Dark Matter Direct Detection Experiments with Xenon in Dual Phase

J. MASBOU
SUBATECH, IMT Atlantique, CNRS/IN2P3, Université de Nantes, Nantes 44307, France

Dual phase (liquid - gas) direct detection xenon experiments have recently demonstrated their exceptional capabilities for rare event detection. They examine the interaction of dark matter particles through their scatter off nuclei in the target. This technology currently achieves the most stringent limits on WIMP (Weakly Interacting Massive Particle) searches: it is evolving rapidly since the last decade and is expected to continue leading the field. The most recent results from LUX, PandaX and XENON Collaborations are reviewed, focused on dark matter sensitivity limits.

1 Introduction

The existence of Dark Matter (DM) is known from gravitational effects, but its nature remains a deep mystery. There is a wide range of astronomical evidence that the visible stars and gas in all galaxies, including our own, are immersed in a much larger cloud of non-luminous matter. It is typically an order of magnitude greater in total mass. Evidences from large-scale galaxy surveys and microwave background measurements is consistent with the existence of this DM, indicating that the majority of matter in the universe is non-baryonic. Current estimates put the DM fraction of mass-energy density of the observable Universe at $\sim$26 %, baryonic matter makes up $\sim 5\%$ while the remainder is accounted for by dark energy. The existence of DM is at present one of the strongest pieces of evidence that the current theory of fundamental particles and forces, summarized in the Standard Model (SM) of particle physics, is incomplete. The nature of this non-baryonic component is still totally unknown, and the resolution of the "Dark Matter puzzle" is of fundamental importance to cosmology, astrophysics, and elementary particle physics [1].

A number of proposed candidates have been put forward over time: one motivated possibility is that DM consists of undiscovered particles that arise naturally in many theories beyond the Standard Model, including supersymmetric theories, theories with extra spatial dimensions. One of the most compelling candidate is Weakly Interacting Massive Particle (WIMP). This particle is well motivated, not only because it resolves the DM puzzle, but also because it simultaneously solves longstanding problems associated with the SM of particle physics. WIMPs are particles formed in the early universe and subsequently gravitationally clustered in association with baryonic matter. They interact weakly with normal matter and have mass near the weak scale.

There are several complementary methods used to determine the nature and properties of DM particle. Direct detection experiments examine the interaction of DM particles with a detector as they elastically scatter off nuclei in the target. DM may also be discovered indirectly by finding evidence of WIMP pairs annihilating somewhere in the galactic neighborhood. Finally, evidence for DM may also come from collider searches. It should be noted that collider and indirect searches for DM can be much less straightforward than direct searches: collider searches alone cannot be used to determine whether or not an eventual discovery of new particles is attributable to DM; halo indirect search results interpretation are also subject to ambiguities due to large astrophysical uncertainties. On the other hand, direct search experiments, in combination with colliders and indirect searches, might not only establish the identity of DM, but may also provide a wealth of additional cosmological information. For this reason, direct detection appears to be one of the most promising techniques to shed light on the nature of the DM.

Large efforts have been pursued to develop experiments which are able to directly test the particle nature of DM. Given the low interaction strength expected, the probability of multiple collisions within a detector is negligible, thus the signature results in a recoil spectrum of single scattering events. In the most common approach, the experiments attempt to measure the nuclear recoils energy produced by collisions between DM candidates and detectors target nuclei. Different technologies have been explored so far to achieve this goal. Among the most promising, dual phase direct detection xenon experiments have recently demonstrated their exceptional capabilities for rare event detection. This technology currently achieves the most stringent limits on WIMP searches: it is evolving rapidly since the last decade and is expected to continue leading the field in the near future. Nowadays, there is a worldwide competition among many collaborations that have chosen the liquid xenon as detecting medium, namely XENON at Laboratori Nazionali del Gran Sasso in Italy, PandaX at Jin-Ping laboratory in China and LUX-LZ at the Sanford Underground Research Facility in the United States.

2 Direct dark matter detection

The direct detection of WIMPs was initially proposed by W. Goodman and E. Witten [2] and has been the subject of numerous studies. This section summarizes the important elements of the interaction of WIMPs with nuclei.

2.1 WIMP-nuclei elastic scatter

The WIMP interaction with the target nucleus results in an elastic scatter. For a detector containing n_N target nuclei, the interaction rate R can be expressed as a function of the interaction cross-section $\sigma_{\chi-N}$, the average velocity $< v >$, the local density of dark matter ρ_0 and the WIMP mass m_χ :

$$R = \sigma_{\chi-N} \frac{\rho_0}{m_\chi} < v > n_N \tag{1}$$

If we consider a speed velocity of the order of a few hundred km/s, in the laboratory frame, WIMP will not be relativistic. The energy of the nucleus recoil E_r can be then simply expressed as:

$$E_r = \frac{m_\chi v^2}{2} \frac{4 m_\chi m_N}{(m_\chi + m_N)^2} cos(\theta_r) \tag{2}$$

with θ_r being the diffusion angle of the recoil compared to the incident direction of the WIMP and m_N the nucleus mass. This corresponds to energies within the 1-100 keV range.

We can then prove that the differential rate is:

$$\frac{dR}{dE_R} = N_N \frac{\rho_\odot}{m_W} \int_{v_{min}}^{v_{max}} f(v) v \frac{d\sigma}{dE_R} dv \tag{3}$$

where $f(v)$ is the WIMP velocity distribution. The minimum velocity is $v_{min} = \sqrt{\frac{m_N E_{th}}{2 m_r}}$ which depends on the energy threshold E_{th} of the detector and on $m_r = \frac{m_N m_\chi}{m_N + m_\chi}$ that corresponds to the WIMP-nucleus reduced mass. v_{max} is the escape WIMP velocity in the Earth reference frame.

2.2 *Interaction cross-section*

The interaction between a WIMP and the elementary constituents of the target nucleus (i.e. quarks) can take place either by exchanging a Higgs boson (scalar coupling) or by exchanging a Z boson (axial coupling). The scalar interaction is called spin-independent (SI), the axial interaction spin-dependent (SD). For a nucleus ${}^{A}_{Z}X$, the cross sections in the zero momentum transfer limits are:

$$\sigma_0^{SI} = \frac{4m_r^2}{\pi}\left(Zf_p + (A-Z)\,f_n\right)^2 \tag{4}$$

$$\sigma_0^{SD} = \frac{32G_F^2 m_r^2}{\pi}\frac{J+1}{J}\left(a_p < S_p > + a_n < S_n >\right)^2 \tag{5}$$

where f_i and a_i are the effective WIMP-couplings to neutrons and protons in the spin-independent and spin-dependent case, respectively. J is the total angular momentum of the target nucleus. $< S_p >$ and $< S_n >$ are the proton and neutron spin content of the target nucleus.

Thus, in order to increase the sensitivity to the spin-independent interaction, it is better to choose a heavy target nucleus: the cross-section is in fact proportional to the square of the atomic number (A). In order to be sensitive to the spin-dependent interaction for which a non-zero spin nucleus is needed and therefore a target containing nucleus with an odd number of protons or neutrons must be used.

In practice, for the interpretation of experimental results, the spin-dependent cross-section is obtained by cancelling one of the two terms of the parenthesis, in equation 5 to account for either a purely WIMP-neutron or WIMP-proton interaction. The limits on the spin-dependent cross-section are then given for coupling to the proton and to the neutron separately. This is made to simplify the presentation and the comparison of the results between the experiments even if, to be rigorous, neither the values of the amplitudes of diffusion nor their sign are known a priori, the sum of the two terms must be taken into account.

2.3 *WIMP halo properties*

At the scale of our galaxy, the spatial distribution of dark matter is constrained by the observations of the rotation curves and by the N - body simulations which reproduce the formation of the galaxies [3]. The WIMPs are distributed, in a first approximation, as a sphere with a density profile $\rho(r) = \rho_0/r^2$ with $\rho_0 = 0.3$ GeV/c^2/cm^3, where the index 0 refer to the Sun. Moreover, the velocity distribution in the galactic frame follows a maxwellian function $f(v) \propto exp(-v^2/v_0^2)$ with $v_0 = 220$ km/s being the velocity of the solar system around the galactic center. To take into account the possible escape of WIMPs from the gravitational attraction of the galaxy, a maximum speed is imposed ($v_{max} = 650$ km/s).

2.4 *Energy spectrum*

The first observable accessible to the detector is the recoil energy spectrum of the nuclei. Figure 1 presents the expected spectra for different target nuclei in the case of a 100 GeV/c^2 WIMP. The shape of the spectra derives from the integral of equation 3 which leads to an exponential decay when one considering a maxwellian velocity distribution. It can be observed that the slope of the spectrum is more important for high mass nuclei: this can be explained as due to the form factor which increase with the atomic number. It is important to highlight that the highest rate is expected at the lowest energy. It is thus crucial to have the lowest possible energy threshold, especially in the case of high atomic number targets such as xenon,

The number of detected events is proportional to the cross-section and to the WIMP mass. Smaller masses give lower recoil energies and therefore less events above the threshold. Larger

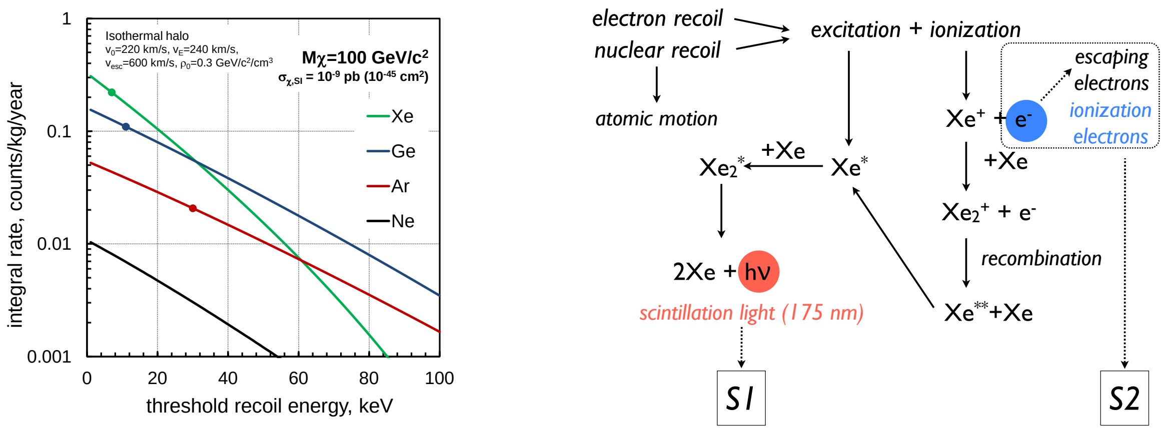

Figure 1 – (left) Expected WIMPs interaction rate as a function of recoil energy for several target materials [4]. (right) Diagram of the processes leading to primary (S1) and secondary (S2) scintillation lights [12].

masses induce a lower density of galactic WIMPs, since density and mass are constrained by astrophysical observations. For a fixed cross-section, this number is maximal for masses around 50 GeV/c^2. To summarize, the detection (or not) of events by an experiment results in an accepted (or excluded resp.) zone in these two parameters space.

2.5 Background discrimination

One of the main limitation for all experiments looking for rare events come from background noise. This noise has several components: an electromagnetic one, corresponding to the interaction of γ and β generating electronic recoils and a second one consisting of induces nuclear recoils from neutrons interacting with a target nuclei. Although the electromagnetic background shows higher rates with respect to the nuclear one, it can be reduced at analysis level through the S2/S1 ratio, leading to a rejection of more than 99% electronic recoils background events with $\sim$50% acceptance for the WIMPs. Neutron background noise is more problematic because the signature is the same as WIMPs. It is therefore crucial to reduce it to the maximum. In the following, the different sources of background will be presented.

Cosmic rays

The high value of the cosmic ray flux at the surface of the earth ($\sim$ 300 m^{-2}.s^{-1} at sea level with $\sim$ 190 m^{-2}.s^{-1} muons) prevents direct detection of dark matter. In order to reduce this flux, it is therefore necessary to build detectors in underground laboratories. For reference, the muon flux is 2.58 $\times$ 10^{-8} cm^{-2}.s^{-1} at LNGS [5], 4.4 $\times$ 10^{-9} cm^{-2}.s^{-1} at SURF [5] and 2.0 $\times$ 10^{-10} cm^{-2}.s^{-1} at Jin-Ping laboratory [6]. This rate is low enough that cosmic muons will not represent a main background to dark matter searches. Nevertheless, they can still induce neutrons either by direct spallation or indirectly, by spallation and capture of the created pions. When these reactions take place in the detector, the neutrons induced by muons can be identified by the large quantity of energy deposited at the same time in the detector by the muon itself. On the other hand, when these reactions occur in the passive shield or in the rock surrounding the laboratory, neutrons induced by the muons can interact in the detector and mimic the interaction of a WIMP.

External radioactivity

The radioactivity in the detector environment comes mainly from the overlying rock, which contains uranium, thorium and potassium at the ppm level (parts-per-million, 10^6). γ radiation produced close to the sensitive volume of the detector can be reduced by selecting materials with low radioactive activity. In order to decrease the surrounding background by suppressing the external contamination, the detectors are enclosed by an active veto whose goal is to increase the purity of the internal volume.

Internal radioactivity

Xenon contains a double beta decaying isotope, ^{136}Xe, with a large lifetime of 2.2×10^{-21} yr. If needed, this isotope can be relatively removed by centrifugation but its contribution is negligible for experiment smaller than few tons mass. Krypton (is naturally present in the commercial xenon) and radon (daughter of uranium) can also contribute to the internal background through electronic recoils. Hard work is done in order to reduce those two contributions. Krypton can be removed from cryogenic distillation [7] and methods to continuously remove the radon are also being used [8].

Neutrinos

With their increasing sensitivities, direct dark- matter detectors will start to be sensitive to neutrino interactions. It can then become a background in electronic [9] and nuclear-recoils [10]. Neutrinos coming from *pp* and ^{7}Be reactions should be the first events detected thanks to their larger fluxes.

3 Detector conception

3.1 Liquid Xenon as target

Noble gases are very good media for particles detection: they produce a fast response to the scattering of a particle by emitting simultaneously a scintillation and an ionization signal in presence of a drift field. An other advantage comes from their high stopping power that is related to their atomic masses (except that for the helium).

Among all the noble liquid, the heaviest one is the radon, Rn. However, due to its very high intrinsic radioactivity, it is not a good candidate for particle detection. The second heaviest liquid noble gas appears to be the xenon, Xe: it represents one of the best candidate as detector medium for dark matter searches. A summary review of the main physical properties of noble liquids is presented in table 1.

As detector media, all noble gases from neon, Ne, up to xenon present similar advantages such as the possibility to create homogeneous detection volumes at a reasonable cost, with high particle stopping powers that depend roughly on the density of the material. They present also the advantage of an accurate interaction position reconstruction thanks to the low transverse diffusion for drifting electrons. This allows the exploitation of their self-shielding capacity through fiducialisation.

In case of the xenon, in addition of being the noble gas with the best stopping power (radon excluded) it also presents the property of having almost no intrinsic radioactivity. All isotopes of xenon found in nature are stable, or long-life double-beta emitter (^{136}Xe, Half-life $\sim 10^{21}$ yr) and can be purified in radioactive krypton and radon at the ppt level (10^{-12} mol/mol) [25]. This property is crucial for low background experiments. Argon, Ar, has the advantage to have a better separation between electronic and nuclear recoils, compared to xenon, through pulse shape discrimination but has also two main disadvantages. The first one consists in its small wavelength emission light ($\lambda = 128$ nm) that requests a light shifter to allow its detection. Then, the argon extracted from the atmosphere cannot be used for dark matter search, due to isotope ^{39}Ar, a β^- emitter, that implies intrinsic background leading to sensitivity limitation. One of the possibility for low-background experiments with argon is then to use low-radioactivity argon, such as depleted argon or argon from underground gas wells. As a result, the cost advantage with respect to xenon is strongly reduced.

Table 1: Liquid Noble main properties for particle detection [11].

Element	Neon	Argon	Krypton	Xenon
Atomic Number (Z)	10	18	36	54
Atomic mass (A)	20.2	40.0	83.8	131.3
Boiling Point [K]	27.1	87.3	119.7	165.0
Liquid Density	1.21	1.40	2.41	2.94
Scintillation [γ/keV]	30	40	25	42
Scintillation Wavelength [nm]	85	128	150	178
Natural radioactivity	No	^{39}Ar Standard : $\sim$ 1 Bq/kg Depleted : $\sim$ 1 mBq/kg	Yes	^{136}Xe ^{85}Kr
Price	$$	$ (Std.)/ $$$ (Depl.)	$$$	$$$$

Liquid xenon is an excellent medium with high scintillation and ionization efficiencies and a low energy threshold (< 10 keV) making it an ideal target for interaction with WIMPs. On one hand, it allows to reach a high sensitivity on spin-interaction cross-sections (as shown in equation 4), the cross-section is proportional to the square of the atomic number that corresponds to A=131 for the xenon. On the other hand, isotopes with an odd number of nucleons, ^{129}Xe (spin 1/2) and ^{131}Xe (spin 3/2) are naturally present in the natural xenon with respective abundance of $\sim$ 26% and $\sim$ 21% making xenon also sensitive to the spin-dependent interaction.

Its atomic number (Z = 54) and its high density ($\sim$ 3 g.cm^{-3}) allow to reduce significatively external radiations coming from the environment and from the walls of the detector. It is thus possible to define a fiducial volume in the most central part of the detector for WIMPs search. All events outside of this volume are rejected. Finally, the background noise can be reduced by the dual scintillation / ionization information, which offers the possibility of rejecting a large part of the electronic recoils.

Finally, the cryogenic associated to the xenon liquidation ($\sim$ 170 K) is simple, the cost of xenon is still fairly affordable to consider experiments containing several tons of liquid xenon.

3.2 TPC Principle

When a particle interacts in the liquid xenon, two distinct signal types are created, as presented in figure 1 (right). A direct scintillation light (S1) is promptly emitted after few nanoseconds

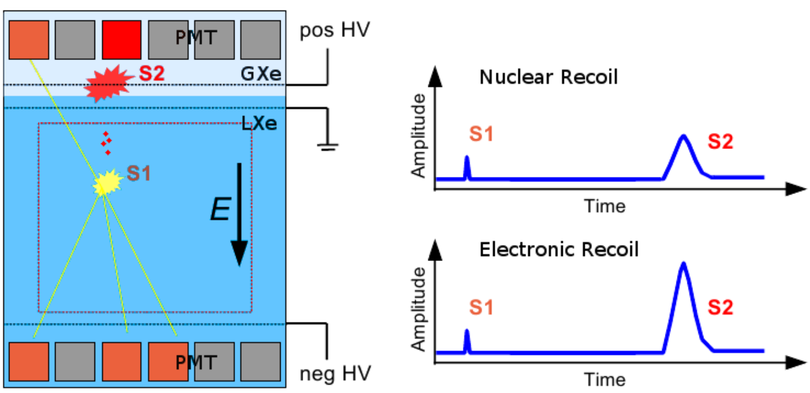

Figure 2 – (left) Dual phase time projection chamber detecting scintillation light (S1) and the ionization charge signal (S2) after interaction in the liquid xenon (LXe). The S2 light is produce at the top of the TPC in the gas phase (GXe) [18]. (right) The time distance between the two signals give the vertical direction of the vertex. The S2/S1 ratio is the discriminant variable between nuclear and electronic recoils [18].

and detected by the photo-sensors (PMTs) placed on top and on the bottom of the chamber. At the same time, ionization electrons start to drift from the initial point of interaction following the direction of the applied external field. Arriving at the grounded gate grid, at the top of the detector, they are extracted into the gas phase by a much stronger anode field. The electrons are re-accelerated and create proportional scintillation light along excitation/ionization tracks through the gas gap. This provides the secondary amplified signal (S2) which enables to reconstruct the original event location along the vertical direction by measuring the time difference Δt between S1 and S2 signals. In addition, the position in the perpendicular plane can be derived from the S2 hit pattern on the top photo-sensors array. The typical position resolution is of the order of few centimeters. This principle is illustrated in figure 2.

The intensities of the S1 and S2 signals will depend on the type of the recoil, i.e. nuclear or electronic. Neutrons lose their energy in almost point-like interactions, leaving electrons behind in a dense concentration, and imply high recombination rates even in strong extraction fields [17]. In contrast, γ radiation undergoes Compton scattering with multiple steps at different interaction sites, thereby enhancing the effective charge yield. As a result to this difference, the S2/S1 ratio can be used to discriminate the nuclear recoil from the electronic one.

4 Recent results and perspectives

4.1 Leptophilic dark matter searches

Due to the orbit of the Earth around the Sun, the net velocity of the WIMPs in the laboratory frame varies with a period of one year. Since the number of events measured is directly proportional to the speed of the WIMPs (see equation 1), an annual modulation of the events distributions is expected. It should be maximized in June and minimal in December and the amplitude of the expected variations is of the order of 7 % [13]. If an experiment detects enough events, it can then be sensitive to this annual modulation. However, this observable does not constitute a single proof, it is possible that the background noise also varies annually. This is the case, for example, for the cosmic muons whose rate depends on the atmosphere's temperature and can be observed in underground sites [14]. A comparison of results from identical experiments built in the two hemispheres might help in shading light on annual modulation interpretations.

The signal observed by the DAMA/LIBRA experiment [15] may be interpreted as coming from a leptophilic dark matter candidate. Since the detector has no nuclear/electronic recoil discrimination power, leptophilic dark matter was evocated to reconcile the observed signal with the null-results from other experiments. The XENON100 experiment [16] performed two analyses focused on an exclusive interaction between the dark matter particle and electrons.

For the first analysis [19], the 34 kg inner fiducial volume has been used to select events belonging to the electronic recoil band. The results are obtained by analyzing the 70 summer live-days only, where the modulation effect seen by DAMA/LIBRA, is stronger. Figure 3 presents the comparison between the expected DAMA/LIBRA rate and the measured XENON100 energy spectra. The difference of the integral counts excludes the DAMA/LIBRA signal as axial-vector coupling between WIMPs and electrons at 4.4 σ significance level, even considering all events from XENON100 background as signal candidates. Mirror dark matter and luminous dark matter are also excluded at 3.6 σ and 4.6 σ respectively.

The XENON100 experiment operated in stable condition for a long-enough period to allow performing a second analysis to study the annual modulation [20]. The corresponding results have been confirmed by XMASS [21]. The measured phase of 112 $\pm$ 15 days disfavored the interpretation of a modulation due to standard DM halo at 2.8 σ confidence level, as it can be seen in figure 3 on the right. In addition, the annual modulation interpreted as a DM signature with axial-vector coupling of WIMPs to electrons was also excluded at 5.7 σ confidence level.

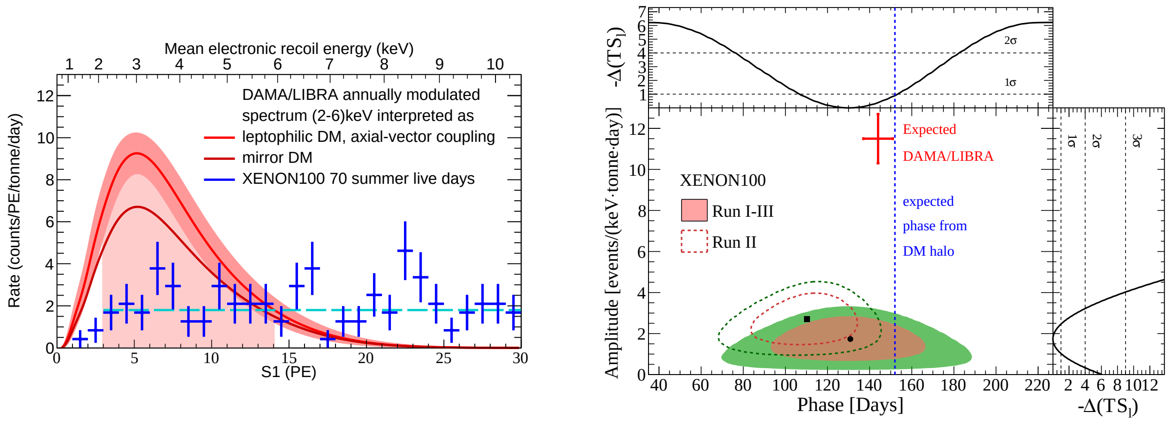

Figure 3 – (left)The DAMA/LIBRA modulated spectrum (red), interpreted as WIMPs scattering through axial-vector interactions, as it would be seen in the XENON100 detector. The 1σ band includes statistical and systematic uncertainties. The (blue) data points are XENON100 data from the 70 summer live days with their statistical uncertainty. The expected average XENON100 rate is also shown (dashed cyan) [19]. (right) The XENON100 best-fit, 95% and 99.73% confidence level contours as a function of modulation amplitude and phase relative to January 1, 2011 for the period of 1 year [20].

4.2 PandaX-II

The PandaX ("Particle and Astrophysical Xenon Experiments") Collaboration is the second phase of the Chinese experiment currently running at the Jin-Ping laboratory (CJPL). It consists in a half-ton scale dual-phase xenon detector. The first results from its 98.7 first days for dark matter searches have been recently reported [22] with a total exposure of 3.3×10^4 kg.day. The most stringent upper limit on the spin-independent scattering cross section (at 90% confidence level) is 2.5×10^{46} cm^2 for a WIMP mass of 40 GeV/c^2 (see figure 5). The PandaX-II experiment continues to take data to explore the WIMP parameters space.

4.3 LUX

LUX, Large Underground Xenon experiment, installed at the Sanford underground laboratory (SURF) in the United-States, released its latest results [23]. The detector employs a total mass of 250 kg of liquid xenon and a $\sim$ 100 kg fiducial mass for the WIMP search. The collaboration reached a 3.3×10^4 kg.day total exposure after 332.0 days of dark matter observations. The data were "salt": real calibration events are added in order to control the quality of the analysis.

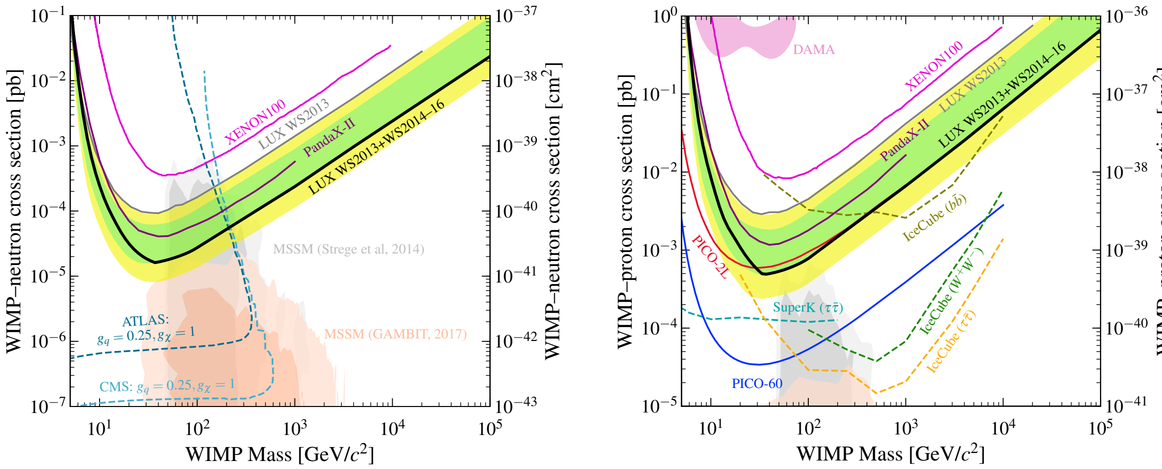

Figure 4 – Exclusion upper-limits for spin-dependent WIMP-nucleon cross-section assuming pure neutron coupling (left) and pure proton coupling (right) [24].

The final limit has a minimum of 2.2 $\times$ 10^{46} cm^2 at 40 GeV/c^2. The most recent spin-dependent results shown presented in figure 4: the upper limits set on the WIMP-neutron (WIMP-proton) cross section of σ_n = 1.6 $\times$ 10^{41} cm^2 (σ_p = 5 $\times$ 10^{40} cm^2) at 35 GeV/c^2, almost a six-fold improvement over the previous LUX results [24]. The spin-dependent WIMP-neutron limit is the most stringent worldwide to date.

4.4 XENON1T

XENON1T experiment just released its first results [25]. It consists of a dual phase (liquid-gas) xenon time projection chamber with a total target mass of 2000 kg of xenon, located at the Laboratori Nazionali del Gran Sasso (LNSG) in Italy. It is the first ton-scale detector of this kind. A blinded search strategy has been put in place to analyze 34.2 live days of data, acquired between November 2016 and January 2017, when an earthquake temporarily interrupted detector operations. With an electronic recoil background of $(1.93 \pm 0.25) \times 10^{-4}$ events/(kg $\times$ day $\times$ keV$_{\mathrm{ee}}$), the detector reached the lowest background ever achieved in a dark matter experiment. The most stringent exclusion limits are derived on the spin-independent WIMP-nucleon interaction cross section for WIMP masses above 10 GeV, with a minimum of 7.7 $\times 10^{-47}$ cm^2 for a 35 GeV/c^2 WIMP mass. XENON1T is still in data taking conditions.

4.5 Future

A fast upgrade of the XENON1T detector is foreseen. The main goal is to increase the current sensitivity reach (1.6 $\times$ 10^{-47} cm^2 after 2 t.y exposure) by an additional order of magnitude. In order to do so, the R&D for the XENONnT experiment is already started, in parallel with the operation of XENON1T. This fast upgrade will be possible thanks to the reuse of most of the detector infrastructures and subsystems. A competitive installation from the LZ (LUX-ZEPPLIN) consortium [27] foresees the same sensitivity by 2020. The expected limits are presented in figure 5.

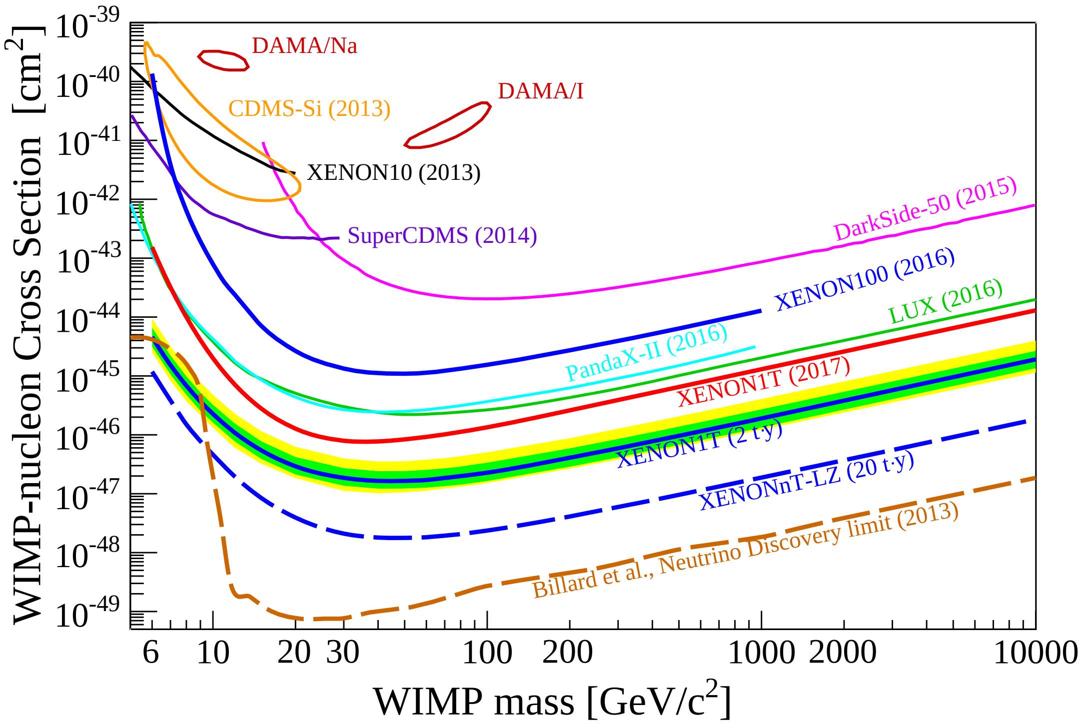

Figure 5 – Most recent and projected exclusion limits from various experiments for spin-independent WIMP-nucleon cross-section.

DARWIN (Dark matter WIMP search with noble liquids) [28] is an European design study. This ultimate dark matter detector is designed to employ a time projection chamber filled with 40 t of liquid xenon. The full instrument will require about 50 t of liquid xenon. DARWIN will be limited by the irreducible background coming from the solar flux of pp-neutrinos. The sensitivity reach of 10^{-49} cm^2 will allow for the detection or the exclusion of WIMPs with masses above $\sim$ 5 GeV/c^2.

Acknowledgments

I would like to thank the kind organizers for their invitation to this great conference: 52nd Rencontres de Moriond Electroweak Interactions and Unified Theories 2017.

References

1. G. Bertone, D. Hooper and J. Silk, in *Phys.Rept.* 405 279-390 (2005)
2. M. W. Goodman and E. Witten., in *Physical Review D* 31 :30593063, (1985)
3. M. Vogelsberger et al., in *Mon. Not. Roy. Astron. Soc.* 395 797811 (2009)
4. V. Chepel and H. Arajo, *JINST* 8 R04001 (2013)
5. D.-M. Mei and A. Hime, in *Physical Review D* 73 053004 (2006)
6. WU Y-C et al., in *Chinese Physics C* 37 8 086001 (2013)
7. E. Aprile et al. (XENON Collaboration), in *Eur. Phys. J. C* 77 275 (2017)
8. E. Aprile et al. (XENON Collaboration), in *Eur. Phys. J. C* 77 358 (2017)
9. O. Y. Smirnov et al. (Collaboration BOREXINO), *Nature* 512 383386 (2014)
10. J. Billard et al., *Phys. Rev. D* 89 023524 (2014)
11. E. Aprile and L. Baudis, in *Particle Dark Matter*, ed. G. Bertone (Cambridge University Press (2010)
12. R. W. Schnee, *Theoretical Advanced Study Institute in Elementary Particle Physics* (proceeding) 629-681 (2010)
13. A. K. Drukier et al., *Physical Review D* 33 34953508 (1986)
14. G. Bellini et al. (Collaboration BOREXINO), *JCAP* 05 015 (2012)
15. R. Bernabei at al. (DAMA Collaboration), *Eur. Phys. J. C* 56 333-355 (2008)
16. E. Aprile et al. (XENON Collaboration), *Astropart. Phys.* 35 573-590 (2012)
17. E. Aprile et al. (XENON Collaboration), *Phys. Rev. Lett.* 97 081302 (2006)
18. M. Schumann, *JINST* 9 C08004 (2014)
19. E. Aprile et al. (XENON Collaboration), *Science* vol. 349 no. 6250 pp. 851-854 (2015)
20. E. Aprile et al. (XENON Collaboration), *Phys. Rev. Lett.* 118, 101101 (2017)
21. K. Abe et al. (XMASS Collaboration), arXiv:1511.04807 (Submitted) (2015)
22. A. Tan et al. (PandaX-II Collaboration), *Phys. Rev. Lett.* 117 121303 (2016)
23. D. S. Akerib et al. (LUX Collaboration), *Phys. Rev. Lett.* 118 021303 (2017)
24. D. S. Akerib et al. (LUX Collaboration), arXiv:1705.03380 (Submitted) (2017)
25. E. Aprile et al. (XENON Collaboration), arXiv:1705.06655 (Submitted) (2017)
26. E. Aprile et al. (XENON Collaboration), *JCAP* 04 027 (2016)
27. D. S. Akerib et al. (LZ Collaboration), arXiv:1509.02910 (2015)
28. J. Aalbers et al., *JCAP* 1611 11 017(2016)