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Direct Searches of Dark Matter with the XENON Project

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A direct approach to dark matter detection is the measurement of the nuclear recoils produced in the scattering of DM particles off the nuclei of target materials, in detectors placed deep underground.
The XENON100 experiment is the second phase of the XENON program, it consists of a double phase xenon-filled time projection chamber deployed at the Laboratori Nazionali del Gran Sasso. The experiment, using 225 live days of data taken from March 2011 to April 2012, set one of the most stringent limits on the WIMP-nucleon spin-independent cross section (2×10^{-45} cm^2 for a 55 Gev/c^2 WIMP mass at 90% CL). The experiment also demonstrated so far the best upper limit on the spin dependent WIMP-nucleon cross section for WIMP masses above 6 GeV, with a minimum cross section of 3.5×10^{-40} cm^2 for a 45 Gev/c^2 WIMP mass at 90% CL.
XENON100 also excludes, at 90% CL, solar axion coupling to electrons at $g_{Ae} > 7.7 \times 10^{-12}$ for a mass of $m_{Axion} < 1$ keV/c^2 and axion-like particles couplings by $g_{Ae} > 1 \times 10^{-12}$ in the $m_{Axion} = 5 - 10$ keV/c^2 mass range.
We also report on the status of XENON1T, the first tonne-scale direct search experiment. XENON1T, currently under commissioning, is expected to start collecting its first science data by the end of 2015.

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1. Introduction

One of the most remarkable cosmological puzzle is that the primary constituents of the Universe are still unknown. An increasing number of astronomical and astrophysical observations unambiguously indicate that the Universe is composed of more than 96% of invisible matter and energy, pointing to the existence of an unknown form of matter. Some of the most popular theories suggest that it should be non luminous, non baryonic and non relativistic (i.e. cold), therefore called Cold Dark Matter (CDM) [1].

Among the most plausible candidates for CDM there are the so-called Weakly Interactive Massive Particles (WIMPs). They are stable particles in thermal equilibrium in the early Universe, which are foreseen in some extensions of the standard model of electroweak interaction, such as Supersymmetry (SUSY), universal extra dimensions, or little Higgs models.

In SUSY, one favorite WIMP candidate is the neutralino, the lightest supersymmetric particle.

Dark matter (DM) does not interact electromagnetically or strongly, however it is a well motivated assumption that it has, in addition to gravity, also weak interaction with standard matter. If this is the case, DM particles can be detected directly by experiments using existing technologies. If WIMPs exist, they are also the dominant mass in our own [2] Milky Way. Although they only interact very rarely with conventional matter, they should nonetheless be detectable by sufficiently sensitive detectors on the Earth. In XENON100, one attempts to observe the nuclear recoils (NRs) produced by WIMP scattering off xenon nuclei.

2. The XENON100 experiment

XENON100 is installed underground at the Laboratori Nazionali del Gran Sasso (LNGS), Italy, below an average rock overburden of 3600 m water equivalent, which reduces the muon flux by a factor $\sim 10^6$. The XENON100 detector is filled with a total of 161 kg of ultra pure liquid xenon (LXe), divided in two optically separated volumes [3]. The inner target volume is a dual phase time-projection chamber (TPC) of 30.5 cm height and 15.3 cm radius containing 62 kg of xenon, the outer volume is operated as an active veto for an efficient suppression of external radioactive background.

The whole volume is viewed by a total of 242 squared (1" $\times$ 1") low radioactivity photomultiplier tubes (PMTs) Hamamatsu R8520-06-A1, especially developed to be operated at the LXe temperature for the characteristic xenon scintillation wavelength (λ=178 nm).

The electric field required for the operation of the TPC is provided by a cathode mesh on the bottom and by a gate and an anode mesh on the top. Forty field shaping rings, regularly spaced along the TPC wall, ensure the homogeneity of the field.

Both TPC and veto are mounted inside a double-walled stainless-stell cryostat, enclosed by a multilayer passive shield. Moreover the shield is continuously purged with boil-off N_2 gas in order to suppress radon background.

A particle interaction in the LXe target creates both excited and ionized atoms. De-excitation leads to a prompt scintillation signal (S1), which is recorded by two arrays of PMT, one placed below the target in the LXe, and the other above it, in the gas phase. Due to the presence of an electric field of 0.53 kV/cm, a large fraction of the ionization electrons is drifted away from the interaction and extracted from the liquid into the gas phase by a strong extraction field of $\sim$12 kV/cm, generating a light signal (S2) given by proportional scintillation in the gas. Since the electron drift velocity in LXe is constant for a given field ($\sim$1.74 mm/μs at 0.53 kV/cm), the time distance between S1 and S2 gives the information of the position of the interaction vertex in the vertical axis. The hit pattern on the PMTs in the gas phase is used to reconstruct the position in the horizontal plane. Three different methods are used to reconstruct the XY position, based on χ^2 minimization, neural network and support vector machine algorithms. In this way a 3-dimensional event position is available. This property allows the definition of an ultra-low-background fiducial volume inside the target. Moreover, the ratio S2/S1 is different for electronic recoil events from interaction with the atomic electrons (from γ and β), and for interactions with the nucleus itself (from WIMPs or neutrons), and is it used to further discriminate the signal against background.

3. The analysis

The XENON100 data presented here, includes 224.6 live days and 34 kg fiducial mass, collected between March 2011 and April 2012. Compared to the previous data set [26], this science run has a longer exposure, a significantly lower intrinsic ^{85}Kr contamination, a reduced electronic noise and a lower trigger threshold. Calibrations were done regularly during the science run with various radioactive sources. ^{137}Cs is used to estimate the electron lifetime [3] in liquid xenon. The features of the electronic recoil (ER) band are determined with ^{232}Th and ^{60}Co sources. A neutron source (^{241}AmBe) is used to characterize the nuclear recoil (NR) response of the detector [4].
A profile likelihood (PL) approach is used to test the background-only and signal hypothesis [5]. The systematic uncertainties in the energy scale and in the background expectation are profiled out and taken into account in the limit. Poisson fluctuations in the number of photoelectrons (PEs) dominate the S1 energy resolution and are also taken into account along with the single PE energy resolution of the PMTs.

3.1 WIMPs search

For the signal model, we assume an isothermal halo with a local density of 0.3 GeV/cm^3, a local circular velocity of 220 km/s, and a Galactic escape velocity of 544 km/s. WIMP interactions can be described in terms of scalar (spin-independent, SI) and axial-vector (spin-dependent, SD) couplings. If the WIMP is a spin-1/2 or a spin-1 field, the contributions to the WIMP-nucleus scattering arise from couplings of the WIMP field to the quark axial current and will couple to the total angular momentum of a nucleus. Only nuclei with an odd number of protons or/and neutrons will yield a significant sensitivity to this channel. Natural xenon contains two nonzero spin isotopes, ^{129}Xe (spin-1/2) and ^{131}Xe (spin-3/2), with abundancies of 26.4% and 21.2%, respectively.
The 90% CL exclusion on spin-independent WIMP-nucleon cross section is shown in Fig. 1 [24]. The minimum of the observed limit is 2.0×10^{-45} cm^2 for a WIMP mass of 55 GeV/c^2; this result, presented in 2012, has been the best limit until the first results from LUX [27] were released, at the end of 2013.

The constraints on the SD WIMP-nucleon cross section are presented in Fig. 2 [25]. XENON100 was able to exclude WIMP-neutron cross section down to 3.5×10^{-40} cm^2 for a WIMP mass of

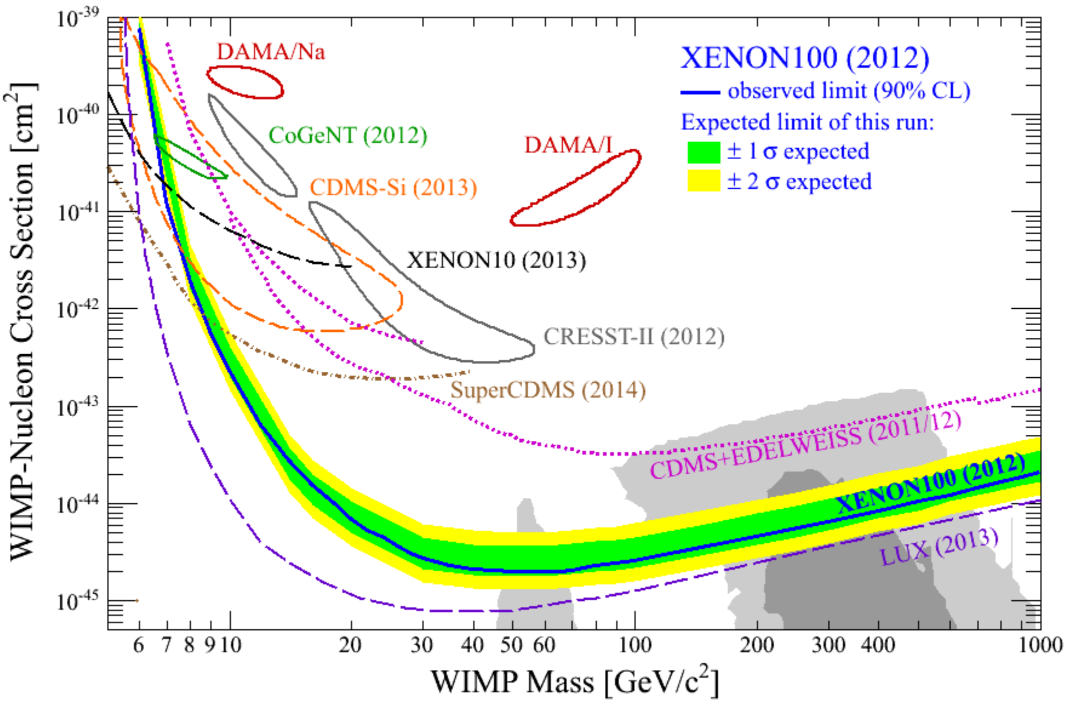

Figure 1: Results on spin-independent WIMP-nucleon scattering from XENON100. The measured limit is shown by the solid blue line. Other experimental limits and detection claims are also shown for comparison[24].

45 GeV/c^2 setting the most stringent limit to date on the WIMP-neutron SD couplings for WIMP masses above 6 GeV/c^2.

3.2 Solar axions and ALPs

Axions were introduced by Peccei and Quinn to solve the strong CP problem as pseudo-Nambu-Goldstone bosons emerging from the breaking of a global U(1) symmetry [6, 7, 8]. Altough this original model has been ruled out, “invisible" axions arising from higher symmetry-breaking energy scale are still allowed, as described, for example, in the DFSZ and KSVZ models [9, 10, 11, 12]. In addition to QCD axions, axion-like-particles (ALPs) are pseudoscalars that do not necessarily solve the strong CP problem, but that were introduced by many extensions of the Standard Model of particle physics.
Solar axions are postulated to be produced in the Sun via Bremsstrahlung, Compton scattering, atomic recombination and atomic de-excitation.
Axions and ALPs are another class of well motivated cold dark matter candidates [13] which interact predominantly with atomic electrons in the medium and can couple to photons, electrons and nuclei. The coupling to electrons, g_{Ae}, can be tested through the axio-electric effect, which is analogous to the photoelectric effect, but with an axion/ALP playing the role of the photon: the axion ionizes an atom and it is absorbed, extracting an electron. Therefore axions and ALPs can scatter off electrons of the LXe target; hence they can be detected in XENON100 by looking at the ER events.

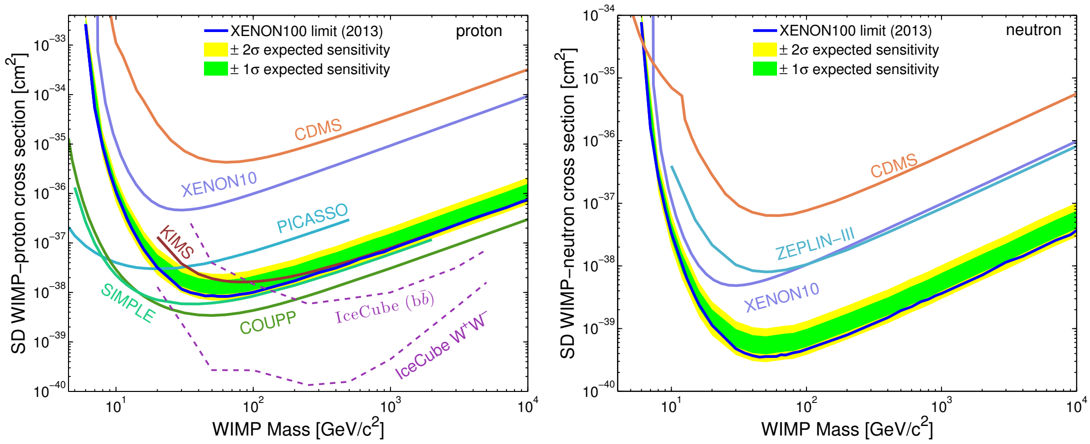

Figure 2: XENON100 90% CL upper limits on the WIMP SD cross section on proton (left panel) and neutron (right panel). Other experimental limits are also shown for comparison[25].

The first axion search performed with the XENON100 experiment is reported in [14].
The expected interaction rate is obtained by the convolution of the flux and the axio-electric cross section. The latter is given, both for QCD axions and ALPs, by [15, 16, 17, 18, 19]:

$$\sigma_{Ae} = \sigma_{pe}(E_A)\frac{g_{Ae}^2}{\beta_A}\frac{3E_A^2}{16\pi\alpha_{em}m_e^2}\left(1-\frac{\beta_A^{2/3}}{3}\right)$$

where σ_{pe} is the photoelectric cross section for LXe [20], E_A is the axion energy, α_{em} is the fine structure constant, m_e is the electron mass, and β_A is the axion velocity over the speed of light, c.
For solar axions, both flux (taken from [21]) and cross section depend upon g_{Ae}^2, thus the interaction rate scales with the fourth power of the coupling. For the ALPs, assuming that they constitute the whole dark matter halo density ($\rho_{DM} \sim 0.3\ GeV/cm^3$ [22]), the total flux is given by $\phi_{ALP} = c\beta_A \times \rho_{DM}/m_A$, where m_A is the ALP mass. The interaction rate for these ALPs depends on g_{Ae}^2, as the flux is independent from the axion coupling. As $\beta_A \approx 10^{-3}$, in the non-relativistic regime the velocities cancel out in the convolution between σ_{Ae} and the flux. Thus the expected recoil spectrum is independent of the particle speed and a mono-energetic peak at the axion mass is expected.
The expected S1 spectrum for solar axions, lighter than 1 keV/c^2, is shown in fig. 3, left panel, as a blue dashed line for $g_{Ae} = 2\times10^{-11}$, which is the best limit so far, reported by the EDELWEISS-II collaboration [23]. Also shown in fig. 3, right panel, is the expected signal for different ALP masses, assuming a coupling constant of $g_{Ae} = 4\times10^{-12}$ and that ALPs constitute all of the galactic dark matter. For both the solar axion search and the ALPs search, the data is compatible with the background model, and no excess is observed for the background-only hypothesis.
The left panel of fig. 4 shows the new XENON100 90% exclusion limit on the solar axions coupling to electrons, at 90% CL. The sensitivity is shown by the green/yellow band ($1\sigma/2\sigma$). For comparison, we also present recent experimental constraints. Astrophysical bounds and theoretical benchmark models are also shown. For solar axions with masses below 1 keV/c^2, XENON100 is able to set the strongest constraint on the coupling to electrons, excluding values of g_{Ae} larger than

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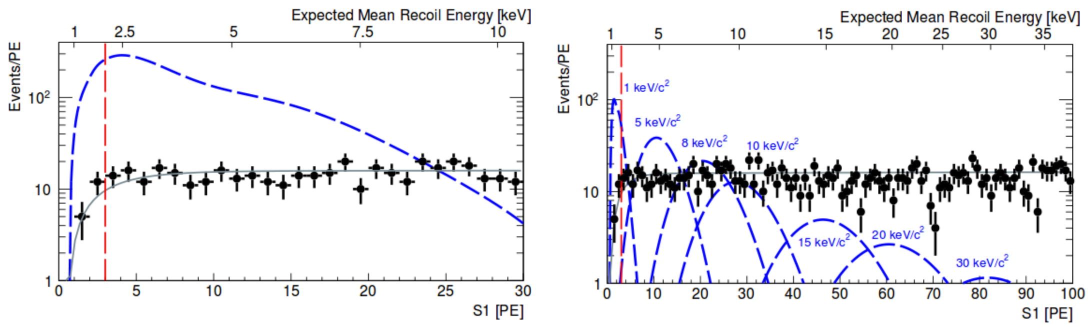

Figure 3: Left panel: event distribution of the data (black dots), and background model (grey) of the solar axion search. The expected signal for solar axions with m_A <1 keV/c^2 is shown by the dashed blue line. Right panel: black dots represent the event distribution in the galactic ALPs search region between 3 and 100 PE. The grey line shows the background model used for the profile likelihood function. The expected signal in XENON100 for various ALP masses, assuming $g_{Ae} = 4 \times 10^{-12}$, is shown as blue lines [14].

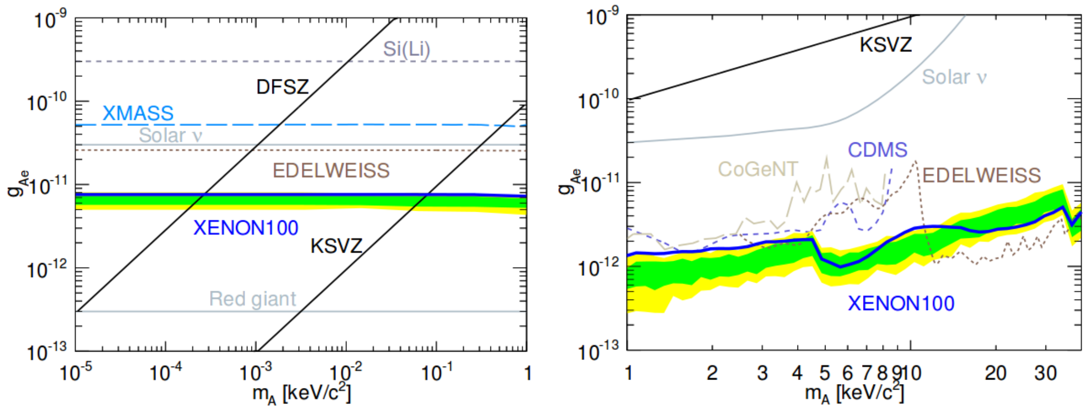

Figure 4: The XENON100 90% limit on the solar axions and on galactic ALPs are shown in the left and right panel, respectively. Other experimental constraints, astrophysical bounds and theoretical benchmark models are also represented [14].

7.7×10^{-12} (90% CL).
The right panel of fig. 4 shows the XENON100 90% CL exclusion limit on ALP coupling to electrons as a function of the mass. In the 5-10 keV/c^2 mass range, XENON100 sets the best upper limit, excluding an axio-electron coupling $g_{Ae} > 1 \times 10^{-12}$ at the 90% CL, assuming that ALPs constitute all of the galactic dark matter.

4. XENON1T

The XENON1T detector is a scaled-up version of the successful XENON100 one: it is a dual-phase LXe TPC of about 1 m height and about 1 m diameter, containing 3.3 t (~2.2 t in the active volume) of high-purity liquid xenon, instrumented with with 248 3" PMTs (Hamamatsu R11410-21) made of extremely low radioactivity materials, and kept under a uniform electric field of about

1.0 kV/cm.
The goal is to reduce the background by a factor of $\sim$100 compared to the one of XENON100. This will be achieved by using a water Cherenkov muon-veto to protect against the external gamma and neutron background, as well as from muon-induced neutrons; in addition, an improved material screening and selection and a reduction of the intrinsic ^{85}Kr and radon using dedicated devices is foreseen. XENON1T detector will be instrumented With realistic assumptions on the detector performance and analysis efficiency, the nominal sensitivity to spin-independent WIMP-nucleon cross sections will be reached in 2 t·y and is expected to be $\sim 1 \times 10^{-47}$ cm^2 at a WIMP mass of 50 GeV/c^2.

5. Beyond XENON1T

While XENON100 is still running, the XENON1T detector, installed in the Hall B of the LNGS, is currently under commissioning.
With a design sensitivity two orders of magnitude better than XENON100, over a broad range of WIMP masses and interaction types, this first LXe TPC experiment at the tonne-scale will have significant discovery potential. In designing the experiment, we have foreseen the possibility for a scale-up by a factor of $\sim$2 of the target mass, replacing only the inner vessel and the TPC, but re-using most of the other subsystems and infrastructures built for XENON1T. The number of PMTs will also almost double. The goal is to improve by another factor $\sim$ 10 improvement in sensitivity in 20 t·y, i.e. by $\sim$ 2023.

References

[1] G. Jungman, M. Kamionkowski, and K. Gries, *Phys. Rep.* **267**, 195 (1996)

[2] M.R. Merriefield, *Astronom. J.* **103**, 1552 (1992)

[3] E. Aprile *et al.* (XENON Collaboration), *Astropart. Phys* **35**, 573 (2012)

[4] E. Aprile *et al.* (XENON Collaboration), *Phys. Rev. D* **88**, 012006 (2013)

[5] E. Aprile *et al.* (XENON Collaboration), *Astropart. Phys* **54**, 11-24 (2014)

[6] R.D. Peccei and H.R. Quinn, *Phys. Rev. Lett.* **38**, 1440 (1977)

[7] S. Weinberg, *Phys. Rev. Lett.* **40**, 223 (1978)

[8] F. Wilczeck, *Phys. Rev. Lett.* **40**, 279 (1978)

[9] M. Dine, W. Fischeler, and M. Srednicki, *Phys. Lett. B* **104**, 199 (1981)

[10] A.R. Zhitnitsky, *Sov. J. Nucl. Phys.* **31**, 260 (1980)

[11] J.E. Kin, *Phys. Rev. Lett.* **43**, 103 (1979)

[12] M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, *Nucl. Phys. B* **166**, 493 (1980)

[13] L. Abbott and P. Sikivie, *Phys. Lett. B* **120**, 133 (1983)

[14] E. Aprile *et al* (XENON Collaboration), *Phys. Rev. D* **90**, 062009 (2014)

[15] F.T. Avignone *et al.*, *Phys. Rev. D* **35**, 2752 (1987)

[16] M. Pospelov, A. Ritz, and M. Voloshin, *Phys. Rev. D* **78**, 115012 (2008)

[17] A. Derevianko *et al.*, *Phys. Rev. D* **82**, 065006 (2010)

[18] K. Ariska *et al.*, *Astropart. Phys.* **44**, 59 (2013)

[19] F. Alessandria *et al.* (CUORE Collaboration), *JCAP* **1305**, 007 (2013)

[20] NIST web site, http://physics.nist.gov/PhysRefData/Xcom/html/xcom1.html

[21] J. Redondo, *JCAP* **1312** (2013) 008

[22] A. M. Green, *Mod. Phys. Lett.* **A27**, 1230004 (2012)

[23] E. Armengaud *et al.* (EDELWEISS-II Coll.), *JCAP* **1311**, 067 (2013)

[24] E. Aprile *et al.* (XENON Collaboration), *Phys. Rev. Lett.* **109**, 181301 (2012)

[25] E. Aprile *et al.* (XENON Collaboration), *Phys. Rev. Lett.* **111**, 021301 (2013)

[26] E. Aprile *et al.* (XENON Collaboration), *Phys. Rev. Lett.* **107**, 131302 (2011)

[27] D. S. Akerib *et al.* (LUX Collaboration), *Phys. Rev. Lett.* **112**, 091303 (2014)

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