DS-20k **project**

Conseil Scientifique IN2P3
sur la matière noire (23 octobre 2023)

1 Executive Summary

Dark matter (DM) is supported by a variety of astrophysical and cosmological measurements but its nature is one of the main puzzles in fundamental physics. As of today, one of the most favored candidates as a DM particle is a weakly interacting massive particle (WIMP) in the mass range above 1 GeV. Noble liquids are ideal candidates as target material and dual-phase noble liquid time projection chambers (TPC) are the present leading technology for WIMP search in this mass range. DarkSide-20k (DS-20k), the next generation of liquid argon experiment, will be the largest ever built for dark matter searches with a TPC filled with 50 tons of purified liquid argon (LAr) and 270,000 silicon photo-multipliers (SiPMs). Its construction has begun at Gran Sasso National Laboratory (LNGS) near l'Aquila (Italy) in September 2022. DS-20k plans to start taking data in 2027, very rapidly extending the physics reach of previous LAr DM experiments and complementing current searches with large liquid xenon detectors.

The ability to suppress the background in such a large TPC is crucial and strongly depends on LAr simulation and event reconstruction which, in turn, rely on the detector calibration. In that respect, the IN2P3 teams are already well positioned in DS-20k: APC is in charge of the offline (simulation and event reconstruction) and CPPM is in charge of designing, building and operating a guide tube calibration system to circulate radioactive sources around the TPC. The synergy between the IN2P3 teams is already well established with the common work performed on the DarkSide-50 (DS-50) data analysis leading to the world best limits on low-mass WIMP. Building on these strong involvements and responsibilities, the goal of the IN2P3 teams is to occupy a central place in the low and high mass WIMP search analyses of DS-20k by mastering the event reconstruction and simulation tools and validating them with calibration data. The first analyses should take place shortly after the data taking starts, as one day of DS-20k exposure corresponds to the whole DS-50 data set.

2 Scientific context

The discovery of the Higgs boson in 2012 by ATLAS and CMS [1, 2] has completed the Standard Model of particle physics (SM), while the absence so far of signs of new physics in the first two runs of the LHC has deeply changed the particle physics research field. The main puzzles are now coming from observational cosmology: what is the nature of dark energy and dark matter? What is the origin of the matter-antimatter asymmetry? In this respect, dark matter is particularly puzzling: its existence is supported by a growing variety of astrophysical and cosmological measurements [3] but none of the SM particles has the required properties to explain all observations.

In this context, all viable DM candidates are predicted by beyond standard model theories. However, they lie in a gigantic mass-coupling phase space which is not possible to probe exhaustively. All experimental efforts should therefore be made to cover the most motivated parts of this phase space. In this respect, WIMP is one of the best motivated dark matter candidates, whose rationale rests on two pillars:

- solves the gauge hierarchy problem (or naturalness problem of the Higgs mass) of the SM [4, 5, 6, 7]: the stable WIMP is the lightest of the new particles predicted at the TeV scale (or below);
- explains the observed relic abundance of dark matter: the WIMPs are produced in the early Universe with the right amount when they are thermally frozen-out by the universe expansion [8, 9].

Both a priori independent problems are solved by adding one WIMP in the O(100) GeV mass range – an apparent coincidence called "WIMP miracle". The first argument is under stress after the absence of new physics signs at the LHC, but the second 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 [10]. Under reasonable astrophysical assumptions on local dark matter distribution, this translates experimentally in expectations of less than 1 signal event per year and per ton of detector target for WIMP masses above O(100) GeV, demonstrating the need for a scalable and background-free detector to make a discovery.

Since several years, the leading technology in the GeV to multi-TeV mass range has been the dual-phase noble liquid time projection chamber. Multi-ton xenon experiments like Xenon-nT [12], LZ [13] and PandaX-4T [14] are presently dominating sensitivity to WIMPs for masses above 4 GeV, probing cross-section down to 9×10^{-48} cm^2 around 30 GeV, as shown in Figure 1 top. Meanwhile DS-50, first generation dual-phase TPC with 50 kg of liquid argon, has obtained the best limits in the low mass range between 1 and 4 GeV [15]. The reason for such a success with the dual-phase TPC technology is that noble liquids are ideal candidates as target materials for WIMP searches: they are relatively inexpensive and intrinsically purer than other materials and hence scalable to TPC filled with ton or multi-ton of liquid. A WIMP entering the detection volume may interact with a nucleon of the liquid; when the atom recoils after a WIMP interaction and de-excites, it produces a high ionization and scintillation photon signal with high yield, which guarantees an excellent energy resolution. The dual-phase technology has the advantage of providing simultaneous access to the scintillation (S1) and to the ionization (S2) signals, as illustrated in Figure 2 left, allowing the reconstruction of the complete event topology with position resolution of O(1) cm in $x - y$ (horizontal plane) and O(1) mm in z (drift - vertical direction). Two types of background can mimic a WIMP signal: i) neutrons for which the detector response, composed of "fast" scintillation light and low number of ionization electrons, is called Nuclear Recoil (NR) and ii) electron/photons, for which the detector response, composed of "slow" scintillation light and high number of ionization electrons, is called Electron Recoil (ER). NR can be suppressed by asking for single scatter event, working deep underground, choosing very low radioactive background materials and implementing a veto around the TPC. For ER, the ratio of S1 to S2 provides the power to separate NR from ER for both liquid argon and liquid xenon TPCs. However, only LAr detectors can exploit a further pulse shape discrimination (PSD) based on the S1 scintillation signal. This is due to argon's

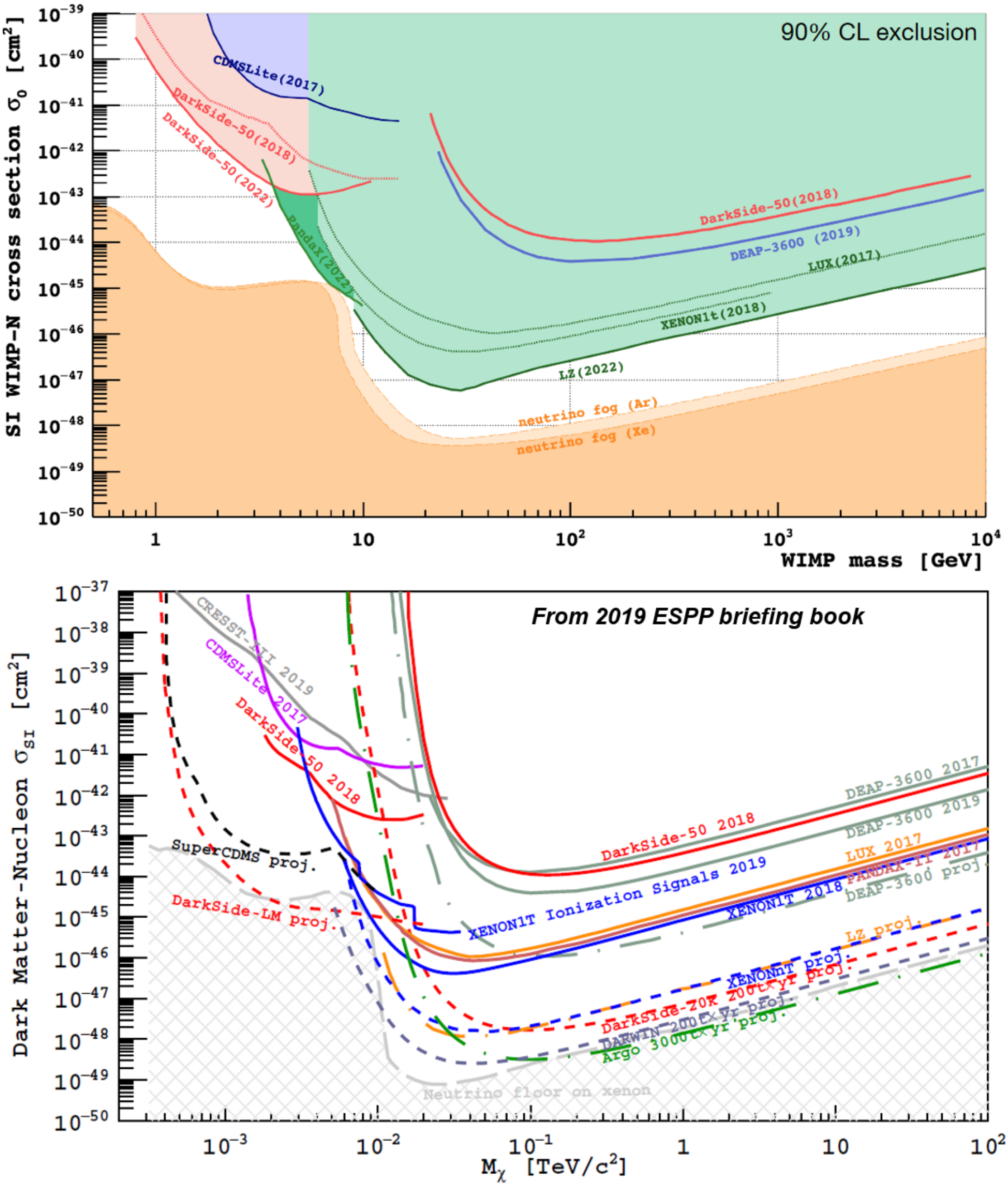


Figure 1: 90% CL exclusion regions of WIMP-nucleon spin-independent cross section vs WIMP mass, from most sensitive experiments (top) and foreseen experiments (bottom [11]). Xenon, PandaX, LZ and Darwin (resp. DS-50, DEAP-3600, DS-20K, Argo) are xenon (resp. argon) TPCs. Other detection techniques are shown in the low mass/low sensitivity (top-left) region. The hatched area indicates the neutrino fog / floor, where interactions of solar/atmospheric neutrinos with the detector start to be an irreducible background. The local dark matter density assumed is 0.3 GeV/cm^3.

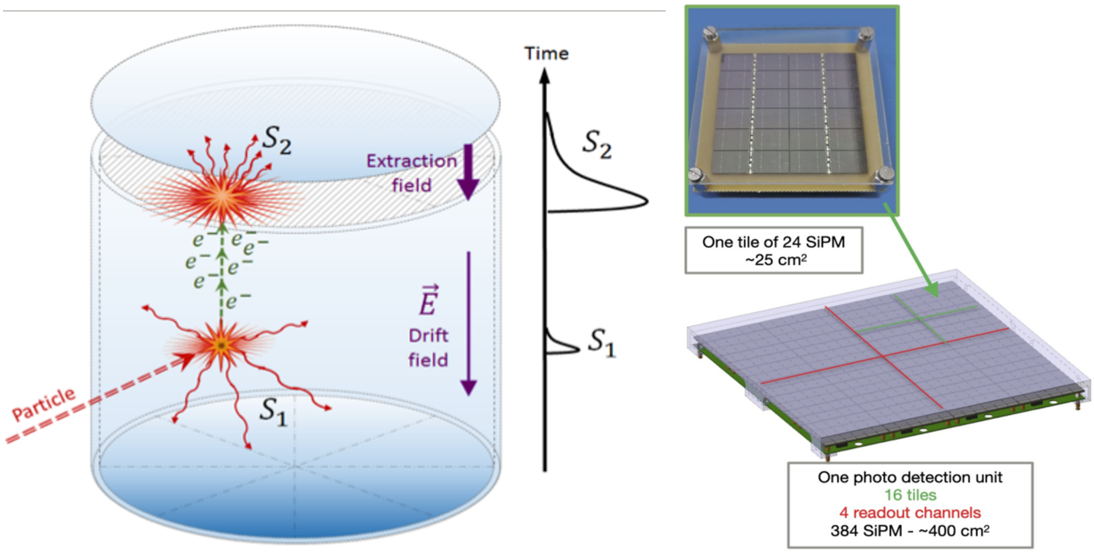


Figure 2: Left: Principle of a dual phase TPC, with both scintillation (S1) and ionisation (S2) signals and schematic representation of the development of the signal in the TPC. Right-top: One DS-20K tile equipped with 24 SiPM and covering 25 cm^2. Right-bottom: One DS-20K photo detection unit (PDU), equipped with 384 SiPMs and corresponding to four readout channels.

intrinsic nuclear properties, whereby two argon excited states, with very different decay times of ~7 ns and ~1.6 μs, are predominantly produced by NR and ER, respectively . This enables an extra rejection factor $> 10^8$ [16, 17] for ER backgrounds. This is a key ingredient for performing an instrumental background-free search.

The complementarity between the liquid argon and xenon technologies is reflected by the APPEC statement that "encourages the continuation of a diverse and vibrant program searching for WIMP dark matter" and "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)" [18]. In case of signal hints, possible mutual cross-checks are possible which will be mandatory to claim a dark matter signal. Further improving the sensitivity by one to two orders of magnitude is within reach in the next decade. In the near future, such leadership will be strengthened by more massive and sensitive experiments, such as XLZD and DS-20K on the road to reaching the "neutrino floor" [1], see Figure 1 bottom.

DS-20K is already in a well-advanced stage. Construction has started in September 2022 and it is planned to start operation in 2027. The detector was designed to reach < 0.1 background event in 10 years of operation (corresponding to 200 t.yr, excluding the irreducible neutrino scattering background) in the high mass WIMP search. To achieve

[1]The 300 ton LAr detector called ARGO, will be built after the completion of DS-20K.

such an exposure, the DS-20k TPC will be filled with 50 tons of purified underground argon (UAr), extracted from deep mines, to highly suppress cosmogenic ^{39}Ar contamination. This is respectively 1000 and 14 times more than in the previous generation experiments, DS-50 and DEAP-3600 [2]. For the first time in a DM-search TPC experiment, it will innovate by using 270,000 high performance SiPMs as photo-sensors, packaged in 700 PDUs, see Figure 2 right.

3 DS-20k project

DarkSide is a multi-stage programme, which began in 2010 with the construction of DS-10, a 10 kg LAr prototype detector. Afterwards, DS-50 with 50 kg LAr, was installed underground at LNGS in 2013, inside an active neutron veto based on a boron-loaded organic scintillator, which is in turn installed inside a 1000 ton water Cerenkov muon veto. It was first filled with atmospheric argon (2013–2014) and then with UAr (2015–2018). In 2018, it provided the most stringent exclusion limits on WIMP-nucleon interactions in the [1.8, 6] GeV/c^2 mass range [15], and demonstrated the capability to operate in complete background-free mode above 20 GeV/c^2 [19]. At the same time, first generation LAr experiments (ArDM [20] at LSC-Spain, DEAP-3600 [21] and MiniCLEAN [22] at SNOLab-Canada, and DS-50) merged in the Global Argon Dark Matter Collaboration (GADMC), gathering around 300 physicists.

DS-20k is the next project of the GADMC collaboration, described in a white paper in 2017 [23]. The DS-20k TDR was presented to INFN in December 2021. Figure 3 top left shows a sketch of the inner detector composed of the TPC whose walls are in acrylic (PMMA) and the stainless steel vessel surrounding it. Cathode and anodes, also made of PMMA and coated with Clevios, provide an electric field of 200 V/cm in the LAr bulk. The anode plate features a diving bell shape with a thickness of 5 cm to contain the argon gas pocket, 7 mm thick, with a $\sim$20 times higher electric field. To minimize type and amount of passive material, the TPC walls are also serving as overall mechanical structure, Faraday cage, grounding, neutron moderator (PMMA is loaded with Gadolinium (Gd)). The TPC–vessel gap is used for the neutron veto and is instrumented with SiPMs on the TPC outside walls (3% of the total coverage). The outer veto is hosted in a proto-DUNE cryostat which will be instrumented with strings of photo-sensors, made with SiPMs, held in place through a set of flanges at the top of the cryostat. The TPC and the inner veto will be filled with 100 tons of UAr, while the outer veto is filled with 700 tons of atmospheric argon.

Since September 2022, the DS-20k construction has started at LNGS. The stainless steel vessel will be filled with UAr by the end of 2026, see Figure 3 bottom. After filling the proto-DUNE cryostat, the data taking should start at the beginning of 2027 with the calibration campaign. The main components are being prepared:

[2]DEAP-3600 TPC was filled with atmospheric argon, not UAr.

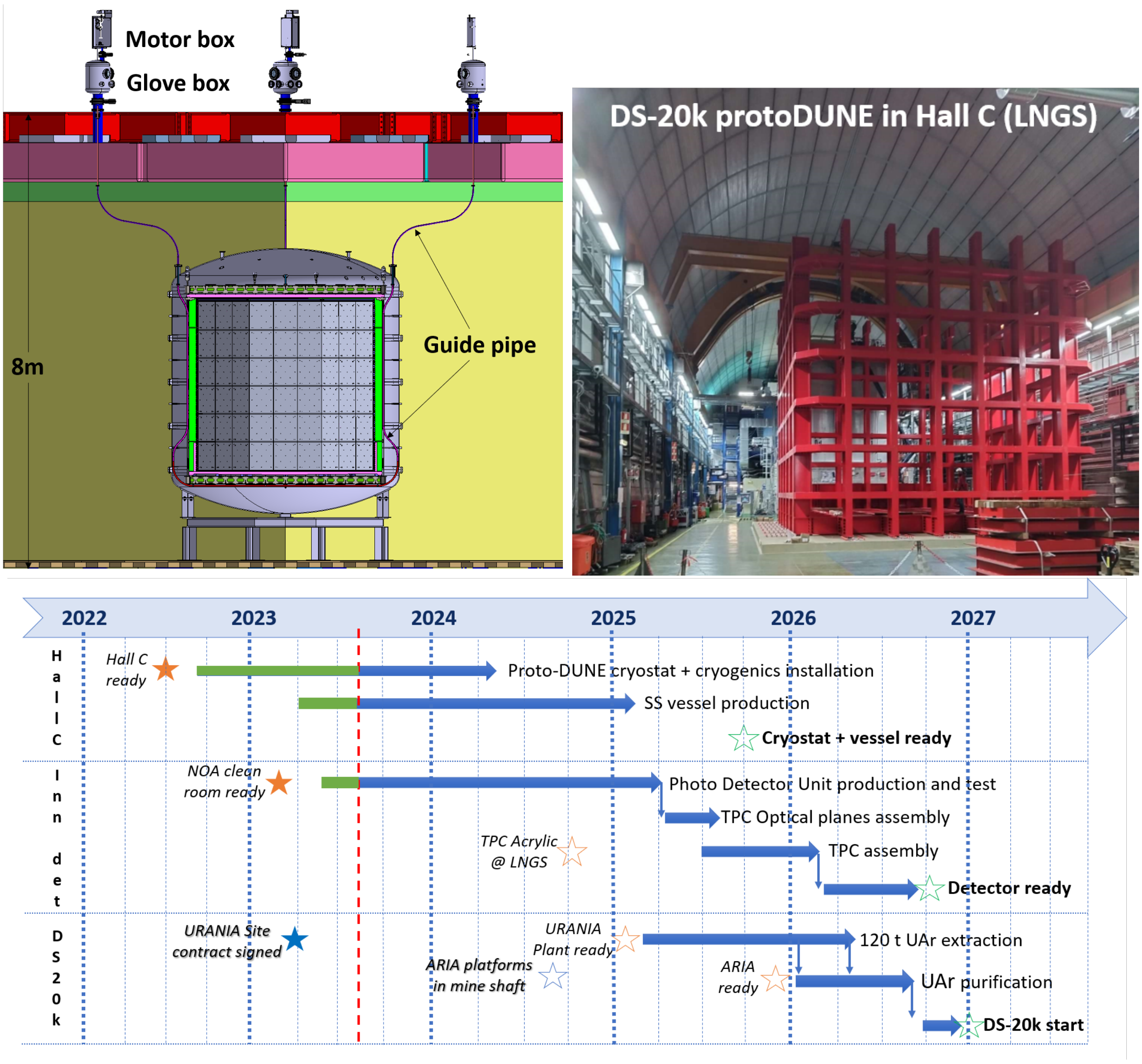


Figure 3: Top left: design of the DS-20K TPC (light green) and veto detectors inside a stainless-steel vessel filled with underground liquid argon. The inner detector is installed in the proto-DUNE cryostat (top walls in purple). The calibration guide tube system is represented around the DS-20K TPC and heading to the top of the proto-DUNE cryostat where the glove boxes for the source insertion and the motor boxes are located. Top right: photo of the proto-DUNE cryostat in the Hall C of LNGS in June 2023. Bottom : DS-20K foreseen timeline until completion in 2027, as of July 2023.

- proto-DUNE cryostat: the warm structure is currently being mounted in the Hall C of the LNGS (Figure 3 top right). The cryostat and associated cryogenics are to be completed in spring 2024. A clean room will be mounted on top of the cryostat to allow the TPC assembly directly in the cryostat. When the TPC and the stainless steel cryostat are completed, the detector is ready (fall 2026), the cryostat roof is put in place and the cryostat is filled with LAr.

- Stainless steel vessel: final specifications are prepared for the tendering process. The vessel should be delivered at LNGS at the beginning of 2025. When the TPC assembly is completed, it is attached to the vessel top cap which is then anchored to the ceiling while the vessel body is mounted in the cryostat. When the latter is completed, the top cap is lifted down in the vessel body, the dome being bolt to the body of the vessel. This should happen end of summer 2026.

- Photo-sensors: the SiPMs, developed with the Fondazione Bruno Kessler have been produced at LFoundry in July 2022. They are being cryo-probed in the NOA clean room facility at LNGS since April 2023. The integration and test of the SiPMs in 700 PDUs are being actively prepared in NOA for the TPC as well as in UK and Poland for the veto. The PDU completion is expected for spring 2025. The two optical planes (top and bottom) gathering the TPC PDU should be ready few months later.

- TPC: procurement of the TPC walls, cathode and anode materials is in discussion with selected companies. With the first batch of material, a TPC mock-up will be built and tested at LAr temperature in an already existing one-ton cryostat, that has been successfully operated at CERN cryolab with its final cryogenics in 2019–22. The mock-up will validate the concepts used for the TPC design and the LAr test should be completed by April 2024. The TPC assembly in the proto-DUNE cryostat should start mid-2025 after preparation and coating of the acrylic that will have been received end-2024 at LNGS.

- UAr: the preparation of sites for the argon extraction and purification is on-going. The Urania facility will extract UAr from the CO_2 wells at the Kinder Morgan Doe Canyon Facility located in Cortez, CO, USA. The Aria facility [24] in the Seruci mine campus of CarboSulcis in Sardegna will insure further chemical UAr purification by using a 350 m tall column, separating the isotopes by cryogenic distillation. Urania should start UAr extraction in January 2025 and gradually send it to Aria. The plan is to extract 120 tons in 18 months. Aria should complete argon purification in summer 2026 and ship all UAr to LNGS in September 2026.

DS-20k is gathering all successful developments carried out for ten years with first-generation (smaller) LAr TPCs, which means that the fundamental concepts of the experiment are well established and the main challenges come from scaling the technologies to higher dimensions. The only exception is the use of SiPMs instead of the standard PMTs used before. The designed SiPMs, made of high-purity materials, have a photo-detection efficiency higher than 40% at 77 K and for a wavelength of 420 nm, a signal to noise ratio greater than 8, and a timing resolution of a few ns. The use of both underground argon and SiPMs will allow to take full advantage of the intrinsic properties of the LAr scintillation that enables a huge separation of nuclear recoils (WIMP induced or background from neutrons) and electron recoils (photon induced backgrounds). However in such a large TPC, the ability to suppress the background and minimize the dead-time [3] strongly depends on event reconstruction and simulation, which, in turn, rely on the detector calibration. In this context, the IN2P3 teams have developed a project centred on the development of a TPC calibration system and on the signal and event reconstruction.

4 IN2P3 contributions and prospects

APC joined the DarkSide collaboration in 2012, LPNHE in 2014 and CPPM in 2020. Each team was evaluated by their Conseil Scientifique (CS) in March 2020, November 2022 and May 2020, respectively. As shown in Appendix A, the relevance of the team involvement in DS-20K was recognized as well as the quality of the work, symbolized by the DS-50 low-mass WIMP search results providing the world best limits [25]. APC is coordinating the DS-20K offline software which includes the signal/event reconstruction and simulation. All the software for the DarkSide Offline was developed at APC: the Geant4-based Monte Carlo, the electronics simulation, the event reconstruction, and all the tools to drive the detector optimization and assess the sensitivity of DS-20K (the software is hosted at the IN2P3 GitLab repository and documented on the French DarkSide website `https://darkside.in2p3.fr/docs`). On the hardware part, CPPM has taken the responsibility for the conception, construction, installation and commissioning of the calibration system to circulate external radioactive sources. In more details, the main contributions from the DarkSide-IN2P3 team since the last IN2P3 CS in October 2018 relate to (number of publications since 2018 are put in parenthesis):

1. **LAr response simulation (2 publications [26, 27])**: the DarkSide Monte Carlo (g4ds) was developed by the APC team, following recommendation given at the 2012 APC CS. The idea was to mitigate the poor knowledge of the physical processes at the basis of scintillation and ionization processes in LAr to take full advantage of the DarkSide sensitivity. The so-called PARIS model [28] was developed and checked successfully with a set-up at the ALTO facility at IPNO [26, 29]. This enabled the team to acquire a leading position in physics analyses. Since 2018, the code, still managed by APC, is regularly updated, e.g. for new version of Geant4. It served as a basis for all the optimisation of the detector (e.g. inner veto, background budget, ...) that was needed for the detector TDR. A new measurement of the ER and NR ionization yields at lower energy recoils has been performed using the DS-50 calibration data (Figure 4) down to 180 eVer and 500 eVnr, respectively [27]. NR ionization yields are compatible with the previous ARIS measurements but have significantly improved both in precision and energy range, as needed for the low-mass WIMP searches. Despite these major improvements, unknowns remain in the modelling of the nuclear recoil fluctuations in the sub-keV regime, see item 5. An effort lead by APC in collaboration with CPPM and other labs of the DS-20K collaboration has started in April 2023 to improve on that using the ALTO facility. For that, the BLEND (^{10}Bo Low-Energy

[3] The background event rate is expected to be about 100 Hz, which, in combination with the maximum electron drift time of 3.5 ms, will cause a pileup of S2 pulses in about 30% of the events.

Neutron Detector) detector is being designed and will take data at the end of 2023 and in 2024.

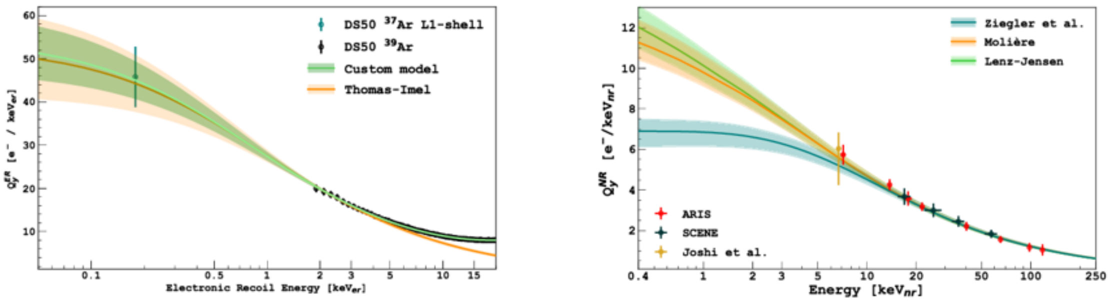


Figure 4: Ionization yields for electronic recoil (left) and nuclear recoil (right) measured using DS-50 calibration data [27].

2. **Signal and event reconstruction**: The SiPMs have many advantages (low dark noise, excellent resolution and high signal to noise ratio) but also disadvantages such as high instrumental noise (after-pulses and cross-talks) and slow time response. In addition, reading 2,500 channels, each of them grouping 96 SiPMs, in a triggerless system, such as the one envisioned in DS-20K, is ambitious and requires fast processing of a large data stream. To exploit at best the SiPM performance, the APC team developed the low-level event reconstruction package based on match filtered waveforms. This custom fast hit finder enables an efficient reconstruction of the scintillation and ionization photo-electron pulse shapes, crucial for background and noise rejection. A typical waveform for one channel, including realistic electronic noise and SiPM instrumental noise and dark count rate, is shown in Figure 5 left, together with the reconstructed hits. This reconstruction was tested successfully on small-size DarkSide prototypes run at Naples. Recently a dedicated effort was made to emulate the DAQ and define the event data model with the needed information for an offline reprocessing. This model meets the specification for data output rate (<60 MB/s, Figure 5 right). Higher-level reconstruction algorithms associating S1 and S2 signals for particle identification, energy and vertex reconstruction (called event reconstruction) have also been developed by APC, some using neural networks. All this work will be the baseline for the DS-20K signal and event reconstruction.

3. **Calibration system for external sources**: In 2019, CPPM has taken the responsibility for the conception, construction, installation and commissioning of the guide tube system that will circulate gamma and neutron radioactive sources around the TPC. The calibration of the TPC is a key ingredient for the understanding of the TPC response to either electrons, photons or neutrons. Guided sources provide energy deposits close to the walls of the TPC with a known position and are complementary to diffuse sources that can be injected in the LAr. The system is composed of two

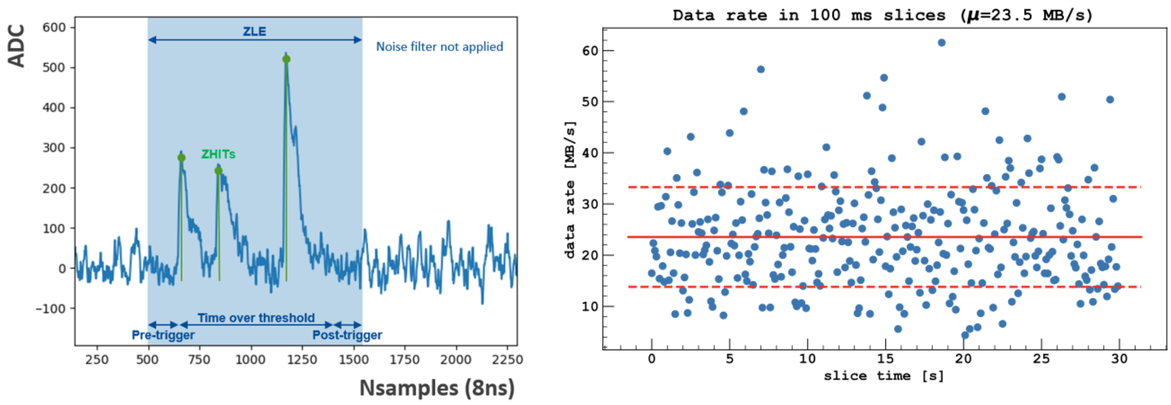
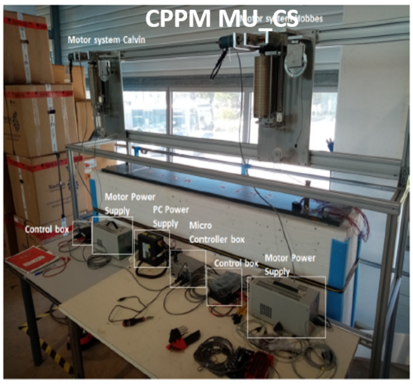


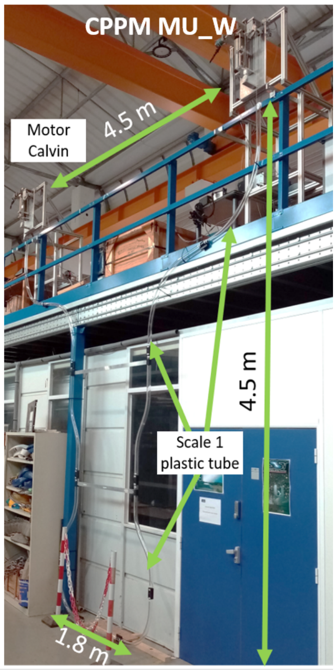
Figure 5: Left: typical waveform of a DS-20K channel, as will be seen by the DAQ. A region with significant activity (ZLE, shaded in blue) is identified and 3 hits are found (ZHITS, green dots). Right: data rate using the event data model developed by APC in DAQ time slices of 100 ms.

20-meter-long stainless-steel tubes of thickness of 1.5 mm and a diameter of 30 mm, see Figure 3 top left. Each tube has an overall U shape, with 15 curves of 40 cm radius. The two tubes are at right angle with each other. Two pairs of glove and motor system boxes are used to introduce sources inside the tubes with constant nitrogen flushing, and located on the cryostat roof. The motor system is adapted from the SNO experiment and has been developed by Queen's University. The main technical challenges of the calibration tube system are: i) operation at LAr temperature, ii) mitigation in case of ice formation in the tube, iii) sustainability of the DAQ (extra 100 Hz), iv) O(1) month time for the calibration, v) negligible alteration of the light collection in the veto. Points iii), iv) and v) were addressed by dedicated simulations performed by CPPM, enabling a first tentative calibration programme to be settled. To address points i) and ii) three mock-ups have been built as illustrated in Figure 6. Pseudo sources were circulated at LAr temperature in a simple U-shape tube of few meters with the final motor system (including control and acquisition programs): during few hours in a poorly isolated cryostat at CPPM (MU_CS) and during one month in a vacuum isolated cryostat at CERN cryolab (MU_CL). Pseudo sources were also circulated in the full scale [4] mock-up (MU_W) at warm at CPPM. The latter enables to study the behaviour of the rope and the source in all the curvatures manufactured at real scale whereas the formers enable to validate the performance in real temperature and timing conditions. The measurements made during the mock-up campaign which lasted from September 2022 to July 2023, including speed of the source, position accuracy and tension of the rope, fulfill the DS-20K requirements as shown in Figure 6 bottom. During the long LAr test (MU_CL) no ice formation in the tube has been observed. Still a mitigation strategy in case of ice formation has been defined and

[4] Only the straight parts are shortened with respect to the final system.

applied successfully during the run. Following these achievements in July 2023, an FDR process has started.





	DS-20k	MU_CS	MU_CL		MU_W
	Requirements / Performance				
Speed of the source (cm/s)	> 1	3	1		2
Position accuracy (cm)	±1	±1	1		±1
Tension (N)	< 150	25-40	15-30		60-90
Ice formation (block)	No	No	Yes but sublimated	No	NA NA
Total distance for all sources (m)	160 (/yr)	> 100	800	100	> 100
Total nb of back&forth / tube	4 (/yr)	44	280	35	>6

Figure 6: Pictures of the three calibration mock-ups (MU_CS, MU_CL and MU_W) operated at CPPM and at CERN and performance obtained during the mock-up tests as compared to the DS-20k requirements.

4. **Radon contamination**: even if radon is a priori not a main background for DS-20k because of the PSD, its contamination should be studied with a lot of care. An important point to be explored is radon emanation and transport. Expertise already acquired in this field and the new development of the IN2P3 R&T radon platform (MICRORADON project) led by J. Busto at CPPM are exploited to measure the radon diffusion on material that will be used by DS-20k. This is complementary with respect to existing resources of the DarkSide collaboration, hence very much appreciated. CPPM is engaged in the definition and the validation of the technique to protect from radon contamination detector components prior to their installation on site. Once produced, components will be packaged into special plastic bags (currently being tested and validated at CPPM) and shipped to LNGS for installation.

5. **Final results of** DS-50 **low-mass analysis (3 publications** [15, 30, 31]**)**: the publications of the first low-mass WIMP search with DS-50 at the beginning of 2018 [25, 32] broke the generally recognized paradigm for which noble liquid experiments are not competitive in the few GeV mass range, a range hitherto dominated by solid-state technology. Many potential improvements were identified at the time of

these publications. A reanalysis, under the initiative and responsibility of the IN2P3 teams (editors of the two main papers) was launched to: i) use all the statistics available during the data taking period, increasing the statistics of the 2018 analysis by 80%, ii) improve the signal selection efficiency, iii) improve the background and signal model, iv) add more realistic systematic uncertainties in the final fit. Following these improvements, the background model is in good agreement with the data down to 4 ionization electrons, improving significantly the separation with the signal (Figure 7 top left) compared to the 2018 published results. The final low-mass WIMP search of DS-50 has been published in 2023 [15], providing an improvement in sensitivity of around 10 in the best case (WIMP mass of 3 GeV) as shown in Figure 7 center left. World best limits are obtained from 40 MeV (1.2 GeV) to 3.6 GeV when (not) considering the Migdal effect [30] as illustrated in Figure 7 bottom left. World leading limits on light dark matter, Axion-Like Particles, dark photons and sterile neutrino interaction with electron final states have also been published [31].

6. DS-20K **sensitivity (1 publication [33])**: detailed simulation studies have also been performed by IN2P3 teams to estimate the sensitivity of DS-20K. Focusing on the first data, a gain of two orders of magnitude over the DS-50 final sensitivity is expected in one month for the high mass WIMP with a robust cut-and-count analysis relying on the PSD. It reaches the level of the expected final sensitivity of DEAP-3600 (Figure 7 top right). Evaluations of DS-20K sensitivity for longer exposure time have also been carried on. For low mass WIMP, a gain in sensitivity over DS-50 by a factor 30 is expected in one year[5] (Figure 7 center right). For high mass WIMP, a discovery potential exceeding the running xenon experiment is expected after 5 years of data taking (Figure 7 bottom right). For the latter, the impact of the description of dark matter in the milky way galaxy halo has been assessed by a dedicated work with theorists from LAM (INSU), LUPM (IN2P3) and CPT (INP) in two projects financed by Institut de Physique de l'Univers (IPhU) of Aix-Marseille University (AMU) in 2021-2024 and CNRS-MITI in 2022-23. Finally, discovery of supernova neutrino via coherent elastic neutrino-nucleus scattering is possible up to the small Magellanic cloud and a sensitivity to neutronization burst up to the milky way edge is expected [33].

The last IN2P3 CS took place just before CPPM joined DarkSide and stated that [34]: "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.". The IN2P3 contributions gathering simulation software (item 1), signal/event reconstruction (item 2) and calibration guide tube system (item 3) are strongly interconnected. The reasons are first that the tools developed in offline enable the calibration strategy definition and second that the calibration data will allow to validate and improve the reconstruction and analysis algorithms. The work performed by the French teams during these last five years is therefore fully in-line with the CS recommendation and significantly reinforces the IN2P3

[5]DEAP-3600 is a single phase TPC and therefore has no sensitivity for low-mass WIMPs.

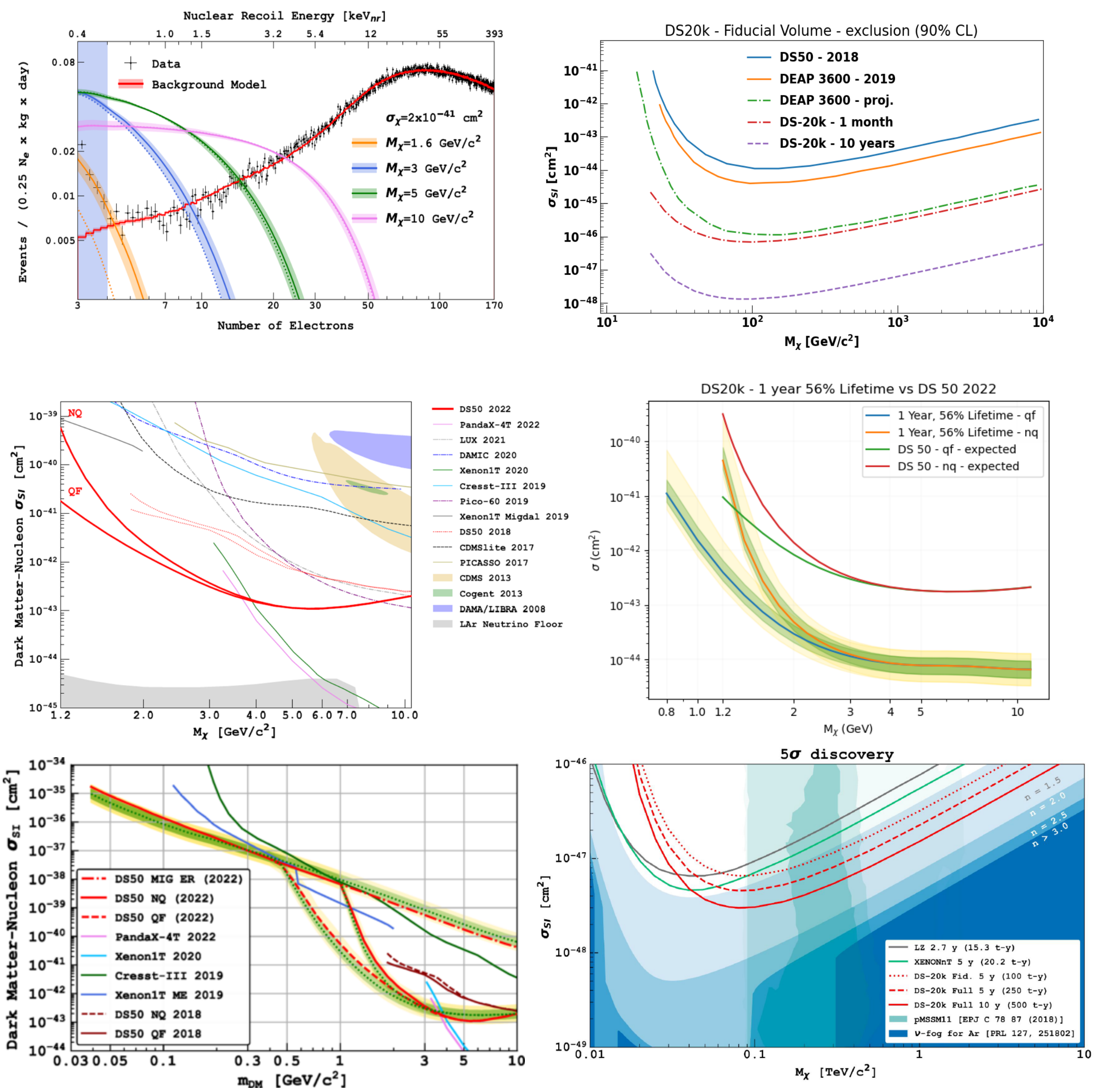


Figure 7: DS-50 low-mass physics results (left) and DS-20K expectations (right). Top left: DS-50 signal and background models compared to data [15]. Center left: DS-50 90% CL upper limits on spin independent WIMP-nucleon cross sections for low-mass searches, using non-quenching (NQ) and quenching (QF) signal fluctuations [15]. Bottom left: Similar assuming the Migdal effect [30]. Top right: DS-20K sensitivity to high mass WIMP after one month of data taking compared to DS-50 [19] and DEAP-3600 current and final expected sensitivities. Center right: DS-20K sensitivity to low mass WIMP after one year of data taking compared to DS-50 [15]. Bottom right: DS-20K discovery potential compared to xenon experiments.

position in DS-20k by including a hardware contribution. In parallel, the French teams were central participants in the production of first-class physics results for the low-mass WIMPs search (item 5).

Figure 8 shows the next steps in the completion of the calibration system and the software reconstruction before the DS-20k physics. The calibration system is presently in the FDR phase and should be concluded by a PRR at the beginning of 2024. In 2026, the guide tubes should be installed around the TPC while the glove and motor boxes will be installed on the cryostat roof. The system will be commissioned at warm and at cold, prior to the start of the calibration programme in 2027, that will be lead by CPPM. The signal and event reconstruction, driven by APC, will be documented in a computing TDR at the beginning of 2024, which will include the needed resources in terms of computing cores and storage. The possibility that CC-IN2P3 becomes a Tier-1 for data collected with DS-20k will be discussed at this time. Mid 2024, a data production will be launched to freeze a first offline version. A data challenge will follow in 2025 that should enable a final version of the code by mid-2026 that can be used for the calibration data analysis, that APC and CPPM will perform to validate the reconstruction approach. During the same period, we will define the data selection and estimate the associated efficiency to be ready for analysing the first physics data sample (high and low mass WIMP) where we plan to occupy a central place, taking full advantage of the experience gathered during the DS-50 low mass analysis.

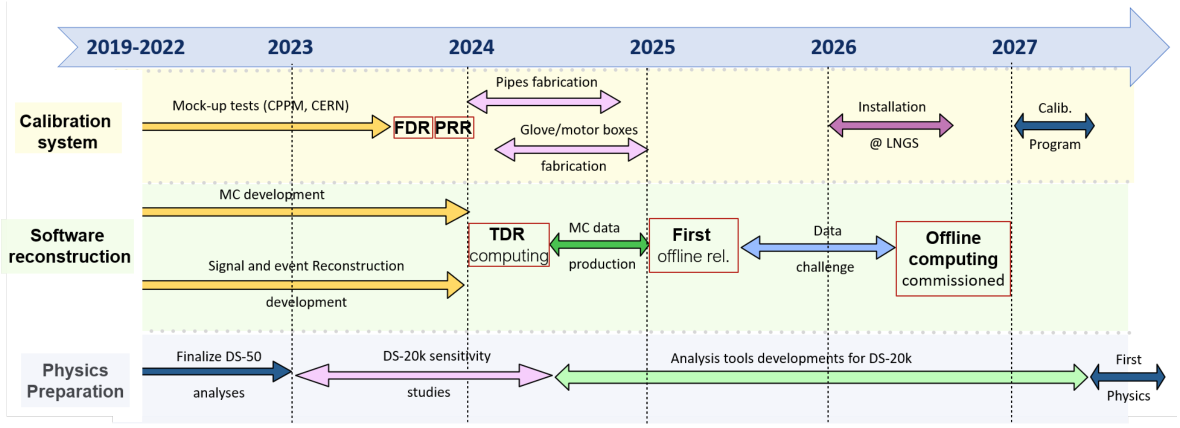


Figure 8: Timeline for the IN2P3 activities in DS-20k.

To conclude, DS-20k will have significant and quick improvements in sensitivity at high and low mass with respect to previous LAr experiments, as demonstrated by the work largely performed by the IN2P3 teams (item 6). Building on our strong involvements and responsibilities, the goal of the IN2P3 teams is to occupy a central place in these search analyses by mastering the event reconstruction and simulation tools and validating them with calibration data. The interplay between software, event reconstruction and calibration is patently tight and they are key elements for the success of the experiment.

5 IN2P3 human and financial resources

Since CPPM officially joined the DarkSide IN2P3 effort in 2020, the number of people with permanent positions in DarkSide is stable and around ten permanent scientists (two professors, five CNRS researchers, three engineers) and two or three PhD students, see Figure 9. This represents around 5% of the DS-20K collaboration. Since 2012, four PhD theses have been completed at APC and LPNHE, one will be defended in January 2024 at ASTROCENT, two are currently on-going (CPPM and APC) and one will start in October 2023 at APC. Every year, internships with master 1 or master 2 student take place at APC (with NPAC), at CPPM and/or at CERN (Summer student programme). In total this represents around 7 FTE/year. Having an IN2P3 post-doc at CPPM to support the effort on the calibration system installation and preparation of the first data analysis would be of great help. To be complete, IN2P3 responsibilities in DS-20K are given in Table 1.

Name	Date	Task
P. Barrillon	2023-	Technical coordinator of DarkSide-France
D. Franco	2016- 2016- 2016-20	L1 manager of “Science, simulation and computing” Member of the Institute, Executive and Management boards Coordinator of DarkSide-France, National contact physicist
F. Hubaut	2020-	Member of the Institute Board
E. Le Guirriec	2020-	Czar of the group at CC-IN2P3
P. Pralavorio	2021-23 2023-25 2023-	Member of the Editorial Board Member of the Financial and Advisory Board Coordinator of DarkSide-France, National contact physicist
I. Wingerter-Seez*	2021-22 2021-22	Member of the Review Office, Executive and Management boards Coordinator of DarkSide-France, National contact physicist

Table 1: French responsibilities in DS-20K since 2016. * Retired early 2023.

Several members of the groups are actively participating in the organisation of the GDR DUPHY by coordinating the activity of WP2 (Low radioactivity techniques), WP3 (Detection of rare-events) and WP4 (Simulation & Analysis). In this framework, several talks were given on DS-50 results, including low-mass WIMP search and low energy calibration as well as on DS-20K work covering calibration and signal reconstruction. Members of the groups, especially students, gave several talks at conferences: TAUP 2023 (DS-50 results), Moriond EW 2023 (DS-20K calibration and DS-50 low-mass results), Blois 2022 (DS-20K project), EXCESS 2022 (low energy DS-50 calibration).

Figure 10 shows the financing of the project. Since the approval of the fiche de projet in January 2023 [35], signed by APC, CPPM and LPNHE directors, IN2P3 is participating to DS-20K – 22 k€ have been allocated to APC and CPPM in 2023. In 2024–26, a

Nom des personnes	Statut	2021	2022	2023	2024	2025	2026
APC		**230%**	**350%**	**300%**	**335%**	**335%**	**310%**
M. D. Franco	DR2	100%	100%	100%	100%	100%	100%
Mme A. Tonazzo	Prof.	10%	10%	10%	10%	10%	10%
M. T. Hessel	PhD	25%	100%	100%	75%		
M. T. Hugues (cot. ASTROCENT)	PhD	25%	50%	40%			
Mme E. Nikoloudaki	PhD			25%	100%	100%	75%
Mme J. Rode (cot. LPNHE)	PhD	50%	40%				
Thèse ANR	PhD				25%	100%	100%
Stagiaires	M2	20%	50%	25%	25%	25%	25%
CPPM		**295%**	**345%**	**295%**	**325%**	**345%**	**345%**
M. J. Busto	Prof.	20%	20%	20%	20%	20%	20%
M. Y. Coadou	CR			50%	80%	100%	100%
M. F. Hubaut	DR1	50%	50%	50%	50%	50%	50%
M. P. Pralavorio	DR2	50%	50%	50%	50%	50%	50%
Mme I. Wingerter-Seez	DRCE	100%	100%				
Mme M. van Uffelen	PhD	25%	100%	100%	75%		
Thèse ANR	PhD				25%	100%	100%
Stagiaires	M2	50%	25%	25%	25%	25%	25%
Laboratoire LPNHE		**70%**	**55%**	**0%**	**0%**	**0%**	**0%**
M. C. Giganti	CR	20%	15%				
Mme J. Rode (cot. APC)	PhD	50%	40%				
TOTAL (FTE)		**5.95**	**7.50**	**5.95**	**6.60**	**6.80**	**6.55**
CPPM		**80%**	**80%**	**90%**	**90%**	**90%**	**90%**
M. Pierre Barrillon	IR	20%	20%	20%	20%	20%	20%
M. Emmanuel Le Guirriec	IR	40%	40%	50%	50%	50%	50%
M. Jérôme Royon	AI	20%	20%	20%	20%	20%	20%
LPNHE		**20%**	**0%**	**0%**	**0%**	**0%**	**0%**
M. Olivier Dadoun	IR	20%					
TOTAL (FTE)		**1.00**	**0.80**	**0.90**	**0.90**	**0.90**	**0.90**

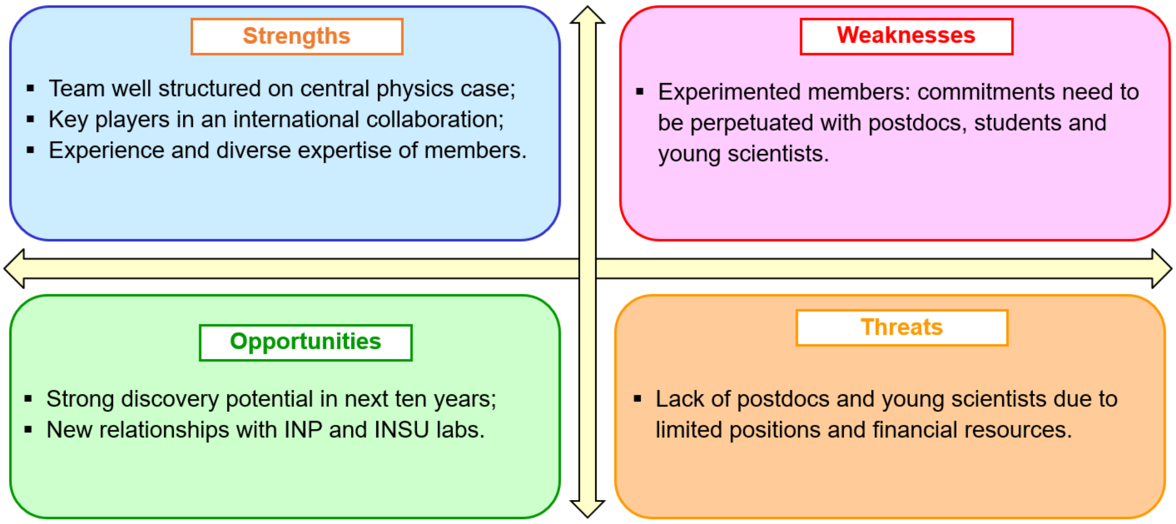
Figure 9: IN2P3 human resources in researchers (green), engineers (purple).

Type	Financements	2021	2022	2023	2024	2025	2026
Equipements		**- €**	**- €**	**9,000 €**	**9,000 €**	**- €**	**- €**
Calibration mock-up @ CERN	IN2P3	- €	- €	5,000 €	3,000 €		- €
Tubes DS20k	IN2P3		- €	4,000 €	6,000 €		
Fonctionnement		**- €**	**- €**	**- €**	**8,000 €**	**8,000 €**	**8,000 €**
MoU - Fond Commun Constr.	IN2P3				8,000 €	8,000 €	8,000 €
Missions		**1,750 €**	**1,750 €**	**14,750 €**	**26,000 €**	**31,000 €**	**28,000 €**
Collaboration (CPPM)	IN2P3	- €	- €	4,000 €	10,000 €	10,000 €	10,000 €
Opération (CPPM)	IN2P3			4,000 €	10,000 €	15,000 €	10,000 €
Collaboration (APC)	IN2P3			5,000 €	6,000 €	6,000 €	8,000 €
COPIN-IN2P3	IN2P3	1,750 €	1,750 €	1,750 €			
TOTAL		**1,750 €**	**1,750 €**	**23,750 €**	**43,000 €**	**39,000 €**	**36,000 €**
Equipements		**11,100 €**	**10,000 €**	**25,000 €**	**5,000 €**	**2,000 €**	**2,000 €**
Neutron detector & RD	Labex APC			15,000 €			
Calibration mockup	RP CPPM	1,000 €					
Calibration mockup	IPhU@AMU	10,100 €	5,000 €	5,000 €			
Calibration mockup	MITI		5,000 €	5,000 €			
Calibration DS20k + info	ANR FIDAR				5,000 €	2,000 €	2,000 €
Missions		**6,700 €**	**15,000 €**	**11,000 €**	**12,000 €**	**8,000 €**	**25,000 €**
Collaboration (APC)	Labex APC	5,000 €	5,000 €		5,000 €		
Collaboration (CPPM)	iPhU@AMU+MITI	700 €	9,000 €	11,000 €	2,000 €		
Collaboration (LPNHE)	RP LPNHE	1,000 €	1,000 €				
Collaboration + opération	ANR FIDAR				5,000 €	8,000 €	25,000 €
Personnels		**14,300 €**	**43,000 €**	**44,500 €**	**58,000 €**	**84,000 €**	**84,000 €**
Thèse Marie van Uffelen	iPhU@AMU	10,000 €	40,000 €	40,000 €	30,000 €		
2 Thèses	ANR FIDAR				28,000 €	84,000 €	84,000 €
Visiteurs étrangers	IPhU@AMU	2,300 €	2,100 €	4,500 €			
Stages	IPhU@AMU	2,000 €					
Stages	RP CPPM		900 €				
TOTAL		**32,100 €**	**68,000 €**	**80,500 €**	**75,000 €**	**94,000 €**	**111,000 €**

Figure 10: IN2P3 budget (orange) and other financing (blue). Note that the 8 k€ for the common funds of the construction is an estimation, that is still under discussion.

contribution will come from common funds for the construction whose amount is still under discussion. Other contributions are coming from a partnership between IN2P3 and ASTROCENT (COPIN), the Labex APC (15 k€ over three years in 2020–22 and 15 k€ in 2023) and IPhU at AMU (30 k€ over four years and one PhD student) as well as CNRS-MITI (20 k€ over two years). The ANR FIDAR has been accepted for 2024-2027 with 350 k€, including one PhD student at APC and one at CPPM. The total cost of the DS-20K project is estimated to be 93 (110) M€ without (with) labor cost. 0.2% is provided by IN2P3. About half of the total cost has been spent (>90% by INFN). No major unassigned cost is identified for the construction.

6 SWOT



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A Excerpt from the lab scientific councils

- Extraits du compte-rendu de la séance du 19 mars 2020 du CS de l'APC : "Whereas it is likely that for the immediate future, experiments with LXe will have the greater sensitivity, the Argon technology is likely to have the greater scientific reach in a number of years. (...) The APC group is well positioned to make significant contributions to this international effort, with expertise in the analysis, data reconstruction, pulse-shape discrimination, modelling and measuring the low energy behavior."

- Extraits du compte-rendu de la séance du 20 mai 2020 du CS du CPPM : "Les détecteurs au Xénon dominent pour le moment l'exploration des hautes masses (>10 GeV), mais l'Argon liquide purifié de 39Ar (DS-20k) a un meilleur potentiel à long terme grâce à son faible bruit de fond, et offre à court terme une sensibilité unique à basse masse (1-10 GeV). (...) Le conseil scientifique (CS) recommande fortement à la direction du CPPM d'approuver la création de cette nouvelle équipe Matière Noire."

- Extraits du compte-rendu de la séance du 28 novembre 2022 du CS du LPNHE : "La production scientifique est tout à fait remarquable : l'analyse basse masse a été significativement améliorée et a gagné en sensibilité, établissant ainsi les meilleures limites mondiales entre 1,2 GeV et 3,6 GeV. Elle reste aujourd'hui la plus sensible en dessous de 4 GeV. Les développements sur la reconstruction des signaux d'ionisation et de scintillation des données des SiPM qui seront utilisés dans DS-20k constituent une contribution significative à l'expérience. Le conseil félicite Claudio pour la visibilité que son activité sur DarkSide donne au laboratoire, et espère qu'une solution viable sera trouvée pour pérenniser la participation du laboratoire à l'expérience."