CONTRIBUTION PROSPECTIVES 2020

Direct dark matter Search with the experiments from the international XENON Collaboration

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Abstract

Understanding the nature of the Universe we live in is needed to move a step forward the development of our civilization. All breakthrough discoveries since millennia have been driven by the human beings curiosity. Since ever, shedding light on the unresolved questions of the nature that surrounds us intrigues scientists and human beings in general.

Among the most fascinating open questions nowadays, the nature of the dark matter present in our Universe plays a particular interesting role within the particle and astroparticle physics communities. Indirect cosmological observations provided strong evidence for an invisible and dominant mass component (5 times more abundant than all visible matter, mainly made of baryons), that so far revealed its presence only by its gravitational interaction. At present, despite all the efforts, we know very little about the properties and the nature of this elusive matter. Since decades, a race in building larger and more sensitive detectors aiming at catching the tiny signal generated by the interaction of the dark matter with the target is going on.

We present in this contribution the prospects for a first discovery of the dark matter by the French teams involved in the XENON international collaboration and in the XENONFrance@IN2P3 project. The collaboration has been welcoming French teams since 2009, the contribution now includes the work of 3 French laboratories: LAL, LPNHE and Subatech.

1 Context and objectives

While the existence of dark matter (DM) is undisputed, its physical characteristics remain elusive. Current estimates by Planck put the DM fraction of mass-energy density of the observable Universe at more than 25%, baryonic matter makes up $\sim 5\%$ while the remainder is accounted for by dark energy [1]. Astrophysical observations indicate that DM could take the form of a new elementary particle of nature, outside the current Standard Model of physics, weakly interacting with the ordinary matter and with itself. A leading candidate explanation is that DM is composed of as-yet undiscovered Weakly Interacting Massive Particles (WIMPs) formed in the early universe and subsequently gravitationally clustered in association with baryonic matter [2–5].

Large efforts have been pursued to develop experiments which are able to directly detect the scattering between DM particles and detectors target nuclei. Different technologies have been explored so far to achieve this goal. Among the most promising, liquid xenon (LXe) time projection chambers (TPCs) have recently demonstrated their exceptional capabilities for rare events detection. This technology is evolving rapidly and is expected to continue leading the field of large mass (above $\sim$10 GeV/c^2) WIMP searches with the next generation of multi-ton noble liquid detectors (see figure 1). Nowadays, there is a worldwide competition among the three collaborations that have chosen the LXe as the most promising detecting medium, namely XENON at LNGS laboratory in Italy, PANDAX in China and LUX-LZ in the United States.

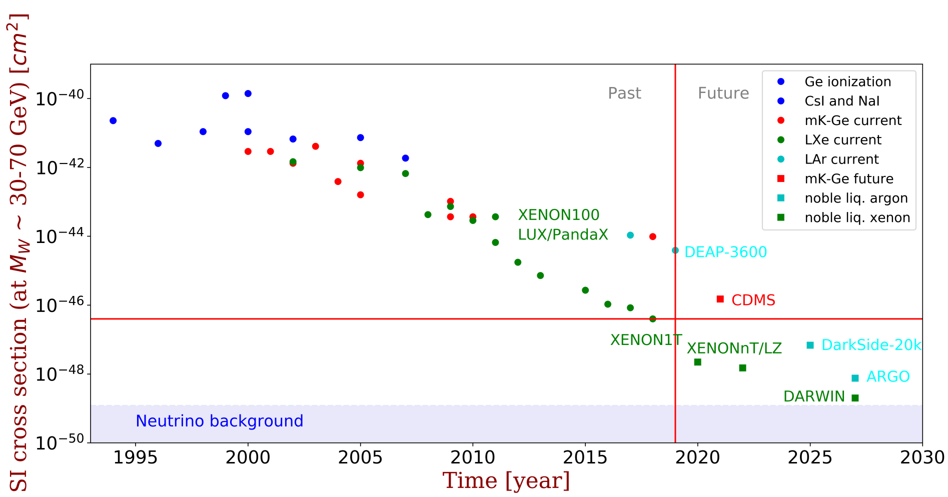

Figure 1: Existing upper limits on spin–independent WIMPnucleon cross sections from various direct detection techniques (circles), along with projections for the future (squares), as a function time.

At the same time, the scientific community is also investing in the search for low-mass ($\sim$1 – 10 GeV/c^2) WIMPs as well as alternative scenarios of light DM candidates with masses down to $\sim$1 eV/c^2 arising in hidden-sector DM theories (see [6] and references therein). Low-mass DM down to $\sim$1 GeV/c^2 can be either probed by performing specific analysis in experiments mainly dedicated to the search of large-mass WIMPs (as it is the case of XENON1T [7, 8]), or using different technologies capable of further lowering the detector threshold down to few eV in order to measure very low energy signals. Various R&D and other experimental efforts are ongoing to exploit the $\mathcal{O}(GeV)$ and/or sub-GeV DM regimes (SuperCDMS, NEWS-G, DAMIC-M, . . .).

In France, several groups working on experiments located underground and looking for rare events, agreed to create a community whose goal is to share their expertise, both theoretical and experimental. This *Groupement de Recherche* (GDR) has been named GDR DULP (Deep Underground Laboratory Physics). The aim of this GDR is to facilitate the synergy between the groups and, at a later stage, the creation of common projects. Triggered initially by the dark matter community, it was then extended to all fields in astroparticle physics whose interest is to profit of the (cosmogenic and radiogenic) low-background environment provided by underground laboratories, like neutrino physics. The scientific program of XENONnT and of the future DARWIN project fits very well in this context, because of the proven performances in direct dark matter search and on the high potential on the search for neutrinoless double beta decay.

The next section (Section 2) details the XENON Project, its genesis, the worldwide records from all detectors built so far and the plans for the near and more far future, while Section 3 deeps into the French participation, since when SUBATECH was the only French laboratory in a collaboration counting 13 institutions only, up to the present, where XENON-France is composed by three IN2P3 institutes (LAL, LPNHE and SUBATECH).

2 The XENON Project

The primary goal of the XENON dark matter project is to find direct evidences for the nuclear scattering of weakly interacting massive dark matter particles (WIMPs) with target nuclei in an ultra-low background liquid xenon detector. The XENON Collaboration has been a pioneer in the field of dark matter direct detection for over a decade. The extraordinary sensitivity of XENON to dark matter is due to the combination of a large, homogeneous volume of ultra pure liquid xenon (LXe) as WIMP target, in a dual phase (liquid-gas) time projection chamber (TPC) operating underground, at the INFN Laboratori Nazionali del Gran Sasso (LNGS) in Italy [9]. To demonstrate the XENON detector concept, the R&D phase [10–14] culminated with a $\sim$10 kg scale TPC prototype (XENON10), operated at LNGS between 2006 and 2007 [15]. XENON10 achieved some of the best limits on WIMP dark matter reported to-date [16–19]. In order to increase the sensitivity to the WIMP-nucleon scattering cross section by more than one order of magnitude with respect to the state-of-the-art in 2007, XENON100, a new TPC with a factor of $\sim$10 more mass and a factor of $\sim$100 less electromagnetic background, was designed. In 2011 XENON100 has set the most stringent limit for a very large range of WIMP masses [20], and remained for years the only LXe TPC in operation with a realistic WIMP discovery potential [21]. After its successful operation (XENON100 was turned off in 2016), the collaboration built the first multi-tons liquid xenon dual-phase time projection chamber: XENON1T was inaugurated in 2015 and took data until December 2018. At present XENON1T set the most stringent limits on spin-independent WIMP-nucleon cross section for WIMP masses above 3 GeV/c^2 [22][8]. Most XENON1T subsystems were designed to also support a significantly larger dark matter detector, with a target of $\sim$6 t. XENONnT aims at improving the spin-independent WIMP sensitivity by another order of magnitude compared to XENON1T [23]. In order to reach the aimed sensitivity, XENONnT will run for three years. During this period an intense activity is foreseen in terms of data taking, analysis and preparation for the final $\sim$50 tons dual phase LXe detector: DARWIN (dark matter WImp search with liquid xenoN) [24]. DARWIN primary goal will be to probe the spin-independent WIMP-nucleon scattering cross section down to 10^{-49} cm^2 for 50 GeV/c^2 WIMPs, where irreducible neutrino backgrounds set in [25]. In the case of an evidence of a DM signal by XENONnT, DARWIN will allow to study with good precision its properties. Besides its excellent sensitivity to WIMPs, its low background will also make it ideally suited for a large number of other rare processes, like for instance solar axions, galactic axion-like particles and the neutrinoless double-beta decay of ^{136}Xe, as well as to measure the low-energy solar neutrino flux with $<$1% precision, and to observe coherent neutrino-nucleus interactions, and detect galactic supernovae.

3 The Roadmap for XENON-France

The SUBATECH laboratory, with the partnership of CNRS/IN2P3, is a member of the XENON Collaboration since 2009, under the group responsibility of Dominique Thers. At that time the XENON100 detector was still operational at the LNGS underground laboratory, in Italy. The SUBATECH group contributed on different aspects of the XENON100 experiment: from data taking and collaboration duties to data processing, analysis, Monte Carlo simulation and quality control. The other french laboratories LPNHE and LAL respectively joined the XENON collaboration in 2016 and 2017 under the responsibilities of Luca Scotto Lavina and Carla Macolino .

The principal contributions of the three French groups to the XENON project are detailed below (neglecting the contribution in XENON100 for reasons of space).

3.1 XENON1T

The impressive performance of the XENON1T experiment during 2 years of data taking and its low-background, demonstrated its capabilities to search for a broad variety of rare-events processes, among which the ones listed below:

- World-wide most stringent limit on the spin-independent WIMP-nucleon scattering [22]
- First observation of two-neutrino double electron capture in ^{124}Xe [26]
- Dedicated search for scalar WIMP-pion coupling [27]
- Best constraint of the spin-dependent WIMP-nucleon cross-section [28]
- Light dark matter searches with ionization signals only [8]
- Search for light dark matter interactions enhanced by the Migdal effect or Bremsstrahlung [7]

Additionally, instrumental papers report a comprehensive description of the experiment [29, 30], while the analysis strategy is detailed in [31, 32].

The French groups contributions to the publication listed above go along the lines of the XENON Collaboration physics strategy and include in particular: investments to the analysis trough detector monitoring and calibration, Monte Carlo studies and signal corrections as well as less -"standard" physics topics searches like, for instance, the neutrinoless double decay of ^{136}Xe and the search for an annual modulation of the dark matter flux.

It is also worth to mention that SUBATECH first and LPNHE later got the responsibility to design and build the computing system of XENON1T located in the Gran Sasso site. Data are stored and treated by using GRID technology. A Virtual Organization has been created and five nodes are used among which the CC-IN2P3 in Lyon who is at present the major contributor in Europe and equivalent to what has been provided in the US site.

The principal technical French responsibility to XENON1T has been the design, construction, commissioning and maintenance of a novel xenon system called ReStoX. ReStoX is an original cryogenic system designed to store, purify and recover the xenon both in liquid or in gaseous phase. It has been successfully built and installed in LNGS in 2014. It still operates efficiently and will be used also for XENONnT experiment.

The XENON1T data-taking ended in December 2018 with the start of the experiment decommissioning and the integration of the XENONnT in the already present infrastructures.

3.2 XENONnT

The XENON collaboration is currently working on the construction and installation of the components needed to upgrade the XENON1T detector to XENONnT. While the production of electrodes and the xenon purification has almost been completed, as well as the recovering system, the assembling of the TPC will take place the next November and the commissioning will start beginning of 2020. The three French groups involved in the project (SUBATECH, LPNHE and LAL) are bringing together their competences, specificities and complementarities in a common program that goes under the name of "XENONnT@IN2P3 package". This program defines the guidelines of the French contribution to the XENON project and its future upgrade for the years to come. The main technical contributions of XENON-France in the XENON1T upgrade (XENONnT) are the following three.

Second Recovery and Storage System: ReStoX2 Given the larger size of the XENONnT detector, a new storage system bigger than ReStoX is necessary. The new system, which is complementary to ReStoX, is called ReStoX2 and has a capacity of 10 tons. ReStoX2 is under responsibility of the three French groups (LAL, LPNHE and SUBATECH). ReStoX2 is a cylindrical vessel with 1.45 m diameter and 5.5 m height. It has an LN2-based inner cooling system made of a parallel-plate heat exchanger. While the ReStoX cooling principle was to cool down xenon efficiently but without freezing it, the ReStoX2 approach is more aggressive: xenon is recovered by crystallization, with a target recuperation flow of one ton per hour. In addition, with the unit ReStoX alone, the collaboration would be paralyzed for long weeks in the event of an internal technical problem. Indeed, to drain ReStoX and recondition the xenon in the bottle using the cryopumping technique, we are currently able to continuously transfer around 10 kg/hour of xenon. It is in this context that we proposed to build the auxiliary unit ReStoX2 around this dual objective: to increase the storage capacity to 10 tons and to boost the emptying and filling stages of the experiment in order to decrease the dead times. The design has been done by our engineer Jean-Marie Disdier in collaboration with the company Costruzioni Generali who was in charge of the construction, and the company DATE who was in charge of the inner heat exchanger. The construction has been carefully followed at all major steps. A postdoc, member of SUBATECH, is on site and took care in the last months of the installation and the commissioning of ReStoX2.

Electrodes As in XENON1T, electrodes are the essential components needed to apply the required electric fields for signal extractions in the TPC detector. The larger size of the XENONnT TPC ($\sim$1/3 increase with respect to the XENON1T TPC diameter) required a thorough qualification of the electrodes that implied new challenges in terms of geometrical dimensions and performances. The LAL group was the major responsible for the design, tests and production of the electrodes for the XENONnT detector. Thanks also to the support of mechanical engineers the LAL group lead all the experimental activities needed to obtain the most performing electrodes in terms of mechanical dimensions, mechanical stability, thermal resistance in liquid xenon, electric field uniformity and cleanliness. These activities required several tests (mechanical and under high voltage) with mockup electrodes of the same size, that were conducted at Laboratori Nazionali del Gran Sasso. This intense R&D activity lasted more than one year and finished around March 2019 when the feasibility of the design was demonstrated. The installation of the real electrodes started on March 2019 and finished on August 2019. Currently the assembled electrodes are under final test inside the XENONnT cryostat filled with liquid xenon while they will be finally installed within the entire TPC from beginning of November 2019. The LAL group, in collaboration with the groups of Rice University and University of San Diego, is the major responsible for all the aforementioned steps needed to provide the five electrodes for the XENONnT TPC.

Software development and computing The request of computing resources allocated by CC-IN2P3 will increase in order to continue having CC-IN2P3 the major contributor of CPU and disk storage in Europe. We are expecting on average a request of 16M HS06h of computing power and 400TB of storage (tapes with dcache technology) per year. In addition, LPNHE will continue having the responsibility of the computing infrastructure at LNGS, that is a fundamental role necessary to guarantee the optimal data flow from LNGS to GRID. LPNHE is also engaged, together with the NYU Abu Dhabi group, on the development of a Xenon Offline data quality Monitoring tool (XoM), a system whose aim is to run a series of analysis algorithms that extract key parameters for the monitoring of the good performances of the detector. This system would also send an alarm in case the parameters deviate from the expected values.

4 International competition and future

In the last ten years a very relevant part of the spin-independent cross section versus WIMP mass parameter space has been scoped, spanning over 6 orders of magnitude on cross section (see for instance Figures 1 and 2) for WIMP masses above $\mathcal{O}$(GeV). Based on the different expertise of several laboratories, the DM international community is now exploring a wide range of detector technologies, part of which is shown in Figure 2). For ∼10 years the XENON experiments have considerably contributed to the evolution of the dark matter direct detection search. Nowadays, the XENON collaboration is indisputably one of the most active in the world.

The reasons behind this success are yet relevant: a naive and strong research addressing an inescapable mystery for the coherent description of Nature, researchers committed to unravel the mystery in a rigorous environment where the surpassing of oneself is proposed, a technology at the forefront of what can be proposed to go even further.

With XENONnT, the collaboration has the ability to push even further the realm of the possible and likely observe for the first time a positive Direct dark matter signal.

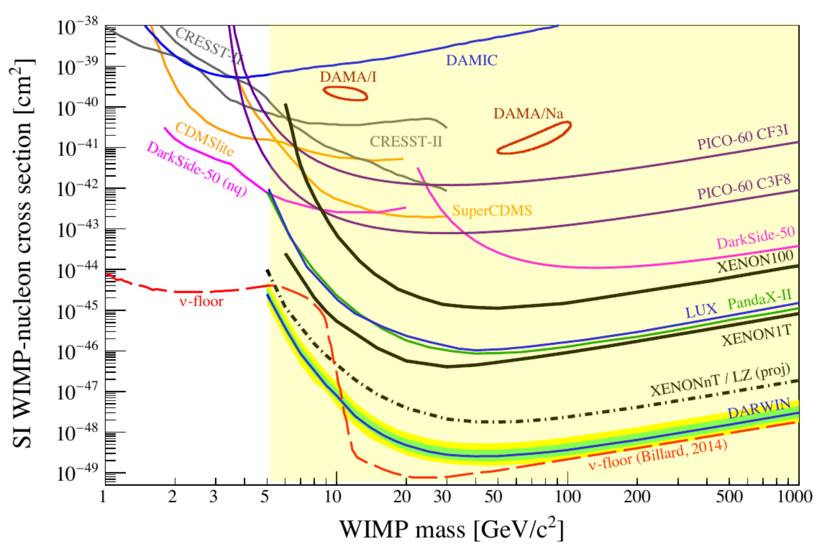

Figure 2: Exclusion limits on spin-independent WIMP-nucleon scattering from current experiments and projections for future planned XENON project detectors plus DARWIN.

The same conclusions have also been drawn at the international level, and today three very large experiments with liquid xenon will be shortly operational:

- The LUX-LZ Collaboration (mostly from USA institutes), who completed the operation of LUX (a detector whose size was in between the one of XENON100 and XENON1T) and that now is building LZ, that has similar sensitivity with respect to XENONnT. LZ is planned to start taking data in 2020.
- The Chinese PANDA-X, who published a sensitivity that was in direct competition with LUX and that is working for an upgraded detector, PANDA-X4.

- The XENON Collaboration (mostly composed by European and USA institutes), that set the best sensitivity to date with XENON1T results and that will be followed soon by its upgrade XENONnT. Part of XMASS Collaboration (running a single phase xenon detector) joined XENONnT with the idea to unify efforts in view of the next generation experiments. XENON1T ended data-taking in December 2018 and XENONnT is planned to start taking science data from early 2020.

In conclusion, if the current international roadmap will not change in the future, XENON1T will lead the dark matter direct detection field until 2020, when the new data coming from its upgrade XENONnT will move a step forward to an unexplored area, allowing to span an additional order of magnitude in WIMP-nucleon cross section. At the same time, other international collaborations will also be capable of reporting comparable results on the search for dark matter, and certainly on $0\nu2\beta$ with ^{136}Xe too. In the context of this world-race, the first results of XENONnT will be crucial to drive the future of direct detection dark matter searches.

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5 XENON-France published papers

Several technical and scientific papers have been published since 2009 by XENON French members.

XENON100 papers

1. **"First Dark Matter Results from the XENON100 Experiment"**
   E. Aprile *et al.* [XENON100 Collaboration].
   arXiv:1005.0380 [astro-ph.CO]
   DOI:10.1103/PhysRevLett.105.131302
   Phys. Rev. Lett. **105**, 131302 (2010)

2. **"Study of the electromagnetic background in the XENON100 experiment"**
   E. Aprile *et al.* [XENON100 Collaboration].
   arXiv:1101.3866 [astro-ph.IM]
   DOI:10.1103/PhysRevD.83.082001, 10.1103/PhysRevD.85.029904
   Phys. Rev. D **83**, 082001 (2011), Erratum: [Phys. Rev. D **85**, 029904 (2012)]

3. **"Likelihood Approach to the First Dark Matter Results from XENON100"**
   E. Aprile *et al.* [XENON100 Collaboration].
   arXiv:1103.0303 [hep-ex]
   DOI:10.1103/PhysRevD.84.052003
   Phys. Rev. D **84**, 052003 (2011)

4. **"Material screening and selection for XENON100"**
   E. Aprile *et al.*.
   arXiv:1103.5831 [physics.ins-det]
   DOI:10.1016/j.astropartphys.2011.06.001
   Astropart. Phys. **35**, 43 (2011)

5. **"Dark Matter Results from 100 Live Days of XENON100 Data"**
   E. Aprile *et al.* [XENON100 Collaboration].
   arXiv:1104.2549 [astro-ph.CO]
   DOI:10.1103/PhysRevLett.107.131302
   Phys. Rev. Lett. **107**, 131302 (2011)

6. **"Implications on Inelastic Dark Matter from 100 Live Days of XENON100 Data"**
   E. Aprile *et al.* [XENON100 Collaboration].
   arXiv:1104.3121 [astro-ph.CO]
   DOI:10.1103/PhysRevD.84.061101
   Phys. Rev. D **84**, 061101 (2011)

7. **"Analysis of the XENON100 Dark Matter Search Data"**
   E. Aprile *et al.* [XENON100 Collaboration].
   arXiv:1207.3458 [astro-ph.IM]
   DOI:10.1016/j.astropartphys.2013.10.002
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8. **"Dark Matter Results from 225 Live Days of XENON100 Data"**
   E. Aprile *et al.* [XENON100 Collaboration].
   arXiv:1207.5988 [astro-ph.CO]

DOI:10.1103/PhysRevLett.109.181301
Phys. Rev. Lett. **109**, 181301 (2012)

9. **"Comment on 'On the subtleties of searching for dark matter with liquid xenon detectors"'**
E. Aprile *et al.* [XENON Collaboration].
arXiv:1208.5762 [astro-ph.CO]

10. **"The distributed Slow Control System of the XENON100 Experiment"**
E. Aprile *et al.*.
arXiv:1211.0836 [astro-ph.IM]
DOI:10.1088/1748-0221/7/12/T12001
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11. **"Limits on spin-dependent WIMP-nucleon cross sections from 225 live days of XENON100 data"**
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