**Contribution Prospectives 2020**

# Search for WIMP dark matter with the dual phase liquid argon detector DarkSide-20k


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**Abstract**:
Dark Matter is one of the main puzzles in fundamental physics and Weakly Interacting Massive Particles (WIMP) are among the best-motivated candidates. As of today, the most sensitive experimental technique to discover WIMPs in the mass range from 2 GeV to 10 TeV is the dual phase TPC filled with ultra-pure argon or xenon. This contribution discusses the potentiality of the next generation of Liquid Argon TPC (DarkSide-20k to be run at Gran Sasso from 2023) in exploring further this mass range. The innovative design of DarkSide-20k offers a high discovery potential, both at low mass using the ionization electron signal as demonstrated by the world-leading result of DarkSide-50, and at high mass, benefiting from the intrinsic pulse shape discrimination power of scintillation signal in liquid argon to reject electronic recoils. The latter provides a background-free experiment for an exposure of 100 ton×years, reaching a sensitivity to WIMP-nucleon cross sections of $1.2\times10^{-47}$ cm$^2$ for WIMPs of 1 TeV mass. The work plan of potential IN2P3 contributions to DarkSide-20k is focused on the calibration and the reconstruction of the silicon photomultiplier response. This offers in the decade 2020-2030 a vast scientific potential coupled with technological opportunities and possible synergies with other IN2P3 areas of expertise.

## 1. Scientific and technological context

The existence of dark matter, supported by a variety of astrophysical measurements, is one of the main puzzles in fundamental physics. However, the nature and properties of dark matter remain largely unknown. APPEC, in its priorities (APPEC17) "*encourages the continuation of a diverse and vibrant programme (…) searching for Weakly Interacting Massive Particle (WIMP)*", a leading dark matter candidate motivated by : i) the observed relic abundance, "miraculously" obtained with the thermal freeze-out of O(100) GeV WIMPs in the early Universe, and ii) naturalness, that needs WIMP-like particles to be present at the TeV scale in order to stabilize the Higgs mass in the Standard Model. The second argument is under stress after the absence of new physics signs at the LHC, but the first one remains strong. The theory prediction for the WIMP mass ranges from sub-GeV to multi-TeV, with a related cross-section down to $10^{-48}$ $cm^2$ in the vanilla models (Cirelli18). Assuming reasonable astrophysical assumptions on local dark matter distribution, this translates experimentally in expectations of 1 event (or less) per year per ton of detector target, demonstrating the need for a scalable and background-free detector to make a discovery.

In its roadmap for the next decade, APPEC recommends "*a strategy aimed at realising worldwide at least one 'ultimate' Dark Matter detector based on xenon (in the order of 50 tons) and one based on argon (in the order of 300 tons), as advocated respectively by DARWIN and Argo.*" As of today, the leading technology in the GeV (DarkSide18; Xenon1T19) to multi-TeV (Xenon1T18) mass range is the dual phase noble (argon or xenon) liquid TPC, which can exploit simultaneously the scintillation (S1) and ionization (S2) signals. The success of this technology is explained by its "intrinsic" scalability, radio-purity, and its unique ability to observe S2 signals down to a few ionization electrons. The prediction for the next decade is shown in Figure 1: the next generation of dual phase experiments should be able to gain two orders of magnitude in cross-section in the overall mass range, with similar sensitivity for Argon and Xenon in the high mass range. The complementarity between Xenon and Argon detectors is therefore strong, as recognised by APPEC, with mutual cross-checks in case of signal hints.

This contribution presents DarkSide-20k, the next generation of liquid argon (LAr) dual phase Time Projection Chamber (TPC), with particular focus on potential IN2P3 involvement. DarkSide-20k is a step towards Argo, the 'ultimate' dark matter detector based on 300 ton LAr, advocated by APPEC, that will be installed at SNOLab in Canada.

Since 2017, the argon effort is regrouped in a unique collaboration, Global Argon Dark Matter Collaboration (GADMC), allowing merging the current efforts (ArDM at LSC-Spain, DEAP-3600 and MiniCLEAN at SNOLab-Canada, DarkSide-50 at LNGS-Italy) and around 350 physicists from 80 institutes. The GADMC is engaged as primary goal to build DarkSide-20k (DarkSide17), scaling and adapting the most efficient technologies from the currently working experiments in an innovative detector design, which will operate in 2023. The target mass consists of 50 tons of underground argon (UAr), extracted from $CO_2$ wells in the US and with low concentration of cosmogenic isotopes. As illustrated in Figure 2, the TPC will be immersed in a LAr bath housed by a 600 $m^3$ protoDUNE cryostat, that will be installed at LNGS by the CERN team. This design solution minimizes materials, and hence background sources, in direct contact with the target mass: ultra-pure acrylic, which defines the TPC walls, and 300,000 low-background and high-efficiency silicon photomultipliers (SiPMs), that will observe light induced by particle interactions. The use of both UAr and SiPM will allow to fully profit from the intrinsic properties of the LAr scintillation that enables the separation of nuclear (as WIMP induced) and electron recoils with a factor $>10^8$. Together with the very efficient muon and neutron vetoes surrounding the TPC, DarkSide-20k is intended to perform an instrumental background-free search (excluding neutrino interactions), ideal for WIMP discovery.

To validate the new experimental design, a 1-ton prototype is currently under construction at CERN and will be shipped to LNGS for a test in low-background conditions. The schedule of the DarkSide program is shown in Table 1.

| | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| DarkSide-Proto | | | | | | | | | | | |
| DarkSide-20k | | | | | | | | | | | |
| Argo | | | | | | | | | | | |

***Table 1****: Foreseen schedule for the DarkSide programme. Blue and green boxes correspond to construction and data taking phases, respectively.*

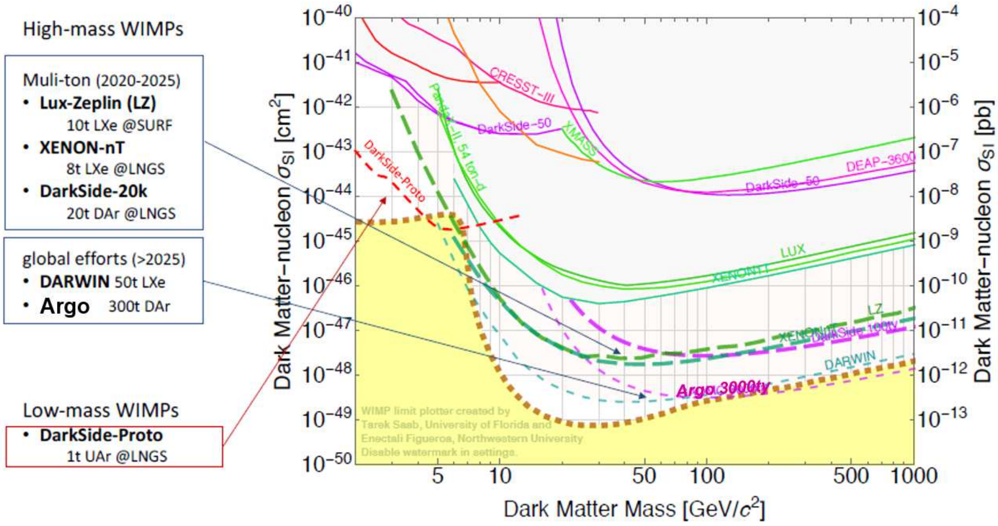


***Figure 1****: Exclusion regions from current publications (full lines) and foreseen experiments (dashed line). The "pinkish" lines relate to dual phase liquid argon TPCs and the "greenish" ones to dual phase liquid Xenon TPCs (Tonazzo18).*

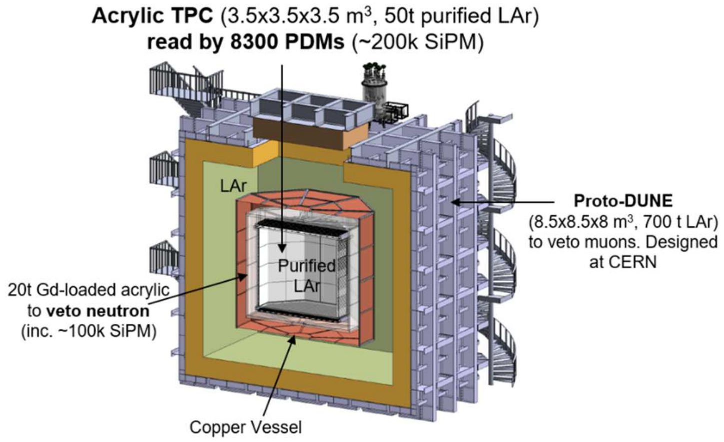


***Figure 2****: 3D drawing of the DarkSide-20k experiment.*

2. **Technological and scientific opportunities for IN2P3 in 2020-2030**

IN2P3 involvement in dual phase argon TPC is now seven years old, when APC joined the DarkSide-50 experiment, followed by LPNHE in 2014. DarkSide-50 (DarkSide15) is a 50 kg dual phase argon TPC that started to operate in Gran Sasso National Laboratory (LNGS) in October 2013. The two central achievements of the French team were [more details can be found in (Franco18)]:

1. Development of an accurate simulation model of scintillation and ionization processes in LAr (DarkSide17_2), exploiting data from a test beam experiment at the ALTO facility in IPNO (Agnes18). This became the new baseline in DarkSide-50 and DarkSide-20k collaborations.
2. Main analyzers of the low mass WIMP search (DarkSide18), world-leading result in the O(GeV) mass range (Figure 1). This pioneering S2-only analysis was possible by using the expertise developed in the simulation and a careful analysis of the calibration data performed with neutron sources around the TPC. The modelling of the data can be appreciated on Figure 3 left.

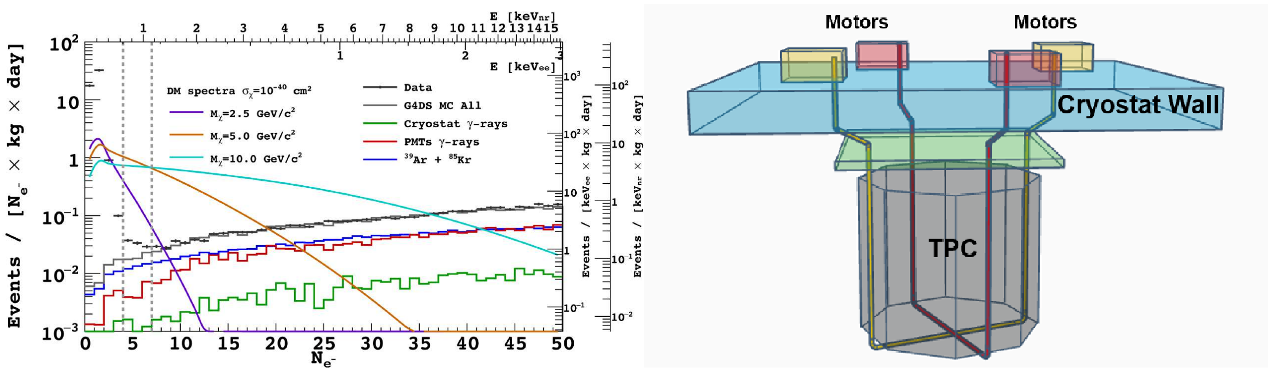


***Figure 3****: Left: S2 signal in number of electrons for 500-days exposure in the DarkSide-50 detector* (DarkSide18). *The simulated background from radioactive components is shown together with the data and the expected signal for WIMPs of few GeV. Right: Simplified design of the guide tube system in the DarkSide-20k experiment.*

These leading contributions offer a very strong basis for the IN2P3 involvement in the DarkSide20k experiment. Since January 2019, CPPM is also an active member in DarkSide-20k. The work plan for the IN2P3 contribution to DarkSide-20k in the coming years is now centered on three main themes:

1. Calibration Strategy. The experience in DarkSide-50 analysis has demonstrated the importance of the calibration to obtain world-class physics results. It is therefore foreseen to design and realize the guide tube system that enables the circulation of gamma and neutron radioactive sources (Figure 3 right). A mock-up will be needed to test the robustness of the design before its installation around the TPC at LNGS.

2. Data Reconstruction. SiPMs, developed in synergies with the FBK manufacturer, are low-noise photo-sensors with excellent single photoelectron resolution, but suffer from a slow charge recovery time. Waveforms acquired with such devices have to be processed with a fast optimum filter in order to recover photoelectron information. Reconstruction software, currently in development under the responsibility of the IN2P3 team, plays then a key role within the experiment, by determining the capability to fully recover

the pulse shape discrimination power (key element for the discovery of high mass WIMPs) and by reducing the data size and hence the computing resources. The reconstruction software will be extended with advanced techniques, like neural networks, for event position and energy reconstruction. It will be tested on prototype data and optimized on calibration sources, in strong connection with item #1 of the IN2P3 contributions.

3. Physics Analysis: the data from the prototype will constitute a very efficient test bench for the preparation of the data analysis in DarkSide-20k, especially with respect to the tuning of the S2 signal (length of the gas pocket, strength of the electric field, understanding S2 signal down to 1 or 2 ionization electrons, …). The French efforts will also continue on the S2 capability by exploring further the sensitivity to other low mass dark matter candidates (e.g. lightest sterile neutrino, axion-like particle). Furthermore, a long-term prototype run at LNGS would enable the possibility to extend limits on low–mass WIMPs (Figure 1) already in 2022. All these activities will be particularly well suited for incoming students.

Before the start of DarkSide-20k data taking, there are many opportunities to reinforce the French contributions. On top of that, several synergies with activities developed within CNRS can be envisioned, as for instance:

1. Synergy with DUNE. IN2P3 is a key player, thanks to its leadership role, in both DUNE and DarkSide, the two forthcoming most performant LAr detectors in the high and low energy ranges, respectively. Despite the differences in ranges, the two experiments have to face similar technological challenges, like cryogenic photodetection, and are highly complementary in their physics cases. In particular, simultaneous DUNE/DarkSide detection of a galactic supernova would allow inspecting the neutrino mass hierarchy by comparing electronic neutrinos detected by DUNE via charged current, and the flavor insensitive detection by DarkSide via coherent scattering off argon nuclei. In order to detect a supernova burst, both experiments have the common problem of defining a dedicated trigger strategy.

2. Radon mitigation: Even if radon is a priori not a main background for the DarkSide-20k experiment, its contamination should be studied with a lot of care. An important point to be explored is radon emanation and transport at very low temperature, and radon mitigation at very low concentration in the Ar gaseous phase. Expertise already acquired in this field, especially at CPPM, can be exploited.

3. Positron Emission Tomography (PET): The current trend in PET instrumentation is to improve both the sensitivity and the timing performance of the tomograph, for which noble gas scintillators are promising. State-of-the-art commercial time-of-flight (TOF)-PET scanners have a coincidence time resolution (CTR) of 214 ps FWHM with inorganic scintillators (LSO:Ce or LYSO:Ce) read out by SiPM arrays (VanSluis19). While extending the axial length of the scanner to 2 m, the EXPLORER total body prototype has recorded 40 times more events than state-of-the-art commercial scanners, which results in a corresponding increase in sensitivity for a whole body scan (Cherry17). Given the speed of light, a CTR of 10 ps FWHM would procure a real-time 3D PET image with 1.5 mm FWHM spatial resolution virtually without the need for tomographic inversion, resulting in an improvement of the activity signal-to-noise ratio (SNR) reconstructed in the image voxels by one order of magnitude (x16) as compared to classical (non-TOF) PET image reconstruction.
Given the very large and fast light yield of LAr(Xe), noble gas intrinsic scintillators can provide excellent time resolution (Chepel97) down to a few hundreds of picoseconds (for LXe) (Doke06). Combined design exploiting scintillation and charge measurement could benefit from both the excellent depth-of-interaction measurement and very good timing performance (Amaudruz09). The use of SiPM with improved quantum

efficiencies, and the possibility to detect Cherenkov radiation that is emitted virtually simultaneously with the photoelectron or Compton recoil electron emission, might foster the development of very large, hyper fast, total body TOF-PET devices approaching the mythic 10 ps FWHM CRT frontier (Thers19).
Expertise already acquired in the field of SiPM Monte Carlo modeling using the GATE (Mehadji19) simulation platform could be transferred to evaluate the possible impact and performance of such a total-body LAr(Xe) TOF-PET scanner design.

4. Collaboration with theorists: several colleagues within IN2P3 or in close contact with us (e.g. from LAM, LUPM, ...) are specialists of dark matter phenomenology and collaboration has started to better understand the impact of Gaia results on the Standard Halo Model used to derive the limits of the direct dark matter experiments.

## 3. Conclusions

WIMPs are excellent dark matter candidates to which the next generation of dual phase argon TPC, DarkSide-20k, offers a high discovery potential, both at low O(GeV) mass using the ionization signal S2 (as demonstrated by the DarkSide-50 world-leading result), and high mass, for which the intrinsic pulse shape discrimination provided by the scintillation signal could give a background-free experiment.

The foreseen contributions from IN2P3 labs (APC, CPPM, LPNHE) will be focussed on two well identified subjects: the calibration, with the building of a guide tube system to distribute radioactive sources around the TPC, and the simulation, that will be adjusted with the prototype data. This should enable to obtain a leading place in the physics analysis of the DarkSide-20k data, available from 2023 on. With this detector and 3 years of running, it is expected to obtain a similar sensitivity to high mass dark matter as the Xenon experiments. This effort is therefore complementary to the Xenon efforts and can provide mutual cross-checks in case of signal hints. Several synergies with DUNE, radon mitigation, medical imaging and theory have also been identified and can be further developed within IN2P3.

This very promising program is fully in line with statements from the last APPEC strategic document (see section 1) and from the October 2018 IN2P3 scientific council: "*Aujourd'hui, parmi les projets de détection directe de matière noire présentés, seuls XENON et DarkSide-50 sont opérationnels et au niveau de la rude concurrence internationale, dans des domaines de masse différents. La participation à ces projets est à soutenir et à renforcer en développant les équipes actuelles. (…) Le projet DarkSide présenté par ces groupes est ambitieux et vise une participation à toutes les étapes du projet, de DS-50 à Argo. Le conseil recommande que le groupe se focalise sur quelques points clés de manière à maximiser son impact dans la collaboration. Le conseil recommande de trouver des forces humaines supplémentaires pour s'engager avant dans un projet de cette envergure.* "

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