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Backgrounds in XENON1T

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Summary: The hunt for dark matter with XENON1T

We are missing 85% of the matter in our Universe. This simple statement motivates thousands of physicists around the world to search for and explain dark matter. The first observations suggesting the existence of more non-luminous (e.g., dark matter and neutrinos) than luminous matter (e.g., stars, planets and gas) are now about 100 years old. However, only in the last decade has the field of experimental dark matter physics really taken flight. The reason for this is that more and more ground, sky and space telescopes have measured very precisely how much mass we are really 'missing'. Figure 1 depicts this best: only 1% of the mass of the Universe can be explained by stars (and planets), and only 14% by (diffuse) gas. Without the missing 85% of the mass we cannot explain the beginning of our Universe, the structure formation we see today or even the fact that we have planets and stars. No manuscript can be comprehensive enough to explain all the theoretical and experimental work going on in this field. This summary simply attempts to answer the five main questions that led to the five chapters in this PhD thesis. After the summary, the author gives a personal recommendation of work to further improve the understanding of XENON1T and future upgrades.

Chapter 1: Why do we believe there is dark matter? The first observations of missing matter (non-luminous) were made in the 1920's. Since then, almost all new observations have painted a more precise picture of how much matter we need in order to explain our Universe. Astrophysical measurements include: the Cosmic Microwave Background, colliding galaxy clusters, gravitational lensing, large-scale structure formation and rotational velocity curves of galaxies. The improved sensitivity of these measurements over the last decade constrain the total matter and energy

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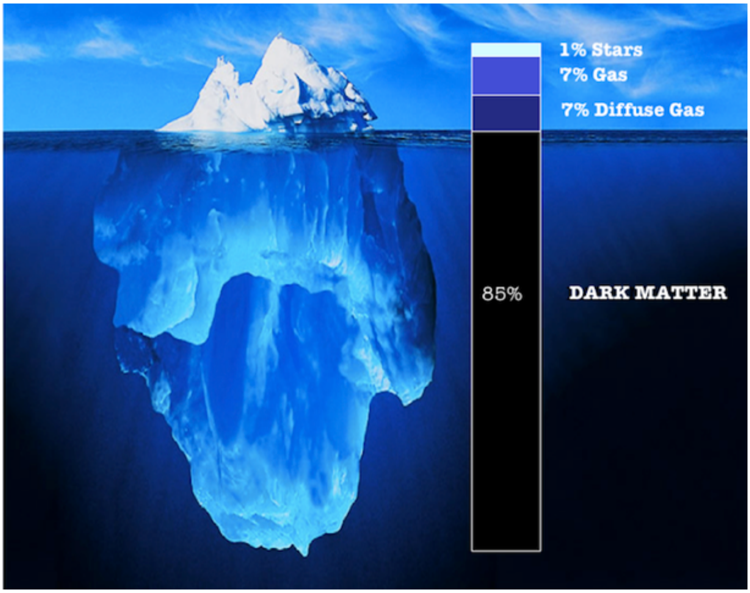

Figure 1: A beautiful iceberg illustrating the extent of our knowledge about the matter content of the Universe. We currently have only observed about 15% of all matter in the Universe (including stars, planets, gas, etc.,). The main part of the iceberg, still being obscured from our vision, corresponds to the missing 85% dark matter. Original image from [1], credits: Ralph Clevenger.

density in our Universe with high precision ($\Omega_m = 0.308 \pm 0.0012$, $\Omega_\Lambda = 0.692 \pm 0.0012$). Of the approximately 30% of matter in our Universe, about 85% is something we call dark matter, and what this consists of is yet to be determined.

Several particle candidates have been proposed to answer this dark matter mystery. These are for example: sterile neutrinos, axions and WIMPs. For WIMPs the relic dark matter density we see today can be explained under the assumption of an interaction cross section on the order of the weak scale. This, together with the fact that WIMP particles fit extensions of the Standard Model of particle physics, makes the WIMP an excellent candidate to search for.

Chapter 2: How do we use the XENON1T detector to find dark matter? The XENON1T experiment (see cover) is located at the underground Laboratori Nazionali del Gran Sasso in Italy. It uses 3.2 t of xenon as target material, which is purified and cooled continuously during operation. 248 light detectors (PMTs) are used to measure every particle interaction. To determine if dark matter interactions are found we compare the number of light flashes seen with the number we expect from Monte Carlo simulations. The detector operates as a dual-phase liquid xenon Time Projection Chamber (TPC), which is explained in figure 2.

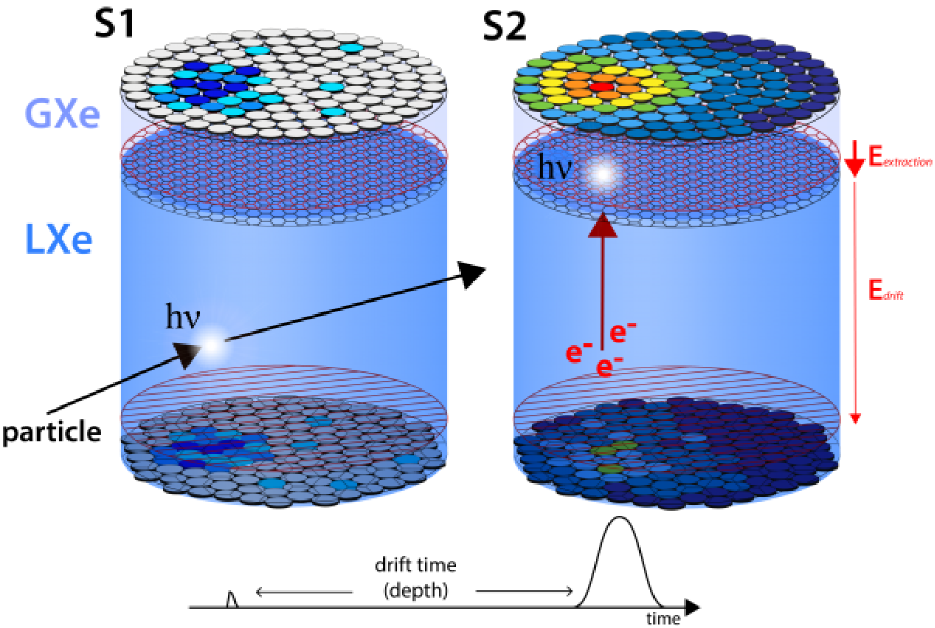

Figure 2: Detection principle of XENON1T, which uses a dual-phase liquid xenon Time Projection Chamber (TPC). Particles interact in liquid xenon (LXe) and produce a direct light signal (S1), and gaseous xenon (GXe) to convert the freed electrons into a delayed light signal (S2). The time and interaction position (x,y,z) is reconstructedvent. From [2].

Figure 2 shows a particle interacting in the liquid xenon and producing a light (left) and charge (right) signal. The primary scintillation light signal (S1) is observed by several of the 248 light detectors (PMTs), placed at the top and bottom of the TPC. For the charge signal, the freed electrons first drift upwards to the liquid-gas interface where they create a secondary scintillation light signal (S2). The ratio of the S1 and S2 signals will determine if we measured a background-like (electronic recoils) or signal-like (nuclear recoils) particle. The pattern of the S2 signal is used for the (x,y) position reconstruction, while the time between the S1 and S2 is used to determine the depth (z).

If a WIMP collides with ordinary matter we expect low energy depositions of about $\mathcal{O}(10)$ keV. As the (spin independent) WIMP-nucleon cross section scales with the atomic number squared (A^2), xenon has a higher detection potential than most other stable elements. At a temperature of about -100 °C and pressure of about 2 bar, xenon is a transparent liquid in which emitted photons can travel freely. The XENON1T experiment measures both the light (photons) and charge (electrons) resulting from any particle interacting in the detector (e.g., alpha, beta, gamma, neutrons and hopefully WIMPs).

Chapter 3: How does XENON1T discriminate between signal and background events? To reconstruct the deposited energy of particles that interact in the liquid xenon we need to correct the S1 and S2 signals for any time- and spatial-dependent signal losses. The S1 (light signal) is corrected for an (x,y,z)-dependent light collection efficiency in the TPC. The S2 (charge signal) is corrected for a time- and depth-dependent electron-lifetime. This is because electrons can be lost if they attach to impurities in the liquid xenon while drifting. The S2 is also corrected for (x,y)-dependent amplification variations due to dead PMTs and warping of the meshes. Krypton calibration data, with its mono-energetic low-energy decay, is used to build the relevant correction maps.

An electric field distortion due to the low electric field configuration, was not expected, but a dedicated correction was found and applied. After a total of 16 data quality and selection cuts, over 80% of events in our low energy region remain. The energy calibration shows a very high total photon detection efficiency of about 14%, which is in accordance with the designed high reflectivity of the TPC walls, high transparency of the meshes and high quantum efficiency of the photo multiplier tubes. The shape and position of the final electronic recoil (background-like) and nuclear recoil (signal like) bands are shown in figure 3.

Electronic recoils produce much larger S2 signals than nuclear recoils (at the same S1 signal). Any event below the mean of the nuclear recoil band (red solid line) is most likely a signal event, and this is where XENON1T is most sensitive to WIMP interactions (nuclear recoils). At a 50% nuclear recoil acceptance XENON1T can detect WIMP-like events in the detector, while at the same time rejecting $(99.82 \pm 0.05)\%$ of all electronic recoil background events.

Chapter 4: Where do the background signals in XENON1T come from? To have a chance of measuring WIMPs scattering off xenon nuclei, XENON1T was designed and built as an ultra-low background experiment. Even with the discrimination power of about 99.8% between nuclear and electronic recoils, the total electronic recoil background should not exceed $\mathcal{O}(1000)$ events. From Monte Carlo simulations we know the main background component in the low energy region (1-12 keV) is from

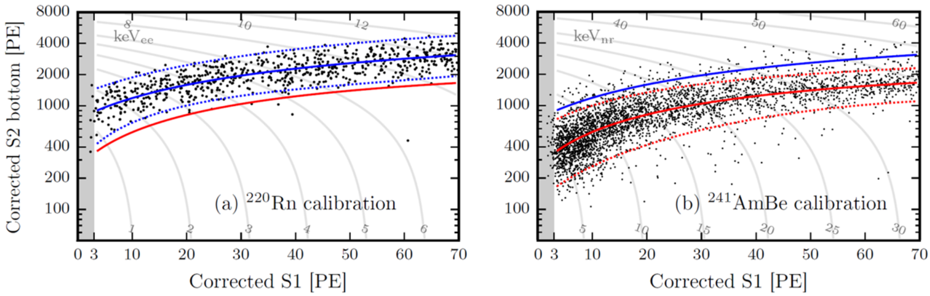

Figure 3: Observed event distribution in $cS2_b$ vs. cS1 for (a) ^{220}Rn electronic recoil (ER) calibration and (b) ^{241}AmBe nuclear recoil (NR) calibration data. The mean (solid) and $\pm 2\sigma$ quantiles (dashed) are shown for both the ER band (blue) and NR band (red). The shift in median cS2 value for the same cS1 value is used to distinguish between signal-like (NR) and background-like (ER) events. From [3].

(naturally occurring) radon (^{222}Rn), or more specifically, from the decay of one of its daughter ^{214}Pb.

To constrain estimates of the concentration of ^{214}Pb, the concentration of its mother isotope ^{218}Po and daughter isotope ^{214}Po are determined by means of an S1-only alpha analysis. Seven alpha lines are identified in figure 4, all originating from the radon and thoron (^{220}Rn, ^{216}Po and ^{212}Po) decay chains. The found concentrations of ^{218}Po $(13.7 \pm 1.1)\,\mu$Bq/kg and ^{214}Po $(4.4 \pm 0.2)\,\mu$Bq/kg give an upper and lower limit on the concentration of ^{214}Pb, respectively. Both isotopes show stable decay rates over time and a homogeneous distribution throughout the TPC. From the alpha spectrum it is clear that the thoron decay chain will not contribute more than $\mathcal{O}(1\%)$ to the total ER background.

The one isotope found in the alpha spectrum that does not originate from within the liquid xenon is ^{210}Po. This isotope is found to originate mostly from the PTFE (Teflon) walls, where it was deposited during construction.

To get a better estimate of the precise ^{214}Pb concentration, its spectrum was determined and compared to the full ER background spectrum. A ^{214}Pb concentration of $(8.4 \pm 1.2)\ \mu$Bq/kg is found, about 16% lower than the Monte Carlo expectations of $10\,\mu$Bq/kg. By fitting all the individual ER background components together, the total ER background rate was found to be $(1.90 \pm 0.24) \times 10^{-4}$ $(\text{kg} \cdot \text{day} \cdot \text{keV})^{-1}$, which is in agreement with the expected $(1.80 \pm 0.15) \times 10^{-4}$ $(\text{kg} \cdot \text{day} \cdot \text{keV})^{-1}$ from simulation. This does not only show that XENON1T has achieved its

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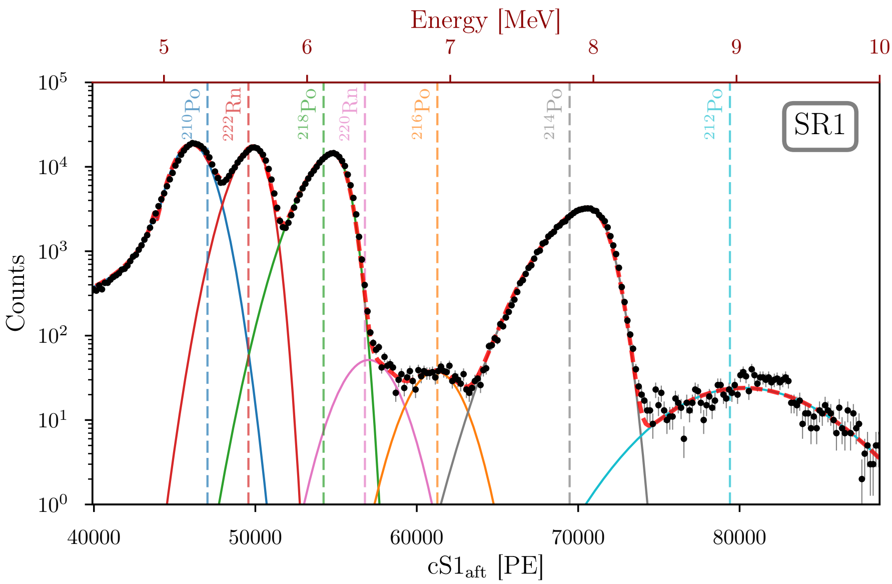

Figure 4: Alpha spectrum of ^{210}Po (blue), ^{222}Rn (red), ^{218}Po (green), ^{220}Rn (pink), ^{216}Po (orange), ^{214}Po (grey) and ^{212}Po (light blue) in Science Run 1. The top axis shows scaling $cS1_{aft}$ to energy, assuming a linear scaling relationship and using the ^{222}Rn peak as anchor. The dashed lines indicate the respective alpha energies.

ultra-low background goals, but also that XENON1T has the lowest low-energy ER background rate of all dark matter experiments.

Chapter 5: Did we find dark matter with XENON1T? No, unfortunately, we did not. But I can proudly say that we are world leading in finding nothing.

For a WIMP search analysis, the fiducial volume needs to be determined. This is the liquid xenon volume within the TPC that maximizes the sensitivity for detecting WIMPs. The sensitivity is influenced by both the total exposure (ton $\times$ year) and the ratio of expected signal over background events. Under the assumption of a flat signal acceptance within the whole TPC, the goal is thus to find the largest liquid xenon volume in which the background is only dominated by the internal (i.e., radon) and not the external (i.e. material) backgrounds.

For Science Run 0 a cylindrical fiducial volume of (1042 ± 12) kg was designed to specifically exclude backgrounds from gas events and wall leakage. The wall leakage was an unexpected background of events originating from the PTFE wall, which is mis-reconstructed with an inward radial bias. This is caused by a lower field configuration, together with the charge build up over time on the PTFE wall, resulting in a ϕ-dependent radial bias of the reconstructed positions. The expected rate of wall events leaking into the Science Run 0 fiducial volume is 0.5 ± 0.3.

The total background expectation of Science Run 0 includes six backgrounds: electronic recoils, nuclear recoils from radiogenic neutrons and from coherent elastic neutrino-nucleus scattering (CEvNS), accidental coincidences from random pairing of uncorrelated lone S1 and S2 peaks, wall leakage and an anomalous background observed in ER calibration data. Both the spectral shape and the rates of each background were fixed before unblinding. The total background expectation in the $\mathrm{cS1} \in [3, 70]$ PE, $\mathrm{cS2}_b \in [50, 8000]$ PE search region was (63 ± 8) events. From the about 16 M events digitized during SR0, only 63 survived the selection criteria after unblinding. Only one of these events was found below the NR median. The data of SR0 is consistent with a background-only hypothesis, which lead to a comparable exclusion limit on the wimp-nucleon cross section to other experiments when published.

For the analysis of Science run 0 and 1 together, resulting in a 1 tonne-year exposure, the spatial reconstruction was improved by including a 3D field distortion correction. The fiducial volume was increased to $(1.30 \pm 0.01)\,\mathrm{t}$ and the spatial distribution of the background models were included into the likelihood analysis. XENON1T reached an ER background level of $(2.2^{+0.1}_{-0.1}(\mathrm{syst}) \pm 0.1(\mathrm{stat}))$ $(\mathrm{kg} \cdot \mathrm{day} \cdot \mathrm{keV})^{-1}$. Again, the data was consistent with the background-only hypothesis. This (final) result of XENON1T, shown in figure 5, on the spin-independent WIMP-nucleon cross section is the most stringent (as of the time of this writing). It is now up to the next generation of detectors to discover a dark matter particle, and to hopefully explain an observation that is now almost a century old.

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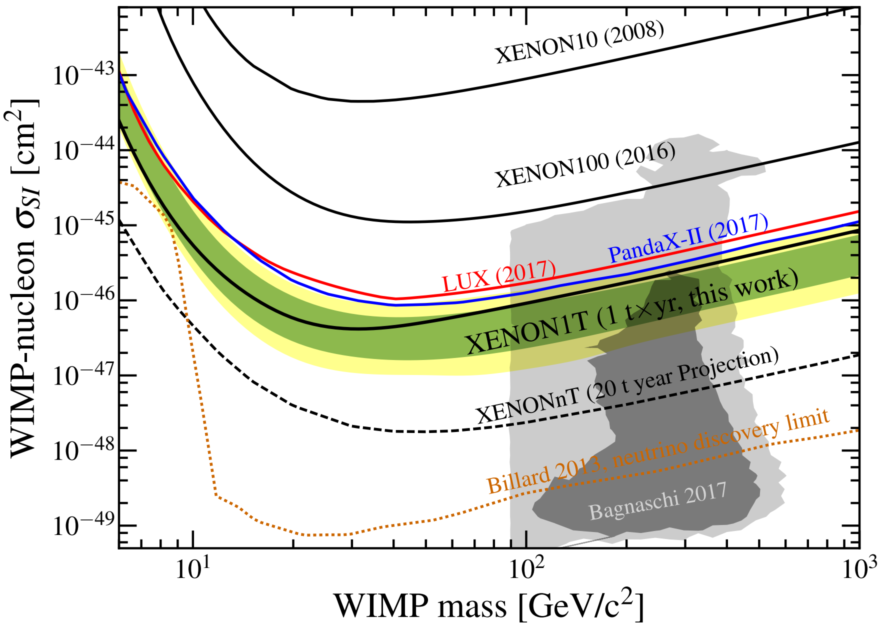

Figure 5: Limit on the spin-independent WIMP-nucleon cross section versus WIMP mass for SR0 + SR1 at 90% confidence (black line). The 1- and 2 σ sensitivity band are given by the green and yellow bands, respectively. For comparison, previous results are shown from XENON10 [4], XENON100 [5], LUX [6] and PandaX-II [7]. The projected sensitivity of XENONnT [8], the upgrade of XENON1T, shows the next step from the XENON collaboration in the search for WIMPs. Not all current theoretical WIMP space [8] can be probed before experiments start measuring more nuclear recoils from CEvNS (orange dotted) [9] than from WIMPs.