R2D2 Project Overview
for the IN2P3 Scientific Council of October 2025

Contents

1 Introduction

The origin of matter in the Universe remains one of the most profound open questions in contemporary physics. Leptogenesis is among the leading theoretical frameworks proposed to explain the observed matter-antimatter asymmetry [1], but it critically relies on the assumption that neutrinos are Majorana particles, i.e. identical to their own antiparticles. Moreover, generating neutrino masses via the Higgs mechanism in extensions of the Standard Model often requires introducing a Majorana mass term. Demonstrating that neutrinos are Majorana particles would therefore not only support the leptogenesis hypothesis but also provide crucial insight into the origin of neutrino mass, while confirming that lepton number is violated, a clear signature of physics beyond the Standard Model.

The most sensitive and direct experimental probe of the Majorana nature of neutrinos is the search for neutrinoless double beta decay ($\beta\beta0\nu$). In this hypothetical process, a nucleus undergoes double beta decay emitting only two electrons and no neutrinos. The observation of $\beta\beta0\nu$ decay would demonstrate lepton number violation and access the absolute neutrino mass scale, establishing whether neutrinos are indeed Majorana particles [2].

Several international experiments are currently exploring complementary detection technologies using different candidate isotopes such as ^{76}Ge, ^{130}Te, ^{136}Xe, ^{100}Mo, or ^{82}Se. These experiments target half-lives beyond 10^{26} years and require detectors with exceptional performance: tonne-scale isotope masses, ultra-low background, energy resolutions of order 1% FWHM or better, and ideally some form of particle identification to tag the two emitted electrons, thereby enhancing the rejection of background events.

While some technologies achieve excellent energy resolution (e.g. germanium detectors and bolometers), others provide scalability (e.g. liquid xenon), or topological discrimination (e.g. gaseous TPCs). However, no single approach to date combines all these critical features in a unified and efficient design. Furthermore, most existing technologies face significant challenges in background control at larger scales, limiting their sensitivity to only a fraction of the inverted mass ordering region.

In this context, the R2D2 (Rare Decays with Radial Detector) project proposes a novel approach based on a high-pressure gaseous xenon Time Projection Chamber (TPC) operated in ionisation mode with a single-channel central anode in a radial geometry. This concept aims to combine excellent energy resolution, electron identification capability, and large isotope mass, while minimising the amount of material within the detector volume and thereby drastically reducing internal radioactivity. Xenon acts both as the detection medium and the $\beta\beta$ isotope, particularly when enriched in ^{136}Xe, and enables direct background evaluation through measurements with and without enrichment using the same detector settings.

The R2D2 concept originates from a prospective study carried out in 2017 on the search for $\beta\beta0\nu$ decay with a radial detector geometry [3]. Building on this idea, an R&D programme was initiated the same year with support from CNRS/IN2P3 and the IdEx Emergence programme of the University of Bordeaux, initially focusing on Spherical Proportional Chambers (SPC), a technology originally developed for dark matter searches [4]. Between 2018 and 2020, two spherical TPC prototypes were built and operated [5, 6], laying the foundations of the detection and analysis methodology. Stable operation at high pressure, promising energy resolution at the level of 1% FWHM in the MeV range, and radial localisation of the interactions using a single anode readout were established [7]. Performance was found to be independent of track length and orientation. This phase naturally led to the development of a cylindrical TPC. The evolution spanned from spherical to cylindrical geometry, from proportional to ionisation mode, from metallic to composite structure, and from micrometric wire to a thick anode read by charge sharing. The cylindrical concept offers better compatibility with xenon, improved robustness against polarisation, enhanced drift features due to the stronger far field, reduced electronic noise via a grounded anode, and additional longitudinal localisation capability through resistive charge sharing. Detector response showed excellent agreement with detailed Monte Carlo simulations, validating the understanding of the signal formation process. Moreover, without avalanche, the response was found to be highly similar for Ar and Xe gases, allowing commissioning with Ar instead of Xe. Latest advanced treatments show improved performance in terms of localisation of multiple energy deposits, energy resolution with further improved background rejection, and two-electron recognition capability.

The next phase of the project focuses on the construction of a low-background demonstrator based on radiopure composite materials, to be operated underground. This setup will aim to validate a background-free regime in the tonne-scale and demonstrate the ability to reconstruct two-electron topologies via waveform analysis. If successful, R2D2 would provide a scalable, cost-effective, low consumption, and competitive technology to explore neutrinoless double beta decay down to the region relevant for the inverted mass ordering, and potentially beyond.

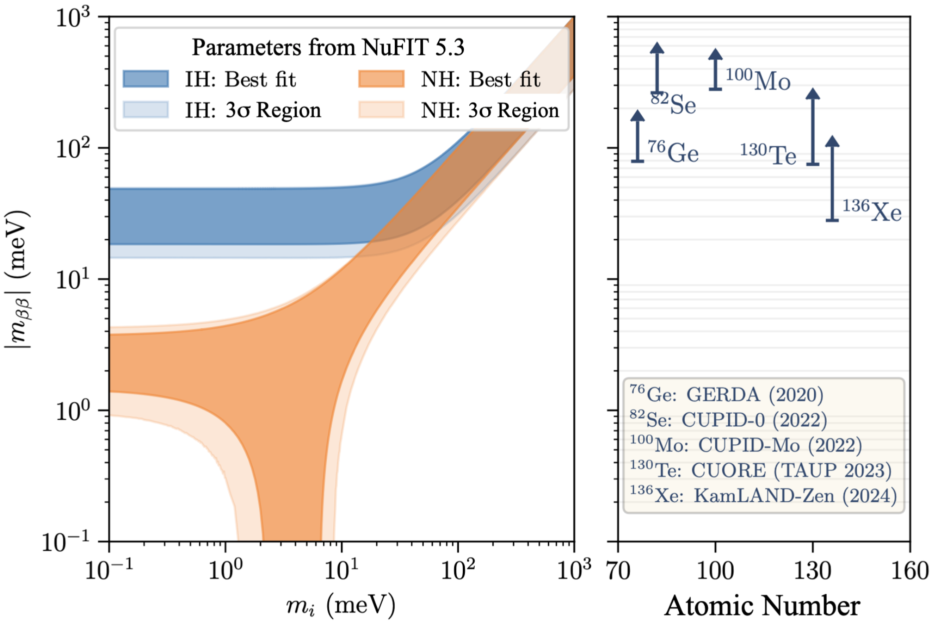


Figure 1: Allowed values of the effective Majorana mass $m_{\beta\beta}$ as a function of the lightest neutrino mass m_i. The coloured bands represent the 3σ ranges based on global oscillation fits (NuFIT 5.3). On the right, the sensitivity limits from representative current experiments using various isotopes are shown.

2 Scientific objectives and context

2.1 Goals

The scientific goal of R2D2 is to either observe or exclude $\beta\beta0\nu$ decay with sensitivity to the effective Majorana neutrino mass $m_{\beta\beta}$ down to a few 10 meV, covering the inverted ordering region and approaching the normal ordering band (see Figure 1).

This requires detectors that combine:

- Excellent energy resolution to isolate the peak at the Q-value.
- Topological identification of the two-electron signal.
- Ultra-low backgrounds in the region of interest.
- Scalability to large isotopic masses.

R2D2 addresses these requirements with a high-pressure xenon gas TPC in a cylindrical geometry, operated in ionisation mode. A central anode collects the charge, allowing the reconstruction of radial tracks. The concept is scalable: a single module (2.5 m long, 1 m diameter) can host about 600 kg of xenon at 40 bar. The use of a composite pressure vessel enables a minimal material budget, with wall thicknesses of a few millimetres, reducing external backgrounds.

The combination of topological discrimination, competitive energy resolution (targeting 1% FWHM at 2.5 MeV), and minimal passive materials makes R2D2 a promising candidate for next-generation $\beta\beta0\nu$ searches.

2.2 State of the art

The search for neutrinoless double beta decay is a central goal of several large-scale international experiments, including GERDA [8], LEGEND [9], CUORE [10], CUPID [11], nEXO [12], PandaX [13], KamLAND-Zen [14], NEXT [15], and SNO+ [16]. These collaborations investigate various isotopes and detection techniques, each optimised for different experimental challenges such as energy resolution, background rejection, or mass scalability. The SuperNEMO experiment [17] offers a complementary approach with full kinematic reconstruction of the two emitted electrons, enabling powerful background discrimination and detailed event characterisation, although its scalability to large isotope masses remains challenging.

The most stringent limits on the half-life of $\beta\beta 0\nu$ decay have been set by:

- **High-purity germanium detectors** (e.g. GERDA, LEGEND), offering outstanding energy resolution and low backgrounds. These detectors can reject a significant fraction of background from α particles and Compton-scattered γ rays. GERDA has reported $T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ years for ^{76}Ge.
- **Bolometric detectors** (e.g. CUORE, CUPID), capable of excellent calorimetry and particle identification. These detectors can reject a significant fraction of background from α particles and Compton-scattered γ rays. CUORE reached $T^{0\nu}_{1/2} > 2.2 \times 10^{25}$ years for ^{130}Te, while CUPID-0 and CUPID-Mo obtained $T^{0\nu}_{1/2} > 1.8 \times 10^{24}$ years with ^{82}Se and ^{100}Mo.
- **Liquid scintillator detectors** (e.g. KamLAND-Zen), offering very large active masses and ultra-pure fiducial volumes shielded by outer scintillator vetoes. These detectors are purely calorimetric, with limited event topology information. KamLAND-Zen currently holds the world-leading limit for ^{136}Xe with $T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ years.
- **Liquid xenon TPCs** (e.g. nEXO), which provide large active masses with improved spatial resolution and some topological discrimination. These detectors aim for excellent background rejection and scalability to tonne-scale targets.
- **Gaseous xenon TPCs** (e.g. NEXT, PandaX), which combine good energy resolution with topological event reconstruction. However, maintaining ultra-low background levels while scaling up remains challenging. These detectors typically use xenon as the emitter isotope, but their current results are still far from the KamLAND-Zen limit.

These constraints correspond to upper limits on the effective Majorana mass $m_{\beta\beta}$ ranging from approximately 30 to 200 meV, depending on the isotope and the nuclear matrix element (NME) used [18], as shown in Figure 1.

There is growing consensus that increasing the isotope mass alone is insufficient to fully explore the inverted ordering region ($m_{\beta\beta} \sim$ 10–100 meV), and it is even more challenging to probe the normal ordering region ($m_{\beta\beta} <$ 10 meV). For example, the NEXT collaboration reported a background rate corresponding to over 1000 events/tonne/year in the region of interest [19], highlighting the difficulty of scaling while maintaining low backgrounds.

In this context, R2D2 adopts a different strategy: minimising the material budget to suppress backgrounds, while preserving both energy resolution and topological information. Once background suppression is demonstrated, the design can be scaled to the tonne scale and beyond, either using a single large module or by replicating smaller ones, with the potential to reach sensitivities beyond the inverted ordering threshold.

2.3 Community involvement

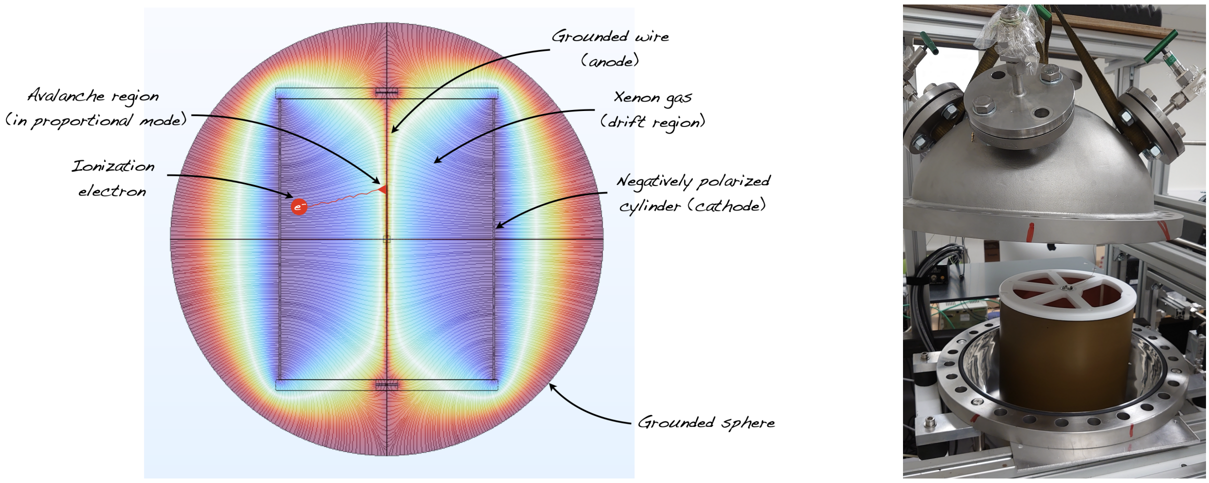
The search for neutrinoless double beta decay addresses one of the most critical open questions in neutrino physics, with profound implications for the understanding of the nature of neutrinos and the origin of mass. It represents a mainstream and strategic research axis within the international community.

The IN2P3 is strongly involved in this domain, taking a leading role in several major experimental efforts. In particular, it leads the SuperNEMO experiment, the CUPID project, and the R2D2 R&D programme. These activities collectively reinforce the visibility and impact of the French community in the global landscape of double beta decay research.

These scientific questions are regularly discussed within the GDR DUPhy and the IRN Neutrino, which provide forums for the various neutrinoless double beta decay projects to share updates and coordinate their efforts. These structures help maintain coherence and foster exchanges within the broader community engaged in this line of research.

3 Project

The R&D carried out since 2018 has addressed and validated most of the key aspects of the proposed detector concept, demonstrating that such a detector could now be a viable and competitive option for the search of $\beta\beta 0\nu$ decay.



(a) (b)

Figure 2: (a) CPC working principle and electric field computed with COMSOL, and (b) CPC set in the spherical vessel before final assembly. The wheel structure (white Teflon) supports the cathode (epoxy-copper type). The anode is attached to the central insert.

The following subsections highlight the state of the art and the main results of the R2D2 R&D effort, before presenting the possible continuation of this work in the proposed R2D2 project.

3.1 Overview and outcomes of the R2D2 R&D

3.1.1 CPC test setup

The conceptual CPC shown in Figure 2a has been realised and operated at LP2i Bordeaux since 2023 inside a spherical chamber certified to withstand pressures up to 40 bar, as illustrated in Figure 2b.

The CPC used for the tests consists of a central anode wire, a cylindrical cathode, and a supporting structure, all enclosed in a certified 33 l spherical pressure vessel developed during the first phase of the R2D2 project. The counter can operate in either ionisation or proportional mode, depending on the electric field configuration. Three anodes were tested: a 50 μm diameter tungsten wire, a 1.2 mm diameter metallic rod, and a 12 mm diameter copper tube.

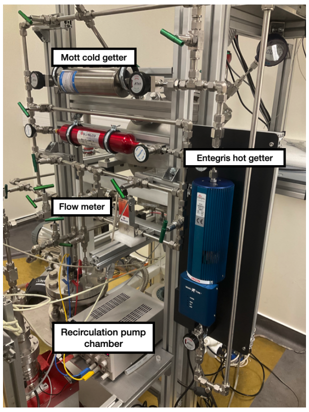
The detector structure was built using Teflon, selected after comparative outgassing tests among several plastic materials. The cathode is a 200 μm thick aluminium sheet, chosen for its mechanical flexibility and low outgassing. All components were baked under vacuum at 100 °C for one week prior to operation.

High voltage is applied to the cathode via a dedicated feedthrough, while the anode is read out through a low-noise electronics chain. Particular care was taken to minimise capacitive coupling and reduce noise, especially at high pressure. Applying the high voltage to the cathode decouples it from the signal readout, allowing the high voltage to be increased without amplifying electronic noise.

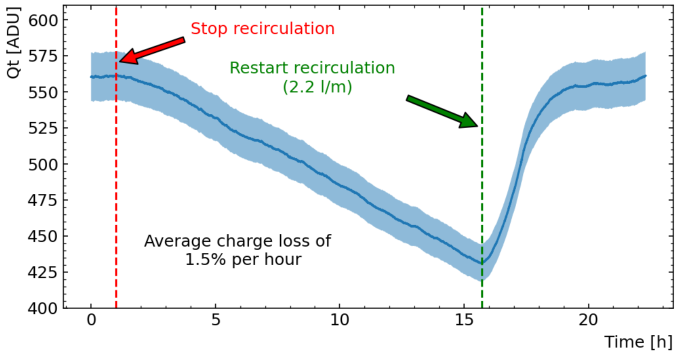
The setup is completed by a ^{210}Po source emitting α particles at 5.3 MeV, used to assess the detector's energy resolution. The polonium is deposited on a silver plate of 0.6×0.6 cm^2, which is positioned on the outer side of the cathode behind a 1 mm radius aperture, allowing the α particles to enter the CPC active volume. The source activity is approximately 10 Bq, corresponding to a detection rate of about 0.8 events per second.

A major strength of this detector concept lies in its intrinsic simplicity: it requires a single central anode to collect the ionisation signal, with two readout channels located at its ends to determine the longitudinal position of the event. This minimalistic design facilitates straightforward duplication and deployment, making it an ideal candidate for modular detector arrays. Moreover, the design is highly versatile, allowing operation with either natural or enriched xenon without any modifications to the detector structure or readout system.

Further details on the detector design, materials, and performance can be found in Ref. [20].



(a)



(b)

Figure 3: Gas purification system and its performance. (a) Recirculation system including cold and hot getters, flow meter, and pump chamber. (b) Time evolution of the reconstructed average charge from 5.3 MeV α particles in xenon at 3 bar; the red and green arrows indicate the stop and restart of recirculation, respectively.

3.1.2 Gas purity and recirculation

High gas purity is essential for the operation of TPCs relying on long drift distances, as electronegative impurities such as oxygen or water can capture ionisation electrons and reduce the collected signal. This point has therefore been one of the main objectives of the R2D2 R&D programme.

Various purification strategies are available. The most effective technique, used by the XENON collaboration, relies on cryogenic copper filters in which oxygen binds chemically to the surface ($2Cu + O_2 \rightarrow 2CuO$) [21]. Alternative approaches include spark discharge purifiers [22, 23], cold and hot getters, or distillation. To avoid the complexity and cost associated with cryogenics and large infrastructures, we opted for a simpler system based on commercial getters. While this choice limits the achievable purity to the ppb level, it remains sufficient for the current R&D objectives. The recirculation system, shown in Figure 3a, includes a Mott MGP-30 cold getter, a SAES MonoTorr PS3-MT3-R-2 hot getter, a KNF membrane pump, and a calibrated flow meter. A drawback of this configuration is that the hot getter is rated for operation only up to 10 bar, which imposes a constraint on the system's use at higher pressures.

The effectiveness of purification was demonstrated in xenon at 3 bar, where the charge signal from 5.3 MeV α particles was monitored over time. As shown in Figure 3b, when the recirculation was stopped, the average signal decreased by about 1.5% per hour and recovered after purification resumed.

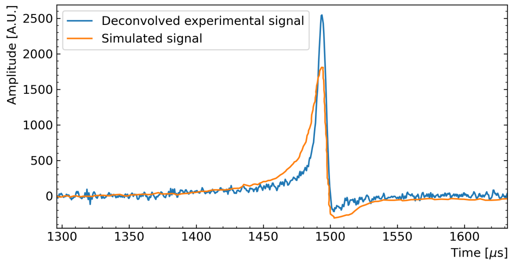
Electron lifetimes were estimated indirectly using GARFIELD++ simulations of the drift time as a function of field. Values up to 1 ms in argon at 10 bar and 2 ms in xenon at 6 bar were obtained. These remain below the levels achieved in liquid noble gas detectors, where lifetimes exceeding 20 ms in liquid argon [24] and 10 ms in liquid xenon [21] have been reported.

To overcome the current limitations in gas purity at high pressure, particularly the 10 bar constraint imposed by the hot getter, the R&D efforts are now focused on developing alternative purification strategies. One promising approach, inspired by the work of Bolotnikov [22], relies on a process in which microscopic titanium particles produced by a high-voltage discharge bind efficiently to electronegative impurities. This technique offers rapid and effective gas purification at high pressure, without the need for getters or cryogenics. Future improvements under consideration include baking the full detector volume and replacing the diaphragm pump with a magnetically driven piston pump. Further details can be found in Ref. [20].

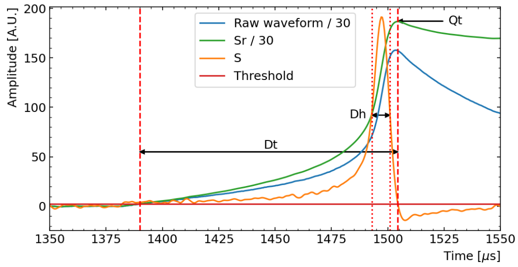
3.1.3 Read-out electronics

At the beginning of the project, a dedicated low-noise charge preamplifier named OWEN (Optimal Waveform recognition Electronic Node) was developed by the Bordeaux electronics service, with specific IdEx funding. It was initially designed for the spherical TPC operated in proportional mode. In ionisation mode, OWEN was replaced by the commercial ORTEC 142PC amplifier, which is currently in use.

The current readout system is based on this low-noise charge-sensitive preamplifier (ORTEC 142PC) connected to the anode, followed by digitisation via a CALI ADC card controlled by the SAMBA acquisition software [25]. The integrator output is sampled continuously at 2 MHz. Events are triggered by



(a)



(b)

Figure 4: (a) Deconvolved waveform from a charge preamplifier corresponding to an α particle emitted by ^{210}Po (blue) compared with a simulated signal due to electrons created at the cathode radial position (orange). (b) Example of a raw waveform (blue line), its deconvolved signal S (orange line), and the reintegrated signal S_r (green line). A scale factor of 30 is applied to both the raw waveform and S_r for visual clarity. The total reconstructed charge Qt is indicated. The horizontal red line represents the threshold, while the vertical dashed and dotted lines denote the total width Dt and the full width at half maximum Dh, respectively.

a fixed digital threshold and recorded over a 3 ms window, with the first 1.5 ms used to estimate the baseline and the second half containing the signal of interest for further processing (see Sec. 3.1.4).

This configuration has proven effective for the first phase of the R2D2 programme. However, to enable longitudinal reconstruction of energy deposits, the next phase will employ a resistive anode. This requires reading out signals on both sides of the anode and replacing charge preamplifiers with current preamplifiers. To this end, a dedicated R&D effort supported at the IN2P3 level has led to the development of a custom ASIC based on SiGe BiCMOS technology. A first operational prototype is expected within a year, and test campaigns for R2D2 are already planned.

This new amplifier design is crucial not only for enabling full 3D reconstruction capabilities in the radial TPC, but also for improving background rejection through topological event classification.

In parallel, exploratory work is ongoing within the THINK project (IN2P3) to integrate artificial intelligence into FPGA-based data acquisition systems. Although pursued independently, this development could significantly contribute to real-time signal processing in future phases of R2D2.

3.1.4 Signal processing

The registered waveforms encode critical information necessary for the precise reconstruction of physical events within the detector. Through detailed studies, the behaviour of the detector and the underlying signal formation mechanisms based on the Shockley-Ramo theorem have been thoroughly understood. The close agreement observed between real data and Monte Carlo simulations (see Figure 4a) validates the accuracy of the detector model and the signal processing framework.

The raw waveforms, initially affected by electronic noise and the detector's response function, are processed with tailored Fourier-based filtering and deconvolution algorithms. These steps recover the physical signals from the measured waveforms, compensating for the convolution with the preamplifier's shaping and effectively suppressing noise contributions.

From the deconvolved signals, key observables (see Figure 4b) are extracted that enable fundamental event reconstruction capabilities:

1. The radial position of energy deposits is determined with a precision better than 1 cm by analysing the duration of the induced currents, leveraging the well-characterised electron drift velocities and the Shockley-Ramo theorem.

2. The distinct tracks of the two electrons emitted in double-beta decay events are identified through localised ionisation peaks (Bragg peaks) along their trajectories, reconstructed from the arrival time and charge sharing at the anode.

3. The total reconstructed charge from the waveforms provides a direct measurement of the deposited energy, achieving an energy resolution at the level of 1% FWHM, as detailed in Sec. 3.1.5.

These achievements form the foundation for high-fidelity event reconstruction and background discrimination in the R2D2 detector. The combination of robust signal processing, validated simulations, and

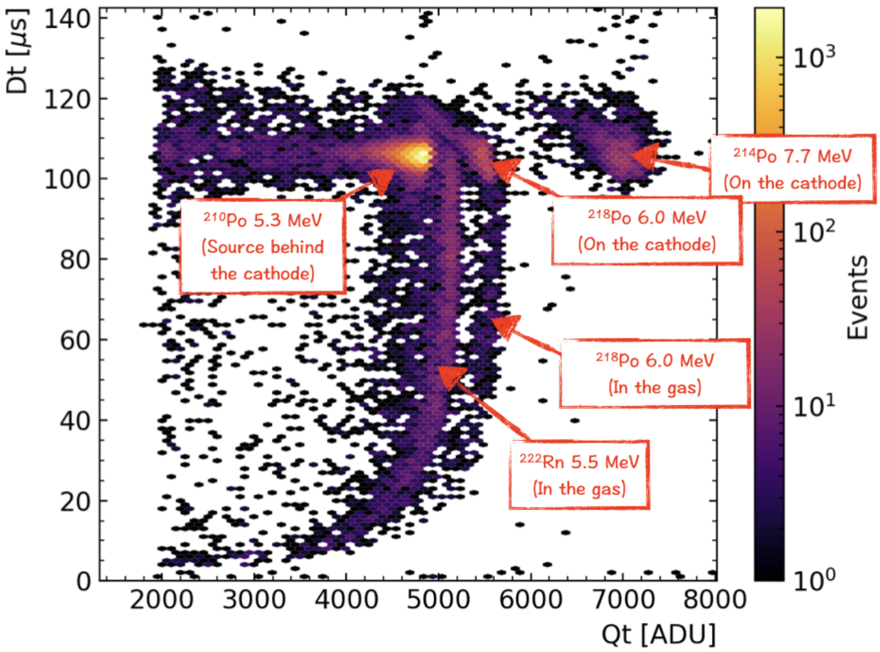


Figure 5: Example of a bi-plot: signal length Dt versus reconstructed charge Q_t, for a run with xenon at 3 bar, a 1.2 mm central anode, and a cathode voltage of -3000 V. Distinct populations corresponding to the ^{210}Po source and radon-induced events are visible.

precise waveform analysis enables reliable extraction of physical observables critical for the experiment's physics goals.

Further technical details can be found in Ref. [20, 26].

3.1.5 Energy resolution

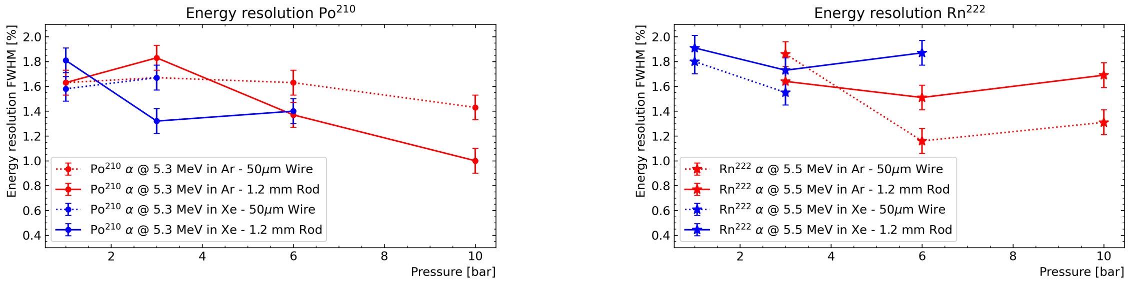
Thanks to the waveform-based observables described in Sec. 3.1.4, a clear selection of the physical event populations was achieved. An example of such discrimination is illustrated in Figure 5, which shows a bi-dimensional distribution of signal length Dt versus reconstructed charge Qt for a run performed with xenon at 3 bar, a 1.2 mm central anode, and a cathode voltage of -3000 V. The distinct populations corresponding to the ^{210}Po α source placed behind the cathode and the diffuse ^{222}Rn α source and its progeny distributed in the gas volume are clearly visible, highlighting the discrimination power of the detector.

Based on such event classification, the different populations were individually selected and their energy spectra fitted to extract the energy resolution. More details on the selection criteria and fitting procedures can be found in Ref. [20]. The corresponding results are shown in Figure 6.

The analysis of the ^{210}Po population shows that an energy resolution of approximately 1.5% can be achieved, independently of the gas pressure and nature (argon or xenon). This indicates that future prototypes may be tested and commissioned in argon while retaining predictive power for xenon performance, provided similar gas purity levels can be ensured.

The use of a thicker anode improves energy resolution, particularly at high pressure. This is attributed to the stronger electric field at the cathode provided by the 1.2 mm wire, which reduces charge loss through electron attachment during drift.

The analysis of radon-induced events confirms the independence of the energy resolution from gas pressure and composition. Moreover, the diffuse nature of the radon source does not degrade the energy resolution, validating the detector's uniformity across radial positions. However, in contrast to the ^{210}Po case, the best resolution for radon is obtained with the thinner (50 μm) anode. This can be explained by the fact that radon events typically occur closer to the central anode, where the impact of drift-length-dependent attachment is smaller. The thinner wire still provides a sufficiently strong electric field to ensure efficient charge collection.



(a) (b)

Figure 6: Energy resolution obtained with 5.3 MeV α's from ^{210}Po (a), and 5.5 MeV α's from ^{222}Rn (b). Blue lines represent xenon measurements, red lines represent argon. Dotted lines correspond to the 50 µm anode, solid lines to the 1.2 mm anode.

A small degradation observed with the 1.2 mm anode could be related to its slightly resistive nature. This might introduce a weak dependence of the signal amplitude on the longitudinal position, an effect that cannot be probed with the current setup. An upgrade involving a resistive anode with readout at both ends is foreseen to enable longitudinal position reconstruction and further investigate this effect.

The development of improved signal processing algorithms has led to energy resolutions better than 1% FWHM (work ongoing). These advancements in data treatment significantly enhance the detector performance and its capability to discriminate signal from background.

3.2 Future of R2D2

Following the successful demonstration of the key features of the detection concept, R2D2 is now poised to enter a new phase focused on constructing and operating a full-scale prototype in an underground environment. The main objective of this phase, envisioned over a three-year timescale, is to validate the radiopurity of the system and confirm the potential for a background-free experiment at the tonne scale. This effort will focus on several key developments, including the design of a composite low-radioactivity vessel, the optimisation of the readout, electronics, and gas filtering system, as well as the definition of suitable infrastructure for underground operation.

Following this initial phase, two additional years are planned for the construction and commissioning of the full detector system.

In parallel, a detailed sensitivity study has already been carried out [26], demonstrating that the proposed approach can reach the inverted ordering regime. These aspects are presented in the following subsections.

3.2.1 Composite Vessel

The R2D2 detector concept relies on a thin-walled, pressurised vessel made of low-radioactivity composite materials to minimise the material budget and thus reduce background levels. This development is carried out in collaboration with IRT Jules Verne [27], which works with industrial partners such as Airbus and Safran and specialises in composite materials for aeronautics and hydrogen applications.

In 2024, a Type 4 composite tank produced by Mahytec (epoxy–glass fibre composite, originally developed for H_2 storage) was acquired to serve as a prototype close to the envisaged final vessel, except for the radiopurity constraint (see Figure 7). This prototype (length 1.8 m, diameter 0.84 m, volume 850 l, mass 250 kg, maximum pressure 60 bar, access opening 6 cm) is being used to identify potential pitfalls in the final design. It also allows us to explore technical alternatives for the internal instrumentation, including the implementation of the cathode, integration of the gas system, design of the HV supply (20 kV), and testing of the resistive anode and associated electronics. A mechanical twin of the tank has also been prepared for implementation tests, allowing the validation of assembly procedures such as the attachment of the aluminised Mylar cathode, the mounting of the central aluminium anode, and the integration of the closing caps. The first detection tests are foreseen before the end of 2025, with the ultimate goal of demonstrating the discrimination of double-beta events within the detector.

In parallel, studies led by IRT Jules Verne indicate that a wall thickness of only 2.5 mm is sufficient to ensure safe operation at pressures up to 40 bar, while keeping the total vessel mass below 60 kg thanks to the mechanical properties of carbon fibre reinforced polymers. The current design builds upon industrial

(a) (b)

Figure 7: (a) Photo of the Mahytec composite tank (epoxy–glass fibre composite) used for H_2 storage and adapted as a prototype of the cylindrical TPC. (b) Internal view of the mechanical twin used for implementation tests, showing the aluminised Mylar cathode and its attachment, the central aluminium anode, and the internal part of one closing cap.

expertise in composite tank technology, particularly the so-called Type 4 vessels, widely used for hydrogen storage, which consist of a polymer liner wrapped with carbon fibres and epoxy resin. More advanced Type 5 tanks, without any metallic or polymer liner, are also being explored as a long-term solution. Both configurations offer excellent strength-to-weight ratios and have been proven in the aerospace and automotive sectors.

A key challenge is to ensure the required radiopurity of the composite materials. While raw carbon fibres and epoxy resins can reach intrinsic radioactivity levels as low as 10 μBq/kg, contamination is often introduced during the sizing step, where chemical treatments are applied to make the fibres compatible with resins. To address this problem, we are working with producers of raw materials (fibres and resins) and with the IRT Jules Verne technology platform to conserve the low radiopurity properties during manufacturing and to develop and qualify low-radioactivity composite vessels. A systematic material screening campaign is planned, including measurements of samples at different stages of the manufacturing process. Current upper limits from unqualified production remain at the level of 1 mBq/kg.

In addition, complementary studies are ongoing to validate the vessel's compatibility with vacuum operation during the initial gas purification phase. Since composite materials are not inherently vacuum-tight, a dual pumping strategy (inside and outside the tank) can be used temporarily until xenon filling is completed. Surface treatments of the epoxy to mitigate degassing are also under consideration.

3.2.2 Resistive anode and read-out electronics

Several crucial developments remain to be completed to ensure the full functionality and performance of the R2D2 readout system.

A key aspect concerns the transition to a resistive anode, which requires positioning the preamplifiers as close as possible to the anode ends to minimise capacitive noise and signal degradation. This entails the design, integration, and testing of a dedicated electronics card hosting new ASIC-based current amplifiers. The low-noise performance of this system, including its interface with the acquisition chain, must be thoroughly validated. Additionally, although only two readout channels are employed, maintaining minimal radioactive background remains essential. To this end, shielding the electronics with ultra-pure copper will be considered to reduce radioactive noise.

Another crucial aspect is the anode itself, which requires finalisation and qualification. The current baseline is a 1 mm thick polymeric tube coated with a few micrometres of resistive Kapton foil, with NiCr layers or conductive paint being also valuable alternatives. This design must be evaluated in terms of radioactivity, mechanical robustness, and electrical uniformity. Test campaigns will be conducted to validate its performance in ionisation mode and ensure compatibility with the required field configurations.

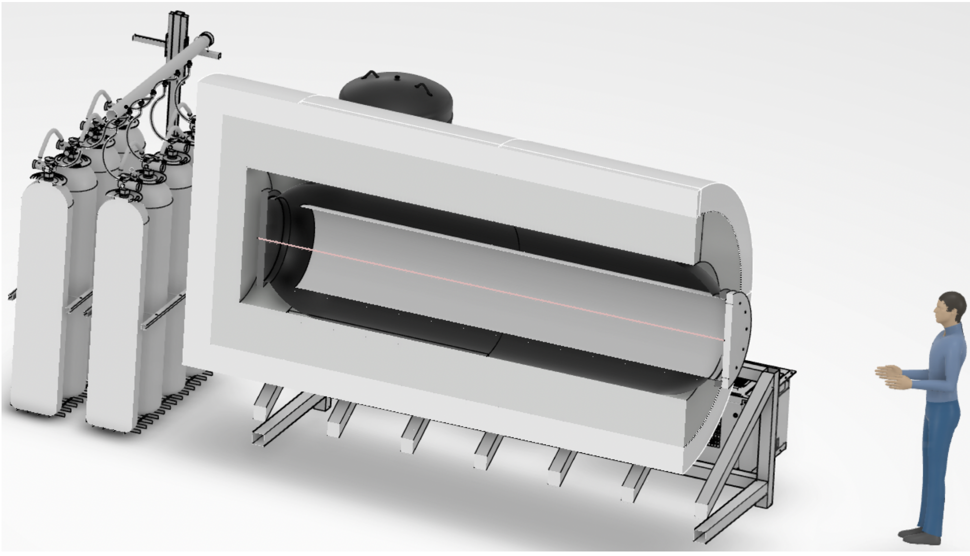


Figure 8: Conceptual illustration of the detector setup used in the R2D2 sensitivity studies.

3.2.3 Infrastructure

The detector requires effective shielding to protect the active volume from external radioactivity, primarily gamma rays and neutrons. A combination of materials such as lead and polyethylene is envisaged for this purpose. Preliminary designs propose an inner layer of approximately 35 cm of lead, corresponding to a total mass of about 75 tonnes, to attenuate external gamma radiation. This is surrounded by an outer layer of 30 cm of polyethylene to suppress the neutron flux.

The exact configuration of the shielding remains under study. Alternatives to polyethylene, such as water shielding, are being considered due to their advantageous radiopurity and cost-effectiveness. Additionally, ultra-pure copper may be employed as an intermediate layer between the iron shielding and the composite vessel to further reduce intrinsic background. The radioactivity of the shielding materials themselves must be carefully assessed to avoid compromising the detector's sensitivity.

The choice of underground laboratory for the installation is critical. The Laboratoire Souterrain de Modane in France appears to have insufficient space due to the upcoming Tesseract experiment occupying the SuperNEMO area. Other candidate sites include the Boulby Underground Laboratory in the United Kingdom and the Gran Sasso National Laboratory in Italy, both of which have expressed strong interest in hosting the experiment and have confirmed their capability to provide the necessary raw low-radioactivity lead for shielding, as well as the required infrastructure.

An essential component of the detector operation is the gas purification and recirculation system. Maintaining ultra-high purity of the gas, free from electronegative contaminants, is crucial to achieving long electron drift lengths and minimising signal degradation. The R&D phase employed a system combining hot and cold getters alongside a recirculation piston pump, achieving an electron lifetime of approximately 2 ms at 10 bar. While this is lower than the performance in state-of-the-art liquid xenon experiments, it provides a solid foundation for further improvement. For the full-scale detector, existing purification technologies developed for noble liquid and gas detectors will be adapted, including cryogenic copper-based filters and spark discharge cleaning methods. The recirculation pump will be upgraded to a magnetically driven piston pump to minimise the introduction of impurities.

The overall footprint required for the detector and its associated recirculation and purification systems is estimated to be around 50 m^2 to ensure safe and efficient operation within an underground laboratory environment.

3.2.4 Sensitivity

The proposed detector setup, conceptually illustrated in Figure 8, has been thoroughly simulated including all relevant background sources. Detailed results are presented in Ref. [26]. The simulations indicate a sensitivity to the effective neutrino mass after 10 years of data taking in the range of 13 meV to 57 meV, depending on the achieved background levels. In a zero-background scenario, this sensitivity improves to a range of 8 meV to 35 meV.

The external gamma background component, estimated at 0.1 events per year, can be relatively easily reduced through enhanced shielding. The dominant background contributions arise from composite vessel radioactivity (1.2 events per year) and radon contamination (0.2 events per year). The present study assumes a radioactivity level of 10 μBq/kg.

Furthermore, ongoing studies suggest that the composite vessel thickness could be reduced by a factor of six, resulting in a total vessel mass of approximately 60 kg. The deployment of multiple detectors to increase the total active mass is also under consideration. The projected sensitivity for a 2-tonne detector, also presented in Ref. [26], indicates the potential to fully exclude the inverted neutrino mass hierarchy.

If the low-background conditions demonstrated with argon are confirmed, the R2D2 setup could be used with natural or enriched xenon, yielding world-leading limits on neutrino mass without requiring modifications to the detector design.

3.3 Scientific Production

Since the beginning of the R&D phase, the R2D2 project has led to a significant scientific output. A total of seven publications have appeared in peer-reviewed journals (see Sec. 3.3.1), and results have been presented at 21 international conferences and workshops, with seven of these leading to published proceedings. Two PhD theses have been defended during this period (see Sec. 3.3.2). The collaboration intends to continue disseminating results through regular conference presentations and publications.

3.3.1 Publications

- R. Bouet *et al.*, "Simulation of a radial TPC for the detection of neutrinoless double beta decay" *Eur. Phys. J. C* **85**, 732 (2025).
- R. Bouet *et al.*, "Perspectives of a single-anode cylindrical chamber operating in ionization mode and high gas pressure" *Eur. Phys. J. C* **84**, 512 (2024).
- R. Bouet *et al.*, "R2D2 TPC: first Xenon results" *JINST* **18**, T10001 (2023).
- R. Bouet *et al.*, "Performance of a spherical high-pressure gas TPC for neutrino magnetic moment measurement" *JINST* **18**, P03031 (2023).
- R. Bouet *et al.*, "Simultaneous scintillation light and charge readout of a pure argon filled Spherical Proportional Counter" *Nucl. Instrum. Meth. A* **1028**, 166382 (2022).
- R. Bouet *et al.*, "R2D2 spherical TPC: first energy resolution results" *JINST* **16**, P03012 (2021).
- A. Meregaglia *et al.*, "Study of a spherical Xenon gas TPC for neutrinoless double beta detection" *JINST* **13**, P01009 (2018).

3.3.2 PhD Theses

- **Pierre Charpentier**, 10 April 2025 - supervised by Anselmo Meregaglia.
  Développement et analyse de données des prototypes du projet R2D2, visant à l'optimisation d'une TPC de xénon sous haute pression pour la recherche de la double désintégration bêta sans émission de neutrino.
- **Vincent Cecchini**, 2 December 2022 - supervised by Anselmo Meregaglia and Pascal Lautridou.
  Développement d'une détection par SPC pour la recherche de la désintégration double bêta sans émission de neutrinos.

4 Origin and calendar

The R2D2 project was initiated in 2017 as an R&D programme aimed at designing a novel high-pressure xenon time projection chamber with excellent energy resolution and high radiopurity (although only the energy resolution was really the goal of the R&D phase), suitable for the search of neutrinoless double beta decay. The preliminary concept was presented to the IN2P3 Scientific Council in 2018, although not for evaluation at that time. Since then, the project has evolved significantly through several technological iterations, including spherical and cylindrical geometries, as well as proportional and ionisation operation modes, supported by extensive prototyping and simulation efforts.

4.1 Milestones

- **2017:** Launch of the R&D programme on spherical TPCs.
- **2018:** Positive evaluation of the IN2P3 Scientific Council and SUBATECH Scientific Council regarding the R&D associated with our approach. Construction of the first SPC prototype and publication of the simulated performances for $\beta\beta0\nu$ detection with an SPC.
- **2020–2022:** Demonstration of energy resolution with a SPC filled with argon, with good performance up to 3 bar; first detection and reconstruction of scintillation light; radial position reconstruction with pure argon; progress in signal processing and triggering. Key results published in JINST and NIM A.
- **2023:** Transition to a cylindrical geometry. First prototype tested in Ar:CO_2 and xenon mixtures, achieving energy resolutions as good as 1.3% at 1 bar. Start of the development of a custom amplifier adapted to a resistive anode in BiCMOS-SiGe technology. Upgrade of the front-end electronics for ionisation mode. Advanced signal processing developed to accommodate non-standard electronics. Final resolution studies published in *JINST* and *EPJC*.
- **23 May 2023:** Positive evaluation by the LP2iB Scientific Council, recommending presentation to the IN2P3 Scientific Council and transition to a Master Project.
- **2024:** Maturation of the cylindrical detection concept (ionisation mode and thick anode). Receipt of a full-scale composite vessel (850 L); start of development of a titanium-based gas purification system; collaboration with IRT Jules-Verne on low-radioactivity composite vessels. Sensitivity estimates for $\beta\beta0\nu$ published in EPJC. BiCMOS-SiGe ASIC design completed. An ERC proposal was submitted and ranked A, though not funded.
- **4 September 2024:** REX review at IN2P3 (Retour d'Expérience) to conclude the R&D phase.

4.2 Future milestones

The next major steps of the R2D2 programme are expected to be achieved within the next three years. These developments aim to deliver a fully operational detector, marking the transition from the R&D phase to a mature experimental setup. The goal is to have the detector ready for data taking within five years, including one year dedicated to construction and one year to commissioning with argon and natural xenon.

- Finalisation and validation of the titanium-based spark purification system, enabling operation up to 40 bar without getter limitations.
- Commissioning of a purification and recirculation system adapted to the full-scale prototype, including monitoring of gas purity and long-term stability.
- Validation of the full-scale detector (without low-background requirements), featuring a 40 cm drift length, built as part of the R&D programme.
- Completion and testing of the ASIC-based read-out electronics, optimised for low-noise operation.
- Validation of the resistive anode concept.
- Qualification of low-radioactivity composite materials for the final detector vessel.
- Development of robust calibration procedures to characterise energy resolution, position reconstruction, and detection efficiency.
- Implementation and validation of a complete simulation chain for background modelling and signal efficiency, supporting the design of the final detector.
- Enlargement and internationalisation of the collaboration to secure the necessary manpower and funding.

4.3 Project evaluations

The R2D2 project has undergone several evaluations by scientific councils over the past years. A first presentation was made to the IN2P3 Scientific Council in October 2018, followed by an evaluation by the SUBATECH Scientific Council in March 2019. At that time, the IN2P3 Council highlighted the importance of demonstrating competitive energy resolution as the decisive criterion for the project, in order to assess its long-term competitiveness with respect to other international efforts. This goal has since been achieved: stable operation at high pressure with energy resolution at the 1% FWHM level has been demonstrated, and the corresponding sensitivity studies have been published and are presented in this document.

The SUBATECH Council, while acknowledging the interest of the proof-of-principle, expressed concern about the limited manpower then allocated to the project. Since then, the situation has evolved substantially, with increased contributions from the local team to both the detector construction (in collaboration with the technical services) and to the development of advanced signal analysis, which proved critical for the reconstruction and demonstration of the achieved energy resolution.

A significant milestone was reached with the evaluation by the Scientific Council of LP2iB in May 2023. The Council commended the collaboration for the substantial progress achieved, particularly the pragmatic transition from the spherical to the cylindrical configuration. This shift was recognised as a major advancement, addressing key challenges related to xenon, high voltage, and high pressure, while remaining aligned with the original objectives of the R&D programme. Given the maturity of the project, the Council recommended that R2D2 be presented to the IN2P3 Scientific Council, with the aim of transitioning from an R&D activity to a full-scale Master Project.

The full texts of the IN2P3 (2018), SUBATECH (2019), and LP2iB (2023) Council reports, together with their opinions and recommendations, are reproduced in the Appendix (translated into English).

In parallel, the collaboration has actively pursued funding opportunities. Several ANR proposals were submitted and, for three consecutive years, reached the second evaluation phase. In 2024, an ERC proposal obtained an A ranking and has been resubmitted in 2025, confirming both the scientific quality and the strong potential of the project.

5 Project position in the worldwide panorama

5.1 Limits and timescale

The current best sensitivities on the effective neutrino mass have been achieved by KamLAND-Zen [14] and GERDA [8], which have set lower limits on the $\beta\beta0\nu$ half-life of $T^{0\nu}_{1/2} > 3.8 \times 10^{26}$ years for ^{136}Xe and $T^{0\nu}_{1/2} > 1.8 \times 10^{26}$ years for ^{76}Ge, corresponding to $\langle m_{\beta\beta}\rangle$ in the range of 28–180 meV depending on the nuclear matrix elements.

The R2D2 project demonstrates competitive projected performance among next-generation experiments. A detector with 580 kg of active xenon, which could be constructed within five years, would be only a factor ∼2.5 less sensitive than future large-scale projects such as nEXO [28], LEGEND1000 [29], or CUPID [11], under the conservative assumption of a 1.5 cm thick composite vessel and a radioactivity level of 10 μBq/kg. These assumptions correspond to an expected background of 1.6 events per year (including 1.2 from the vessel and 0.2 from radon), plus an additional 0.2 events per year from external gamma rays and shielding radioactivity, which can be effectively mitigated.

Ongoing R&D focuses on validating the assumed radioactivity level of 10 μBq/kg for the composite material and on reducing the vessel thickness by a factor of up to six, which would lower the overall background. In this configuration, with an almost zero-background detector, the projected sensitivity becomes comparable to that of the aforementioned large-scale experiments. An alternative route would be to increase the active mass to about 2 tonnes while maintaining the baseline background, leading to similar gains in sensitivity. These scenarios are illustrated in Figure 9, which compares the expected limits on $\langle m_{\beta\beta}\rangle$ for various experiments. The variation in the width of the error bands mostly reflects the different assumptions adopted by each collaboration regarding the spread of nuclear matrix element uncertainties, rather than intrinsic differences in experimental sensitivity.

In terms of timeline, R2D2 is fully competitive. All next-generation experiments aim for final results around 2040. If fully funded, R2D2 could start data taking by 2032, delivering final results within the same timeframe. The cost of the detector is modest (approximately 3 M€, excluding ^{136}Xe enrichment), and it does not require cryogenics. Its low power consumption also reduces environmental impact.

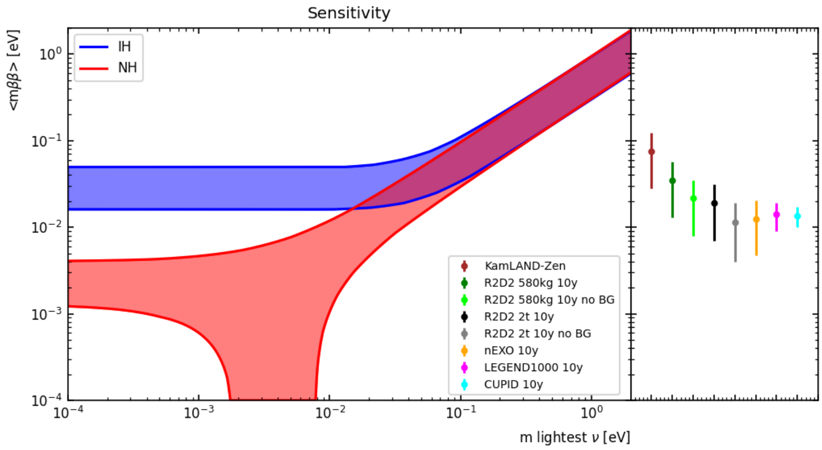


Figure 9: Current and expected limits on $\langle m_{\beta\beta} \rangle$ at 90% C.L. for various experiments.

Importantly, the design allows for twin detectors, one filled with natural xenon and the other with ^{136}Xe, potentially deployed in different underground laboratories. This configuration would enable differential measurements between signal and background. Combined with the ability to vary the target medium (Ar or Xe), the isotopic content (natural or enriched Xe), and the gas pressure (up to 50 bar), R2D2 offers strong redundancy to confirm any potential signals.

5.2 Role and contribution of IN2P3 in the R2D2 project

To date, the R2D2 project has been funded exclusively by French institutions, primarily through IN2P3 and Bordeaux University, with additional support from the internal budgets of LP2i and SUBATECH. This strong local support has enabled the critical development and initial construction phases, positioning IN2P3 as the leading institute driving the project forward. The funding contributions from IN2P3 amount to approximately 200 k€ in direct support, alongside a substantial investment in personnel resources, estimated at over 2.5 M€ in human resources costs dedicated to research and development since 2017.

The collaboration currently includes colleagues from Bratislava and Prague, and contacts have been established with Italian and UK groups, who may potentially join during the next phase of the project. The R2D2 detector should be developed and deployed within the IN2P3 framework, as the institute possesses the unique technical expertise accumulated over several years of R&D on this specific detector technology. Given the significant investment of both funding and manpower at IN2P3, it would be highly inefficient and detrimental to the project's progress if construction and operation were transferred elsewhere.

The existing organisational structure, illustrated in Figure 10, reflects the collaboration during the R&D phase. It should be noted that CEA, which played an important role during the initial phase with the SPC, will no longer participate in the next stage. Discussions are ongoing with potential new collaborators, particularly from Italy and the UK, whose involvement may contribute to strengthening the project's expertise and international visibility, while preserving the leadership of IN2P3.

IN2P3 teams are highly visible in the community through leading roles in detector design, data acquisition electronics, and low-background techniques. Although installation at LSM does not appear feasible at present, discussions with other underground laboratories such as Boulby and Gran Sasso indicate their willingness to host the detector. In this context, it remains essential to maintain IN2P3's leadership, even if the detector is ultimately located abroad. Continued support and coordination within IN2P3 will be crucial to reinforce this leadership, notably through promotion at international conferences and the establishment of strategic partnerships.

6 Resources

The R2D2 project currently involves four IN2P3 laboratories: LP2i Bordeaux, SUBATECH, LPSC/LSM, and CPPM. Since its inception, the project has grown significantly in terms of human resources, with contributions from both scientific and technical staff. The overall level of engagement is summarised in

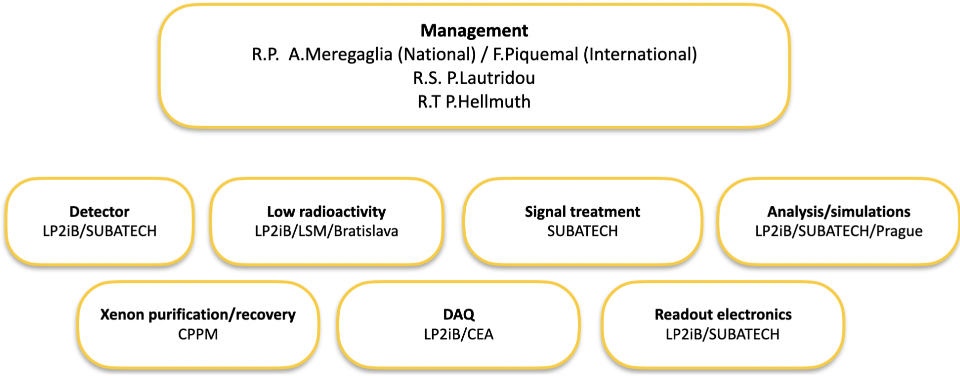


Figure 10: Organisational chart of the R2D2 collaboration during the R&D phase. Note that CEA participation ends at this stage, while Italian and UK groups could join in the upcoming project phase.

Table 1, which shows the annual full-time equivalent (FTE) effort from IN2P3 laboratories and other partners. The decrease in participation from laboratories outside IN2P3 is primarily due to the withdrawal of CEA, which is being gradually compensated by the involvement of new international partners, such as the Bratislava group.

Category	2018	2019	2020	2021	2022	2023	2024
Physicists IN2P3 (FTE)	1.5	1.5	2.6	2.6	3.6	2.6	2.6
ITA IN2P3 (FTE)	0.6	1.8	1.9	2.1	2.4	2.4	1.9
Total IN2P3 (FTE)	2.1	3.3	4.5	4.7	6.0	5.0	4.5
Other labs not IN2P3 (FTE)	0.2	0.2	0.1	0.1	0.1	0.1	0.1
Fraction IN2P3 (%)	91	94	98	98	98	98	98

Table 1: Annual FTE contributions to the project from IN2P3 laboratories and other non-IN2P3 partners over the period 2018–2024. The last row indicates the fraction of the total effort provided by IN2P3 laboratories.

6.1 Human resources

The total IN2P3 contribution has progressively increased since 2018, reaching a peak of 6 FTE in 2022, before declining slightly in subsequent years (Table 1). The contribution from non-IN2P3 partners has remained marginal over the period considered, with IN2P3 consistently accounting for more than 90% of the total effort.

Table 2 details the annual FTE involvement of physicists, including both permanent researchers and PhD students. Table 3 presents the corresponding breakdown for technical and engineering staff (ITA). These data show a balanced and sustained effort from both categories, with strong contributions from LP2i Bordeaux and SUBATECH in particular.

The current level of involvement remains significant in 2023 and 2024, although a reduction is observed after the 2022 peak. While most contributors are already identified within IN2P3 laboratories, sustaining the required effort in the coming years, especially for the operation and characterisation of future prototypes, may require dedicated reinforcement, in particular on the technical side.

6.2 Financial resources

The overall cost of the R2D2 project is estimated at approximately 3 M€, with about 2.4 M€ allocated to the experimental setup and an additional 0.6 M€ for the required argon and xenon gases (natural xenon). The breakdown of these projected costs is summarised in Table 4.

In preparation for the construction of the full detector, a dedicated effort is planned to finalise the selection and characterisation of the materials to be used for the vessel, with particular emphasis on

Name / Lab	Status	2018	2019	2020	2021	2022	2023	2024
LP2i Bordeaux								
CECCHINI Vincent	PhD	-	-	0.5	0.5	0.5	-	-
CHARPENTIER Pierre	PhD	-	-	-	-	1.0	1.0	1.0
JOLLET Cécile	MdC	0.1	0.1	0.1	0.1	0.1	0.1	0.1
MEREGAGLIA Anselmo	DR	0.4	0.5	0.6	0.6	0.6	0.6	0.5
PIQUEMAL Fabrice	DR	0.2	0.1	0.1	0.1	0.1	0.1	0.2
SUBATECH								
CECCHINI Vincent	PhD	-	-	0.5	0.5	0.5	-	-
LAUTRIDOU Pascal	DR	0.6	0.6	0.6	0.6	0.6	0.6	0.6
CPPM								
BUSTO Jose	Prof	0.2	0.2	0.2	0.2	0.2	0.2	0.2
TOTAL (FTE)		1.5	1.5	2.6	2.6	3.6	2.6	2.6

Table 2: Full-time equivalent (FTE) involvement of physicists, including PhD students, from IN2P3 laboratories during the years 2018–2024.

Name / Lab	Status	2018	2019	2020	2021	2022	2023	2024
LP2i Bordeaux								
BOUET Raphael	IE	-	0.4	0.6	0.7	0.6	0.6	0.3
CHIRON Hubert	IE	-	0.5	-	-	-	-	-
CLAVERIE Gerard	IR	-	-	-	0.1	0.1	-	-
DRUILLOLE Frederic	IR	-	0.1	0.2	0.1	0.2	0.2	0.1
FAURE Remi	IE	-	-	-	-	-	-	0.1
HELLMUTH Patrick	IR	-	0.1	0.6	0.6	0.5	0.5	0.2
MANSOUX Bruno	IR	-	-	-	-	-	-	0.4
MUNOZ Francis	IE	0.1	0.2	-	-	-	-	-
ROCHE Mathieu	IR	0.1	0.1	0.1	0.1	0.1	0.1	0.1
THOMAS Bertrand	IR	0.1	0.1	0.1	0.1	0.1	-	-
SUBATECH								
BUI Joseph	T	-	-	-	-	0.1	0.1	-
CADIOU Arnaud	IR	-	-	-	-	-	-	0.1
CHARRIER Didier	IR	-	-	-	-	0.1	0.4	0.2
GUILLAMET Meriadeg	IE	-	-	-	0.2	0.2	-	-
MILLETTO Thierry	AI	-	-	-	-	0.1	0.1	0.1
SIMONNEAU Julien	AI	-	-	-	-	0.1	0.2	0.1
LPSC / LSM								
DASTGHEIBI FARD Ali	IR	0.2	0.2	0.3	0.2	0.2	0.2	0.2
ZAMPAOLO Michel	IE	0.1	0.1	-	-	-	-	-
TOTAL (FTE)		0.6	1.8	1.9	2.1	2.4	2.4	1.9

Table 3: Full-time equivalent (FTE) involvement of ITA staff from IN2P3 laboratories during the years 2018–2024.

Item	**Estimated cost (k€)**
Vessel construction (composite tank)	400
Electronics	50
Cathode and anode	50
Purification system	150
Radon mitigation	300
Recovery and circulation (few L/min)	500
Argon	100
Natural xenon	500
Shielding (provided by underground laboratory)	500
Clean room and electrical infrastructure	100
Miscellaneous (transport, running costs, etc.)	250
Pumping tank	100
Total detector infrastructure (excl. gases)	**2400**
Gases (Ar + Xe)	**600**

Table 4: Estimated cost breakdown for the R2D2 experiment. Values are indicative and may evolve depending on the detector design choices and availability of funding. The shielding is expected to be covered by the hosting underground laboratory.

ensuring their radiopurity and mechanical properties. We ask for 300 k€ over the period 2026–2028 to support this activity. This includes 250 k€ for collaborative work with the IRT Jules Verne aimed at validating low-radioactivity composite materials, and 50 k€ for studies on epoxy surface treatment and degassing. These optimisation tasks are essential to secure the detector performance and long-term operation, but are not included in the estimated 3 M€ construction cost of the full experiment.

In the next three years, the objective is to consolidate and enlarge the collaboration, which is a necessary step to ensure the long-term viability of the project and to build a sufficiently broad base of expertise and manpower (on the order of 100 people) for the construction and operation phases. This evolution will also strengthen the case for securing broader funding from external sources. The 3 M€ construction cost could be fully or partially covered by such sources, including ERC, RI2, regional support, or other national and international programmes. It is expected that the hosting laboratory will contribute the shielding.

7 Technical realisations

The R2D2 project includes the construction of several key components, each relying on well-identified expertise within the collaboration. Most tasks will be carried out internally within IN2P3 laboratories, with some contributions from external partners and possible subcontracting for specific systems. The collaboration focuses its core technical developments on the composite vessel, radon mitigation system, charge readout, simulations, and data analysis, where the main competencies reside. Meanwhile, for other critical subsystems such as gas recirculation and recovery, purification, and calibration, active efforts are underway to identify and engage additional partners, broadening the collaboration and securing the necessary expertise and manpower. The technical developments are based on the results of recent R&D efforts and do not present major risks, with the exception of the vessel construction, which remains the main technological challenge due to the stringent low radiopurity requirements. Although simulations and data analysis remain core strengths of the collaboration, additional support would be beneficial.

Low-radioactivity vessel. The vessel will be developed in collaboration with the IRT Jules Verne, with the aim of producing a composite structure that satisfies both mechanical requirements and stringent radiopurity constraints. Radiopurity measurements will be performed using high-purity germanium (HPGe) detectors at LSM and ICP-MS analyses by collaborators in Bratislava. Continued access to the HPGe detectors at LSM, including technical support at the 0.2 FTE level from LPSC-LSM (in line with current involvement), is essential to this effort.

Charge readout and HV feedthrough. The central resistive anode and high-voltage feedthrough will be developed at SUBATECH, building on the experience and tools acquired during the R&D phase. A dedicated technical effort at the level of 0.5 FTE is required to carry out this work.

ASIC-based readout electronics. Work on the ASIC readout system is ongoing at SUBATECH and will continue over the next two years. Maintaining the current level of technical support (0.3 FTE) is essential to complete the development, although a modest increase would accelerate the effort. The associated readout electronics board will be fabricated at LP2i Bordeaux, where approximately 1 FTE from the electronics service will be needed. This effort will cover not only the design, testing, and production of the board, but also the development of a dedicated data acquisition (DAQ) system to replace the legacy infrastructure that is no longer supported.

Purification, recirculation, and recovery systems. The gas purification system is being developed at LP2i Bordeaux, building on existing prototypes and requiring about 1 FTE from the instrumentation service over the next two to three years for final design, integration, and optimisation. While some aspects of the recirculation and recovery system will draw on internal expertise and experience from previous large-scale xenon experiments, the project seeks collaborations with external partners to strengthen these areas. Elements such as magnetically driven piston pumps or ReStoX-like recovery systems may be subcontracted or provided through international collaborations (e.g., LNGS).

Radon mitigation. A dedicated radon removal system is being developed at CPPM, largely supported until now by an independent ANR grant. For the integration within R2D2, a dedicated technical support of 0.3 FTE would ensure a smooth transition and adaptation to the specific detector requirements.

Manpower needs and collaboration. Overall, the project relies on consolidating and continuing existing technical resources, with moderate increases in specific areas. To expand expertise and capacity, new collaborators are actively sought for simulation efforts, detector optimisation studies, calibration, purification, recirculation, and simulation.

Technological challenges. The technical developments are based on validated designs and do not present major risks. The main technological challenge lies in the construction of a composite vessel achieving a radiopurity of 10 μBq/kg, which remains a key requirement for the success of the experiment.

8 SWOT Analysis

The development of the R2D2 project has been examined through a SWOT analysis, summarised in Table 5. This overview highlights the main internal strengths and weaknesses, as well as external opportunities and threats that may impact the project's success. In particular, the strong physics case, low environmental footprint, and technical maturity constitute important assets. Conversely, the limited size of the current collaboration and the pending validation of the low-radioactivity vessel are challenges that must be addressed. Mitigation strategies include attracting new collaborators, notably early-career researchers, and pursuing targeted testing campaigns to qualify key components. Furthermore, the project's modularity and relatively low cost offer a clear path to scalability and flexibility in future deployment.

Strengths	Weaknesses
– Neutrinoless double beta decay: a key contemporary physics question – Competitive sensitivity at lower cost than large-scale projects – Cryogenics-free, low power consumption, environmentally friendly – Technical know-how already established at IN2P3	– Limited and ageing collaboration – Low-radioactivity composite vessel not yet validated – Few involved laboratories at present
Opportunities	**Threats**
– Possibility of a modular, multi-site deployment – Attract new collaborators and expand international network – Developments with IRT Jules Verne with strong potential for industrial impact, particularly in applications related to gas storage	– Risk of similar concepts being adopted elsewhere – Technology bottleneck: vessel radiopurity – Insufficient resources could delay development

Table 5: SWOT analysis of the R2D2 project: an overview of internal and external factors influencing its development.

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Appendix A Scientific Council Reports

A.1 IN2P3 Scientific Council (October 2018)

NEWS shares with R2D2 the same prototype of a spherical TPC, called SEDINE, installed at LSM, but they are respectively focused on dark matter and on the search for neutrinoless double beta decay. In 2016, the SEDINE prototype operated for a little over one month, showing good performance. The central challenges of spherical TPCs are the development of low-background sensors and the achievement of high energy resolution. The latter is the decisive criterion for the R2D2 programme.

The R&D of R2D2 started in 2017. The international NEWS collaboration, initiated four years ago by CEA and LSM, is structured around an ANR project of the same name covering the period 2015–2019. Four French laboratories with 14 members are involved, including three people from IN2P3 for 1.2 FTE, with the major contribution coming from IRFU.

With regard to R2D2, a long-term strategy with respect to worldwide competition has not yet been proposed, as everything depends on the energy resolution achieved with the current high-pressure prototype. Thus, the competitiveness of the final detector will have to be assessed in perspective with the other experiments under construction at the time of a future council.

A.2 SUBATECH Scientific Council (March 2019)

The Subatech team is composed by only one person whose main contribution to the two projects, NEWS-G and R2D2, is the development of data processing tools for this one channel experiments where the improvement of signal to noise is crucial. It is difficult to defend and support the work of an isolated researcher in a collaboration, even if this collaboration is of a rather small size.

However, the Council considers his work useful and supports his activities, mainly his contribution to NEWS-G. The R2D2 experiment seems to be of the kind of a proof of principle with a very uncertain future. At the same time, it would be desirable that P. Lautridou gets also involved in other activities, that could require his expertise in collaboration with French laboratories.

A.3 LP2iB Scientific Council (May 2023)

The Council congratulates the members of R2D2 for the significant progress made in the R&D. The work carried out since 2017 has led to important and positive developments, with major results obtained from the prototypes. The Council supports the collaboration's pragmatic decision to move towards the cylindrical solution. This marks a very positive evolution of the project, addressing in particular the challenges associated with xenon and high pressure/voltage, while maintaining the original objective of the R&D: building a detector with excellent energy resolution, sufficient isotope mass, and a simple geometry allowing for high radiopurity. A simulation of the cylindrical detector version should be performed as soon as possible to confirm the results from the spherical version, possibly by the Czech colleagues if they join the collaboration. Strategically, it is also necessary to evaluate whether the next step should involve a copper cylinder certified for 40 bar for radiopurity studies, or whether a large composite cylinder is the best intermediate option.

The LP2iB plays a major role in the collaboration, which should continue, although expertise is well distributed across other laboratories. More broadly, it seems important to continue expanding the R2D2 collaboration at the international level. In terms of human resources, all members of the Neutrino team are involved in several projects, so at a minimum, funding for PhD students and postdocs must be planned. Ideally, the next step would be to secure ANR funding.

The Council considers the project mature enough to be presented to the IN2P3 Scientific Council, with the aim of becoming a Master Project R2D2 (no longer an R&D effort).

Appendix B Responses to Scientific Council Questions

Question 1: Have the technical or technological achievements of the R2D2 R&D been clearly identified? What are the conclusions of this R&D, particularly in terms of performance and expected sensitivity?

Answer: The R&D was primarily undertaken to demonstrate the viability of a single-channel radial TPC operated at high pressure and its achievable energy resolution. These objectives have been successfully demonstrated and published [20], with the main outcomes of the R&D detailed in Section 3.1. It was shown that the proposed detector can be stably operated, provided that a sufficiently pure gas is used, a condition that can be ensured with existing purification techniques. It was further established that an energy resolution at the level of 1% FWHM can be achieved. The development of signal processing in ionisation mode enabled clear vertex reconstruction and the potential identification of the two electrons. The main milestones of the programme are summarised in Section 4.1.

Furthermore, the sensitivity of a full-scale experiment based on this technology has been computed, published [26], and is reported in Section 5.1. The projected sensitivity is competitive with that expected from other large-scale experiments, while being achievable at significantly lower cost, both for detector construction and operation, provided that the composite vessel attains the required level of radiopurity. This remains the last open question, for which we are requesting dedicated funding, and will constitute the main focus of the next three years of work in collaboration with IRT Jules Verne.

Question 2: How have these achievements been valorised (publications or otherwise), and how is their transfer within the institute organised with a view to possible future reuse?

Answer: The results have been disseminated at international conferences, workshops, and seminars, and through seven publications over seven years of R&D, as detailed in Section 3.3. We have also participated regularly in the IN2P3 R&D workshops to share results and challenges within the institute network. For example, we highlighted the need for expertise in handling and welding high-pressure equipment, since any preparation requiring certified welding had to be outsourced, even for minor tasks, which increased costs. Today, the institute has acquired the know-how to build and operate the detector, thanks to the physicists directly involved as well as the mechanical and electronic services.

Since the beginning of the project, we have worked on the development of embedded AI on FPGA for signal selection. We benefitted from Bordeaux University IdEx grants (50k€) and a dedicated PhD student. This work triggered the IN2P3 THINK R&T programme.

The development of the new readout electronics is strongly linked to an R&D effort supported at the IN2P3 level, which led to the creation of a custom ASIC based on SiGe BiCMOS technology.

Question 3: What are the current resources and level of involvement of the teams? How is this involvement structured within our laboratories? Is it compatible with the other existing commitments of the teams to other institute projects?

Answer: The involvement of physicists and technical personnel is detailed in Section 6.1. At present, this involvement is compatible with the existing activities of the institute. However, clear planning and formal approval for R2D2 will be required in the coming years. Despite efforts to secure funding (ANR, ERC) and non-permanent personnel (PhD students and PostDocs), without dedicated funding and long-term support there is a risk that team members may be reassigned to new projects or increase their commitments to existing ones, which could weaken R2D2 and jeopardise its success if funding is obtained only at a later stage.

Question 4: What is the current standing of this proposal for neutrinoless double beta decay measurements (choice of isotope and technology), and how does it compare in terms of competitiveness, ability to bring together an international community, sensitivity, timeline, and maturity level, within the international context described above?

Answer: The choice of xenon as the target isotope is well motivated. Xenon is relatively easy to enrich in ^{136}Xe and has already been selected for large-scale experiments such as KamLAND-Zen and nEXO, confirming its suitability for competitive searches. Today, more than one tonne of enriched ^{136}Xe exists worldwide. The recent decision in the United States to halt the nEXO project may create an opportunity for R2D2 to attract additional interest and possibly new international partners.

From the technological perspective, the R2D2 concept combines competitive energy resolution, scalability, and the potential for background suppression through a minimal material budget and topological discrimination. These features make it a credible and competitive option within the international landscape. A more detailed comparison with ongoing projects in terms of competitiveness, sensitivity, timeline, and maturity level is provided in Sections 2 and 5.

Question 5: Taking into account the available resources and strengths, what scientific outcomes and impact can be expected?

Answer: The potential scientific impact of R2D2 is high. The project can achieve sensitivities on a timeline competitive with other international experiments, at significantly lower cost and with reduced environmental impact, with the specific advantage of two-electron identification (see Section 3.1.4). Achieving this goal, however, requires appropriate resources. In particular, sustained manpower at the current level, with a slight reinforcement within IN2P3, is essential, together with the establishment of a genuine international collaboration, for which we are actively giving seminars in different countries and contacting various collaborations worldwide.

In addition, guaranteed funding is needed to demonstrate the radiopurity of the composite vessel and to proceed to the construction of a low-background detector. Without adequate support for this transition from R&D to a full experiment, the project cannot realise its potential. Conversely, if these conditions are met, R2D2 has the capacity to deliver a major scientific return for the community.