XENON Project Status Report

for the IN2P3 Scientific Council, Fall 2023

Scope: XENONnT, associated R&D (XeLab)
and future experiments (DARWIN)

1. Executive Summary

The fact that dark matter exists, as evidenced by numerous indirect observations in astronomy and cosmology [1], is seen as a striking indication that there must be new physics beyond the Standard Model (BSM) of particle physics. The postulated dark matter particle has not been directly observed yet, and theoretical predictions about its mass, couplings and production mechanisms span a large parameter space. A well-motivated candidate, which arises naturally in several BSM models, is the weakly interacting massive particle (WIMP) [2]. It might be directly detectable in sensitive Earth-based detectors, as it is expected to scatter off the detector's target nuclei. Most models predict an exponentially falling nuclear recoil spectrum, with mean energies of a few keV [3].
The XENON dark matter project aims at the detection of WIMP dark matter with dual-phase time projection chambers (TPC) filled with a liquid xenon (LXe) target.
The current phase of the project, the XENONnT detector, is currently operating, with a scientific production that started very recently, in 2022, with the results of the first Science Run, that showed how XENONnT is the detector with the lowest background ever built so far.
The XENON-France groups (SUBATECH and LPNHE) are strongly involved in the XENON Dark Matter Project. Today, the major axes of expertise in which we are internationally recognized are : liquid xenon technology, computing and data analysis. Together with our colleagues of XENON Collaboration, we plan to continue our science program at least up to 2026, when we plan to reach our ultimate design goal.
XENON-France is actively contributing as well to the design of the next generation detector DARWIN (DARk matter WImp search with liquid xenoN [1][2]) that will follow XENONnT employing multi-tonne liquid xenon time projection chamber at its core. Its primary goal will be to explore the experimentally accessible parameter space for WIMPs in a wide mass-range, until neutrino interactions with the target become an irreducible background. We present the concept of the DARWIN detector and discuss its physics reach, the recent news about how the Collaboration is growing in size (the XLZD Consortium), the internal organization in working packages underlying the role of the XENON-France community, the ongoing detector design and R&D efforts, with particular emphasis of the one that is under construction at LPNHE: XeLab.

2. Scientific challenges

XENONnT Project has been presented at the latest IN2P3 Scientific Council in 2018. Their report has been highly positive, the Council recognising our strong contribution to the project and recommended us to finalize the commissioning of the ReStoX2 subsystem and to participate in the data analysis effort of the experiment. Also, we have been encouraged to actively participate in the DARWIN project, as a natural evolution of XENONnT, and identify a clear role within this project. This section and the next ones demonstrate that we fulfilled all recommendations and went beyond them by completing other new milestones like computing and novel R&D on electrodes.
Direct Dark Matter experiments employ underground, Earth-based detectors, looking for Dark Matter particles expecting to scatter off the detector's target nuclei. Most models predict an exponentially falling nuclear recoil spectrum, with mean energies of a few keV [3]. The technique used by XENON Project is

the building of growing size dual-phase TPCs filled with LXe targets. All detectors belonging to this Project have been built at the Laboratori Nazionali del Gran Sasso (LNGS, located at a depth of 3600 meter water equivalent). The LNGS is not the deepest one, but certainly the biggest and the most equipped one, hence well suited for ambitious ton-scale detectors.
The first WIMP search conducted with XENON10 featured a target mass of 14 kg (25 kg total). It was followed by XENON100 (62 kg target, 161 kg total mass). The next one, the XENON1T experiment, was the first WIMP dark matter detector operating with a liquid xenon target mass above the ton-scale. Out of its 3.2 tons liquid xenon inventory, 2.0 tons constituted the active target of the TPC. The XENON1T upgrade, XENONnT, with its 4 tons as active target, is now currently operating, with a scientific production that started in 2022.
In France, many other groups have been or are involved in Direct Dark Matter detection. LXe TPC technique showed its capability to be scaled up easily to larger masses and lower background, with an increasing sensitivity to WIMPs of about an order of magnitude every three years. The XENON Project is currently the only one that is scoping unexplored regions of the parameters space at large WIMP masses. Others IN2P3 French groups are involved in dark matter direct detection programs, among which the one listed below, that recently published results: :

- **DAMIC-M**, a project using CCD cameras, funded by ERC, extremely sensitive to light dark matter candidates The detector, running at LSM published exclusion limits on dark sector stronger than XENON ones, in a mass range where LXe cannot compete. For those reasons, this technology can be seen as complementary to the XENON project one.
- **DarkSide-50**, a dual phase TPC using liquid argon located at LNGS. While the standard analysis at high WIMP masses is less sensitive compared to the one of the current running multi-ton xenon detectors (because of the little target size), their S2-only analysis presented a better sensitivity compared to XENON1T in the range of 1-3.5 GeVc^2 WIMP mass.
- **DarkSide-20k**, whose construction is in preparation, aims to reach similar sensitivities of XENONnT at high WIMP masses using a liquid argon dual phase TPC of 50 tonnes active mass.
- **NEWS-G**, searches for light dark matter using spherical proportional counters filled with light gaseous targets. With its latest detector S140 at SNOLAB using methane, they obtained a world-leading result on spin-dependent sensitivity under 2 GeV/c^2 WIMP masses. This is another experiment that is complementary to XENON.

Figure 1 shows the current status of dark matter search in 2022, with limits and expected sensitivity for future detectors.

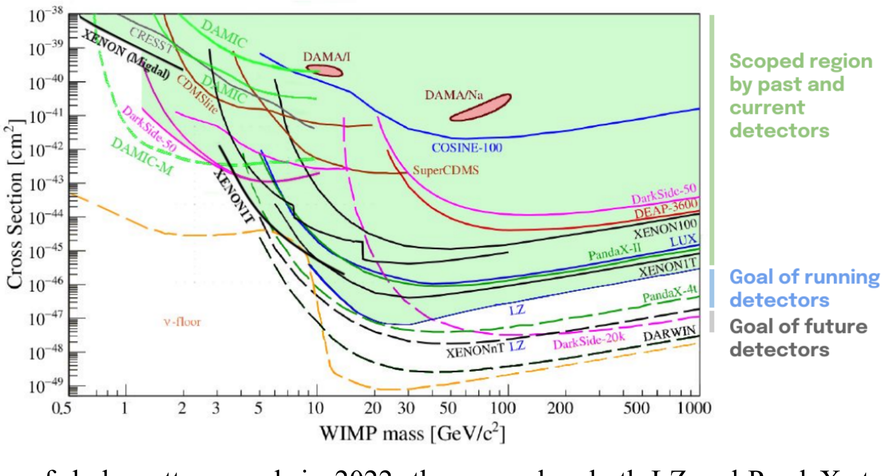

Figure 1: Status of dark matter search in 2022, the year when both LZ and PandaX started to publish their first results with a non-blinded method (XENONnT following in 2023). LXe TPC are leading on almost the totality of parameters space, from 50 MeV/c^2 up to >TeV scale

XENON-France is as well involved to many bodies supported by IN2P3, in most of them with managing responsibilities, showing a very high activity in the field:

- **GDR DUPhy** (Deep Underground Physics) [5]: we participated in the creation and initial brainstorming of this GDR, meant to group together the communities that share the common interest of rare event physics, namely in underground laboratories. The main two axes of DUPhy are Dark Matter and neutrinoless double beta decay, both covered by the physics reach of XENON and next generation LXe detectors. The XENON-France participation in this GDR is very strong. Three members of XENON (D. Thers, L. Scotto Lavina and R. Gaior) have a management role. Among the 4 meetings held so far, two of them have been organized by SUBATECH and LPNHE. In addition, as it is detailed in figure 2, XENON contributions, most of them on science results, represent the relative majority of the whole mass of contributions.

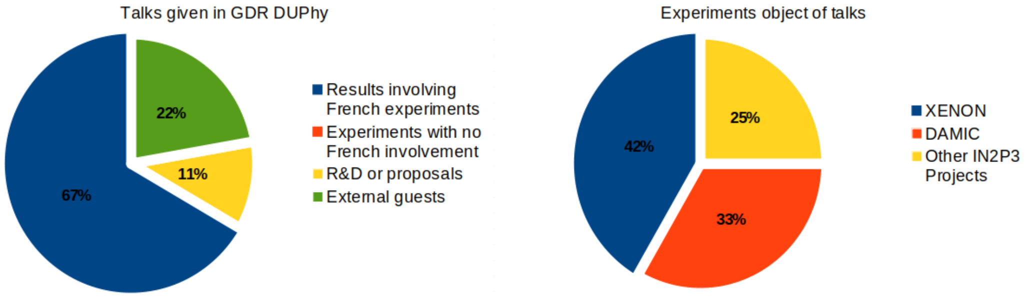

Figure 2: Among the 9 laboratories in DUPhy, XENON-France contributes with its 2 laboratories (22%). Among all talks, 67% are on results on experiments in which France is directly involved (left pie chart). Among them, 42% are direct contributions from XENON-France only.

- **IRN Terascale** [27]**:** IRN Terascale is a international research network dedicated to the experimental and theoretical search for new physics at the TeV scale. J. Masbou (SUBATECH) is co-coordinating the Dark Universe working group that is focused on the synergies between theoretical and experimental searches. XENON regularly presents its latest results on this IRN. In 2022, we had a joint Terascale-DUPhy workshop held in SUBATECH, with particular focus on Dark Matter searches and where XENON-France contributed with three talks.
- **DMLab** [6]: CNRS has strengthened the partnership with Helmholtz Association, with the creation of an International Research Laboratory (IRL) named DMLab. DARWIN, together with MADMAX, are the only two flagship projects of DMLab concerning direct detection of dark matter (MADMAX for axions and DARWIN for WIMPs). The person co-leading DARWIN is J. Masbou (SUBATECH). The first in-person meeting of DMLab was held in 2022 [7]. The immediate benefit of this IRL is an increasing activity between XENON-France and KIT (PIs : Klaus Eitel and Kathrin Valerius) on three axes (computing, liquid xenon technology and R&D on TPC electrodes).
- **ILANCE** [8]: An ongoing discussion with our XENON and DARWIN colleagues from Tokyo University has been placed for a common R&D on the monitoring of the xenon purification. For this reason, we joined the ILANCE laboratory, an IRL between CNRS and the University of Tokyo. The person following this discussion is R. Gaior (LPNHE).
- **CNRS-Australia Network** [9] : S. Diglio (SUBATECH) triggered several partnerships with the groups of Prof. Elisabetta Barberio at The University of Melbourne, Australia. She is the PI of the International Emerging Action (IEA) entitled “XEnon Time Projection Chambers: R&D for Future Generation Experiments, searching for Dark Matter and Neutrinoless Double Beta decay (0vbb)” (XERD-DM-0vbb) started in 2021. With this IEA the members of the SUBATECH laboratory and the School of Physics at the University of Melbourne, joined their efforts to prepare the playground for the next generation liquid xenon detector. In this respect, the two groups are contributing to R&D activities as well as to analysis via the search for dark matter candidates and investigation of the nature of neutrinos using the XENONnT data. The members of this project are also part of the

Melbourne-CNRS Network [10]. In particular, four PhD students jointly supervised by SUBATECH and Melbourne teams members and a Y. Xing (IN2P3 Postdoc based at SUBATECH) are part of the network. The first PhD thesis in *cotutelle* between SUBATECH (via the IMT Atlantique *tutelle*) and the University of Melbourne started in 2021. This has been followed by two joint PhDs granted by the "joint PhD CNRS-The University of Melbourne" [11] call in 2022. A fourth one will start in the fall 2023 in the context of the Australia-France Network of Doctoral Excellence, AUFRANDE [12]. The members of the Network organized several in-person meetings in Australia and in France since the start of this collaboration, to work on the common program and to plan future joint contributions. In the context of the evolution of these ongoing activities, two additional institutions joined the network: the group at LPNHE led by L.Scotto Lavina and the group at the University of Sydney, led by Prof. Celine Boehm. With the goal to further reinforce the French and Australian joint contributions in preparation for the ultimate observatory for dark matter and neutrino physics, the four groups recently submitted an International Research Project (IRP) entitled XERD-DM-ν : XEnon Time Projection Chambers: R&D for Future Generation Experiments, searching for Dark Matter and investigating the nature of neutrinos (ν).

At the international level, the competition has been so far basically among experiments using the same target: with LUX first, now with LZ experiment in the US, and with PandaX in China. The three collaborations (XENON, LZ and PandaX) published recently the outcome of their research for an excess of nuclear recoils (the so-called standard WIMP analysis). With similar sensitivities and exclusion limits, they are leading the field of dark matter search. In a nutshell, XENONnT presents the lowest background while LZ collected higher exposures. It is worth mentioning that XENONnT is the only one using a blinded analysis method [25]. Figure 3 shows the current scenario, where the three LXe-based detectors are competing with each other.

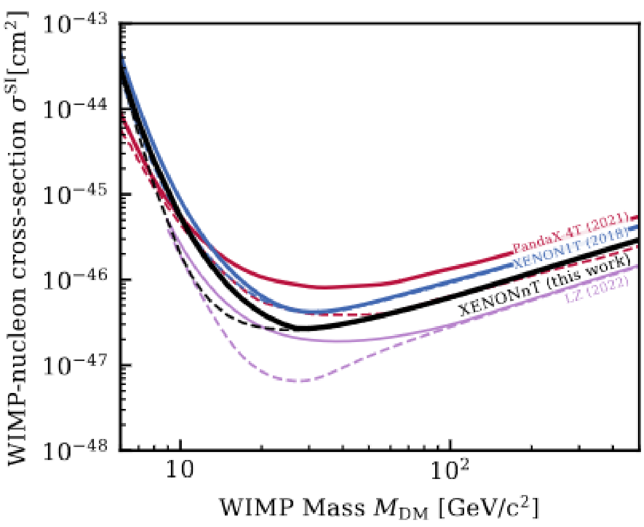

Figure 3: Status of dark matter search now (2023). Solid curves show the 90% CL exclusion limit using a power-constraint to restrict it at or above the median unconstrained upper limit. Dashed curves : no power constraint applied. XENONnT is the only result using blinding procedure, and it presents less under-fluctuations [25].

Besides the standard high-mass WIMP search, XENON and the future DARWIN experiment are capable of obtaining competing or even world-limiting results in other fields. Namely:

- Even if LXe TPCs were not meant to go down the GeV threshold, they demonstrated to give major contributions for light dark matter candidates as well. The search for tiny signals in XENON was initiated at SUBATECH with a XENON100 publication on single electrons signal, with L. Scotto Lavina and J. Lamblin (MdC now at Grenoble) as corresponding authors, then LPNHE took this subject as its main analysis task by particularly focusing on the leptophilic dark matter search, as it will be detailed later. This interest of XENON-France on single electrons translated as one of the two R&D axes present in the XeLab Project.

- The science scope of XENON is not limited only to Dark Matter. XENONnT, and even more DARWIN in the future, can be seen as an Astroparticle Observatory, given the many results on different fields other than Dark Matter. This includes a fair sensitivity to high energy (O(MeV)) channels like double beta decays of the 136Xe isotope with or without neutrinos emissions (2vbb/0vbb). With the former PhD thesis subjets of C. Therreau [47] and M. Pierre [42, 46] and the current ones of M. Bazyk and J. Loizeau, the SUBATECH team is being very active in this field.

The current roles of XENON-France within XENON and DARWIN Collaborations are:

- L. Scotto Lavina (LPNHE, IN2P3), D. Thers (SUBATECH) : PIs of XENON and DARWIN
- L. Scotto Lavina (LPNHE, IN2P3) : co-leader of the Xenon Storage and Recovery System ReStoX1 (for XENON1T, then XENONnT)
- J. Masbou (SUBATECH) and L. Scotto Lavina (LPNHE, IN2P3) : co-leaders of the Xenon Storage and Recovery System ReStoX2 designed and built for XENONnT
- L. Scotto Lavina (LPNHE, IN2P3) : co-leader in computing since 2011 (XENON100, XENON1T, XENONnT, DARWIN)
- L. Scotto Lavina (LPNHE, IN2P3) : member of XENONnT Editorial Board
- S. Diglio (SUBATECH, IN2P3) : member of XENONnT Speakers Bureau
- J. Masbou (SUBATECH) : member of the XENONnT Press Release Team
- Plus some rotating responsibilities of postdocs in the last 5 years:
    - G. Bruno (SUBATECH, run coordinator in XENONnT)
    - Y. Xing (SUBATECH, Data Quality Manager in XENONnT)

In addition, SUBATECH group co-organised with Coimbra Universit y for two consecutive years (2022 and 2023) the international workshop XeSAT, a conference where all subjects working on LXe on a wide scope (high energy, astroparticle and nuclear physics, medical applications, industry) are gathered together to present their advancements on LXe technology.
Presented roles give to XENON groups in France very high visibility in the national territory, in the XENON, DARWIN and XLZD communities and internationally.

3. Project

The XENON collaboration as well as the next generation DARWIN project aim for the direct detection of Dark Matter or, in absence of a signal, to cover the totality of the parameters space experimentally available. In addition, these observatories allow us to advance in the exploitation and knowledge of particle physics, nuclear physics, astrophysics, solar physics, and cosmology. At the present stage, the XENON-France interest is declined to three parallel activities that will be separately developed below: XENONnT, DARWIN and the related R&T (XeLab).

3.1.a XENONnT. Science activities

XENONnT is a IN2P3 Master Project. Our primary goal is operating the already existing detector XENONnT until getting close to the aimed exposure of 20 tonnes × year, where the expected sensitivity to spin-independent WIMP-nucleon interactions reaches a cross-section of 1.4×10^{-48} cm^2 for a 50 GeV/c^2 mass WIMP at 90% confidence level, more than one order of magnitude beyond its predecessor XENON1T. We plan as well to extend the scientific production we have done with XENON1T (that will be detailed in the section 4). We list below the data analysis roadmap for XENON-France.

Introduction. The nature of dark matter and properties of neutrinos are among the most pressing issues in contemporary particle physics. LXe TPC is the leading technology to cover the available parameter space for WIMPs, and features as well extensive sensitivity to many alternative dark matter candidates. On top of that, these detectors can also study neutrinos: the search for neutrinoless double-beta decay; the improvement of our knowledge on double electron captures; the measurement of the coherent elastic scattering from solar neutrinos; finally the capability of detection of neutrinos from supernovae. There is therefore an increasing interest in our community to explore those new physics channels in a more systematic approach with respect to what we were doing in the past.

Search for coherent elastic scattering of Solar 8B neutrinos
LPNHE PhD thesis of Q. Pellegrini, expected defense on Fall 2025
Supervisors : L. Scotto Lavina and B. Andrieu
Neutrinos from the Sun can produce observable nuclear recoils via coherent elastic scattering off nuclei in liquid xenon. The coherent elastic neutrino-nucleus scattering (CEvNS) process produces the same signature as the one expected from DM-nucleus interactions, and thus the two can only be distinguished by their recoil spectra. Solar 8B neutrinos are expected to contribute the greatest number of CEvNS events. These events fall near the energy thresholds of such detectors, with a spectrum indistinguishable from 6 GeV Dark Matter mass equivalent. XENON1T already investigated the possibility to search for those neutrino interactions [17], but its sensitivity was not yet enough to accumulate a statistically significant number of events. Still, we showed how including neutrinos in the background model, improved sensibly the sensitivity for dark matter search at low masses. With XENONnT we are expecting a higher sensitivity due to the larger detector mass (a factor 3) and the higher scintillation gain (about 30%). We can further improve this result by increasing the rejection power of the main background present in this analysis: the accidental coincidence of scintillation and ionization signals incorrectly paired by the reconstruction software, that mimics real interactions. This work can be performed together with the help of dedicated Monte Carlo simulations and a very precise detector characterization. The modeling of neutrino scattering signals in XENONnT, the background rejection and the final search for low mass dark matter will be the main mission of Quentin Pellegrini. This work will lead to a publication.

Search for coherent elastic scattering of Supernova neutrinos
LPNHE PhD thesis of L. Daniel Garcia, expected defense on Fall 2024
Supervisors : L. Scotto Lavina and B. Andrieu
Certain kinds of supernovae can produce observable nuclear recoils via coherent elastic scattering off nuclei in liquid xenon. The coherent elastic neutrino-nucleus scattering process (CEvNS) produces the same signature as the one expected from DM-nucleus interactions. In this case, we can distinguish the two processes not only by studying the energy recoil spectra, but also looking at the rate over time. In a TPC based on liquid xenon, neutrinos coming from a core-collapse supernova located anywhere in the Milky Way are expected to be detected with a good significance [18]. The main mission of Daniel Layos Garcia, who started his PhD thesis in May 2022, is to exploit the full potential of XENONnT on detecting this signal. The work first consists in reviewing the production mechanisms of neutrinos in core-collapse supernovae, then their travel to the Earth, with the goal of having the most precise estimation of the neutrino flux expected to reach the XENONnT detector, as well as the detector of the future DARWIN Project (200 tonne*year after 4 years). Beyond the CEvNS, other SN neutrino interaction channels will be studied, particularly those involving the muon and neutron veto's of XENONnT, like inverse beta decay which has a similar rate than CEvNS. Layos is working in collaboration with the postdoctoral researcher E. Masson and with another PhD student, Melih Kara from KIT (his thesis focusing on TPC data, while Layos one on Vetoes) in the context of DMLab activities. This work will lead to a publication.

Search for light leptophillic Dark Matter

LPNHE (China Scholarship Council) PhD thesis of Y. Pan, expected defence on Fall 2025

Supervisors : L. Scotto Lavina and F. Gao (XENON PI from Tsinghua University, China)

The major role of LPNHE on XENON Project analysis efforts has always been centred around the capability of the detector of being sensitive to very tiny signals, where a particle interacting to the xenon medium produces only one to few ionization electrons. This capability opened to XENON the possibility to be sensitive to two channels: 1) to the light WIMPs models (hence nuclear recoils), with masses at 1-10 GeV, 2) to dark matter scattering through electrons, with mass sensitivity down to keV and MeV scale (model dependent).

In both cases, the major source of background comes from isolated electrons or small electron clusters originating by several mechanisms (delayed emissions of electrons from liquid to gas phase, photoionization, electron emission by electrodes, etc…). LPNHE contributed strongly to this subject, by characterizing this background and by finding the tools to reject it by keeping the signal acceptance sufficiently high. This is also strongly connected with the second science goal of XeLab, where we aim to develop a background model for those electrons. The LPNHE group focused on the second channel, also called leptophilic dark matter for its peculiarity to scatter off electrons. This channel includes: 1) Dark matter - electron interaction, in which a fermion or scalar boson DM candidate scatters off an electron bound in a xenon atom; 2) Bosonic Dark Matter, basically a pseudo-scalar DM, such as axion-like particles (ALPs), or vector-boson DM candidates, such as dark photons, that would be detectable through absorption by xenon atoms within the TPC; 3) Bosonic Dark Matter via Solar Dark Photon, originating in the Sun. This is the thesis subject of Yongyu Pan, a student whose 4-years long PhD is funded by the China Scholarship Council. This work will lead to a publication.

Simulation of the secondary scintillation mechanism.

S*enior scientist B. Andrieu with the informatic engineers O. Dadoun and N. Garroum*.

One of the major issues that we were expecting with XENONnT was the difficulty to increase the electrons liquid-gas extraction field of the TPC, due to the sagging of the electrodes: as the voltage difference between the two concerned electrodes increases (namely called anode and gate grid, both composed by parallel wires), the electrostatic induction sums up to the other forces and decreases the distance among them, resulting into a non-homogeneous response of the detector. This is basically the reason why we are developing new ideas with XeLab for next generation detectors. LPNHE has been involved in the development of the full simulation of the XENONnT proportional scintillation signal, that will include for the first time the actual experimental conditions of the electrodes. This work, basically based on GEANT4 development and data / Monte Carlo comparisons, is being carried out by Bernard Andrieu and Olivier Dadoun. They also performed a full simulation of the transport of VUV light photons through the TPC, generated by the secondary scintillation mechanism. On top of that, Nabil Garroum, with the goal of better understanding the problematics of the electrodes in XENONnT and improve their performances in our local activity XeLab, performed with *COMSOL multiphysics* a full simulation of the forces applied to the XENONnT electrodes by coupling thermodynamics, electrostatics and gravity.

High energy searches

SUBATECH (IMT-Atlatique) & The University of Melbourne cotutelle PhD thesis of M. Bazyk, expected defense on January 2025

Supervisors : S. Diglio, D. Thers and E. Barberio (The University of Melbourne)

Thanks to their ultra-low background, LXe multi-ton dark matter direct detection experiments have proven their capability to extend their physics reach beyond dark matter by exploring other physics channels in higher energy regions (O(MeV)) such as double electron capture, $2\nu/0\nu\beta\beta$ of 136Xe and 134Xe and others [42]. As a follow-up of the work initiated by the former PhD student Maxime Pierre (corresponding author of the above-mentioned [42] paper), Marina Bazyk is preparing the ground floor for the analysis at high energy with the data collected by the XENONnT detector. In particular, she is working on two main aspects: the estimation of systematic uncertainties on light and charge yield measurements at high energies; the development of background modelling for the inference framework that will be used for all analyses in the context of high energy region searches (0νββ, double electron capture, 2νββ and others). In the context of the *cotutelle* program, she will also contribute to the update of neutrinoless double beta decay sensitivity studies for the DARWIN/XLZD future detector. This work will lead to one or more publications.

Search for low mass Dark Matter via the Migdal effect

SUBATECH (CNRS) & The University of Melbourne cotutelle PhD thesis of L. Principe, expected defence on Fall 2025

Supervisors : S. Diglio, D. Thers and E. Barberio (The University of Melbourne)

One possibility to extend the sensitivity of the XENON detector to the sub-GeV mass region of dark matter candidates, is to use the so-called Migdal effect. This effect predicts that a nuclear recoil interaction can be accompanied by atomic ionization and excitation, resulting in a detectable ER-like signal. The XENON collaboration, already exploited the Migdal effect using data from the XENON1T experiment, probing low-mass dark matter down to about 85 MeV/c^2 [40]. This search can be even more constraining, by using the data delivered by the XENONnT experiment. This will be the main topic of Lorenzo Principe's thesis. Lorenzo is a member of the France-Australia network (joint PhD student between SUBATECH and The University of Melbourne) and is primarily based in Nantes. In addition, taking advantage of the fact that experts in Migdal effect are at The University of Melbourne, it seems very interesting to propose a thesis on this subject. In particular, what the theorists Lorenzo would be working with in the future have highlighted in [45], is that until now the analyses using the Migdal effect to access masses of the order of GeV are based on calculations of the Migdal effect in a vacuum. In reality, the recoil nucleus moves towards another atom and enters its potential. The emitted electrons could then be reabsorbed by this temporary molecular potential. It would therefore be very important to quantify this effect so that it can be taken into account in future analysis of the XENONnT data and also in sensitivity studies for the next generation DARWIN detector. This work will lead to one or more publications.

Alternative-to-WIMPs Dark Matter candidates searches

Australia - France Network of Doctoral Excellence (AUFRANDE) – Actions Marie Skłodowska-Curie

SUBATECH (IMT-Atlatique) & The University of Melbourne cotutelle PhD thesis of A. Ravindran, expected defence on fall 2026

Supervisors : S. Diglio, D. Thers and E. Barberio (The University of Melbourne)

In the fall of 2023, Ananthakrishnan Ravindran will start his joint thesis in the context of the very competitive AUFRANDE program [12]. Ananthakrishnan's thesis will focus on the direct search for alternative Dark Matter candidates to WIMPs with the XENONnT experiment and on the study of future prospects with the next generation of liquid xenon detectors as part of the DARWIN and XLZD projects. For the latter, R&D and performance studies aimed at optimizing the design of this future liquid xenon observatory will be carried out in collaboration with industrial partners that are part of the project. The choice of the specific Dark Matter model will be dictated by the schedule of priorities for the XENONnT experiment. The details of the programme will therefore be defined during the first year of the thesis that will be mainly devoted to contributions to activities of common interest and necessary to the XENON collaboration, such as detector monitoring and calibration, signal corrections and on-site operations. This work will lead to one or more publications.

Direct search for dark matter with XENONnT and high-energy studies

SUBATECH PhD thesis of J. Loizeau, expected defence on fall 2024

Supervisor : J. Masbou

Operating in a low-noise environment for dark matter search, XENONnT is designed to detect the signal produced by the elastic collision of WIMPs with a xenon target nucleus. This rare, low-energy signal requires experiments whose response is perfectly known over long data acquisition periods. Regular calibrations using an internal Kr-83m source have therefore been set up to ensure the stability of the detector. Johan's work focuses on the quality of the spatial reconstruction. Thanks to its very low background, XENONnT also enables the study of other rare processes, such as the search for double ß decay without neutrino emission, a prospect made possible by the natural presence of Xe-136, a double ß- emitter. Detection of such decay could help determine the nature of neutrinos. The signal is an electronic recoil whose energy is high compared with the energy expected in the search for dark matter. A dedicated analysis has been set up to reconstruct these high-energy events. His work focuses in particular on the selection of events (single or multiple interactions) and on the quality of the energy reconstruction, where resolution is a key parameter for the sensitivity of the analysis.

3.1.b XENONnT. Technical activities

On top of the presented data analysis effort, we also have technical activities and responsibilities. We list here the major ones.

Operations and maintenance of the storage systems.
J. Masbou, L. Scotto Lavina, D. Thers
Subatech and LPNHE are co-responsible for the two sub-detectors ReStoX1 and ReStoX2. They require regular maintenance and are also strongly used during cryogenic operations. As an example of operation: the transfer of liquid xenon from the detector vessel to the storage systems and the subsequent transfer back. Those activities have always been ensured until 2022 by a postdoctoral researcher employed by Subatech. Currently, there is no researcher from XENON-France permanently at LNGS following those operations. In addition, XENON-France employed in latest 5 years an engineer expert on cryogenics (Jean-Marie Disdier) full time on-site.

Computing and Data Management.
L. Scotto Lavina, B. Andrieu, E. Masson
L. Scotto Lavina became in 2019 responsible for the Computing of the XENONnT experiment. After covering the same role for XENON100 and partially for XENON1T (interruption due to the moving from Subatech to LPNHE), he designed the Data Flow for the experiment, the computing infrastructure at LNGS and coordinates the daily data transfer since the beginning of the operations. The XENONnT data flow of the experiment has been working uninterrupted for three years. The main core of the XENONnT data management is a software called aDMIX [19] (advanced Data Management In Xenon) publicly available and released with BSD licence, of which L. Scotto Lavina is the main contributor. XENON data is too large to be stored at any one site, so it has to be distributed on GRID storage at several sites around the world. The major contribution in Europe is provided by CC-IN2P3. Bernard Andrieu took the responsibility to monitor the activity of aDMIX, to produce the internal documentation of the package and to assume, together with the postdoc Erwann Masson, the role of Data Managers for the Collaboration.

Monitoring of Xenon Data Quality
Y. Xing, L. Principe, R. Gaior, Q. Pellegrini, M. Bazyk, S. Diglio
The automated data quality control of XENONnT detector evolved over time and XENON-France always had a primary role on it. SUBATECH has been always responsible for the monitoring of parameters like Light Yield, Charge Yield, and xenon purity: this monitoring is fundamental to ensure the good quality of the data that will be later used for science searches. Starting from 2018, the responsibility

was firstly covered by S. Diglio and later by postdocs and PhD students of the SUBATECH group (in chronological order: C. Therreau, M. Pierre, M. Bazyk and Y. Xing). In 2022, the XENON Collaboration agreed to have a more coordinated data quality monitoring activity by using more automated methods and by defining a new role in the Organigram of the Collaboration: the Data Quality Manager (DQM). The first DQM is being Yajing Xing, from SUBATECH. Her contract with SUBATECH finishing in December and with no new postdoc being employed, this role will be unfortunately given to another postdoc in the collaboration.

The Xenon Offline data quality Monitoring (XOM) is an automated tool that processes data acquired every day with the state of the art of the analysis tools provided by the Collaboration, producing a plethora of quantities that are necessary to determine the health of the detector, hence the quality of data. Those quantities are then stored in a dedicated database and shown by a graphical web application. It has been developed by Romain Gaior (LPNHE), who completed both the front-end (the web application) and the back-end (the software in charge of running the analysis algorithms). Currently, the project is being followed also by the PhD student Quentin Pellegrini (LPNHE). XOM is publicly available and released with BSD licence [20]. This software will now be used by the DQM. On top of that, another tool has been introduced recently by the Collaboration, which makes use of a Grafana Dashboard and several plugins that retrieve information from many informatics subsystems. This is now maintained by the PhD student Lorenzo Principe (SUBATECH).

Operations on site at LNGS and collaboration duties

In order to ensure the best possible management of a large-size instrument like XENONnT, members of both French groups guarantee a constant involvement in all duties related to the correct functioning of the experiment, they include: regular shifts on the experimental site, participation to the collaboration meetings on a 3-months basis, participation to the weekly meetings on data analysis, detector operations, Monte Carlo simulations, experimental developments and management activities concerning publications and participation to conferences.

3.2 DARWIN

XENON-France is strongly involved in designing the next generation detector DARWIN [13], initiated by the well established DARWIN Collaboration [14] (about 200 members from 35 institutions in Europe, USA, Asia and Australia) who is recently evolving into the newborn XLZD Consortium [14]. XLZD is basically the fusion of the three communities XENON, LZ and DARWIN. With this new Consortium, we wrote a very exhaustive “White Paper” [16] signed by more than 500 scientists. The detector baseline would employ 40 tonnes of LXe in the TPC (but set up in such a way to be easily scalable up to 80 tonnes), with sensitivity for the detection of particle dark matter, neutrinoless double beta decay ($0\nu\beta\beta$), and a wide variety of astrophysical sources. This next-generation xenon-based detector will therefore be a true multipurpose observatory to significantly advance particle physics, nuclear physics, astrophysics, solar physics, and cosmology.

With noble liquid TPC detectors growing in size, several challenges are arising. From one side, we are using the current detectors LZ and XENONnT as playground to solve them in advance (as it was successfully done in XENON1T in view of building XENONnT). On the other side, the purpose of DARWIN/XLZD R&D activities is to develop new techniques that could improve or replace the current ones. This R&D phase is still ongoing and a finalized design of DARWIN will not happen before 2027 with an aimed start of operations from 2032. In this very rich and exciting context, XENON-France is actively working on many fronts:

1. **Liquid xenon technology.** Developing a new Xenon Storage and Recovery system capable of storing larger amounts of xenon. The new system, that we currently call ReStoX3, merges the features of the

storages built for XENON1T and XENONnT, namely the capability to recuperate directly in liquid phase with a precise control of the vessel pressure (feature that we developed in ReStoX1), with the ultra-fast recuperation by crystallization that is necessary to act as well as pressure relief system (feature present in ReStoX2). The responsible for the design of this system is J. Masbou (SUBATECH), who got financial resources by the *Région des Pays de la Loire* ("Rising star" Project) to work on the design of storage and recovery systems for next generation experiments. Because of several technological constraints, it would be inefficient for a new ReStoX system to store more than 50 tonnes of xenon (this limit could even be smaller in case the detector site will be in a mine). Since the plan of XLZD Consortium is to develop a multi-stage approach with an ultimate detector containing up to 100 tonnes of xenon, we plan to also study how to interconnect several storages with each other and with the rest of the cryogenic plant. A new ReStoX3 system might correspond to the main technical contribution of XENON-France in DARWIN, as it has been for the previous detectors.

2. **Computing.** Developing a new data management framework, that valorizes the EGI resources (EGI stands for European GRID Infrastructure), namely the current computing facilities in Netherland, Italy and France, and encouraging the new, emerging ones in Germany. Given the importance of this task, the DARWIN collaboration created in 2023 a dedicated Working Group, whose leader is L. Scotto Lavina (LPNHE). The CC-IN2P3 computing center is being strongly used by the XENON Collaboration for XENON1T and XENONnT detectors. XENONnT transferred, stored and processed about 4PB of data, accumulating today at a rate of about 1PB per year. A great contribution in terms of storage is provided by CC-IN2P3, whose storage capacity is increasing over time. This is very important to highlight the CC-IN2P3 GRID site and in general the whole EGI network for fundamental science [21]. Still, in XENONnT, half of the resources used come from US (OSG) and the only existing analysis hub is in Chicago University. We plan for DARWIN to increase the role of Europe in computing, both in terms of increasing CPU+storage resources allocated for DARWIN, but also to create an analysis hub in Europe.
3. **Experiment CDR.** XENON-France is also involved in the preparation of the Conceptual Design Report (CDR) from what concerns cryogenics. The final design will make profit of the experience we accumulated with XENON1T first and XENONnT later. During those years, as we have always done with the previous experiments, we managed to develop solutions for the next-generation detector by applying them directly to the detector under operation, using the last year of operation to demonstrate the new technology. A remarkable example is the purification using xenon directly in liquid phase, tested with XENON1T, that allowed us to reach an electron lifetime of about 20 ms, far beyond the needs of XENONnT and DARWIN.
4. **Solar neutrinos.** The participation to the studies of the DARWIN physics reach concerning the nuclear recoil searches (i.e. the standard WIMP model), namely the background coming from the coherent elastic neutrino-nucleus scattering (CEvNS) from solar (8B) neutrinos (B. Andrieu and Q. Pellegrini). This is a straightforward by-product of the Q. Pellegrini thesis, whose subject is focused on XENONnT data and Monte Carlo Simulations.
5. **Supernovae Neutrinos.** The optimization of the water Cherenkov veto to make DARWIN efficient not only to discriminate against the neutron background, but also to detect neutrinos originating from a supernova in the Milky Way. This is a straightforward by-product of the D. Layos Garcia thesis, whose subject is on supernovae detection with the XENONnT detector, a work based mainly on Monte Carlo simulation of both XENONnT TPC, Neutron Veto and Muon Veto and modelling of neutrinos from supernovae.
6. **Neutrinoless double beta decay (0vbb).** Sensitivity studies on the search for neutrinoless double beta decay, with a baseline design of the DARWIN detector, has been already published in [46]. The former PhD student of the SUBATECH group Maxime Pierre, under the supervision of S. Diglio, strongly contributed to this study, specifically in the evaluation of intrinsic background components. As a follow-up of M. Bazyk and J. Loizeau thesis (see section 3.1.a), these results will be updated and

extended to estimate the half-life sensitivity of 136Xe to the 0vbb search for different possible geometries of the XLZD/DARWIN detector.

7. **R&D on detector performances.** The design, construction, commissioning and operations of the XeLab detector, which will be detailed in the next section. Both XENON-France groups participate in this effort, with L. Scotto Lavina as Scientific Coordinator and N. Garroum as Technical Coordinator.
8. **Current and future search for dark matter trough LXe and NaI(Tl) detectors**
   The University of Melbourne & SUBATECH (CNRS) cotutelle PhD thesis of O. Stanley, expected defence on Fall 2025
   Supervisors : E. Barberio (The University of Melbourne), P. Urquijo (The University of Melbourne), S. Diglio and D. Thers
   In the context of the collaboration between France and Australia, the joint PhD Owen Stanley (primarily based in Melbourne) is involved in two dark matter projects: SABRE and DARWIN. Concerning this latter, Owen is planning to work on two main aspects: 1) sensitivity studies on the search potential to sub-GeV dark matter candidates masses exploiting the Migdal effect ; 2) participation in R&D activities with the XeLab platform
   The former will be done in close collaboration with theorists in Melbourne and with the other joint CNRS-Melbourne PhD student, L. Principe (see also section 3.1.a), while the latter foresees Owen's involvement in Slow Control and PMTs characterization.
9. **Light Dark matter via the Migdal effect.** Sensitivity studies on the search potential to sub-GeV dark matter candidates masses exploiting the Migdal effect with the DARWIN detector will directly derive from the joint work of the two PhD *cotutelle* students between SUBATECH and The University of Melbourne: L. Principe (see section 3.1.a) and O. Stanley.
10. Finally, we actively contributed to the collective work of writing of the above-mentioned "**White Paper**" [16], that lists the features of the aimed next generation dark matter detector.

3.3 XeLab

The XENON detector is essentially a Time Projection Chamber filled with a two-phase xenon (liquid/gas). When we moved from XENON1T to XENONnT, which implied an increased volume of the target and reduced radioactive background, two technological challenges emerged. First, it was found that increasing the size of the electrodes, which generate the electric fields of the TPC, exposes them to distortion problems due to gravity and the electrical induction generated between them. Then, a new source of background noise appeared: solitary electrons crossing the TPC whose signal resembles that expected in the case of a low-mass dark matter particle.

With the goal of increasing the transparency and the radiopurity of the electrodes, when we upgraded XENON1T in XENONnT, we abandoned the technology of the hexagonal meshes and started to use parallel thin wires. The fabrication of those electrodes has been done at IJCLab. They did a remarkable work that included not only the fabrication but the construction of a small facility capable of applying, with high precision, the right tension to each wire. Based on those studies, it was already clear that the sagging of those wire-based electrodes was expected to be high. For this purpose, they added a few perpendicular wires on the two most critical electrodes (the gate and the anode, both responsible for the electric field in the gas phase, used to extract the electrons from the liquid to the gas phase). Unfortunately, this solution turned out to be not optimal. XENONnT has never been able to raise the extraction field to high values, obtaining an extraction efficiency of about 50% (against the 100% that normally we had in the past). Nevertheless, we decided to start data taking and have our first science run, with the idea to start in parallel the construction of new electrodes, based on a different design. LPNHE and Subatech decided to take the challenge and develop an original concept of wireless electrodes, based on the presence of spacers (to completely eliminate the sagging). The new design recalls the technology resulting from recent developments carried out at Subatech around MIMELI-based electrodes and "micro-pattern" type detectors.

The objective of this project is therefore the construction at the LPNHE of XeLab, a liquid xenon TPC dedicated to the study and manufacture of these new systems for producing the proportional scintillation signal. If we already know that these new electrodes introduce a distortion of the electric field, the tests will show that they are negligible, we then have to verify that they are able to achieve the expected performance in terms of signal amplification, energy resolution and uniformity of the detector response. In addition, these electrodes must be designed to minimize the production of lone electrons in the TPC to reduce this source of background noise.

Currently, there is no site in France with an existing cryostat capable of hosting this R&T. The Subatech laboratory already has a device that uses liquefied xenon (XEMIS1, designed as a prototype for medical research) but it is based on the principle of a monophasic TPC. The LPNHE Laboratory, which has a fixed nitrogen network allowing the liquefaction of xenon (connected to a 13,000 litres tank managed by the Sorbonne University's low temperature service) and a room to house this detector, has been chosen as the ideal candidate to host this project.

XeLab has been conceived to allow us to also perform other technology developments:

- The cryogenic system mounts a novel **nitrogen-based three-way heat exchanger** connected to the purification system to provide cooling power at very stable conditions.
- The **inner cryostat is equipped with a copper belt**, cooled down via nitrogen, stable with time and capable of providing very high cooling powers.
- We are building a **small storage and recovery system**, called mReStoX (read it: mini-restox), that is a very practical solution for any laboratory that wants to store and transfer relatively small amounts of liquid xenon. This system will be patented.
- Based on an idea developed by our DARWIN colleagues at the University of Freiburg, we are developing a slow control, completely open source, based on **RaspberryPIs**. The logic will be implemented with the industrial CODESYS standard and data will be displayed with Grafana. It's a robust system that could be scaled up for DARWIN.
- The capability of XeLab of being filled and emptied very quickly and to **extract a TPC from the top** with an easily customizable feedthrough, makes it ideal for quick tests on TPCs. We hope to attract many other projects, also from other laboratories, that might need to use liquefied noble gases for several purposes (characterization of new photodetectors or charge collectors, calibrations, etc.).
- XeLab will employ **novel PMTs** recently built by Hammamatsu, the R12699-406-M4, that has a very high Quantum Efficiency, and it is extremely compact (low geometrical losses). We aim to characterize those PMTs during the early stages of the project. This will be done by a PhD student (O. Stanley) is in *cotutelle* with the University of Melbourne
- Finally, we are performing **detailed simulations with COMSOL multiphysics** for the new electrodes. Once operative, we will compare data with simulations, reinforcing our capability on relying on those simulations for large scale electrodes.

XeLab is in an advanced construction phase, with an experimental room with adequate capacity, a nitrogen line already available in the experimental room, a cryogenic system that has been recently installed, a TPC with a finalized design and a baseline of the new electrodes designed and under improvement with mechanical/electrostatically coupled simulations.

XeLab has been organized into 5 working groups. In the list below are shown only the people that are expected to contribute above a certain fraction of their time.

1. Cryogenics, safety and experimental room : N. Garroum (IR), F. Girard (postdoc), Y. Orain (AI). L. Scotto Lavina (DR)
2. Slow Control : R. Gaior (IR), Y. Pan (PhD)
3. DAQ : F. Girard (postdoc), R. Gaior (IR), E. Morteau (IR), Y. Pan (PhD), O. Dadoun (IR)

4. TPC and Electrodes : Y. Xing (postdoc, **leaving**), E. Morteau (IR), A. Cadiou (IR), J. Simmonneau (IR), N. Garroum (IR), D. Thers (EC)
5. Simulations and screening : E. Masson (postdoc, **leaving**), O. Dadoun (IR), B. Andrieu (CR), S. Diglio (CR)

Among those people, at the end of 2023 we will lose two postdocs (E. Masson at LPNHE and Y. Xing at SUBATECH) whose contributions have been fundamental to reach the current status of the project. Provided of having enough manpower, the construction of XeLab will be completed in 2024, when we start its commissioning.

4. Genesis and calendar

XENON Project has a long story. The first WIMP search conducted with XENON10 featured a target mass of 14 kg (25 kg total). It was followed by XENON100 (62 kg target, 161 kg total mass). The next one, the XENON1T experiment, was the first WIMP dark matter detector operating with a liquid xenon target mass above the ton-scale. SUBATECH joined the XENON Collaboration in 2009 by:

- Contributing to the operations and data analysis of XENON100, as well taking the leading role of computing. Computing was led by Jacob Lamblin (MdC) first, then by Luca Scotto Lavina (CNRS) from 2010 (at that time working at SUBATECH). Since then, the computing of all XENON detectors has always been led by Luca Scotto Lavina.
- Designing, building and operating the Storage and Recovery system for XENON1T (ReStoX1). The project at SUBATECH was led by Dominique Thers and a postdoc, then the team was reinforced by Luca Scotto Lavina who later became the Working Group co-leader of ReStoX1, together with Elena Aprile from Columbia University. The ReStoX concept has been patented [28]. With the limited budget available at that time, we contributed in terms of capital cost to the building of a new coaxial heat exchanger connecting the ReStoX system. This heat exchanger has revolutionised the way how liquid xenon can be efficiently transferred with small thermal losses between several sub-systems. It has been build and tested in SUBATECH [4] by using it on the XEMIS detector (a prototype for medical imaging using Compton scattering in LXe).

The LPNHE-XENON group was created in 2016, when Luca Scotto Lavina moved from SUBATECH to LPNHE creating a new group. After the positive report of LPNHE Scientific Council dedicated to Dark Matter in September 2018, XENON passed from Activity to the status of a Project. In the same year, XENONnT was promoted by the CS IN2P3 to the status of Master Project. Since 2018, both groups have grown, now composed of about 30 people among researchers, engineers, postdocs and students.
Since 2018, we contributed with 5 PhD theses (if we limit the calculation on XENON Project):

- Kevin Michenau (PhD SUBATECH, thesis defense in 2018) [48], measurements of single electron signals with XENON100
- Chloé Therreau (PhD SUBATECH, thesis defense in 2020) [47], XENONnT energy resolution in the MeV energy range
- Jean-Philippe Zopounidis (PhD LPNHE, thesis defense in 2020) [29], study of leptophilic dark matter with XENON1T data
- Sid El Moctar Ahmed Maouloud (PhD LPNHE, thesis defense in 2022) [30], study of leptophilic dark matter with XENONnT data
- Maxime Pierre (PhD SUBATECH, thesis defense in 2022) [42,46], study of neutrinoless double beta decay search with XENONnT

We received by IN2P3 the equivalent of 6 years of postdoctoral contracts:

- Ernesto Lopez Fune (LPNHE, 2 years), contributing to the study of leptophilic dark matter with XENON1T data, in particular by computing the theoretical calculations of the dark matter - electron scattering
- Joaquim Palacio (SUBATECH, 2 years), leading the ReStoX activities on LNGS site
- Gianmarco Bruno (SUBATECH, 2 years), leading the ReStoX activities on LNGS site and working as run coordinator for the experiment

Since the latest Scientific Council in 2018, with XENON Collaboration, we published 40 papers, with more than 6000 citations, an average of 163 citations per paper, and peaks of 2000 citations in a single publication (like the first long science run of XENON1T [22]). Half of them on science results on Dark Matter search (mostly PRL and PRD), but also on other physics, like the first detection of two neutrino double electron capture in 124Xe, the longest half-life ever observed directly (Nature) [31].

5. State of the art

As it was already stated above, since the latest Scientific Council of IN2P3, we continued demonstrating how, with 2nd generation dark matter detectors, the LXe TPC technology represents the most efficient one, in particular by scaling the detector's size at small steps and by reducing at same time the background. Today, the current generation dark matter detectors, XENONnT, LZ and PandaX, are competing for taking data smoothly and efficiently in order to reach their design goals. As said in previous sections, XENON-France is strongly engaged in operating the detector (computing, simulations, data quality monitoring) and in data analysis.
XENON Project demonstrated that those detectors are not only capable of searching for the mainstream WIMP model, but also many other physics:

- **Different dark matter models that can be probed:**
  - Low-E Nuclear Recoils (NR)
    - SI elastic scattering [25]
    - SD elastic scattering [25] (LXe-specific)
    - WIMP-pion coupling [32]
    - Effective Field Theory on WIMPs (+iDM) [33] (LXe-specific)
    - Mirror DM [34]
  - Electronic Recoils (ER)
    - dark photons [35]
    - Bosonic SuperWIMPs, Magnetic dark matter [35]
    - Solar axions and Axion-like Particles [35]
    - Luminous DM [34]
  - Both (NR+ER)
    - Inelastic DM [36]
    - Annual modulation search [37]
    - Low mass WIMPs (<10GeV) [38]
    - Multiply-Interacting Massive Particles (MIMPs) [39]
    - Migdal Effect and Bremsstrahlung [40]
- **New physics can be scoped:**
  - Neutrinos
    - Solar 8B neutrinos (CEνNS → NR) [17]
    - Solar pp and 7Be neutrinos (ER) [41]
    - neutrinoless double-beta decay [42] (LXe-specific)
    - Neutrino magnetic moment [35]
  - Rare events
    - Double electron capture [42] (LXe-specific)
    - Gravitational wave search [43]
  - External trigger
    - Supernovae (CEνNS and Inverse Beta Decay) [16]

We have studied most of this with XENON100 and XENON1T detectors, and will be further explored and greatly improved by XENONnT. In the above list, the mention "LXe-specific" indicates that those researches can be done thanks to the exceptional isotopic richness of natural xenon.
The timeline for the 3rd generation LXe dark matter detectors is very attractive. We tried our best to draw in the table below our best knowledge on the subject. XENONnT, together with LZ and PandaX detectors, represent the most sensitive detectors to date for the research of WIMPs. The design exposure will not be accumulated before 2026. LXe detectors and DARWIN in particular are present and supported by the APPEC roadmap [44], with a European support currently stronger than in US. Our US XLZD colleagues participated in the SNOWMASS collective work and are waiting for the P5 reports to get an answer about a possible 3rd generation dark matter programme with liquid xenon (which should happen by the end of the year). In Europe, the German Helmholtz foundation applied for a strong financial support for DARWIN and also this will be known by the end of the year. The result of P5 can severely affect our future schedule. If supported, the XLZD programme will be boosted, and we might also consider stopping LZ and XENONnT in advance in order to start the DARWIN programme as soon as possible. Here, we aim for a quick reaction from IN2P3 on funding the DARWIN program, as it has done in the past for the XENON Project. Vice versa, if the outcome of P5 will not be supportive of the building of a LXe 3rd generation dark matter detector in next five years, our LZ colleagues will probably run LZ detector for a longer period. In this pessimistic scenario, we still want to profit of the large support from APPEC, the DARWIN European groups are recently speculating the possibility to have a fast upgrade of XENONnT (in the table arbitrarily called "DARWIN 0"), as an intermediate step between the 2nd and the 3rd generation, waiting for the next P6 in US. This upgrade could be done relatively quickly (2 years) since only few XENONnT subsystems require an upgrade (basically the cryostat and the TPC). In this context, the XeLab project and its R&D on electrodes could play a crucial role in enhancing the performances of the proportional scintillation mechanism.

Année	2023	2024	2025	2026	2027	2028	2029	2030	2031
Projects									
XENON									
LZ					?				
PandaX xT		?				?			
DARWIN/XLZD 0									
DARWIN/XLZD									
R&D									
XeLab									

Table 1: Timeline of current experiments XENONnT and LZ (the information of the Chinese PandaX is not available) that will end their science programme in 2026, compared with the expected timeline of DARWIN project, that will likely start in 2031. PandaX is requiring funding for a 3rd generation detector (40 tonnes) called PandaX-xT, its timeline is just a speculation by assuming the typical construction+commissioning delays of a LXe TPC and by assuming that the funding swill optimistically arrive now. In this scenario, it is evident the attractivity of a DARWIN 0 detector, that will act as a reliable bridge between the 2nd and the 3rd generation.
Given the current scenario, it is then difficult to foresee now which will be the chosen strategy by our XLZD community: either a single, larger detector (>50 tonnes) starting taking data in 2031, or with an intermediate short-term step (few tonnes more than XENONnT) that here we call *DARWIN 0*. Indeed, the success of XENON Project has always been the choice of using small upgrades in terms of detector size, accompanied by a reduction of the background, therefore the idea of moving forward through an intermediate step would allow continuity to the project, minimizes the risks and solves the problem of the slowness of the procurement of xenon gas. This would be another step towards the ultimate detector, whose performances are impressive, as shown in figure 4. The baseline of the final DARWIN design implies 200 tonnes x year, which means 5 years of data taking with a detector using 40 tonnes of fiducial volume (50 tonnes of LXe in total). The 1000 tonnes x year scenario is in a next upgrade with 80 tonnes of fiducial volume, where we would be able to go down the neutrino floor. In view of participating in the next upgrade of XENONnT (DARWIN 0), XENON-France requires the procurement of a relevant

amount of XENON gas, a purchase that IN2P3 should consider as strategic, in particular given the strong reduction of its cost in the global market in those recent months.

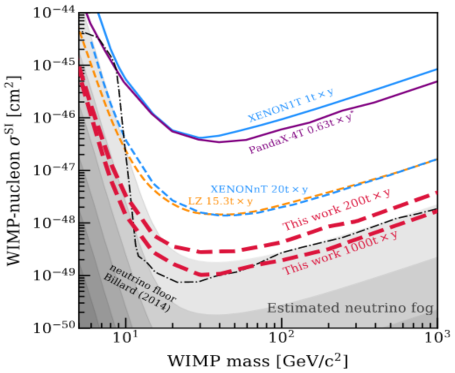

Figure 4: Sensitivity on Spin-Independent WIMP-nucleon cross-section for a 3rd generation LXe dark matter detector with 200 tonnes x year or 1000 tonnes x year.

6. Resources

Human resources

We show below the current situation of SUBATECH and LPNHE groups in terms of permanent researchers, technical support, postdocs and PhD students, showing in particular the FTE of researchers and of Engineers and Technicians.

SUBATECH [Researchers = 1,1 FTE, Engineers+Technicians = 0,6 FTE, Postdocs = 1 FTE, Students = 5 FTE]

- Dominique Thers, IMT Atlantique (PI XENON)
- Sara Diglio, IN2P3 CR
- Julien Masbou, Nantes Université MdC
- Yajing Xing, postdoc IN2P3, contract ends in December 2023
- Johan Loizeau, IMT-Atlantique PhD
- Marina Bazyk, IMT-Atlantique & The University of Melbourne PhD
- Lorenzo Principe, CNRS PhD (joint CNRS-The University of Melbourne)
- Owen Stanley, The University of Melbourne (joint CNRS-The University of Melbourne)
- Anantakrishnan Ravindran, IMT Atlantique (AUFRANDE program)
- Eric Morteau, IMT Atlantique IR (on XeLab)
- Arnaud Cadiou, IN2P3 IR (on XeLab)
- Julien Simmonneau, IN2P3 IR (on XeLab)

LPNHE [Permanent researchers = 2 FTE, Engineers+Technicians = 1,1 FTE, Postdocs = 2 FTE, Students = 3 FTE]

- Luca Scotto Lavina, IN2P3 DR (PI, XENON IN2P3 coordinator, scientific coordinator of XeLab)
- Bernard Andrieu, IN2P3 CR (joined in 2020, formerly in neutrino group)
- Erwann Masson, postdoc IN2P3, contract ends in October 2023
- Frederic Girard, postdoc IN2P3, 2-years contract started in May 2023
- Layos Daniel Garcia, IN2P3 PhD
- Quentin Pellegrini, Sorbonne PhD
- Yongyu Pan, Sorbonne-CSC PhD (CSC = China Scholarship Council)
- Romain Gaior, IN2P3 IR Electronics (*chercheur experimentaliste*)
- Olivier Dadoun, IN2P3 IR Informatics
- N. Garroum, IN2P3 IR Informatics (technical coordinator of XeLab)
- Y. Orain, IN2P3 AI Mechanics (on XeLab)

SUBATECH group has been relatively stable in terms of permanent researchers. However, the recent loss of the MdC (IMT Atlantique) Jean-Pierre Cussonneau who was active both in XENON+DARWIN and XEMIS Project (medical imaging using liquid xenon) has been replaced by a new position (Nicolas Beaupere, IMT Atlantique) who is being 100% on XEMIS. In addition, the postdoc Y. Xing will complete her contract in December 2023. Those changes have a negative impact on the capability of the group to keep the engagements in front of the XENON Collaboration. The situation became even more unbalanced if we consider the many extra activities of senior people (teaching, commissions, networking, etc…). The only way to compensate for those losses are a **CR position together with a postdoctoral position for SUBATECH laboratory**.

The LPNHE group has been created in 2016, by a single researcher (L. Scotto Lavina) coming from Subatech laboratory, and it is constantly growing in size. LPNHE applied for a MdC Sorbonne University on dark matter, and we might have quite some chance to obtain it within the next few years, but this is not confirmed yet. The group recently had a postdoctoral position focusing on XeLab (Frederic Girard), but it is losing one postdoc focusing on XENON data analysis (E. Masson). **The priority for LPNHE is to have a new postdoctoral position** that helps boost the intense activity on data analysis (3 PhD students) and on computing. This point is extremely crucial: on computing, we want to keep the leadership in XENON, as well as contribute for a future involvement on DARWIN 0; on data analysis, this is necessary to boost the current activities and aim for corresponding authorships, which is extremely selective in XENON (we successfully obtained it only when the work was done by a solid pair postdoc plus PhD student).

Financial resources

The participation of XENON-France on XENONnT relies primarily on the financial support of IN2P3 of 150k€ that, together with local resources (namely Region Loire-Atlantique for SUBATECH and DIM-ACAV+ from Île-de-France for LPNHE), allowed us to fund the ReStoX2 system, whose cost was around 300k€. On top of that, we receive by IN2P3, as outcome of EAP (Entretiens Annuels Projet) by the DAS, the budget for maintenance, missions (conferences, collaboration meetings and shifts) and contributions to the Collaboration Common Funds (4k€ for each member who signs paper excluded PhD students). The budget given yearly by IN2P3 has been used as well to recruit an expert cryogenic engineer, permanently located at LNGS, who participates in the daily cryogenic operations of the detector. Below is a small table showing what the two laboratories received so far during the last two years and an extrapolation of costs by also considering the growing size of the two groups (please refer to the human resources request above). We want to stress that this budget does not cover the extra activities such as DMLab, ILANCE, Australia partnership, since for those activities we profit from external resources.

	Obtained		Expected		
Group	**2022**	**2023**	**2024**	**2025**	**2026**
Subatech	39k€	39k€	52k€	52k€	52k€
LPNHE	31k€	36k€	42k€	42k€	42k€
Common Funds	40k€	36k€	48k€	48k€	48k€
Total	110k€	111k€	142k€	142k€	142k€

Table 2: A highlight of the budget received by IN2P3 in the last 2 years (representative of the cost of an already running detector), plus the expected annual requests that we will ask the IN2P3 direction, accounting for an increased size of the two groups.

We require that IN2P3 continues supporting us with the proposed financial weight shown in the table, since it corresponds to the minimum necessary to keep our engagements in front of XENONnT experiment. On top of that, we also require that IN2P3 performs a **strong investment on the purchase of xenon gas**, in this period that is very favorable in the global market (after reaching a peak of 15k euros per kg, now the cost is back to 3k euros per kg and it is continuing decreasing). The purchase of 200 kg of xenon (expected to cost about 400k euros) would allow us to **contribute to the next XENONnT upgrade**.

On top of that, for the XeLab project, the table below shows the budget received so far by IN2P3 (30k€ in 2021, 40k€ in 2022 and 40k€ in 2023). All the rest has been funded by other resources (external funds, support from the local laboratories). **We require that IN2P3 continue supporting the XeLab R&D project with a financial volume compatible with the one provided so far (20k€ per laboratory per year) for the next 5 years.** This would allow us to complete the XeLab programme on electrodes at high speed and to open to the second part of the project for the modelling of the single electrons background signal.

Source	2021	2022	2023	Total
Expected Budget	€ 160.000	€ 58.500	€ 46.000	€ 264.500
LPNHE	€ 120.000	€ 10.000	€ 6.000	€ 136.000
Subatech	€ 10.000	€ 8.500	€ 0	€ 18.500
IN2P3 -> LPNHE	**€ 30.000**	**€ 20.000**	**€ 20.000**	**€ 70.000**
IN2P3 -> Subatech	**€ 0**	**€ 20.000**	**€ 20.000**	**€ 40.000**
Total IN2P3	**€ 30.000**	**€ 40.000**	**€ 40.000**	**€ 110.000**
Financial coverage (%)	**100**	**100**	**100**	**100**

Table 3: Budget that has been used so far to build XeLab and its entire infrastructure (including the works to have a fixed liquid nitrogen line at LPNHE), compared with the resources received directly by IN2P3 to the two groups. We request for next years the same yearly contribution we had in 2023.

6. Technical realizations

XENONnT does not need new technical realizations given that it is already taking data. The construction of the future DARWIN detector is still too far to be included in our short term requests to IN2P3 in this Scientific Council. Also, DARWIN 0, intended as a fast upgrade of XENONnT, should not require any extra cost apart from the procurement of xenon as we mentioned above. Vice versa, XeLab, as R&T project, requires several technical realizations. So far we built the entire cryogenic system and we are in the assembling phase. The cryogenic system has been built by external companies (the French DATE for the cryostat and purification circuit and the Italian Costruzioni Generali for the mReStoX). The 11 kg of Xenon gas have been bought by Messer. What remains to do is the construction of the TPC and the actual R&D on electrodes (which implies the construction of several prototypes with different materials). This activity will be done entirely locally, by profiting of mechanical facilities present at SUBATECH and at LPNHE, without outsourcing their construction. In particular:

- We want to improve the safety and the performances of the cryogenic system, with extra nitrogen dewars and new interfaces with the already existing cooling systems.
- The LPNHE, who is hosting the XeLab project, is strongly investing in terms of technical resources, developing new competences around noble liquids and in particular electrodes.

Because of those two points, we require that IN2P3 provides a **reinforcement of the resources for the mechanical service of LPNHE**.

Bibliography

[1] P.A.R Ade et al. (Planck), Astron. Astrophys. 594, A13 (2016); V. Springel et al., Nature 435, 629 (2005).
[2] G. Steigman, and M.S. Turner, Nucl. Phys. B 253, 375 (1985).
[3] M. W. Goodman and E. Witten, Phys. Rev. D 31, 3059 (1985).
[4] W.-T. Chen et al. Proc. of ICEC24-ICMC2012, arXiv:1205.3874 [astro-ph.IM]
[5] https://gdrduphy.in2p3.fr/
[6] https://dmlab.in2p3.fr/
[7] https://indico.in2p3.fr/event/28147/
[8] https://ilance.cnrs.fr/
[9] https://oceania.cnrs.fr
[10]https://research.unimelb.edu.au/strengths/initiatives/international-training-groups/melbourne-cnrs-network
[11]https://international.cnrs.fr/wp-content/uploads/2021/12/CNRS-UoM-PhD-Call-Final.pdf
[12] https://aufrande.eu/
[13] J. Aalbers et al. (DARWIN Collaboration), *DARWIN: towards the ultimate dark matter detector*, JCAP 11, 017 (2016), arXiv:1606.07001
[14] http://darwin.physik.uzh.ch
[15] https://xlzd.org/
[16] J. Aalbers et al., *A Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics* arXiv:2203.02309 [physics.ins-det]
[17] E. Aprile et al. (XENON Collaboration), Phys. Rev. Lett. 126, 091301, arXiv:2012.02846 [hep-ex]
[18] R. F. Lang at al., Phys. Rev. D 94, 103009, arXiv:1606.09243 [astro-ph.HE]
[19] https://github.com/XENONnT/admix/
[20] https://github.com/XENONnT/xom
[21] https://www.egi.eu/article/finding-dark-matter-is-like-looking-for-a-needle-in-a-haystack/
[22] *Phys.Rev.Lett.* 121 (2018) 11, 111302, e-Print: 1805.12562 [astro-ph.CO]
[23] E. Aprile et al. (XENON Collaboration), Phys. Rev. Lett. 129, 161805, arXiv:2207.11330 [hep-ex]
[24] E. Aprile et al. (XENON Collaboration), Phys. Rev. D 102, 072004, arXiv:2006.09721 [hep-ex]
[25] E. Aprile et al. (XENON Collaboration), Phys. Rev. Lett. 131, 041003, arXiv:2303.14729 [hep-ex]
[26] S.E.M. Ahmed Maoulod, PhD thesis, https://theses.hal.science/tel-03978219
[27] http://terascale.in2p3.fr/
[28] Patent EP2618038A2 Facility and method for supplying liquid xenon (CNRS, Ecole des Mines, University of Nantes, Air Liquide)
[29] J.P. Zopounidis, PhD thesis, https://tel.archives-ouvertes.fr/tel-03793329
[30] S. E. M. Ahmed Maouloud, PhD thesis, https://theses.hal.science/tel-03978219
[31] E. Aprile et al, (XENON Collaboration), Nature 568, 532 (2019), arXiv:1904.11002
[32] E. Aprile et al, (XENON Collaboration), Phys. Rev. Lett. 122, 071301 (2019), arXiv:1811.12482
[33] E. Aprile et al, (XENON Collaboration), https://arxiv.org/abs/2210.07591
[34] E. Aprile et al, (XENON Collaboration), Science 2015 vol. 349 no. 6250 pp. 851-854, arXiv:1507.07747
[35] E. Aprile et al, (XENON Collaboration), Phys. Rev. Lett. 129, 161805 (2022), arXiv:2207.11330
[36] E. Aprile et al, (XENON Collaboration), Phys. Rev. D 103, 063028 (2021), arXiv:2011.10431
[37] E. Aprile et al, (XENON Collaboration), Phys. Rev. Lett. 118, 101101 (2017), arXiv:1701.00769
[38] E. Aprile et al, (XENON Collaboration), Phys. Rev. Lett. 123, 251801 (2019), arXiv:1907.11485
[39] E. Aprile et al, (XENON Collaboration), Phys. Rev. Lett. 130, 261002 (2023), arXiv:2304.10931
[40] E. Aprile et al, (XENON Collaboration), Phys. Rev. Lett. 123, 241803 (2019), arXiv:1907.12771
[41] J. Aalbers et al. (DARWIN), Eur. Phys. J. C 80, 1133 (2020), arXiv:2006.03114
[42] E. Aprile et al, (XENON Collaboration), Phys. Rev. C 106, 024328 (2022), arXiv:2205.04158
[43] E. Aprile et al, (XENON Collaboration), arXiv:2306.11871
[44] Direct Detection of Dark Matter -- APPEC Committee Report, arXiv:2104.07634
[45] P. Cox et al, Phys.Rev.D 107 (2023) 3, 035032
[46] F. Agostini et al. (DARWIN), Eur.Phys.J.C 80 (2020) 9, 808, arXiV:2003.13407
[47] E. Aprile et al, (XENON Collaboration),Eur.Phys.J.C 80 (2020) 8, 785, arXiV:2003.03825
[48] Kevin Micheneau, PhD thesis, https://www.theses.fr/2018NANT4036