SuperNEMO Demonstrator experiment

IN2P3 Scientific Council

French SuperNEMO collaboration
http://supernemo.org

September 2025

TABLE OF CONTENTS

1. Summary

The goal of the SuperNEMO collaboration is to develop a unique technological approach to search for neutrinoless double beta decay (0νββ). Its distinctive feature is its ability not only to detect the process, but also to identify the underlying mechanism, thereby exploring the new physics beyond the Standard Model through the possible Majorana nature of neutrinos.

A demonstrator corresponding to a single module of what could become a future large-scale detector is currently taking data at the Modane underground laboratory (LSM). Its primary goal is to study technological scalability. However, with 6.11 kg of ^{82}Se, its extremely low-background design, and its ability to track and identify each particle, the SuperNEMO Demonstrator can potentially surpass the current best sensitivity for 0νββ decay of ^{82}Se. It also remains highly competitive for investigating alternative mechanisms, such as V+A currents or Majoron emission. Furthermore, by leveraging its sensitivity at lower energies through full topological reconstruction, SuperNEMO can perform high-precision measurements of Standard Model double-beta decay 2νββ. This is useful for nuclear calculations of weak interaction processes in general and, of course, for the entire double-beta decay community, while also exploring a range of Beyond-the-Standard-Model processes through detailed studies of 2νββ event kinematics.

Analysis of the first data, recorded since April 10, 2025, shows very preliminary but encouraging results, although they are currently dominated by the radon background, as expected in the absence of a radon-free air facility. The high-quality double-beta physics data phase, scheduled to begin in October 2025 once the LSM radon-free air system is operational, should allow the experiment to reach the expected sensitivities for the various physics channels to be studied, subject to the floor-occupation constraints at LSM.

The collaboration is therefore fully committed to high-quality data collection and analysis. For the SuperNEMO Demonstrator's full potential to be fulfilled, the collaboration is relying on IN2P3 to optimize – if possible - the available acquisition time, and to continue its support for the experiment. This support includes running costs, involvement of IN2P3 personnel for data analysis, and contribution to the detector dismantling program according to the scenarios currently under study.

2. Scientific Challenges

2.1 Scientific question

The SuperNEMO project was conceived to develop a **unique technological approach** to the study of **neutrinoless double-beta decay** (0νββ), building upon the expertise and achievements of its predecessor, NEMO-3 [1]. NEMO-3 was operational at LSM from 2003-2011, and generated 20 world's-best physics results double-beta-decay processes [2].

The primary scientific objective of SuperNEMO is the search for neutrinoless double-beta decay, a rare process that **violates lepton-number conservation** by two units. In standard double-beta decay (2νββ), a rare but Standard-Model–allowed second-order process, two neutrons of a nucleus convert into two protons, emitting two electrons and two antineutrinos: (A,Z)→ (A,Z+2) +2 e^-+2$\bar{\nu}_e$. In contrast, neutrinoless double-beta decay occurs without neutrinos, a transformation forbidden in the Standard Model: (A,Z)→ (A,Z+2) +2 e^-.

Beyond the observation of a **new Physics** process, the observation of this decay would constitute direct evidence that **neutrinos are Majorana** particles, meaning they are their own antiparticles. This is true whatever the underlying mechanism (Schechter Valle theorem) [3]. If neutrinos are found to be Majorana particles, this would offer an intuitive explanation for their neutral charge, which is unique among the fermions. Furthermore, the Majorana mass term for neutrinos appears naturally in most extensions of the Standard Model.

Such a discovery could have large implications not only for **neutrino physics**, but also for **particle physics** and **cosmology** more broadly. Key examples include:

- **Neutrino mass generation**: Establishing the Majorana nature of neutrinos would provide crucial insights into the origin of their tiny masses compared to leptons or quarks. This could potentially be accounted for by theoretical frameworks such as see-saw mechanisms requiring Majorana neutrinos [4]. Neutrinoless double-beta decay can also give a constraint on absolute neutrino mass, complementary to measurements from cosmology, neutrino oscillations and beta-decay end-point measurements [5].
- **Matter–antimatter asymmetry**: Majorana neutrinos could play a central role in explaining the observed baryon asymmetry of the Universe. In particular, the process of leptogenesis, mediated by the decay of heavy Majorana neutrinos, offers a compelling mechanism for generating this matter–antimatter asymmetry.
- **Physics beyond the Standard Model (BSM)**: The observation of neutrinoless double-beta decay would serve as a powerful probe of new physics associated to lepton-number violation. Such a signal might be accompanied by novel processes involving additional interactions with previously unknown particles. The mechanisms underlying this new physics can be constrained by detailed studies of the kinematic properties of double-beta decay events.

While the neutrinoless double-beta decay search is one of physics most pressing questions, the Standard Model double-beta decay, as a doubly-weak process, is highly sensitive to nuclear effects such as the quenching of the axial-coupling constant g_A [6]. Precision studies of the kinematics of this process can serve as a powerful testbed for nuclear theories, as well as searches for new physics such as decays involving right-handed neutrinos [7].

2.2 Current state of the art

Neutrinoless double-beta decay is the subject of extensive international research efforts. Discovery of this process is the most practical way to probe the Majorana nature of neutrinos, and would offer unique capabilities to investigate fundamental aspects of particle physics complementary to reactor- and accelerator-based experiments.

Experimental searches for double-beta decay rely on highly-sensitive detectors operated in ultra-low-background environments in underground facilities.

Signal detection is primarily based on measuring the energy of the two electrons, which the sum is expected to be at the $Q_{\beta\beta}$ value or, in some exotic modes, to follow a continuous energy spectrum up to the $Q_{\beta\beta}$ value (Figure 1).

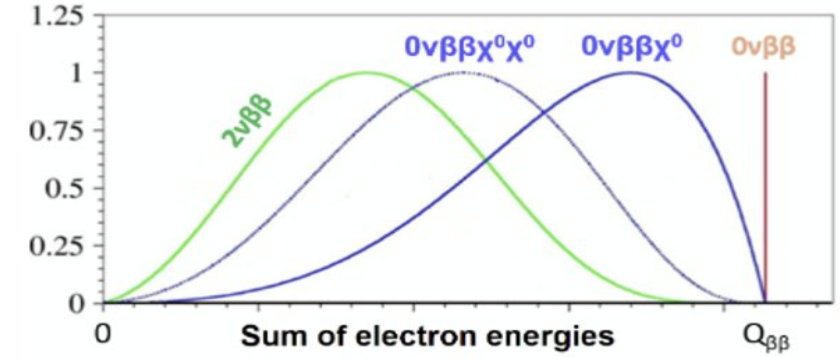


Figure 1: Shapes of theoretical two-electron summed energy spectra for 0νββ with Majoron emission (blue), for the n=1 (0νββχ⁰) and n=3 (0νββχ⁰χ⁰) spectral indices, for 0νββ decay (red) and for 2νββ decay (green).

With the exception of SuperNEMO, experiments use a calorimetric approach, in which the isotope under study is embedded directly in the detector material. This method enables measurement of the **total decay energy** with excellent efficiency. Some calorimetric experiments, particularly those employing time projection chambers (TPC), can record short particle tracks, but information on the emitted particles is limited. In contrast, SuperNEMO adopts a tracker–calorimeter approach, where the isotope is physically separated from the detection apparatus. This design allows detailed reconstruction of electron energies, full tracks, particle identification and angular correlations, offering powerful discrimination between signal and background events, as well as sensitivity to the underlying physics mechanisms driving the decay.

Several mechanisms could lead to neutrinoless double-beta decay. The most widely studied process is the exchange of light Majorana neutrinos via V–A currents. For years, experimental sensitivities have traditionally been compared based solely on this mechanism, even though new physics could of course manifest itself in other ways. In such a mechanism, the key physics parameter obtained is the effective neutrino mass $\langle m_{\beta\beta}\rangle$ which is connected to the decay half-life $T_{1/2}$ (0νββ) via the axial coupling constant g_A, a phase space factor $G_{0\nu}$ and nuclear matrix elements $M_{0\nu}$ by $(T_{1/2}^{0\nu})^{-1} \propto g_A^4\, G_{0\nu}\, |M_{0\nu}|^2\, \langle m_{\beta\beta}\rangle^2$. There are still significant discrepancies between the different calculations for nuclear matrix elements leading to very high levels of uncertainty [5]. Due to these large nuclear matrix element uncertainties, and taking into account natural abundance, enrichment feasibility, physical and chemical properties, and background considerations, no isotope appears strongly favored for the 0νββ quest. It is therefore important to search for neutrinoless double-beta decay in multiple isotopes.

2.3 IN2P3 mobilization on double beta decay searches

IN2P3 has been involved in the NEMO experiments since their inception in the 1980s and more recently has supported the CUPID R&D for a next-generation experiment. Several other recent R&D initiatives, such as R2D2 and LiquidO, are also supported to develop new technologies for double beta decay studies. More generally, investments have been made in low-background equipment essential for double beta experiments, including the PRISNA platform at LP2i, as well as various infrastructures and their operation at LSM.
Both the Neutrino IRN and the DUPhy (Deep Underground Physics) GDR include double-beta decay within their research scope. The IN2P3 researchers and engineers of SuperNEMO are actively involved in these IRN and GDR. Five of them coordinate work packages within these networks, and one serves as the co-director of the DUPhy GDR. Several physicists, PhD students, and postdocs from IN2P3 laboratories, as well as from other institutions in the SuperNEMO collaboration abroad, have also presented their work at meetings organized by these networks.

2.4 Links with related research communities (Health, INSU, INP, etc.)

The developments carried out within the collaboration, notably at CPPM, on radon trapping have fostered partnerships with INP (CINaM, Centre Interdisciplinaire de Nanosciences de Marseille) and INC (Institut de Chimie Radicalaire de Marseille, Institut Jean Lamour Nancy) laboratories.

3. Project Description

SuperNEMO employs a pioneering tracker-calorimeter technique, inherited from the NEMO-3 experiment. It is currently operating at the **Demonstrator** level, with the detector designed as the basic unit for possible future large-scale experiments.

3.1 SuperNEMO Demonstrator principle

Detector description

The SuperNEMO Demonstrator combines a thin, independent double-beta decay source located at the center of a tracking volume that records the trajectories of charged particles. Surrounding this tracking volume is a segmented calorimeter that measures the energy and timing of individual particles. Figure 2 shows the SuperNEMO Demonstrator along with its overall dimensions. This design benefits from a source that is separate from the detector, making it isotope-agnostic, and from the ability to measure individual particles.

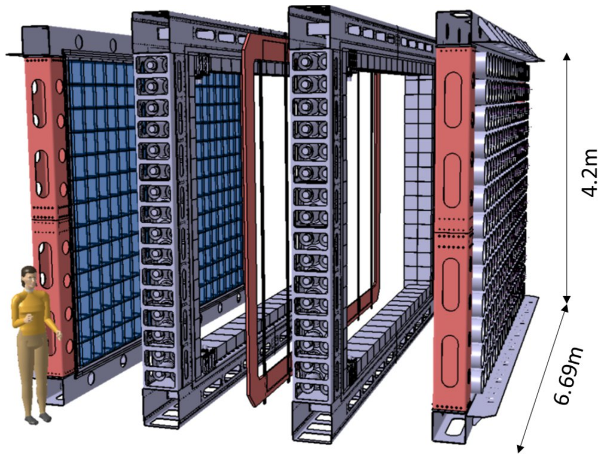
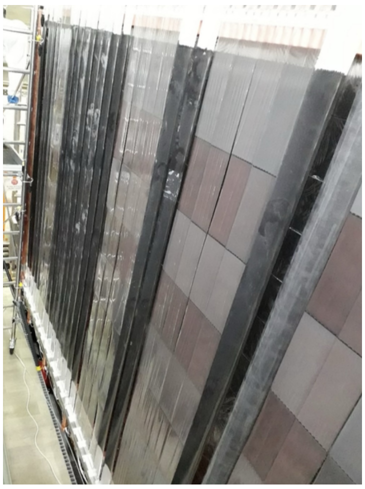


Figure 2: Exploded view of the SuperNEMO Demonstrator.



Source: The Demonstrator uses **6.11 kg of ^{82}Se** as the ββ source, in the form of 34 foils, each 2.7 m high, 135 mm wide, and approximately 300 µm thick (Figure 3). Selenium was enriched and purified. Several different purification and foil fabrication methods were used to test and compare their effectiveness. Main objectives were to reach a radiopurity inside the sources better than 10 µBq/kg and 2 µBq/kg for the ^{214}Bi and ^{208}Tl respectively, compared respectively to the 220 µBq/kg and 113 µBq/kg obtained in NEMO-3. The first four ^{82}Se foils fabricated were measured for 262 days with the following promising results: A(^{214}Bi) < 300 µBq/kg and A(^{208}Tl) = 24 ± 20 µBq/kg (90% C.L.) [8]. Furthermore the new foil production method developed for SuperNEMO (LAPP) showed a better flatness compared to NEMO-3 method.

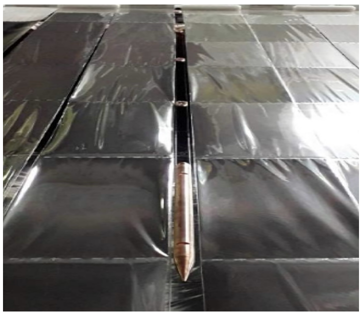
Figure 3: ^{82}Se foils inside the SuperNEMO Demonstrator. The foils prepared with the new production method are the ones with multiple pads.

Tracker: The tracker is composed of two tracking volumes, containing a total of **2034 vertical drift cells**, allowing three-dimensional reconstruction of the tracks of charged particles (Figure 4).
The approximate dimensions of one tracking chamber are 3.1 m high, 5.0 m wide, and 0.44 m deep, with a total active tracking volume of about 13 m³. The tracking detector gas is a radiopure mixture of 95% helium, 1% argon, and 4% ethanol.
A **radon-trapping facility** is used for gas purification, complemented by a **helium recycling system** that allows helium to be reused at a flow rate of ~10 L/min (0.6 m³/h). Main challenge is to reach a Rn activity lower than 0.15 mBq/m³ inside the tracker, compared to 6 mBq/m³ in NEMO-3. Rn activity measurement performed during R&D on quarter-sections of the tracker showed a possible value of 0.16 mBq/m³ could be achieved. [9] An activity measurement for the whole detector is ongoing, but is currently affected by the absence of the LSM anti-Rn factory.

Figure 4: Some of the tracker's 15,000 wires and 4068 copper cathode rings comprising the 2034 Geiger cells.

Calorimeter: The calorimeter is composed of **712 Optical Modules** (OMs) made out of polystyrene-based scintillator (except for 8 OMs using polyvinyltoluene scintillators), and Hamamatsu 5" or 8" photomultiplier tubes. Each OM is wrapped in Teflon and Mylar to optimize light reflection, and surrounded by an individual pure-iron magnetic shield. The 520 OMs forming the two main walls parallel to the Se foils are directly coupled to the scintillator (256x256x190 mm³), for optimal light collection (Figure 5). The key performance parameter of the calorimeter is its energy resolution, with a target FWHM of ~8% at 1 MeV, representing a substantial improvement over the 14–17% achieved in NEMO-3. The average FWHM obtained from the production of OMs for the two main walls done at LP2i was 8.2 % [10]. As with all other parts of the detector, all components of the calorimeter have been screened for radiopurity.

Figure 5: One calorimeter wall



Calibration tools: Energy and timing calibration are ensured by an automated deployment system of 42 **^{207}Bi sources** [11] from the central frame. It is used on a weekly basis for regular absolute energy calibrations. In addition a light-injection system, using pulsed ultra-violet (385 nm) LEDs and optical fibers that deliver light to the plastic scintillators enables daily monitoring of the stability of the PMTs. Again, all components were subject to radiopurity screening.

Figure 6: Close-up of a string of seven ^{207}Bi calibration sources, with the plumb bob that allows them to be deployed between the ^{82}Se source foils

Surroundings*:* Additional components have been installed around the detector for background suppression:

- A copper magnetic **coil** providing a 25 G magnetic field surrounds the detector to distinguish signal electrons from background positrons. The field is currently off to avoid reducing the detection efficiency of double-beta events, and could be activated after background evaluation.
- A gas-tight **anti-radon tent**, flushed with de-radonized air produced by the LSM anti-Rn facility, will prevent radon from the laboratory air from entering the detector (Figure 7 left).
- Two **shielding** layers enclose the detector to reduce background from natural radioactivity in the underground laboratory: **iron** shielding to reduce γ-ray flux and **polyethylene** shielding to reduce neutron flux (Figure 7 right). Two sides of the Demonstrator do not include neutron shielding as explained in Section 4.1.

Figure 7 (Left) Anti-Rn tent. (Right) γ and neutron shieldings.

Electronics and acquisition:
The electronics for the tracking chamber provides the readout and digitization of tracker signal times for 2034 anodes and 4068 cathodes channels. A bespoke system provides individually-tunable high voltage to 2034 channels. The 712 signals from the calorimeter are recorded using a novel high-frequency digitizer providing a measurement of the waveform on 1024 samples. Calorimeter HV is provided by commercial CAEN boards.The trigger system performs temporal and spatial coincidence between hits from the tracker and calorimeter in order to record only events of interest, such as electrons ($\beta\beta$ candidates) and delayed α (for Rn background estimation).

Software and computing: Simulation and analysis are carried out using the modern and open-source SuperNEMO homemade C++ software *Falaise* [12] based on the generic framework *Bayeux* [13].

Detection principle

The detection principle of the SuperNEMO technology is illustrated in Figure 8, with the example of the first double-beta candidate measured in April 2025. The figure shows a zoomed top view, with the ^{82}Se foil represented as the vertical line at the center. Two tracks, in red and blue, which originate from the ^{82}Se source are reconstructed from activated tracker cells shown as small circles (the circle radius size indicates the drift time of the ionization electron to the cell's central anode). Two associated optical modules, shown in red, are triggered by each electron.

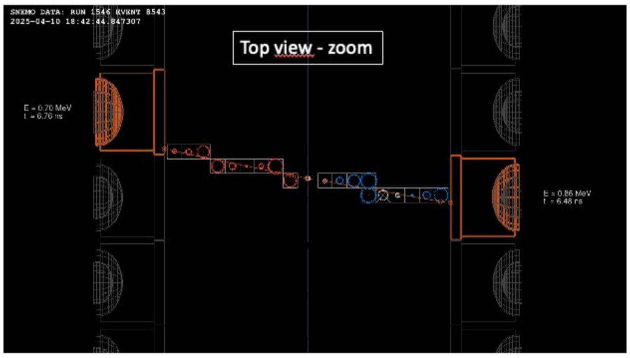


Figure 8: Double-beta candidate observed by the SuperNEMO Demonstrator (April 10th 2025).

The technique offers particle identification and full topological reconstruction of the two-electron signature characteristic of double-beta decay. This enables effective background suppression and quantification via dedicated topological studies, plus potential discrimination between different neutrinoless double-beta decay mechanisms by analyzing the angular distribution and individual energies of the emitted electrons [14]. These capabilities also allow for detailed topological studies of two-neutrino double beta events, including to the excited states, which provide valuable input for nuclear calculations and searches for BSM physics.

3.2 SuperNEMO Demonstrator objectives

As a Demonstrator, the current SuperNEMO detector has the primary objective of **demonstrating** the feasibility of the unique tracker-calorimeter approach for a possible next generation of experiments searching for double-beta decay. However, its size also allows it to be used for conducting **physics investigations**. Both aspects are detailed below along with remarks on the potential to scale up the technology.

Technical objectives :

From a technological perspective, the Demonstrator aims to validate:
- the calorimeter performance in terms of energy and time resolutions, linearity and stability.
- the operation of the tracker, with optimization of the gas mixture and a new improved tracker geometry (taller and with less material than NEMO-3).
- the different calibration systems (the automated deployment system and the LED-based system)
- the radiopurity of the double-beta source foils regarding new purification and fabrication processes.
- the level of radon contamination achieved through the new strategies implemented, including material selection, the tracker's sealing, the gas purification, the anti-radon tent and the new anti-radon facility developed by LSM.
- the level of external background fluxes generated by gamma-rays and neutrons produced in the laboratory, particularly for neutrons where significant discrepancies exist between measurements, with the most recent data published in 2012. The goal, if possible, is to eliminate external background in the $0\nu\beta\beta$ region of interest, as well as at both lower and higher energies, to obtain the purest possible $2\nu\beta\beta$ spectrum. As a reminder, NEMO-3 is the only double-beta experiment to have obtained a two-electron spectrum with no events above the $Q_{\beta\beta}$ region of interest.
- the level of backgrounds due to *internal* neutron production by (α,n) reactions and ^{238}U spontaneous fission in the materials of the Demonstrator.

- /the evaluation of the relative effects of magnetic field on double-beta decay identification efficiency and on neutron-induced background rejection. The goal is to assess whether the benefits outweigh the disadvantages, which is expected to depend heavily on the level of neutron flux.
- the very recently developed He recycling system including some technical challenges on removal of ethanol (added in the gas mixture for tracker operation) followed by suppression of any radon contamination.
- several novel electronics developments affecting the readout strategy: waveform recording for calorimeter energy deposition using SuperNEMO-developed *Wavecatcher* boards (first large-scale deployment of this new technology with many external applications); measurement of the cathode's activation time from the anode signal derivative (reducing the need for cathode channels by one half); home-made high-voltage system for the tracker, new trigger design with improved delayed alpha detection.
- the new software *Falaise* developed to simulate, reconstruct and analyse double-beta decay and relevant background processes for low-background experiments. Elements of this software - for example event generator of nuclear decays, and generic tools for simulation, recording and analysis of data for experimental particle and nuclear physics projects - will have applications beyond SuperNEMO.

Physics objective

For the commonly considered 0νββ decay via light neutrino exchange and V–A currents, it is clear that with 6.11 kg of ^{82}Se, the Demonstrator cannot match the half-life sensitivity of current large-scale calorimetric experiments using ^{136}Xe, ^{76}Ge or ^{130}Te. However, it can still improve the best existing limit for this process with ^{82}Se. Given the remaining uncertainties in decay probabilities across isotopes, exploring multiple isotopes remains essential to the international 0νββ program.

The strength of SuperNEMO, even at the Demonstrator scale, lies in the fact that the underlying mechanisms of 0νββ decay remain unknown, and their determination requires signatures not accessible to other experiments, such as full event topology, including single-electron energy and angular distributions. SuperNEMO's ability to access this information provides unique opportunities to search for different processes, such as decays mediated by right-handed currents. The strong background suppression inherent to the technology also makes the Demonstrator competitive in exploring processes at energies below $Q_{\beta\beta}$. An example is the search for 0νββ decay with the emission of Majoron(s), hypothetical bosons expected to mediate the breaking of lepton number conservation [15] (See Section 5.1).

Additionally, taking advantage of this lower-energy sensitivity, SuperNEMO will study the Standard Model double-beta decay process (2νββ). Approximately 100,000 events will be fully reconstructed within the detector for an exposure of 17.5 kg.years with ^{82}Se, facilitating a detailed topological analysis that will provide valuable insights for nuclear calculations (g_A, SSD/HSD...). Beyond-Standard-Model processes - other than 0νββ decay - can also be explored through precise studies of the shape of 2νββ events. Once more, the measurement of the individual energy of the electrons and their angular distribution provides unique information for further studying these 2νββ events.

Expected studies and performances are described in Section 5, placed in the international context.

Extrapolation to larger scales

Difficulties in extrapolating the current 6.11 kg ^{82}Se module to a larger-scale experiment were already identified and openly presented to the Scientific Council of IN2P3 in 2018. However, in the event of a 0νββ decay discovery, the collaboration is convinced that these issues (notably the complexity of sub-detector design, which will require significant person-power and revised design) would largely be mitigated by the unique potential of the method to investigate the new physics involved.

Additionally, the NEMO concept, in which the ββ decay source is separate from the detection module, is isotope-agnostic, enabling the study of any solid ββ isotope. Some of these isotopes offer excellent sensitivity with a smaller mass, allowing for a more compact detector. One of SuperNEMO's objectives was precisely to enrich new isotopes of great interest for double-beta research, such as ^{150}Nd and ^{96}Zr which had never previously been studied at a large scale (beyond demonstrations producing a few grams). Significant progress has been made in this area by SuperNEMO, with particularly successful R&D that has resolved technological challenges related to ^{96}Zr, enabling the enrichment of this isotope at a relevant level for large masses. This is especially exciting when one considers the relative potential for these isotopes to probe the $\langle m_{\beta\beta} \rangle$ phase space: a $\langle m_{\beta\beta} \rangle$ value equivalent to that accessible with 1 ton of ^{76}Ge, corresponding to proposed next-generation experiment LEGEND-1000, could be achieved with just ~80 kg of ^{150}Nd, or ~120 kg of ^{96}Zr (based only on the isotopes' relative phase-space factors, taken from [16]) Practically, sensitivities are likely to be even greater with these isotopes as their higher $Q_{\beta\beta}$ values (3.35 MeV for ^{96}Zr and 3.37 MeV for ^{150}Nd, compared to 2.04 MeV for ^{76}Ge) place their region of interest above the range of problematic backgrounds generated by natural radioactivity from isotopes such as ^{222}Rn and ^{214}Bi, reducing technological challenges. The collaboration has made extensive studies into the feasibility of a

100 kg "full SuperNEMO" detector, proving that in principle it is viable to access an equivalent neutrino-mass range to that studied by next-generation detectors.

Demonstrating the capability of the SuperNEMO technology, in terms of background rejection and event identification, remains of paramount importance for the future of the field. Clear evidence for this is the inclusion of SuperNEMO among the few selected projects covered in general review presentations at international conferences, and review articles. This is affirmed by the 2019 APPEC double-beta decay committee report [17], which states that: "*the SuperNEMO tracker-calorimeter approach remains the best way to explore a signal above 50 meV with multiple isotopes combined with a full topological reconstruction of the final state events, and further R&D may be able to push this further into the inverted ordering region*."

3.3 Current status and results of the Demonstrator experiment

The construction of the SuperNEMO Demonstrator began at LSM in 2015. Commissioning data have been collected since 2017 with different parts of the detector. The full construction of the detector, including the shieldings, was completed in October 2024. However the water part of the neutron shielding was removed and has not been reinstalled due to possible long-term safety concerns. Data taking with the full detector started on April 10th, 2025 and has continued for the past five months under high radon conditions waiting for the operation of the LSM anti-Rn facility. The collaboration plan based on expected sensitivity is to run for a total exposure of ~17.5 kg.y, corresponding to 2.86 years (34.32 months) of double beta data taking (see section 5). Commitments to other experiments mean LSM can currently only guarantee running up to Dec 2026, corresponding to 15 months of running without radon background assuming the LSM anti-Rn facility will be continuously operational 1st of October 2025. This corresponds to **1.12 years** of double beta decay data including 90% of duty cycle; so 39% of our requested runtime. (This schedule allows for 1 year of dismantling in 2027, our estimate including contingency, see Section 7).

Current results

A very **preliminary** analysis was performed on **64.8 days of data** recorded up to this summer (without the LSM anti-Rn facility). Since calibrations are ongoing, this analysis only takes into account a subset of the calorimeter's optical modules. In particular, the calorimeters located at the top, bottom and small sides of the detector are not included at this stage. The time-of-flight analysis is also still very preliminary, as the time calibrations have not yet been completed. The preliminary energy spectrum obtained for two-electron events is shown in Figure 9.

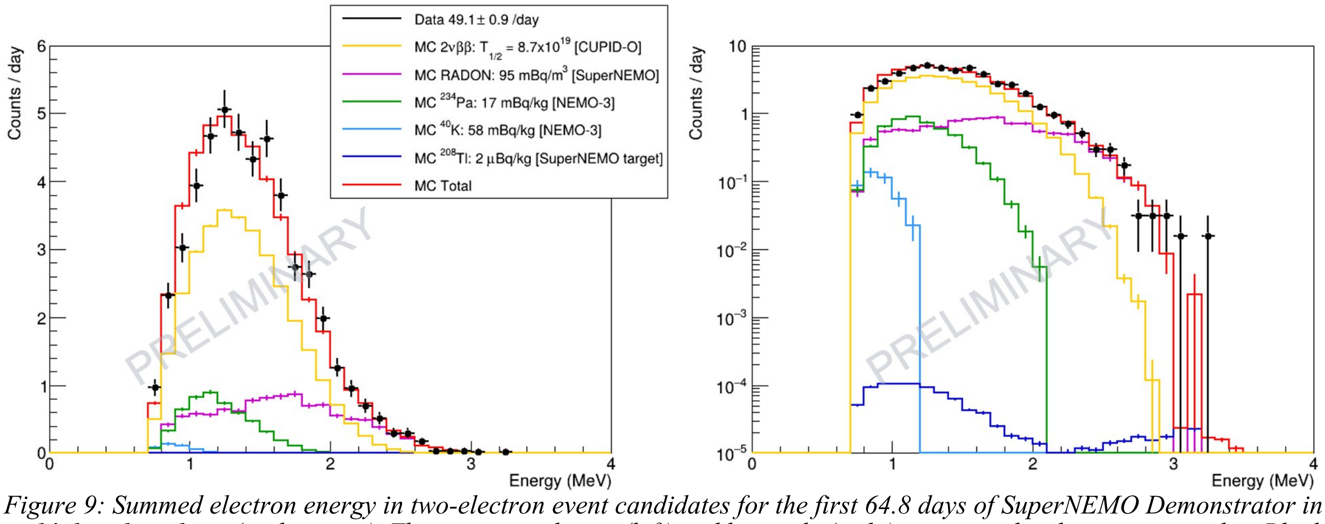


*Figure 9: Summed electron energy in two-electron event candidates for the first 64.8 days of SuperNEMO Demonstrator in its **high radon phase** (preliminary). The spectra, in linear (left) and log scale (right) are normalized in counts per day. Black points show data, with predicted 2νββ signal in yellow, normalized to CUPID-0's ^{82}Se half-life. Background predictions are added for Rn (measured BiPo activity), ^{234}Pa and ^{40}K (activities in NEMO-3's ^{82}Se foils), and ^{208}Tl (target activity).*

This spectrum exhibits an energy distribution dominated by the expected 2νββ decay shape. No events above 3.4 MeV are reconstructed at this stage, highlighting the strong background rejection potential of the technology.
However, and as anticipated, the spectrum above 2 MeV is dominated by the radon level present in the detector, due to the absence of the LSM radon-free air facility. This background was analysed using dedicated BiPo-type events (one electron followed by a delayed alpha as shown Figure 10 left) and measured around 95 mBq/m³ inside the tracker for the initial 64.8-day period (Figure 10 right). This measurement was performed with a reduced helium flushing rate of 3 L/min into the tracker. Under nominal conditions, with a flushing rate of 10 L/min, this is expected to correspond to a radon level of ~20 mBq/m³. This nominal flux will only be implemented at the start of the double-beta data-taking phase with the radon-free air facility. The radon concentration currently observed

in the tracker is explained by the activity inside the anti-radon tent, which was measured at about 30 Bq/m³, and which corresponds to the laboratory air currently injected into the tent. The new facility is expected to achieve a radon reduction factor of about 10,000 (6,500 was measured with the previous NEMO-3 facility [18]), giving confidence that the radon level inside the tracker can be lowered to the target value of approximately 0.15 mBq/m³ (roughly 100 times lower than the 20 mBq/m³ achievable under current conditions).
At lower energies, there is also an expected excess of events in data associated to internal contaminations in the source foils. These background are currently being quantified using dedicated event topologies. Meanwhile, predicted spectrum for ^{234}Pa and ^{40}K were added using the measured contamination in ^{82}Se foils of NEMO-3, as they were the two main backgrounds identified for the 2νββ analysis [19].
Data is in overall good agreement with the total predicted spectrum from simulation, while a lightweight excess of events is observed around 1 MeV. This provides hints on improvement of the radiopurity of SuperNEMO's ^{82}Se foils compared to NEMO-3.

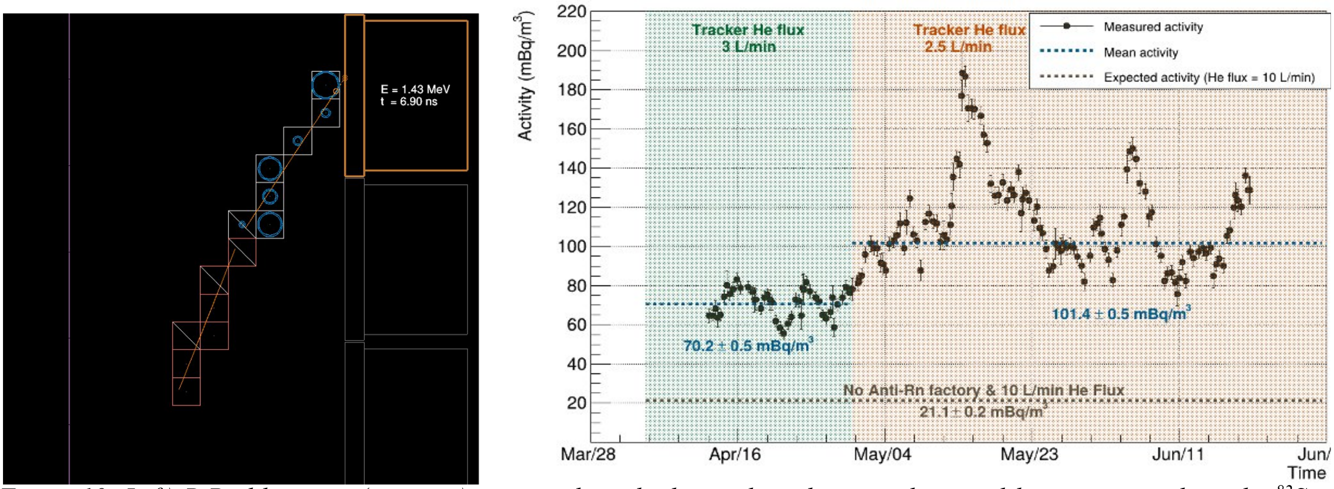


Figure 10: Left) BiPo-like event (top view) measured inside the tracker; the central vertical line corresponds to the ^{82}Se source foil, the delayed alpha track is visible in red and the electron track in white, associated to an energy deposit in the OM (yellow square). right) Evolution of the radon activity inside the tracker during the initial 64.8-day period. During this period, the tracker was operated with two different helium flushing rates.

3.4 Scientific outputs

Theses

36 theses defended from 2008 to 2024 across the whole SuperNEMO collaboration, including 20 at IN2P3:

- **LP2i:** X. Aguerre (2023); R. Salazar (2021, with U. Texas); V Palušová (2021, with Comenius U.); A. Pin (2020); M Macko (2019, with Comenius U.); A. Huber (2017); B. Soulé (2016); C. Hugon (2013); E. Chauveau (2010); T Cam Ha Nguyen (2010)
- **IJC Lab**: M. Hoballah (2022), C. Girard-Carillo (2020); S. Calvez (2017); G. Eurin (2015, witih UCL); S. Blondel (2013); M. Bongrand (2008)
- **CPPM**: H. Tedjditi (2021)
- **LPC Caen:** G. Oliviero (2018); A. Chapon (2011)
- **LAPP:** T. Le Noblet (2017)

Planned theses: **7** collaboration theses, already started, should be defended in the coming years, including 3 at IN2P3: Y. Vereshchaka (IJCLab, 2022-2025); M. Granjon & A. Lahaie (LP2i, 2023-2026)

Publications

10 articles have already been published on SuperNEMO. **Two papers** are going through the submission process, and expected later this year (see Appendix A). **Five papers** are in preparation, concerning radon, tracker design, calibration, angular reconstruction sensitivity and helium recycling system.
In addition **23 articles** on NEMO-3 have been published between 2001 and 2023, including 5 physics results papers since the last presentation at the IN2P3 scientific council in 2018. Most of these papers are relevant for SuperNEMO and can be considered as contributing to the analysis preparation for the experiment.
SuperNEMO has also been frequently presented at international conferences, with **18 talks** and **13 posters** presented since the last IN2P3 Scientific Council in 2018.

4. Origins and Timeline

4.1 Timeline

The project was initiated through preliminary discussions within the NEMO-3 collaboration, first at the French level and later expanded internationally. The first joint meeting of the NEMO-3 and SuperNEMO collaborations took place in 2006. The objective was to design a next-generation double beta decay experiment, using an experimental approach similar to that of NEMO-3, which would be capable of improving the sensitivity to the $0\nu\beta\beta$ half-life by two orders of magnitude and, in the context of the time, confirming or refuting the experimental results of the Heidelberg–Moscow experiment [20].
R&D started in 2005 and a Demonstrator phase corresponding to one module of a potential larger modular experiment was proposed in 2011. Construction of the Demonstrator started in 2015 at LSM, with the first commissioning data recorded in 2017. Physics data taking with the complete detector started on 10th April 2025 in a high-radon level mode, due to the absence of the radon-free air facility. LSM plans for this facility to operate continuously from 1st October 2025. Main key dates of the SuperNEMO Demonstrator project are listed below.

Initiation

Date	Action
2003	First discussions within NEMO-3
2005	First review at IN2P3 scientific council
2006	SuperNEMO collaboration created
2011	Decision to build a Demonstrator module

Construction milestones

Date	Action
January 2015	**Preparation of the floor at LSM to host the Demonstrator**
September 2015	Clean tent installation at LSM
April 2016	**Half Demonstrator installed**
November 2016	Full calorimeter construction achieved
December 2016	Gas mixture system ready
August 2018	Calibration system operational
September 2018	Source foil installed
November 2018	**Sub-system assembly - Detector completed (without shielding)**
December 2019	Cabling completed
September 2020	Tracker leaning issue solved
September 2021	Magnetic coil installed
May 2022	Feedthrough issue fixed and gas tightness achieved
December 2022	Tracker HV boards installed and commissioned
March 2023	Clean tent dismantled
May 2023	Anti-radon tent installed
March 2024	Delivery of iron shielding from China
August 2024	Gamma shielding completed
September 2024	Helium recycling system installation achieved
October 2024	Neutron shielding completed
October 2024	**Full detector ready**

The collaboration was confronted with **major challenges** over time, whether technological or due to external circumstances, which had a significant impact on the duration of the construction:

1. **Calibration system issue**: The entire system had to be redesigned and reconstructed following an observation (in 2017) of ^{207}Bi calibration sources becoming stuck in the detector during their deployment. This prevented the installation of the double beta source, delaying the full assembly of the detector until November 2018.
2. **Tracker deformation:** Shorts between the cathode ring and cathodic wires were observed in mid-2019, affecting hundreds of tracker cells. The cause was identified as being due to a slight deformation of the tracker frame over time, due to a design flaw. Several months were required to confirm this hypothesis and to develop a procedure and specialized tools to correct the alignment of the two tracker volumes. These volumes contained over 15,000 wires, each 40 or 50 µm in diameter, mechanically connected to the source frame holding extremely fragile 350 µm-thick selenium source foils. Although the lifting operation was planned, and equipment prepared, by March 2020, the operation was delayed by COVID-19 until September 2020. When it was finally carried out, it was successful, reducing the number of short circuits from 293 (14%) to 34 (1.7%).
3. **COVID pandemic:** The global pandemic led to the revision of the schedule of all experiments, which affected staff availability and delayed many operations. These schedule changes, together with travel restrictions, also

reduced manpower availability for the installation, resulting in a delay of approximately one year on several operations including the coil and anti-radon tent fabrication and installation.

4. **Tracker electrical feedthroughs:** In order to route signal and high voltage to the inside of the tracker whilst maintaining gas tightness, 226 electrical feedthroughs were designed. They consisted of pins moulded with Duracon (a plastic material similar to Delrin), into which cable bundles are plugged on either side. Ageing was observed in 2021 by appearance of cracks due to shrinking of Duracon in the dry atmosphere of the LSM. This issue led to significant gas leakage into the tracking chamber, as well as high-voltage breakdown on pins. A recovery operation was performed between January and April 2022 to dismount and repair all the 226 elements, by pouring a specific glue (Stycast) through the cracks.
5. **Tracker HV board malfunction:** The bespoke tracker high-voltage system was designed by the University of Manchester. The 57 boards were fabricated in 2018 by a company in China. Due to the low quality of production, including many faulty components, almost none of these boards were viable. As a consequence, all boards were re-manufactured by STFC in the UK in 2021 and progressively delivered to LSM over 2022.
6. **Iron shielding supply & Ukraine invasion:** The shielding of 320 tons of radiopure iron has been delayed by several years for multiple reasons. First, no funding plan had been anticipated within the collaboration for this component of the shielding (presented at the 2018 IN2P3 scientific council), which ultimately proved to be much more expensive than expected. The lack of resources made it necessary to seek a more affordable solution outside France, typically in China. Administrative procedures with the selected Chinese supplier also turned out to be complex. In addition, the Russian invasion of Ukraine had several consequences on this procurement: the planned Russian funding was withdrawn, and the shutdown of iron production in Ukraine shifted steel production priorities in China, sidetracking our order in favour of new priorities. Finally, at the time of delivery, the 2024 Suez Canal closure caused a further delay of several months in maritime transport.
7. **Helium shortage**: Following a fire at a Russian gas processing plant in 2021, which disrupted helium production, and the subsequent invasion of Ukraine by Russia, the world faced a shortage of gaseous helium. In response to this shortage and rising costs, as well as ecological concerns over the potential waste of helium, the collaboration, supported by IN2P3, decided to develop a helium recycling system that had not been included in the original project (SuperNEMO was originally designed to operate like NEMO-3, releasing helium into the laboratory). The development and installation of this new system required a significant portion of manpower, causing delays in other construction operations.
8. **Water shielding leaning:** Two of the six neutron-shielding walls were composed of 50 cm width polyethylene tanks filled with water and produced by MRP. The two walls consisted of 76 and 73 tanks of 400 L with a total height of 7 m. Unfortunately, an inclination of 1.5° on one wall (safety margin was 5°) observed in October 2024 raised concerns about long-term stability. As a precaution, the collaboration, with LSM consultation, decided to dismantle both walls. A procedure was immediately prepared and actioned in November 2024. After two months of analysing the issue with LSM and preparing several technical reports on possible reconstruction options, it became clear that several actions needed to be undertaken regarding reconstruction methods, tools, and LSM floor analysis. Considering the time required for these operations, and on the basis of the Demonstrator sensitivity to the physics, IN2P3 ultimately instructed to the collaboration not to proceed with rebuilding.This issue required the mobilization of most of the collaboration to study technological solutions and evaluate their impact on background levels and physics sensitivities (neutron simulations in various new shielding configurations). All these processes resulted in a five-month delay in data taking, with the authorization obtained from IN2P3 at the end of March 2024.

Note that the Ukraine invasion led to a loss of resources and manpower from Russia affecting several aspects of the funding, construction and running of the experiment.
We would also like to remind that temporary difficulties with IN2P3 funding for SuperNEMO, in the critical first few years when construction was due to start, delayed the procurement needed for the French deliverables; required substantial design revisions of several subsystems; and affected the continuity of the teams. This led to significant delays in the fabrication and subsequent integration of the detector.

Data taking milestones

Date	Action
February 2017	Commissioning data with half-Demonstrator
23 March 2025	IN2P3 approval for starting the running
10 April 2025	**Official start of physics data taking (without LSM anti-Rn factory)**
October 2025	Radon-free air expected - Start of double beta physics data taking
Spring/Summer 2026	Review meeting with IN2P3 after 1 year of running
31 December 2026	Current end of running (due to LSM space commitments)

The end of data taking is currently determined by space constraints at the LSM, which requires the SuperNEMO area to be freed for January 2028. A dismantling schedule of 12 months has been studied by the collaboration and approved by LSM. It includes three months of contingency, mainly due to access constraints and work in the underground laboratory. In such scenario, double beta physics data taking will correspond to only 1.12 years, assuming a start of the anti-Rn facility the 1st of October 2025 and considering the current duty cycle value of 90%. The collaboration hopes to extend this period to a total of ~ 2.9 years in order to maximise the science results (Section 5).

All different key steps are summarised in Figure 11.

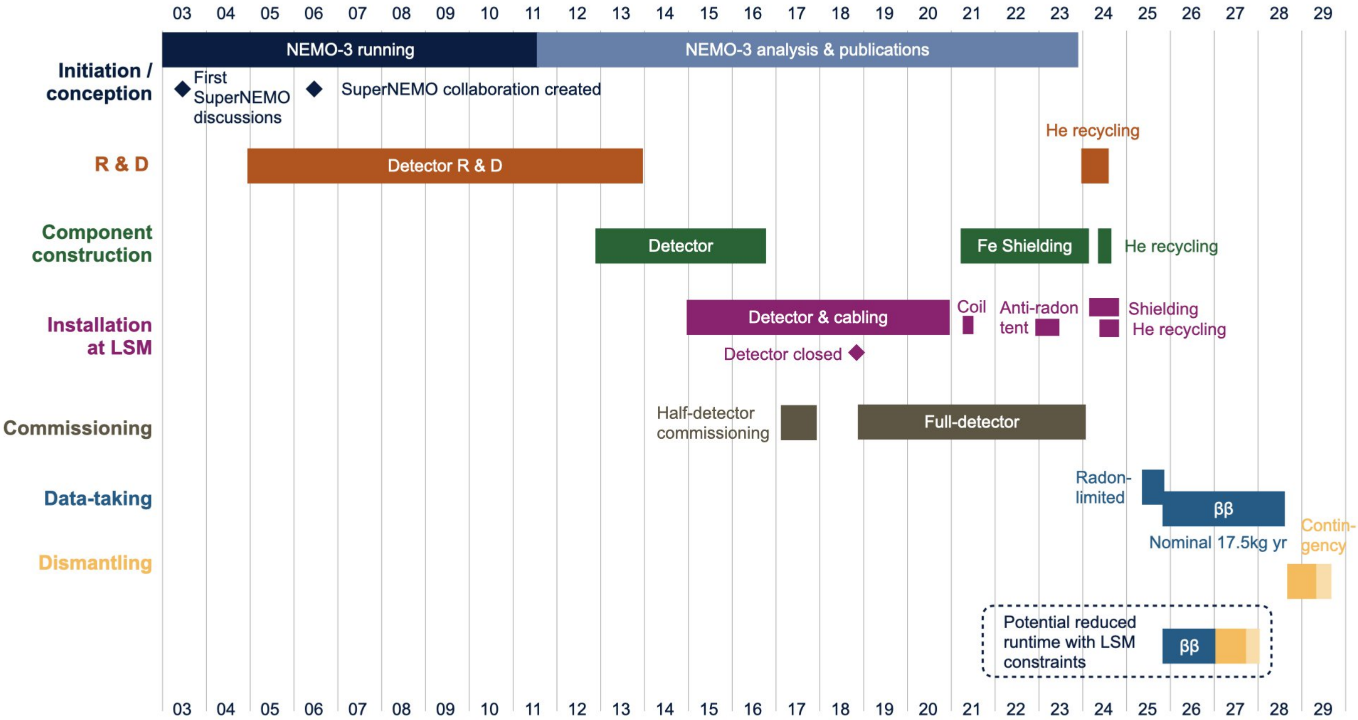


Figure 11: Summary of a few key milestones of the SuperNEMO project, from the R&D phase to the running Demonstrator at LSM, including construction, installation and commissioning steps.

4.2 Reviews and Councils

Reviews and Councils	Date	Conclusions
IN2P3 Scientific council	**2005**	SuperNEMO R&D approved
APPEC review	2005	SuperNEMO international project included in APPEC Roadmap
IN2P3 scientific council	**2011**	The Scientific Council took a positive recommendation for the Demonstrator and underline the quality of the work, results of NEMO-3 and R&D for SuperNEMO.
IN2P3 technical review	2011	The review made 14 recommendations concerning collaboration organisation, financing, and task responsibilities. They added: The strengths of NEMO were carried over into SuperNEMO through a modular approach that facilitates industrialization and task distribution
IN2P3 Mechanical review	2012	Recommendations for optimal Demonstrator assembly: supply, calorimeter shielding and mounting, tracker interface, and cabling
IN2P3 Fe shielding review	2018	At LSM with mechanical external experts, approved the design.
IN2P3 Cabling review	2018	At LAL with external experts, reviewed cabling strategy
IN2P3 Scientific council	**2018**	The council acknowledges the considerable work and perseverance of the team that have led to the construction of the Demonstrator, currently being assembled at LSM. This is a very fine achievement that must be brought to completion under the best possible conditions. There are still a number of challenges to be met, particularly concerning the iron shielding, for which there is uncertainty of supply and a lack of funding. (...) It is important to maintain sufficient staff involvement to ensure a strong scientific return from the Demonstrator runs.
APPEC	2019	"Scaled-up version of SuperNEMO Demonstrator is the only way to determine $0\nu\beta\beta$ mechanism in the event of discovery"
IN2P3 Project review	2022	Grant funding to build the Helium recycling system
LSM Strategic Committee	2025	Not communicated.
IN2P3 review for neutron shielding and running	**2025**	IN2P3 direction has decided that SuperNEMO "can start taking data now (as soon as everything is ready), with the present neutron-shielding configuration".

In addition to these general reviews, the SuperNEMO project has been examined by the scientific councils of the various laboratories involved: CENBG/LP2i (2008, 2014, 2017, 2025), CPPM (2013, 2023), LAL/IJCLab (2005,2007), LAPP (2013), LPC-Caen (2016, 2017).

5. Positioning

5.1 State of the art

So far, experiments have only been sensitive enough to allow limits to be set on the half-life of neutrinoless double-beta decay. The results are usually compared for the most commonly-studied process, corresponding to the exchange of a light neutrino via a V–A current. Table 1 shows, for each isotope studied, the best current sensitivity obtained in terms of half-life $T_{1/2}^{0\nu}$ and effective mass $\langle m_{\beta\beta} \rangle$.

Isotope	$Q_{\beta\beta}$ (keV)	Experiment	Location	Mass (kg)	Exposure (kg.yr)	$T_{1/2}^{0\nu}$ (10^{24} yr)	$\langle m_{\beta\beta} \rangle$ (meV)
^{48}Ca	4628	CANDLES-III	Japan	0.27	0.045	0.062 [21]	3400-14900
^{76}Ge	2039	GERDA	Italy	44.2	127.2	180 [22]	79-180
^{82}Se	2998	CUPID-0	Italy	5.3	8.82	4.6 [23]	263-545
^{96}Zr	3355	NEMO-3	France	0.0094	0.031	0.0092 [24]	7200-19500
^{100}Mo	3034	CUPID-Mo	France	4.2	1.17	1.4 [25]	310-540
^{116}Cd	2813	AURORA	Italy	1.162	5.81	0.22 [26]	1000-1700
^{130}Te	2527	CUORE	Italy	206	288.8	22 [27]	90-135
^{136}Xe	2457	KamLAND-Zen	Japan	745	2097	380 [28]	28-122
^{150}Nd	3371	NEMO-3	France	0.037	0.19	0.02 [29]	1600-5300

Table 1: *Best current sensitivities in the search for neutrinoless double-beta decay via light neutrino exchange (V–A) for the main isotopes of interest. The sensitivity to the effective mass $\langle m_{\beta\beta} \rangle$ is calculated from the phase-space values published in* [16] *and the nuclear matrix elements given in* [30]–[38], *with g_A=1.27.*

The current best sensitivity for this process has been achieved with ^{136}Xe in the KamLAND-Zen experiment (liquid scintillator calorimeter). For ^{82}Se, the best result was obtained with CUPID-0 (bolometric calorimeter). The next generation of experiments currently aims to push sensitivities to $\langle m_{\beta\beta} \rangle$ down to tens of meV probing the full parameter space relevant to the inverted neutrino mass ordering.

Some experiments, especially NEMO-3 with its event topology, can also study more exotic processes proposed by certain beyond-the-Standard-Model theories. Best sensitivities to some of these process are given by Table 2.

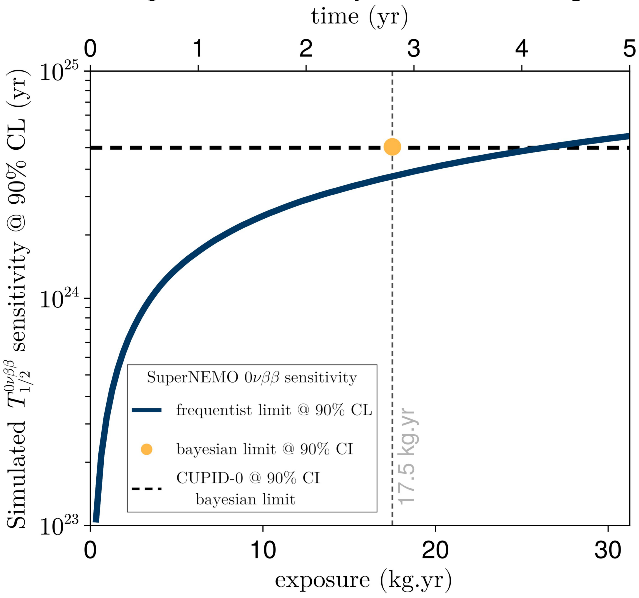
Process	Parameter	Experiment	Isotope	Result	Reference
0νββ V+A λ	$\langle \lambda \rangle$	NEMO-3	^{100}Mo	0.9-1.3 × 10^{-6}	[39]
0νββ V+A η	$\langle \eta \rangle$	NEMO-3	^{100}Mo	0.5-0.8 × 10^{-8}	[39]
0νββ χ0	$\langle g_{\chi 0} \rangle$	EXO-200	^{136}Xe	0.4-0.9 × 10^{-5}	[40]
0νββ χ0χ0	$\langle g_{\chi 0} \rangle$	EXO-200	^{136}Xe	0.3-2.5	[40]
2νββ bosonic ν	$\sin^2\chi$	NEMO-3	^{100}Mo	<0.27	[41]
2νββ LIV	$\mathring{a}_{of}^{(3)}$	NEMO-3	^{100}Mo	=[-4.2;3.5] × 10^{-7} GeV	[41]
0ν4β	$T^{1/2}_{2\nu}$	NEMO-3	^{150}Nd	>(1.1-3.2) × 10^{21} year	[42]
0νββ SUSY	λ'_{111}/f	NEMO-3	^{100}Mo	(4.4-6.0) × 10^{-2}	[39]

Table 2: *Best results from double-beta decay experiments for parameters associated with searches for processes involving right-handed V + A neutrino exchange, Majoron emission, the possible bosonic component of the neutrino, Lorentz invariance violation (LIV), quadruple beta decay, and supersymmetric processes*

5.2 SuperNEMO Demonstrator performance positioning

0νββ V-A sensitivity

The sensitivity of the SuperNEMO Demonstrator to this mechanism remains competitive with the best existing limits for ^{82}Se (see Table 1), but as a Demonstrator with a limited source mass, it cannot, by design, match the world-leading $\langle m_{\beta\beta} \rangle$ sensitivity of KamLAND-Zen. The total number of background events expected for 17.5 kg years' exposure of ^{82}Se with the SuperNEMO Demonstrator is summarised in Figure 12 right. This estimation is based on the target radiopurity values for internal contamination of ^{208}Tl and ^{214}Bi in the source foils, and target radon level in the tracking chamber. The neutron component accounts for the current shielding configuration, without the two walls of water tanks. The main background comes from 2νββ decay due to the moderate energy resolution of SuperNEMO calorimeter and the relatively short 2νββ decay half life of ^{82}Se. It corresponds to a background index of 2.7 10^{-4} counts/(keV.kg.y). The corresponding $T_{1/2}$ sensitivity to 0νββ decay in the V-A mode over time, using a frequentist analysis approach, is shown in Figure 12 left. The expected Bayesian sensitivity is also given for 17.5 kg.y of exposure showing that the current world's-best limit given by CUPID-0 would be surpassed after 2.86 years of data taking.



Background	Events for 17.5 kg.yr in [2.7-3.1] MeV
2νββ	0.98 ± 0.13
^{208}Tl	0.04 ± 0.01
^{214}Bi	0.09 ± 0.01
Radon	0.23 ± 0.04
Neutrons	0.60 ± 0.30
Total	**1.9 ± 0.4**

0νββ efficiency	16.5 %

Figure 12: *Left: Half-life sensitivity for 0νββ decay via V-A current as a function of exposure with the SuperNEMO Demonstrator. Right: Summary of expected background event counts and detection efficiency for the search of 0νββ with 17.5 kg.year exposure.*

0νββ V+A sensitivity

Left-right symmetric models postulate the existence of new right-handed bosons. In these models, a neutrinoless double-beta decay could occur through a mechanism involving a V+A current at either the leptonic or the hadronic vertex. The signature of this decay is identical to that of the V-A decay, except that one of the electrons would be right-handed; this affects the allowed phase space for the angle between the two electrons produced, as well as their relative energies. SuperNEMO's technology is currently the only way of measuring these individual energies and angles, making it highly sensitive to this decay. Preliminary conservative estimates suggest the SuperNEMO Demonstrator will surpass the world's best limits on these processes for ^{82}Se in one year, and for all isotopes in 2-4 years, subject to the model.

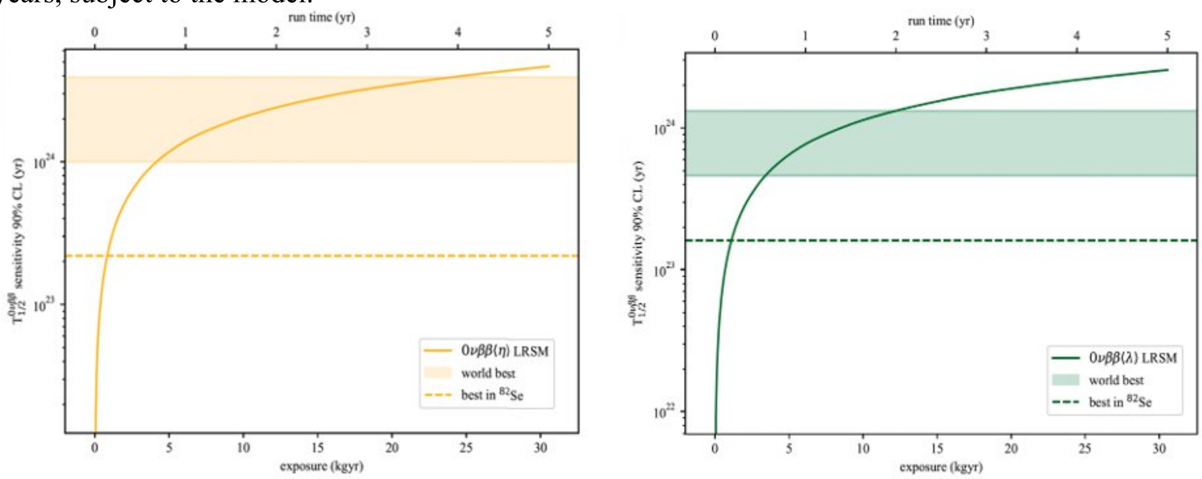


Figure 13: Half-life sensitivities to 0νββ in left-right symmetric models with V+A currents at (left) the leptonic vertex (parameter ⟨η⟩) and (right) both the hadronic and leptonic vertices (parameter ⟨λ⟩), compared to world's best limits for ^{82}Se [43] *and all isotopes* [39]. *Estimate is conservative, and may improve with the final reconstruction.*

0νββ + Majoron sensitivity

Some 0νββ theories involve the emission of one (or more) Majorons χ0, Goldstone bosons associated with the spontaneous breaking of lepton-number symmetry. For such decays, the 0νββ signal becomes a continuous spectrum in the summed kinetic energy of the two electrons (Figure 1), due to the energy being shared with the extra scalar particle(s) χ0. Sensitivity to the half-life of this 0νββ decay mode with the SuperNEMO Demonstrator is expected to surpass the world's current best limits with about 2 years of data taking for the 0νββχ0 process, and 1 year for the 0νββχ0χ0 case, due to our excellent background rejection across the full energy range.

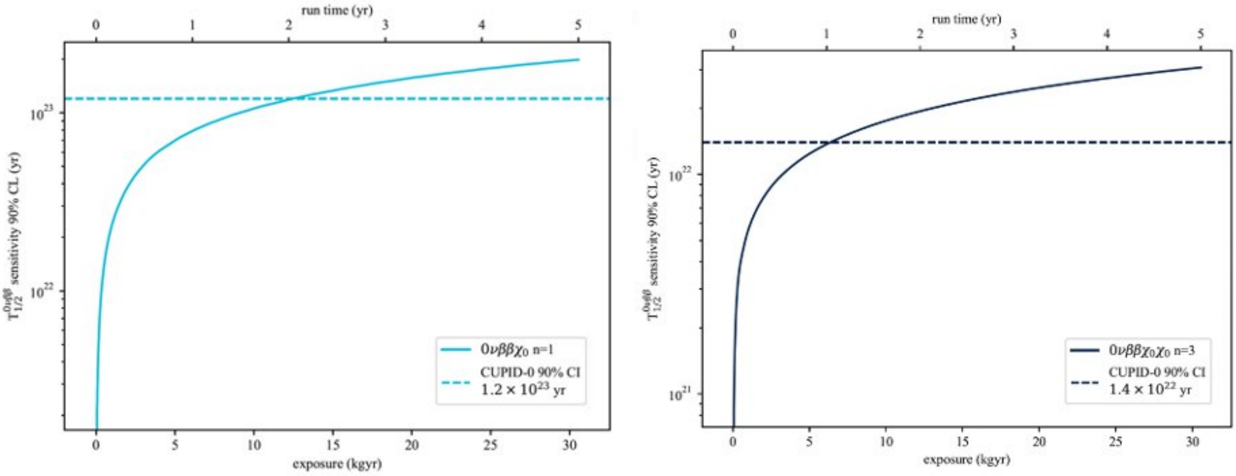


Figure 14: Half-life sensitivities to 0νββ with 1 χ0 (left) or 2 χ0 (right) bosons, as a function of the Demonstrator exposure, compared to world's best limit for ^{82}Se [44].

Excited states

^{82}Se ββ decay could also occur to excited states of ^{82}Kr. The SuperNEMO Demonstrator reconstructs the full topology of the decay in a dedicated channel with two electrons and one or two gammas, with the measurement of energy and time for each particle detected. This allows powerful background rejection [45] A preliminary study shows an expected sensitivity to the half-life of the ^{82}Se 2νββ decay to the 2^+_2 excited state of 1.9 × 10²² years at 90% CL for a 17.5 kg.y exposure, surpassing the current world's-best limit.

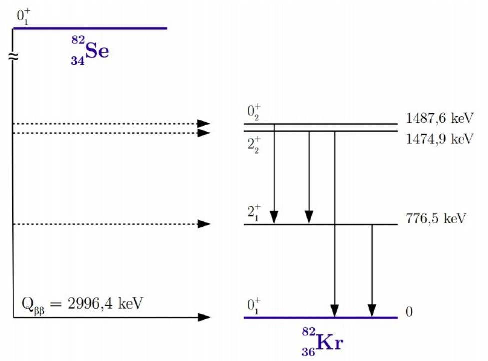
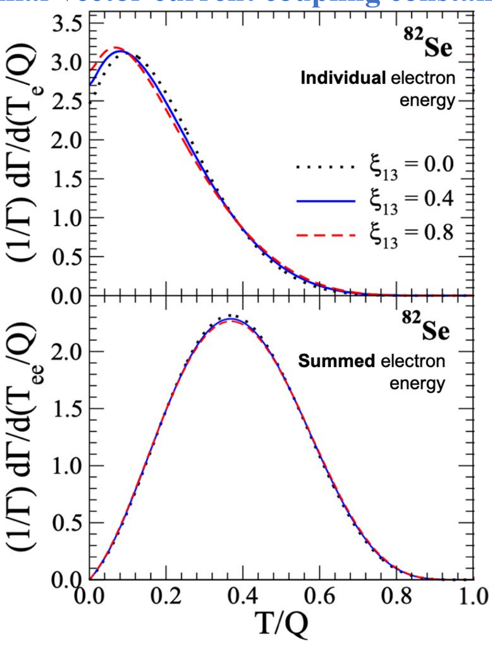


Figure 15: ββ decay scheme of ^{82}Se towards ^{82}Kr.

Axial-vector current coupling constant (g_A)



The 0νββ rate may be significantly affected by a possible quenching of the axial-vector coupling constant, currently taken equal to 1.27. Recent theoretical work [46] is showing that g_A can be constrained by the shape of the 2νββ energy spectrum shape. The effect is particularly strong in the single electron energy spectrum (Figure 16). SuperNEMO being the only experimental technique having access to this observable, a unique opportunity to constrain (or measure) g_A is expected, dependant the on background level at low energies, which is currently being evaluated.

Figure 16: Expected single-electron energy (top) and sum of the electrons' energies (bottom) distributions for different values of ξ_{13} whose value depends on the nuclear matrix elements and g_A values.

Bosonic neutrino and Lorentz invariance violation

The low-background measurement of the 2νββ decay spectrum by the SuperNEMO Demonstrator will allow measurement of possible deformations, possibly due to 0νββ decay with the emission of Majoron(s), but also potentially from 2νββ decay due to Lorentz invariance violation, or 2νββ decay with a bosonic neutrino. Each decay has a different spectral index (see Figure 17), enabling discrimination between processes. Sensitivities will depend on the final 2νββ background level in the source foils, which is in the process of being estimated.

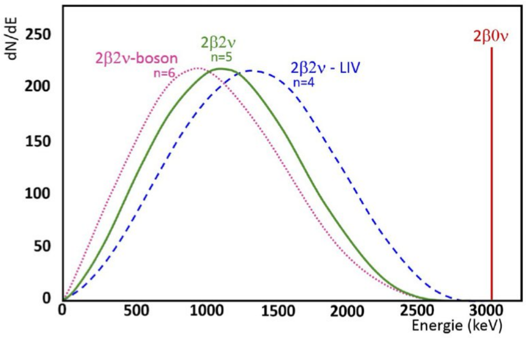


Figure 17: Spectrum of the summed kinetic energy of the two electrons for standard 2νββ decay (green; spectral index n = 5) compared to the shape of the perturbation to the standard 2νββ decay due to Lorentz invariance violation 2ν-LIV (blue; n = 4) and spectrum for 2νββ decay with bosonic neutrino 2ν-Boson (pink; n = 6) and 0νββ (red).

5.3 IN2P3 Contributions

As an international collaboration, SuperNEMO has been designed and built with the funding and expertise of all partners. A large part of the contributions benefited from IN2P3 expertise in topics necessary for double beta research, in particular on:

- Ultra low radioactivity
- Photodetection
- Electronics and acquisition
- Mechanics for large detectors
- Software development and computing facilities (CC-IN2P3)
- Underground facility (LSM)

Responsibilities

IN2P3 is a leading contributor to the project. Firstly, SuperNEMO is hosted at LSM with its world-class underground infrastructure and expert personnel. In addition, IN2P3 members have held many responsibilities on the detector since the onset of the project, through R&D, and now in its exploitation phase. Main contributions of IN2P3 laboratories to the project are listed below by sub-system or task.

Double-beta sources: Selenium was enriched in Russia, and purified in both Russia and the USA. IN2P3 laboratories played a major role in developing a new foil-production method at **LAPP** [47], and in producing 70% of all foils. IN2P3 was also heavily involved in controlling the radiopurity of the foils, using HPGe measurements at **LP2i** and **LSM**, as well as a dedicated BiPo detector - installed at the Canfranc Laboratory - under **IJCLab** responsibility [48].

Tracker: Tracker construction and operation were the UK's responsibility. IN2P3 contributed through radiopurity controls (**LP2i, LSM**), and development and construction of the helium recycling system in collaboration with the Scottish team (**CPPM**). As radon is the main enemy of tracker gas purity, various strategies were employed to reduce its presence in the tracker, in which IN2P3 took a leading role: material selection (**LP2i**), emanation measurements (**LP2i**), diffusion studies (Czech collaborators), development of a radon purification system for the gas (**CPPM**), installation of a radon-free air tent (**IJCLab**), and connection to the anti-radon facility at LSM.

Calorimeter: Calorimeter R&D and construction were the responsibility of the French teams (**LP2i, IJCLab**), with scintillator production led by the Russian and Czech collaborators, and the veto optical modules installed on the top and bottom parts of the detector constructed by the UK. A dedicated electron beam spectrometer has been built at **LP2i** for R&D tests and production qualification [49]. This beam is now used by other experiments.

Calibration: The design and construction of these systems was the USA's responsibility; however, calibration campaigns are now under IN2P3 responsibility (**LP2i**). The characterisation of the 42 calibration ^{207}Bi sources was carried out within a joint France-Czech PhD.

Surroundings: IN2P3 laboratories were responsible for the magnetic coil (**LPC-Caen**), anti-radon tent (**IJCLab**), and gamma shielding (**LP2i, IJCLab, LAPP**). The latter involved a call-for-tender procedure conducted with DR15-CNRS.

Electronics: The main ASIC component ("*FEAST*") was designed by **LPC-Caen**. The "*WaveCatcher*" board for high-resolution calorimeter timing was developed at **IJCLab** [50]. The trigger design and implementation was an IN2P3 responsibility **(IJCLab, LPC-Caen).**

Software and analysis: The collaboration developed its own software, which was initiated and largely developed by **LPC-Caen**. LPC-Caen is also responsible for the computing infrastructure at CC Lyon (CZAR) and for the servers hosted at LSM.

Detector integration: Construction and integration of the detector were carried out by IN2P3 colleagues (**LSM, IJCLab, LP2i, LAPP and LPCCaen**), along with collaborators from the UK, USA, Czechia, Slovakia and Russia; engineering leadership was provided by **IJCLab** with strong support from **LSM**.

Management: IN2P3 personnel have been heavily involved in the management of the project from its inception, serving as spokespersons (F. Piquemal, **LP2i** 2008–2017; C. Marquet, **LP2i** since 2018), technical coordinator (C. Cerna, **LP2i** 2011–2017; A. Jeremie, **LAPP** since **2018**), Physics coordinator (E. Chauveau, **LP2i** since 2018), Run coordinator (E. Chauveau, LP2i since 2024), and Chair of the Institutional Board (Y. Lemière, **LPC-Caen** since 2023). Two physicists have also continuously been present on-site at LSM for several years to oversee the progress of the construction (Y. Lemière, **LPC-Caen** 2019–2020; E. Chauveau, **LP2i** since 2020). Figure 18 illustrates in blue the tasks for which IN2P3 is responsible.

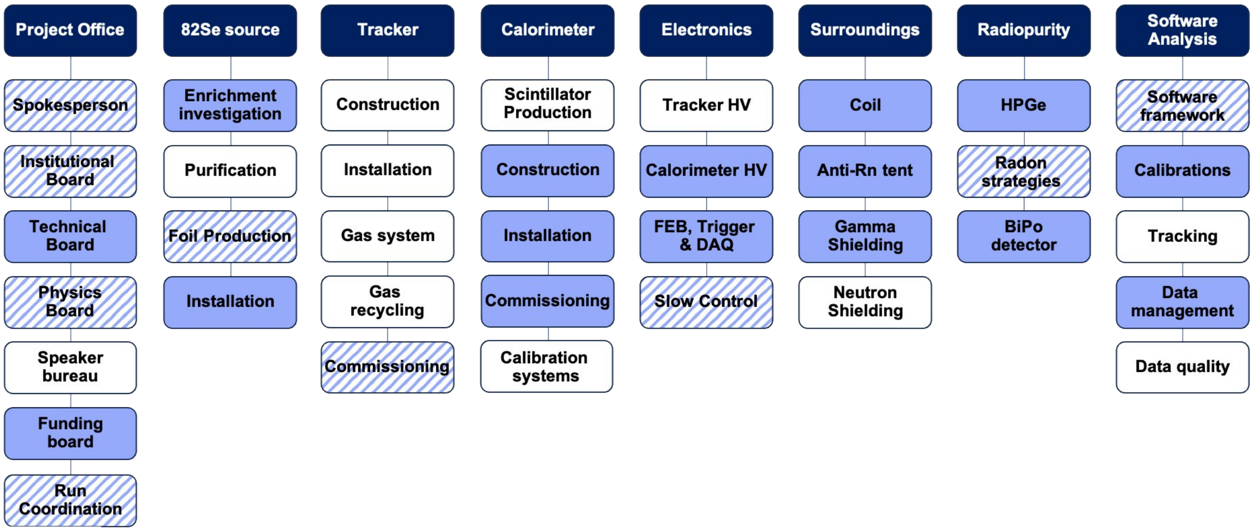


Figure 18: *Main tasks of the SuperNEMO Demonstrator. Blue and hashed blue boxes indicate the tasks for which French collaborators have full or shared responsibility, respectively.*

Figure 19 shows the current SuperNEMO organisation chart.

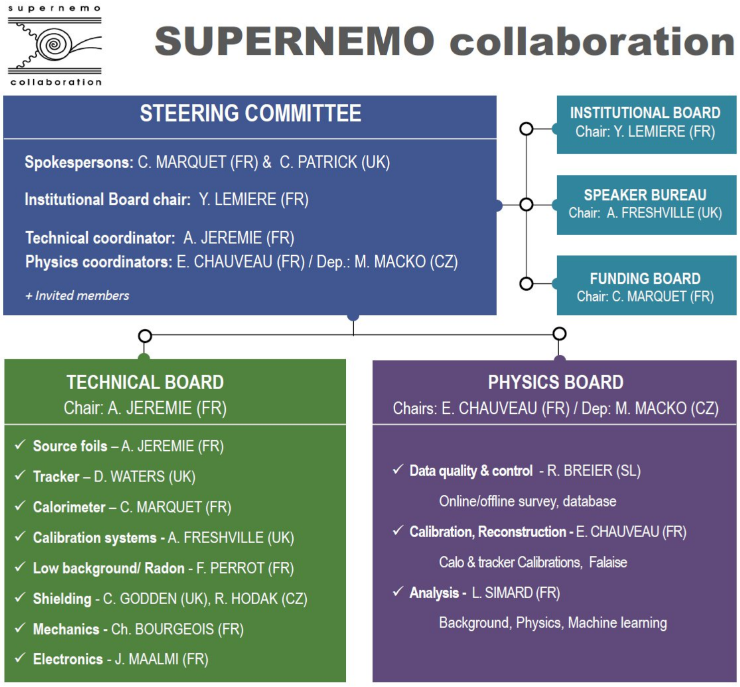


Figure 19: *SuperNEMO organisation chart.*

6. Resources and Means

6.1 Human resources

The IN2P3 laboratories involved in SuperNEMO are the CENBG/LP2I, CPPM, LAL/IJCLab, LAPP and LPC Caen. The list of personnel involved in the project is given in Table 3, with currently involved people in bold.

Permanent physicists

Currently active staff are indicated in bold, and are listed with their full-time equivalent effort.

Lab	Person	Corps	FTE
CPPM	**J Busto**	**PR**	**0.25**
IJCLab	**M Bongrand**	**CR**	**<0.1**
	X Garrido	MDC	
	S Jullian	DR	
	C Macolino	CR	
	X Sarazin	DR	
	L Simard	**MDC**	**0.4**
LAPP	**D Duchesneau**	**DR**	**0.1**
LP2I	**E Chauveau**	**CR**	**0.8**
	P Hubert	DR	
	C Marquet	**DR**	**0.8**
	F Perrot	**MDC**	**0.3**
	F Piquemal	**DR**	**<0.1**
	M Pravikoff	CR	
	JS Ricol	CR	
LPC Caen	B Guillon	MDC	
	Y Lemière	**MDC**	**0.2**
	F Mauger	**PR**	**0.2**

Postdoctoral researchers

We currently have no SuperNEMO postdocs in IN2P3. However, we are grateful for the assistance of **H Tedjditi,** currently a postdoc on radon at CPPM.

Lab	Person
CPPM	C Hugon
	O Llido
IJCLab	H Gomez Maluenda
LAPP	A Minotti
	A Remoto
LP2i	G Lutter
	G Oliviero

20 IN2P3 PhD students have defended theses on SuperNEMO, with **3 PhD students** currently active (see Section 3.4).

Technical staff

Lab	Person	Corps	FTE
CPPM	**O Angelini**	**T**	**<0.1**
	T Weicherding	**T**	**<0.1**
IJCLab	M Baltazar	T	
	C Bourgeois	**IR**	**<0.1**
	D Breton	**IR**	**<0.1**
	M Briere	AI	
	T Caceres	IE	
	J Colin	AJT	
	R Dorkel	AI	
	O Duarte	IR	
	S Jenzer	IR	
	B Leluan	T	
	P Loaiza	IR	
	J Maalmi	**IR**	**<0.1**
	G Mercadier	T	
	A Migayron	AI	
	O Vitez	T	
LAPP	E Chabanne	IR	
	JM Dubois	AI	
	A Jeremie	**IR**	**0.3**
	T Leflour	IR	
	S Lieunard	IE	
	J-L Panazol	IE	
	T.Yildizkaya	AI	
LP2i	**C Cerna**	**IR**	**<0.1**
	F Delalee	IR	
	P Hellmuth	IR	
	C Huss	IE	
	J Jouve	IE	
	E Maillard	**IE**	**<0.1**
	F Mesples-Carrere	T	
	I. Moreau	IR	
	A Nachab	IR	
	A Rebii	IR	
	M Roche	IR	
	A Tempel	AI	
LPC Caen	J Hommet	IR	
	F Lebourgeois	AI	
	C Pain	T	
	H de Préaumont	IE	
	J Poincheval	**IE**	**0.05**
	P Desrues	AI	
	B Bougard	T	
	F Noury	T	

Table 3: IN2P3 personnel in the SuperNEMO collaboration, with current members in bold.

The evolution of the human resources over time is illustrated in Figure 20.

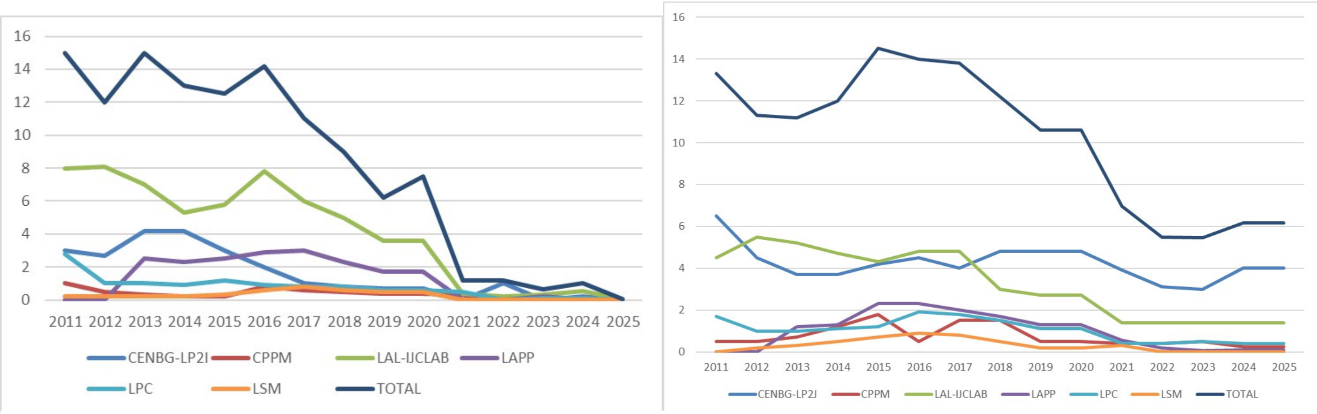


Figure 20: Full-time equivalent effort on SuperNEMO from IN2P3 labs during the period from 2011 to 2025. Left) Technical staff. Right) Physicists.

The diagrams above show the continuous decrease in the number of technical staff from 2016 to 2021, gradually declining as the main components of the Demonstrator were constructed. Then, a sharp drop is observed in 2021 upon completion of the main parts of the detector. A decrease in the number of physicists involved is also apparent, resulting from their engagement in other projects and from the departure of postdoctoral personnel.Today IN2P3 currently comprises approximately 1/3 of scientific contributors (a further 1/3 come from the UK, funded by STFC, with the final 1/3 from other countries).

Request to IN2P3:

The current personnel request focuses on ensuring IN2P3's continued involvement in the analysis, potentially through the recruitment of new PhD students and postdoctoral researchers over the coming years. In addition, discussions with IN2P3 management are planned to address personnel participation in the dismantling operations. The total number of *person.weeks* needed amounts to 166. We propose to share within the collaboration with 66 *person.week*s from IN2P3 staff and the rest from outside collaborators.

6.2 Financial resources

The total cost of the SuperNEMO Demonstrator, as well as the breakdown of shared costs, is shown in Figure 21. Surrounding components include the gamma and neutron shielding, the coil and the anti-radon tent. Radiopurity costs correspond to the HPGe detectors purchased from Russia and the Czech Republic and installed at LSM, as well as equipment for radon screening. The tracker cost includes the new helium recycling system. BiPo refers to the BiPo3 detector. Regarding funding sources: the ANR contribution corresponds to the BiPo ANR project; NEMO3 represents the estimated cost of reusing 5″ PMTs and part of the iron shielding; ILIAS is the contribution from this European double-beta decay network (2004–2008) toward the ^{82}Se enrichment; and "EDELW" refers to the estimated cost of the polyethylene plates of Edelweiss lent to the project for the neutron shield.

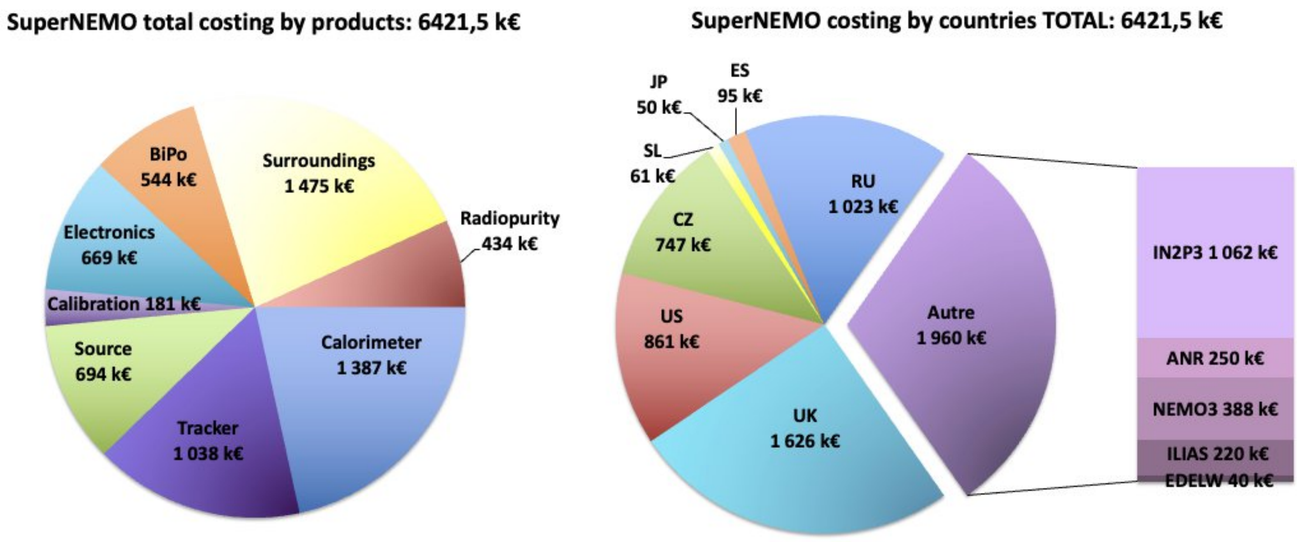


Figure 21: Total cost of the SuperNEMO Demonstrator, divided by (left) detector component and (right) national contributor. French contributions are included in the mauve section, which is broken down to the right.

This total cost does not include expenses related to personnel salaries and missions. Missions cover collaboration meetings; and travel for detector construction, commissioning, and operation; amounting to approximately €60,000 per year on average for the IN2P3 share.

Request to IN2P3:

Currently, the running costs amount to approximately €150,000 per year, covering tracker gas supply and decommissioning expenses. The decommissioning costs are estimated at €80,000, not including travel for dismantling missions, which will need to be provisioned in due course. These running costs are shared proportionally among the authors contributing to publications, with 35% covered by IN2P3, 35% by the UK, 19% by Czechia, and 11% by Slovakia.

7. Technical Achievements

Many important technical contributions from IN2P3 have already been achieved. They are described in Section 5. In the coming weeks, the final technical interventions will consist of two operations. First, the helium recycling system is currently being activated. Second, the commissioning of the connection between the SuperNEMO anti-radon tent and the radon-free facility will be carried out once the radon-free air system is fully operational.

The final important technical task will be the dismantling. We have estimated that the time needed for this operation and for evacuation of the detector elements from LSM will be 9 months. We added 3 months of contingency to include holidays, or tunnel closures. Figure 21 shows the dismantling schedule. Each item includes the time needed for evacuation from the tunnel with an escort.

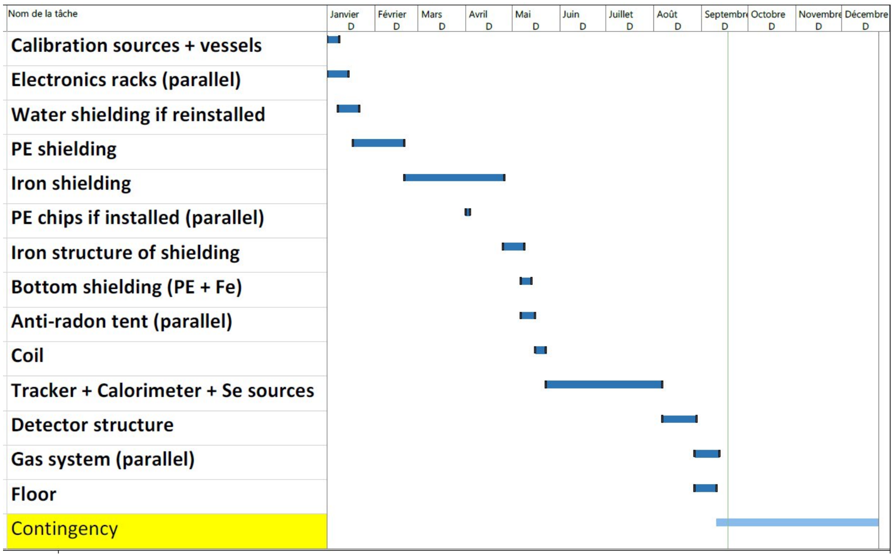


***Figure 21**: Preliminary dismantling schedule approved by LSM.*

For the dismantling of SuperNEMO, we need 2 to 3 persons per operation, but to gain some time, a few operations have been programmed in parallel. The precise skill of each person needed will be defined and documented later.

Technical outcomes

A non-exhaustive list of technical outcomes of the SuperNEMO project benefitting industry or other scientific experiments is given below:

- Progress in enrichment of new ββ isotopes of interest (^{96}Zr, ^{150}Nd).
- New chemical purification method using reverse chromatography.
- BiPo detector for high sensitivity measurement on ^{214}Bi and ^{208}Tl contamination for thin materials, shared with other experiments (DARKSIDE, CUPID).
- Development of a MeV-scale monoenergetic electron beam used by industrial partners (CARMELEC, NUVIA) and other physics experiments (LiquidO, GANIL, CELIA).
- Development of a detector for β/γ radiation protection, now commercially available (CARMELEC/EDF).
- Characterization of proton beams used in proton therapy (UCL) with some SuperNEMO scintillators.
- Methods for product authentication based on low-background gamma spectrometry techniques: wine dating, authentification on protected designation of origin ...

- New waveform digitisation board *WaveCatcher* based on *SAMLONG* analogue memory, used today by various experimental project in >40 laboratories and in industry by >10 companies.
- Novel high-voltage system with hundreds of individually-tunable channels, at a lower price than commercial equivalents.
- Detailed optical simulation for scintillation detector used by industry (CARMELEC, CERAP) and other experiments (LiquidO).
- Event generator *BxDecay0* for double beta decay in various classical and exotic processes.
- Radon mitigation and monitoring techniques: high sensitivity radon detector, radon concentration line, emanation chamber, radon trap, radon tightness measurement of sealing materials.
- Helium recycling system useful for other experiments and industrial companies (at lower price than commercial equivalents) .

8. SWOT

We propose two separate SWOT analyses: one for the current demonstrator, and another for the SuperNEMO approach itself, in the event that an opportunity to build a large-scale experiment should arise in the future.

SWOT for the current SuperNEMO Demonstrator

Strengths

- Access to **the full kinematic reconstruction** and two-electron identification
- Proof of technological concept with **real data,** providing valuable input for any future scale-up
- **Background rejection** across full ββ energy range
- Robust **background measuremnt**
- Flexibility to study **BSM physics beyond 0νββ**
- Significant number of **theorist** collaborators

Weaknesses

- Limited **isotope mass** (6.11 kg of ^{82}Se) constrains sensitivity to 0νββ.
- Limited **detection efficiency**
- Limited **energy resolution** o(calorimeter and electron's energy losses in source foils and tracker)
- **Complex detector design** makes construction, operations, calibration, and maintenance more challenging.
- Possible **unexpected background** from Demonstrator results

Opportunities

- **Unique capability** to measure **2νββ decay** process and related **nuclear calculations**
- Possible to obtain the **best results on ^{82}**Se for several BSM processes
- **Many tools** developed to benefit community
- Contributes to maintaining low radioactivity and rare-event physics **expertise in Europe**
- Attractive wide range of **physics analysis**

Threats

- **Limited running period**, constrained by LSM commitments, threatens the Demonstrator achieving its physics potential
- **Radon-free air system** delays may limit the ability to achieve world-leading sensitivities
- Two walls of **neutron shielding** missing due to construction issues
- Limited **manpower** for data analysis and for dismantling

Mitigation

- **Emphasize** the **Demonstrator's unique role** as a test bench for the tracker-calorimeter technology in ββ decay searches and raise awareness within the community, particularly among theorists.
- Maintain **visibility** and **scientific impact** through conference presentations and publications highlighting unique physics results.
- Ensure robust documentation and **knowledge transfer** to support a potential next-generation experiment.
- Apply to all possible **funding calls** to secure PhD students and postdocs for data analysis.

SWOT for a SuperNEMO-like large-scale experiment

Strengths	Weaknesses
• **Unique technological approach** offering full kinematic reconstruction and particle identification • Ability to study a **wide range of double-beta decay isotopes** • Excellent **background discrimination** capabilities	• **Complex** construction and integration • Inherently **large** detector required, reducing mass **scalability** compared to homogeneous calorimeters • Difficulty in achieving comparable **energy resolution** to homogenous calorimeters • Design & construction constrained by **radiopurity**

Opportunities	Threats
• Unique experiment capable of directly observing the "**golden event**" **ββ signature** • Only technology currently available that can **distinguish 0νββ mechanisms** in the event of discovery. • Potential **leadership role** in the global double-beta decay program in case of discovery	• High construction and operation **costs** may limit funding opportunities • **Competition** from other experimental approaches that can scale more easily to larger source masses • Possible delays in isotope production especially in the **geo-political context** • **Helium** supply fluctuations due to potential shortages • Limited space availability in **underground labs**

Mitigation
• **Invest in R&D** to improve detector **compactness** and **scalability** • Helium recycling will reduce dependence on consumables • **Highlight** unique physics reach and complementarity with other experiments to **secure funding**, especially in case of parallel discovery

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Appendix A: List of SuperNEMO articles

1. Fabrication of thin planar radiopure foils with 82Se for the SuperNEMO Demonstrator, *For submission to JINST* (arXiv 2509.08931), 12 September 2025
2. The impact of helium exposure on the photomultipliers of the SuperNEMO experiment, *JINST (2025) 20 P06018*
3. Calorimeter commissioning of the SuperNEMO Demonstrator, *Submitted to JINST* (arXiv 2412.18021), 17 March 2025
4. Measurement of the distribution of 207Bi depositions on calibration sources for SuperNEMO, *JINST 16 (2021) T07012*
5. Development of methods for the preparation of radiopure 82Se sources for the SuperNEMO neutrinoless double-beta decay experiment, *Radiochimica Acta, 108 (2020) 11*
6. Calorimeter development for the SuperNEMO double beta decay experiment, *Nucl.Inst.Meth.A (2017) 868 98-108*
7. The BiPo-3 detector for the measurement of ultra low natural radioactivities of thin materials, *JINST 12 (2017) P06002*
8. Construction and commissioning of the SuperNEMO detector tracker, *Nucl.Inst.Meth. A (2016) 824 507-509*
9. Spectral modeling of scintillator for the NEMO-3 and SuperNEMO detectors, *Nucl.Inst.Meth. A (2011) 625(1) 20-28*
10. Probing new physics models of neutrinoless double beta decay with SuperNEMO, *Eur. Phys. J. C (2010) 70: 927*
11. Results of the BiPo-1 prototype for radiopurity measurements for the SuperNEMO double beta decay source foils, *Nucl.Inst.Meth. A (2010) 622(1) 120–128*
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