenon under an applied electric field and into the gaseous xenon phase (Baudis et. al, 2018). The delay time from the moment the s1 signal is detected to the moment s2 is detected can be used to infer the three-dimensional position inside the detector in which the particle interaction occurred (Aprile et. al, 2020). Moreover, the ratio of the intensity of these two signals provides insight into the exact type of recoil activity exhibited by the collision. By identifying such collision properties—the type of recoil and collision activity along with their position—the possibility that these interactions are caused by WIMPs may either be verified or denied.

Background Sources

For the accurate detection of scintillation signals produced solely from WIMP-particle collisions, background signals such as cosmic rays, irrelevant nuclear and electronic recoil, and cosmic rays must be distinguished from potential signals of WIMPs. Mitigation techniques such as muon vetoes are implemented in the detector to help with such differentiation, while direct improvements to the detector itself have led to increased sensitivity and accuracy of signal collection.

Most importantly, the selection of xenon as the main target material is a crucial aspect of the cryogenic system design aimed at limiting experimental background signals. As a chemically inert noble gas, its lack of radioactivity leads to reduced concerns regarding internal radiation disturbing detector signals when the purity is maintained throughout.

Cosmic Rays and Electronic Recoil Background.

Cosmic rays are a major source of background for signal detection, as they introduce external sources of radiation that may tamper with the scintillation signals or be detected by the PMTs. In particular, the introduction of high sources of energy due to cosmic ray muons tends to enter the liquid xenon detector and collide with the atomic nuclei, causing sources of background that are irrelevant to WIMP collisions (Lavina, 2018).

The permeation of gamma rays and other sources of radiation also provides strong background signals. For instance, the imparting of X-ray photons through photoelectric interactions interferes with the liquid xenon concentration to increase experimental uncertainty (Di Gangi, 2021). Additionally, β decay of external materials such as tritium, radon, and lead isotopes also invoke electronic recoil, leading to the production of background (Aprile et. al, 2020).

With cosmogenic microwave background and gamma rays interfering with scintillation detection, the precise location of the detector along with its utilization of muon veto systems act to discourage such background sources. With the XENONnT detector situated below the Italian Alps, cosmic rays are mostly shielded from entering due to the excess of rocks acting as obstacles for these rays to bypass (Maouloud, 2023). Moreover, muon veto systems are integrated for the shielding of muons, including those introduced through cosmic rays, from entering the detector. Essentially, the muon veto system is composed of a stainless steel cylindrical tank containing deionized water to keep away external neutrons and gamma radiation while tagging muon tracks for easy identification and exclusion from data (Di Gangi, 2021).

Nuclear Recoil Background.

Neutron and neutrino interactions may also produce scintillation signals that resemble those of WIMP-nucleus interactions, acting as another major source of experimental background. Neutron scatterings—which cause the unmediated dispersal of free neutrons—can imitate WIMP interactions as significant experimental noise (Di Gangi, 2021). The scattering of neutrinos and neutrons including the elastic scattering of solar neutrinos and that of radiogenic neutrons would challenge the effective exclusion of these background signals and hinder the sensitivity of the detector.

Thus, to combat such background noise in nuclear recoil, a neutron veto system was installed in the XENONnT detector. The neutron veto system is focused on the identification of radiogenic neutron-induced background signals using a 33 m^3 volume of water with added volumes of gadolinium sulfate octahydrate (gd sulfate) (Aprile et. al, 2024). In essence, this veto system involves the thermalization, the approach to thermal equilibrium within physical systems, of neutrons for capturing and tagging, followed by the detection of photons stimulated by the release of gamma rays in the neutron capture process (Mancuso, 2020). The integration of the neutron veto system allows for the capturing of neutron scattering, ultimately reducing the possibility of nuclear recoil backgrounds.

4. Experimental Results and Analysis

Experimental data and science runs have revealed critical aspects of the recent XENONnT detector, with an emphasis on the detector's improved sensitivity and accuracy compared to previous detectors of the XENON project.

Collected Data

In a 2020 report on the projected WIMP sensitivity of XENONnT, a 99.9% Electronic Recoil rejection rate was projected for a given reference region. Compared to the 99.7% rejection rate of XENON1T, this represented a 0.2% increase in sensitivity regarding the exclusion of Electronic Recoil background signals (Aprile et. al, 2020). However, such projections of XENONnT were derived from experimental parameters found in XENON1T rather than directly from the experiment itself, thus failing to provide a statistical basis for the increased sensitivity.

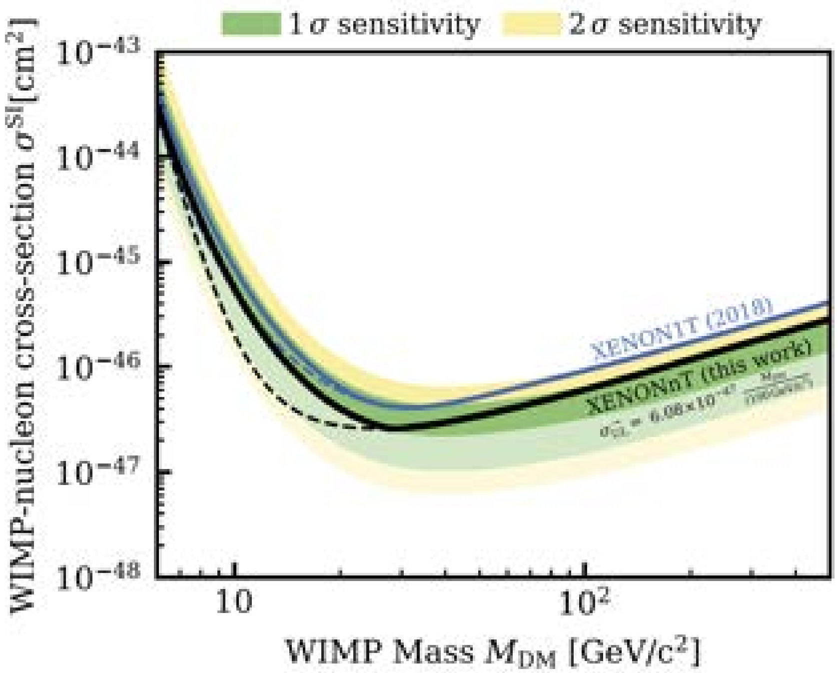

Figure 4. The upper limit of WIMP-nucleon cross-sections at 90% confidence level for XENON1T and XENONnT. The cross-sections of the detectors are shown as a function of the detecting WIMP mass, highlighting a decrease in the cross-sections and an improvement in detector sensitivity (Aprile et. al, 2023).

The most statistically significant and chronologically relevant pieces of empirical data were published by Professors Elena Aprile et. al on July 28, 2023. Upon identifying "nuclear recoil events with energies between 3.3 and 60.5 keV," they failed to discover any significant signals that suggested the definite presence of WIMPs. However, compared to the sensitivity and functionality of XENON1T, the results of the first science run reveal major improvements. In particular, the upper limit of the detected WIMP-nucleon cross-section was narrowed to 2.58×10^{-47} cm^2 for a WIMP mass of 28 GeV/c^2 at a 90% confidence level. Combined with Figure 3, XENONnT ultimately reduced the WIMP-nucleon cross section per WIMP mass (Aprile et. al, 2023).

Additionally, XENONnT reached a total Electronic Recoil background level of (15.8 ± 1.3) events/ton yr keV, which equates to a 5 times reduction from that of XENON1T (Aprile et. al, 2024).

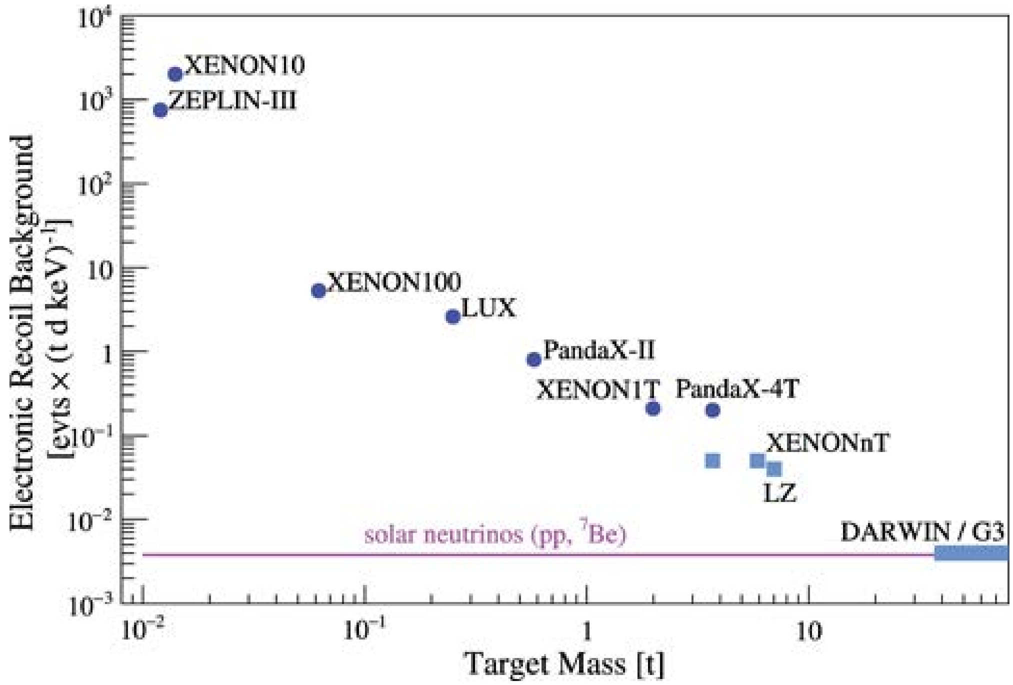

Figure 5. This figure demonstrates an exponential decrease in the background rates in liquid xenon Time Projection Chambers, without electronic recoil or nuclear recoil elimination. With the importance of background reduction for direct collision detectors, this represents a key achievement for enhanced sensitivity in large-scale dark matter detection. XENONnT is positioned with the Lux Zeplin detector and graphically demonstrates a decreasing trend in electronic recoil background when compared to previous XENON project experiments XENON100 and XENON1T (Aalbers et. al, 2022).

Data Analysis

Prominently, the collected data from the first science run of the XENONnT detector—while failing to detect significant particle interactions that could potentially be identified as WIMPs—have experimentally substantiated how XENONnT exhibits increased sensitivity and capacity in signal detection. Compared to XENON1T, it has a greater capability of background rejection, speaking for its higher projected accuracy and ability to extract WIMP collisions among experimental backgrounds focused on nuclear and electronic recoil signals.

The decrease in the upper limit of the WIMP-nucleon cross-section signifies that the experimental parameters of XENONnT have become more stringent. This implies the enhanced sensitivity and background reduction of the detector since improvements to the detector's background removal system would be necessary for more precise limits on the WIMP-nucleon cross-section. With the reduced upper limit, XENONnT demonstrates its capacity to detect weaker signals and better exclude background signals for data analysis. In correlation, the 5-times reduction of the total electronic recoil background level explicitly conveys the improvements to the detector's ability to remove noise. As electronic recoil backgrounds mimicked WIMP signals to distort scintillation signals, an improved recoil background removal rate promises enhancements to future experiments for improved accuracy and sensitivity.

5. Conclusion

In conclusion, XENONnT, utilizing liquid xenon to detect scintillation signals prompted by WIMP-nucleus collisions, is a next-generation technological advancement for the direct detection of dark matter. Its use of the Dual-phase TPC, installed with photomultiplier tubes, combined with the increased xenon volume and improved storage system compared to XENON1T has led to enhanced sensitivity and background reduction. Moreover, veto systems and endeavors to reduce external and intrinsic sources of radiation and nuclear/electronic recoil have also contributed to such improvements, as evidenced by the findings of Aprile et al.

To further improve upon the current circumstances of the XENONnT detection experiment, a greater number of quantitative data for the interaction signals would have to be produced. The statistical insignificance of the data collected by Aprile would later obtain statistical significance or reveal trends once more data collected in future science runs on the XENONnT detector. To support this process, a greater volume of liquid and gaseous xenon could be used, as that would lead to even further sensitivity for signal detection as well as provide an increased number of signals each science run. With such improvements, WIMP detection would progress at a more rapid pace, hopefully verifying the existence of dark matter in its entirety.

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