DRD2: Liquid Detectors v5

J. Asaadi[c], W. M. Bonivento[n], J. I. Crespo-Anadón[e], C. Cuesta[e], A. Deisting[d], J. E. Y. Dobson[q], G. Fiorillo[f], D. Franco[p], E. Gramellini[a], R. Guenette[a], M. Kuźniak[m], J. Martin-Albo[l], K. Mavrokoridris[j], J. Monroe[b], M. C. Piro[h], F. Retière[i], R. Santorelli [e], S. Schoppmann[d], H. Th. J. Steiger[d], A. M. Szelc[g], M. Wurm[d], M. Yeh[k], A. Zani[o]

a: University of Manchester, United Kingdom

b: University of Oxford, United Kingdom

c: University of Texas Arlington, United States

d: Johannes Gutenberg-Universität Mainz, Germany

e: Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Spain

f: Università degli Studi di Napoli "Federico II" & INFN Sezione di Napoli, Italy

g: University of Edinburgh, United Kingdom

h: University of Alberta, Canada

i: TRIUMF, Canada

j: University of Liverpool, United Kingdom

k: Brookhaven National Laboratory, United States

l: Instituto de Física Corpuscular (IFIC), CSIC & Universitat de València, Spain

m: Astrocent, Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences, Poland

n: INFN Sezione di Cagliari, Italy

o: INFN Sezione di Milano, Italy

p: APC, Université de Paris Cité, CNRS, Astroparticule et Cosmologie, France

q: King's College London, United Kingdom

6th December 2023

Contents

1 Introduction

Liquid scintillator targets have been used since the 1950s for the discovery of neutrinos and today are widely used in particle and nuclear physics experiments. Current physics applications of liquid detectors are in the domain of rare event searches, addressing fundamental open questions in science today across neutrino physics, dark matter searches and astro-particle experiments. Liquid detectors primarily employ target media of water, liquid scintillator, or cryogenic noble liquids, notably liquid argon (LAr), xenon (LXe) and helium (LHe). The objectives of this Detector R&D (DRD) Collaboration are to advance the four detector R&D themes (DRDTs) for liquid detectors that have been identified in the framework of the ECFA Detector R&D Roadmap. These are:

- **DRDT 2.1 - Develop readout technology to increase spatial and energy resolution for liquid detectors.** Developments should achieve readout of more highly-pixellated detectors with greater photon collection capabilities, increased quantum efficiency, and higher granularity.
- **DRDT 2.2 - Advance noise reduction in liquid detectors to lower signal energy thresholds.** The physics goals of future liquid detectors require lower sensor and electronics noise, as well as developments to measure simultaneously more components of the energy partition: i.e. light, charge and heat.
- **DRDT 2.3 - Improve the material properties of target and detector components in liquid detectors.** R&D on material properties for liquid detectors aims to improve the emission properties of the target, for example through doping of Xe in Ar, H in Xe, Gd in H_2O, Xe, Te and Gd in liquid scintillator, and to achieve lower radiogenic backgrounds from the detector components, via target purification, material radioassay, and cryogenic distillation to change isotopic or atomic content.
- **DRDT 2.4 - Realise liquid detector technologies scalable for integration in large systems.** Dedicated developments should achieve applications of the previous DRDTs in future detectors 10-100$\times$ larger than the current state-of-the-art, with detector sensor areas reaching 10, 100 and ultimately $1000\,\mathrm{m}^2$. This is a steep change in complexity for liquid detectors, with decade-long construction, in underground or undersea environments, with value engineering for industrial production.

This proposal articulates the planned collaborative activities across the community engaged in liquid detectors R&D, developed through the series of ECFA Roadmap Implementation Workshops and community consultation activities throughout 2021-23. Section 2 describes the collaboration's R&D plans in the key Working Packages of charge readout, light readout, target properties optimisation and scaling-up challenges. Common test facilities and software tools are described in section 3. Section 4 summarizes opportunities for industrial collaboration and partnerships. Section 5 describes the networking and training plans of the collaboration, and section 6 proposes a structure for the Liquid Detectors DRD Collaboration. The resources, both requested and existing, associated with the planned activities are listed in section 7.

2 Planning of Work Packages

2.1 Work Package 1: Charge Readout

Work Package 1 addresses **DRDT 2.1 - Develop readout technology to increase spatial and energy resolution for liquid detectors** and **DRDT 2.2 - Advance noise reduction in liquid detectors to lower signal energy thresholds**. The objectives of Work Package 1 are to develop novel approaches to charge readout.

There are different approaches to charge readout that involve significantly different techniques. The three tasks that have been formed each address a specific aspect of charge readout. These are:

- **Task 1.1:** Pixels and Multiple Modality Readouts. This addresses direct readout of the ionization electrons characteristic of noble element detectors and combining the charge readout with other signal types such as light or heat.
- **Task 1.2:** Charge to light conversion, electroluminescence and charge amplification. This addresses the technologies that amplify the ionization electrons by converting the charge into light via different mechanisms. These processes results in light signals that are readout by photon detection technologies.
- **Task 1.3:** Ion Detection. By association with the creation of ionization electrons, the produced positive ions can also be readout. The slow diffusion of these heavy ions is not strongly impacted by diffusion effects, contrary to the ionization electrons, leading to significantly improved spatial resolutions. Furthermore, the detection of ions produced in decays (such as double beta decays) could lead to background-free experiments if the daughter ion is detected in coincidence with the ionization electrons. While there are some activities in these research areas, the efforts are not yet at the level to form a task group. This topic also directly overlaps with DRD1, where ion detection in gas has more involvement. Current efforts will be targeted by DRD1 and not be represented in DRD2 at the moment.

Goals	Deliverables	Timeline of milestones and major deliverables				
		Milestones 2024	Milestones 2025	Milestones 2026	Milestones 2027-2030	> Milestones 2030
WP1: Charge Readout						
T1.1: Pixels and Charge + Light Readouts						
T1.1.G1: Design a fC charge sensing pixel readout optimized for low energy detection and minimized power consumption.	T1.1.G1.D1 Prototype of lower pixel thresholds to the limit of CMOS capabilities (2027).	M1.0 Lower threshold to $\mathcal{O}(1000\,\mathrm{ENC})$	M1.1 Lower threshold to $\mathcal{O}(500\,\mathrm{ENC})$		M1.2 Lower threshold to $\mathcal{O}(< 200\,\mathrm{ENC})$	M1.3 Push threshold down to $\mathcal{O}(< 100\,\mathrm{ENC})$
	T1.1.G1.D2 Prototype of lower power consumption (2027)	M2.0 Lower power to $\sim$100 µW/ch	M2.1 Lower power to 50-100 µW/ch		M2.2 Lower power to <50 µW/ch	
T1.1.G2: Design of a scale-up pixel readout with $\mathcal{O}$(100 million) channels	T1.1.G2.D1 Design of a pixel readout with $\mathcal{O}$(100 million) channels (2030)	M3.0 Design demonstration of $\mathcal{O}(10^5)$	M3.1 Design demonstration of$\mathcal{O}(10^6)$		M3.2 Design demonstration of$\mathcal{O}(10^7)$	
T1.1.G3: Design of an architecture capable of capturing multimodal signals	T1.1.G3.D1 Design of maximal photocathode coverage and QE in an integrated fC charge and VUV light sensing scheme for pixel TPCs (2030)	M4.0.0 Complete simulation of embedded photodetector technology M4.1.0 Measurement low γ flux in ASe horizontal geometry M4.2.0 Prototype of ASe vertical geometry M4.3.0 Report on organics & ZnO viability M4.4.0 Integrated Pixel/SiPM demonstrations (SoLAr)	M4.0.1 Full simulation package for multiple modality pixels M4.4.1 Small scale prototype for embedded photodetector technology	M4.1.1 Design of joint readout scheme for ASe horizontal geo M4.2.1 Measurement at low γ flux in ASe vertical geo M4.3.1 Report on other material viability (Perovskites, Nanoplatelets, etc)	M4.1.2 Small scale prototype ASe horizontal geo M4.2.2 Design of joint readout scheme & small scale prototype for ASe vertical geo M4.3.2 Measurement at low γ flux in perovskites & nanoplatelets M4.4.2 Publication of performance for embedded photodetector technology	M4.123.3 Mid-scale prototype for multiple modality (data taking and validation) M4.4.3 Mid-scale prototype for pixel embedded photodetectors (data taking and validation)
	T1.1.G3.D2 Design of a novel fast (O(GHz)) clock/timing architectures for charge & Q+L readout (2030)	M5.0 Design and prototype 50 MHz frequency	M5.1 Design and prototype 100 MHz frequency	M5.2 Design and prototype 500 MHz frequency	M5.3 Design and prototype 1 GHz frequency	
T1.2: Amplification structures, charge to Light conversion, and granular light readout of dual phase detectors						
T1.2.G1: Granular S2 light	T1.2.G1.D1: Prototype demonstrating camera-based particle tracking (2030)	M6.1 First tests of photosensitive TPX4 cameras	M6.2.1 Test of prototype TPC with TPX4 camera M6.2.2 Design of VUV optics	M6.3 Tests of integrate VUV image intensifier and TPX4 camera	M6.4.1 Tracking tests, assessment of physics capability of long TPX4 camera TPC runs	M6.5.1 Scalability demonstration of TPX4 camera TPC readout M6.5.2 Report on R&D results towards experimental implementation of a TPx4 readout TPC
	T1.2.G1.D2: Prototype demonstrating SiPM-based particle tracking (2030)				M7.0 Demonstration of mm tracking and sub-resolution percent energy resolution	
	T1.2.G1.D3: Report on camera-based S1 detection (2030)				M6.4.2 Demonstrate S1 detection with a TPX4 camera using WLS-coated GEMs or S2 induced by S1 via the photo-electric effect	
T1.2.G2: Optimisation and characterisation of charge amplification structures	T1.2.G2.D1: Report on novel devices to for charge amplification in dual-phase detectors (2027)		M8.1 Prototype demonstrating single electron sensitivity using novel amplification structures	M8.2.1 Report on the optimisation of large-area cryogenic glass thick GEMs M8.2.2 Demonstrate ER/NR discrimination; M8.2.3 Demonstrate the feasibility of new techniques to generate intense proportional scintillation		
	T1.2.G2.D2a: Design of a charge-to-light conversion stage for single-phase LXe detectors with a scalable technology (2029)			M9.1 Demonstrate single electron sensitivity using novel electroluminescence structures	M9.2.1 Demonstrate ER/NR discrimination M9.2.2 Design of a m^2-scale testing device for the developed structures M9.2.3 Development of integration techniques for m^2-scale (and beyond) electroluminescence structures testing	
	T1.2.G2.D2b: Prototype of a single-phase LAr charge amplification stage allowing low energy particle detection (2027)		M10.1 Demonstrate stable charge amplification	M10.2 Demonstrate sub-keV detection threshold		
	T1.2.G2.D3: Report on the feasibility of novel amplification strategies for single- and mixed-phase detectors (2026)		M11.1 Report on the feasibility of LAr/LXe 10 l scale detector with bubble-assisted amplification and/or electroluminescence			
T1.2.G3: Demonstration of the scalability of the technologies developed in T1.2.G1 and T1.2.G1	T1.2.G3.D1: Report on LAr / dual phase Ar large scale tests with TPX readout (2030)			M12.1 Demonstrate large-area imaging with TPX4 camera readout in protoDUNE	M12.2 Evaluate tracking and physics capabilities in protoDUNE runs	
	T1.2.G3.D2: Report on large scale tests with a single-phase LXe and dual-phase Xe charge-to-light conversion stage (2030)		M13.1 m^2-sized demonstrator of a dual-phase LXe electroluminescence stage	M13.2 m^2-sized demonstrator of a single-phase LXe electroluminescence stage	M13.3 Report on the scalability to several m^2 scale	M13.4 Design for possible experimental implementation of larger than m^2-sized dual or single-phase LXe electro-luminescence structures

Table 1: Deliverables and milestones of WP1: Charge Readout.

The initial deliverables and milestones of this Work Package, for Tasks 1.1 and 1.2, are defined and mapped to the community's current involvements and further aspirations in Table 1.

The estimated FTE and non-FTE resource required to carry out the planned R&D activities are summarized in tables 10 and 11 in section 7, respectively.

The DRD2 focus for Tasks 1.1 and 1.2 is primarily on deployment of readouts within liquid nobles. The main cross-cutting topics within this Work Package include electronics development for these readouts, which is addressed within DRD7 (liaison E. Gramellini). Task 1.3, ion detection, while is important and has some promising potential, it is not currently represented in the DRD2 proposal but will probably be in the future. Furthermore, some topics related to ion detection in gas are currently covered in DRD1 (liaison K. Mavrokoridis).

2.1.1 Task 1.1: Pixels and Charge + Light Readouts

The Task 1.1 leaders are J. Asaadi (University of Texas Arlington) and E. Gramellini (University of Manchester), in collaboration with the institutes listed for the deliverables of DRDT1.1 in table 2.

Institute	**PI**	**T1.1**			**T1.2**		
Deliverable		**G1**	**G2**	**G3**	**G1**	**G2**	**G3**
T1.1: Pixel and Charge + Light Readouts							
CIEMAT	Gil-Botella			×			
Fermilab	Blaszczyk	×		×			
INFN Napoli	Fiorillo			×			
ORNL	Demarteau, Febbraro	×	×	×			
UC Santa Cruz	Abbaszadeh			×			
University of Bern	Weber	×	×	×			
University of Granada	Garcia-Gamez, Sanchez	×	×	×			
University of Hawaii	Nishimura, Varner	×	×				
University of Manchester	Gramellini, Guenette, Soldner-Rembold	×	×	×	×		
University of Milano-Bicocca	Terranova			×			
University of Pennsylvania	Mauger, Newcomer, Van Berg	×	×				
University of Texas at Arlington	Asaadi	×	×	×			
Wellesley College	Battat	×	×				
T1.2: Amplification structures, charge to Light conversion, and granular light readout of dual phase detectors							
Freiburg	Schumann					×	×
JGU Mainz	Deisting				×	×	×
LIP-Coimbra	Chepel					×	
Liverpool	Mavrokoridis				×	×	×
LPNHE	Scotto Lavina					×	×
Manchester	Guenette				×		
NIKHEF	Colijn					×	
USC	Gonzalez Diaz						×
UC Riverside	Westerdale					×	×
UC Santa Barbara	Caratelli					×	
Weizman	Breskin				×	×	

Table 2: Collaborating institutes on the deliverables of WP1: Charge Readout. Deliverables are defined in table 1.

Scientific motivation and context: The detection strength of noble liquid time projection chambers (TPCs) hinges on the correlated emission of ionization charge and scintillation light. Fine grained, large scale pixelated TPCs with enhanced light collection capabilities would enhance the fidelity of event reconstruction of accelerator neutrinos interactions, and allow for lower energy detection thresholds to explore signatures from dark matter (DM), supernova and solar neutrinos. Compared to traditional wire designs, pixel-TPCs offer advantages [1, 2] of robustness against single point failure, simplicity of construction, and lower electronic noise levels. A benefit of pixelated readouts is the native 3D nature of the data, where the charge readout segmentation coincides with the physical spatial segmentation. Preliminary studies comparing pixelated and wire readouts for GeV-scale accelerator neutrino interactions, as well as low energy neutrinos from a supernova burst, demonstrate significant improvements in efficiency and purity of ν_e and ν_μ identification [3]. High-efficiency VUV photon detection is necessary to push the detection threshold at low energy for solar or DM events. Key R&D areas to make large scale-pixel TPCs a reality are: designing a femto-Coulomb charge readout optimized for low energy detection with minimal power consumption, designing an architecture capable of hosting order of 100 million channels and capable of capturing both charge and light (multimodal signals).

Proposed Research: for this proposal period, the activities planned are in the following main areas.

Charge Readout at kTon scale. The Q-Pix concept proposes a tiling scheme with an array of low-power, self-triggering pixel detectors designed to meet the scalability challenge. Q-Pix readout is based on using pixel-scale self-triggering 'charge integrate/reset' (CIR) blocks with local clocks running with unconstrained frequencies and dynamically established data networks. Strings of reset-timestamps are transmitted periodically out of the tile and a linear transformation from local clock frequency to central master clock allows recovery of the universal time. ΔQ over timestamps differences define the current seen by the pixel. The design of the Q-Pix tile and the network between the "N" ASICs will be built to make it intrinsically fault-tolerant and robust to possible failure modes. Each ASIC on the tile will have signal sensing, self-triggering, local clock, time-stamping, buffering, input/output, and state machine capabilities. Preliminary studies suggest the power consumption of such a readout is as low as 20 μW and the quiescent data rates for kiloton scale detectors is less than 100 MB s^{-1}.

Light Readout with Embedded Photodetectors (SoLAr) In the SoLAr detector concept, the proposed approach is to record charge and light monolithically by an integrated all-silicon anode plane. The light detection system is based on SiPMs with charge collection pads on the same unit. The unit corresponds to one photon detection readout channel and four charge readout channels. Units are assembled to tiles of 32 cm × 32 cm with 50 × 50 full silicon units. This detector element will be tested at prototype level, and then integrated in $\mathcal{O}(\mathrm{m}^2)$ area readout planes for SoLAr. A mid-scale prototype will be deployed at the Boulby Underground Laboratory.

Light Readout with Multiple Modality Pixel (MMP) Multiple modality pixels simultaneously read out both light and charge on the same pixel, providing a granular light detection system and near-complete photocathode coverage without augmenting the number of readout channels. The proposed approach is to develop photo-sensitive coatings with targeted QE $\geq$ 80% applied to a modified charge-readout pixel geometry. Work on amorphous selenium based horizontal windowless devices [4, 5] has recently demonstrated the viability of this material as basis for VUV photosensors in LArTPCs. However, several different photosensitive materials (perovskites, nanoplatelets, organic and amorphous semiconductors) and sensor geometries (windoless horizontal or vertical devices) offer opportunities for improvement. A prototype phase will see the development of cryo-resistant photon detectors sensitive to 128 nm and 178 nm light, charge and light readout integration, and a comparative performance characterization in a common testing platform to optimize detector QE and noise. The next phase of the project will build a $\sim$m^3 demonstrator for deployment at the SNS and subsequently at the CERN neutrino platform.

Overall Goals: **T1.G1:** Design of a fC charge-sensing pixel readout optimized for low energy detection and minimized power consumption.
T1.G2: Design capable of scaling of pixel readout to O(100 million) channels. **T1.G3:** Design of an architecture capable of capturing multimodal signals.

2.1.2 Task 1.2: Amplification structures, charge to light conversion, and granular light readout of dual-phase detectors

The Task 1.2 leaders are K. Mavrokoridis (University of Liverpool) and A. Deisting (Johannes Gutenberg Universität Mainz – JGU Mainz); in collaboration with the institutes listed for the deliverables of T1.2 in table 2.

Scientific motivation and context: Charge amplification and conversion to light in dual-phase TPCs has been key to reaching unprecedented sensitivities in the search for dark matter (DM) candidates, in argon [6] and xenon [7, 8] targets. In a dual-phase TPC, ionisation electrons produced when a particle deposits energy in the detector are extracted to the gas phase, allowing signal amplification similarly to gaseous detectors. Typically, a wire mesh or grid is positioned above the liquid-gas interface so that electroluminescence (EL) light (termed the S2 signal) is developed in a uniform electric field between the liquid surface and the electrode. This amplification of the ionisation electron signal allows measurement of interaction energies below 1 keV, as compared to current single-phase liquid TPCs with a 30× higher energy threshold [9]. There is scope for improvement with micro-pattern gaseous detectors (MPGD) positioned in the gas phase to achieve further charge multiplication and secondary scintillation. Gaseous electron multipliers (GEMs) and thick GEMs (THGEMs) are some of the most recent developments within the field of MPGDs; these have proved important for their simplicity and effectiveness, and can be made radio-pure [10]. R&D plans in the next 3-5 years include optimization studies of manufacturing very large area GEMs for cryogenic operation, increasing light production from avalanche electron multiplication in hole multipliers operated in cryogenic Xe and Ar vapour, the development of cryogenic resistive materials to improve detector stability, exploration of electrochemically etched meshes and grids, and development of new amplification structures (*e.g.* [11]) to maximize the active volume. The last point is of particular importance for dual-phase xenon TPC with a mass of several $\sim$10 t given the price of Xe.

Single phase TPCs offer an attractive alternative to mitigate some of the constraints of dual-phase TPCs, in which amplification in the gas phase above the liquid restricts possible detector layouts, requires precise control of the liquid level between electrodes, and ever-higher cathode voltages are needed for subsequent generations of larger experiments. Single-phase TPCs can tackle this challenge by splitting the detector volume in several sub-TPCs with shorter drift volumes, but currently there are no reliable and scalable approaches to amplify electrons by producing S2 light or by charge amplification in the liquid. Amplification is needed to lower the energy threshold for particle detection to a level competitive with dual-phase TPCs, and thus research on amplification stages for single-phase detectors has attracted great interest – e.g. [12–14]. There are also 'hybrid' approaches which aim at creating gas pockets at specific locations in the liquid ("bubbles"), which would allow to build dual-phase detectors, where the gas phases can be placed anywhere in the active volume [15].

Proposed Research: for this proposal period, the activities planned are in the following main areas.

Granular S2 light readout of ionisation charge An active area of R&D in LAr TPCs is to capture the amplified secondary scintillation light by high spatial resolution and speed cameras, for example the TPX3

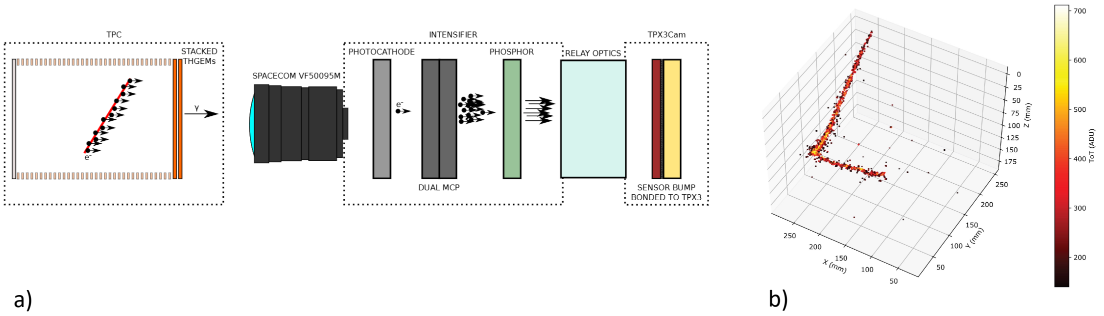

Figure 1: a): Optical TPX camera based TPC detection principle. b) A stopping muon liquid argon interaction as imaged with a TPX3 camera mounted on the 1-ton ARIADNE detector. Images taken from [16, 17]

cameras employed by the ARIADNE 1-ton and ARIADNE+ 15-ton liquid argon TPCs operated at the CERN neutrino platform [16–18]. The raw data from TPX3 cameras are natively 3D and zero suppressed, thus providing a straightforward event reconstruction as illustrated in Figure 1. With appropriate lenses on the front of the camera a large area can be imaged (*i.e.* $1\,\mathrm{m} \times 1\,\mathrm{m}$ at 4 mm/pixel resolution) creating a very cost effective system for large scale detectors. Near-future R&D proposes optimisation and characterisation of next-generation TPX4 cameras within liquid argon TPCs, to explore alternative approaches by imaging S2 light with an array of SiPMs, and a combined development of SiPM arrays and cameras to achieve mm^2 tracking with sub-percent energy resolution. The possibility of detecting S1 light with cameras will also be explored. (The S1 signal is the light produced during the primary interaction of a particle in the liquid.) This R&D line aims to study the scaling of this technology by integrating large amplification structures (i.e. glass THGEMs) and granular S2 light camera systems in the ProtoDUNE cryostat at CERN. This would provide confirmation of the applicability of the new technologies for the kton scale planned neutrino experiments. Synergies with other complimentary technologies requiring also very large scale testing in the ProtoDUNE cryostat are foreseen.

Optimisation and characterisation of charge amplification structures R&D plans include the development of novel EL structures for dual phase detectors – *e.g.* floating THGEMs [11], thin pillars on aligned meshes or, novel micro-structures; the development of amplification stages producing EL in LXe, and such stages producing EL and/or charge multiplication in LAr; and, mixed phase detectors relying on bubble creation. The foreseen application for these liquid detectors are DM experiments and the measurement of CEνNS (Coherent elastic neutrino-nucleus scattering), hence the resulting prototype detectors relying on EL will need to demonstrate single electron sensitivity, the capability to discriminate between energy deposits due to nuclear and electron recoil, and then the scalability of the adopted technologies. The feasibility of large amplification stages ($\mathcal{O}(\mathrm{m}^2)$ to $\mathcal{O}(10\,\mathrm{m}^2)$) will be demonstrated from 2025 onwards. Possible facilities are NUXE, a 100 kg scale LXe/LAr test facility at UC San Diego (US), and the PANCAKE (*cf.* [19]) detector development platform located at the University of Freiburg, Germany, (400 kg LXe).

Overall Goals: **T1.2.G1:** Publication on demonstration of granular S2 light readout of ionisation charge in TPC, following milestones in table X (give year after funding start when achieved); **T1.2.G2:** Report on characterisation of optimised charge amplification structures, following the milestones in table X (give year after funding start when achieved); **T1.2.G3:** Demonstration of scalability of D1 and D2 [in mid-scale prototype TPC] (give year after funding start when achieved)

2.2 Work Package 2: Light Readout

Work Package 2 addresses **DRDT 2.1 - Develop readout technology to increase spatial and energy resolution for liquid detectors** and **DRDT 2.2 - Advance noise reduction in liquid detectors to lower signal energy thresholds**. The objectives of Work Package 2 are to develop advances in light readout for liquid detectors. The key tasks are:

- **Task 2.1:** Increased sensor quantum efficiency. This effort is targeted at efficiency in the VUV and at cryogenic temperatures.
- **Task 2.2:** Higher efficiency wavelength shifting (WLS) / collection. The wavelength shifting is to address the conversion of VUV light from noble element scintillation to visible light, where sensors are more efficient. The increase in light collection targets both the VUV and visible light (post wavelegnth shift).
- **Task 2.3:** Improved sensors for liquid scintillators (LS)/Water. This topic covers developments that directly overlap with DRD4, as it targets visible light at room temperatures. The task is defined for the purpose of coordinating the efforts with DRD4 for the applications to Liquid Detectors and is not formally formed here.

Goals	Deliverables	Timeline of milestones and major deliverables				
		Milestones 2024	Milestones 2025	Milestones 2026	Milestones 2027-2030	Milestones >2030
WP2: Light Readout						
T2.1: Increased Sensor Quantum Efficiency						
T2.1.G1: Sensor optimisation	T2.1.G1.D1 Design optimisation for low-noise, high fill-factor (2027)	Digital SPAD design	Digital SiPM design	SIGHT and SiPMs for full wavelength range coverage development	organic photosensors prototypes available	
	T2.1.G1.D2 Purpose-optimised coatings for LAr/LXe wavelengths (2028)	reflectivity reduction strategies exploring graphene	narrowband coatings optimised for VUV	VUV characterisation measurements of prototypes	novel coatings materials development and characterisation	
	T2.1.G1.D3 Report on optimised surface passivation for VUV (2029)		apply BSI-CCD passivation strategies	device integration of samples	PDE characterisation measurements	
T2.1.G2: detector integration optimisation	T2.1.G2.D1: Report on demonstration of 2D/3D integration processes (2026)	Demonstrated 2D/3D integration process for FSI-SPADs	Cryogenic PDE characterisation	Demonstrated 2D/3D integration process for BSI-SPADS achieving low noise	optimisation for ultra-low radioactivity	
	T2.1.G2.D2: Prototype of cryogenic SiPMs with enhanced PDE, reduced noise and connectivity for 3D integration (2028)	Development of FSI SiPMs with medium-to-fine pitch TSVs; Start of development of BSI SiPM. Study/improvement of correlated noise in FSI/BSI SiPMs at cryogenic temperatures.	Optimize for cryogenic compatibility of FSI SiPMs with TSVs; Development of BSI SiPM. Study/improvement of correlated noise in FSI/BSI SiPMs at cryogenic temperatures.	Study/improvement of correlated noise in BSI SiPMs at cryogenic temperatures.	addition of VUV surface passivation to BSI and characterization	
	T2.1.G2.D3: Prototype of cryogenic SPAD and readout electronics technology on a commercial CMOS foundry (2030)	Sensor design of a prototype mini-SiPM pseudo-matrices and front-end readout electronics using LFoundry LF11is technology	Tapeout preparation of CMOS test structures; design of PCB carriers for characterisation	Characterisation activities	Design of a full-scale sensor matrix and readout electronics tier; hybrid 3D stacking of sensor and electronics	
	T2.1.G2.D4: Segmentation optimised for measurement strategy (2028)	PIONEER facility development	measurements in LXe/LAr	Characterization of the optical segmentation impact on energy resolution	Simulation benchmarking using LoLX; compare Opticks and Chroma performance; PIONEER run at high energy (70 MeV).	
T2.1.G3: characterisation facilities for VUV	T2.1.G3.D1 PDE vs. λ,T measurement (2026)		Liverpool & Napoli cryogenic PDE measurement facilities construction CIEMAT cryogenic characterisation facility development	measurements at access facilities programme operational		
	T2.1.G3.D2: Report on sensor noise characterisation (2028)	Microscope for Injection and Emission of Light (MIEL) operation at TRIUMF	study of noise burst / rare events (potentially attributed to package and / cosmic rays)	RAL PPD SiPMs/fibres & Oxford & Zurich LAr/LXe characterisation operational	measurements at access facilities programme operational	
	T2.1.G3.D3: Paper on rare-event search qualification (2030)	BUTTON underground sensor test facility in water/scintillation construction	Nikhef SiPM and materials characterisation facility development	SoLAIRE underground sensor test facility m in LAr/LXe development	underground measurements access facility programme operational	
WP2.2: Wavelength shifters and increasing light collection						
T2.2.G1: Better scalable wavelength shifters and reflectors	T2.2.G1.D1: Technical report of optimized WLS (2030)	Optimal WLS candidates selected (for water and noble liquids)	Polymeric WLS synthesis optimized; Broader WLS survey completed	WLS characterization facility commissioned; Determined solubility/long term stability	Polymeric WLS production scaled-up to $\mathcal{O}(100\ \mathrm{m}^2)$; Stable WLS solution for LXe demonstrated;	WLS and WLS-reflector production and installation scaled up to $\mathcal{O}(1000\ \mathrm{m}^2)$
	T2.2.G1.D2: Construction of 4π evaporation source (2030)	Prototype commissioned	Test 4π TPB coatings characterized; Understood performance of large-scale WLS	Final 4π evaporator design ready	4π evaporation crucible constructed and tested	
T2.2.G2: Optimized light collectors and concentrators	T2.2.G2.D1: Design report of VUV light collectors at cryogenic temperatures (2028)	Design and construction of testing facility; simulation of proposed concepts	Commissioning of the facility; prototype collectors built	Full characterization of prototype collectors at testing facility	Proposal for X-ARAPUCA optimization	
	T2.2.G2.D2: Design report of WLS-fiber-based light readout for liquid scintillator (2030)	Design and construction of testing facility	Commissioning of testing facility; prototype readout built	Full characterization of prototype readout at testing facility	Proposal for light collection optimization	
	T2.2.G2.D3: Prototype of novel flat light concentrator for the VUV (2030)	Report on proposed concentrator concepts	Adhesion/durability of WLS coatings in water; Directional WLS metasurface: proof of concept	Development of flat light concentrators: proof of concept	Large-scale light concentrator based on metasurfaces or flat light concentrators	

Table 3: Deliverables and milestones of WP2: Light Readout.

The initial deliverables and milestones of this Work Package are defined and mapped to the community's current involvements and further aspirations in table 3.

The estimated FTE and non-FTE resource required to carry out the planned R&D activities are summarized in tables 10 and 11 in section 7, respectively.

The main cross-cutting topics within this Work Package include electronics development for these readouts, which is addressed within DRD7 (liaison: E. Gramellini). The DRD2 focus here is primarily on the sensor development for cryogenic detectors within task 2.1, whilst the DRD7 focus is on the development of the front end electronics themselves, and the area where we envision close collaboration in particular with DRD7.4 (cryogenic ASICs) and DRD4.3 is on integration developments. Task 2.3, sensor improvement for liquid detectors, is covered within DRD4 (liaison F. Retiere), by agreement of the DRD proto-collaborations.

2.2.1 Task 2.1: Increased sensor quantum efficiency

The Task 2.1 leaders are J. Monroe (Oxford), F. Retière (TRIUMF), and P. Agnes (GSSI), in collaboration with the institutes listed for the deliverables of T2.1 in table 4.

Institute	**PI**	**T2.1**			**T2.2**	
Deliverable		**G1**	**G2**	**G3**	**G1**	**G2**
T2.1: Increased Sensor Quantum Efficiency						
Astrocent	Kuźniak	×				
BUTTON consortium	Coleman			×		
CIEMAT	Cuesta/Palomares			×		
FBK	Gola	×	×	×		
GSSI	Agnes	×	×			
INFN Torino	da Rocha Rolo	×	×			
INFN Napoli	Fiorillo			×		
Nikhef	Pollmann			×		
Open University	Skottfelt	×				
PIONEER consortium	Malbrunot		×			
RAL/STFC Interconnect	Lipp	×	×	×		
TRIUMF	Retiere	×	×	×		
University of Coimbra	Matias	×				
University of Heidelberg	Fischer	×	×			
University of Liverpool	Vossebeld	×	×	×		
University of Manchester	Price	×		×		
RAL PPD	Shepherd-Themistocleous			×		
Royal Holloway	Monroe	×		×		
Royce Institute	Parkinson	×				
Universite de Sherbrooke	Pratte	×	×			
University of Texas, Austin	Asaadi	×				
University of Zurich	Baudis			×		
T2.2: Higher efficiency WLS/collection						
Astrocent	Kuźniak				×	
CIEMAT	Gil-Botella/Cuesta					×
Edinburgh	Szelc				×	
Fermilab	Escobar					×
IFIC	Martín-Albo					×
INFN Napoli	Fiorillo				×	×
LIP Coimbra	Silva				×	
Manchester	Guenette					×
Nikhef	Pollmann				×	
Sussex	Hartnell					×
TUM	Schönert				×	
University of Zurich	Baudis				×	
York	Krauss					×

Table 4: Collaborating institutes on the deliverables of WP2: Light Readout. Deliverables are defined in table 3.

Scientific motivation and context: LXe and LAr emit in the challenging VUV wavelength range, where quantum efficiencies in PMTs are lower than for optical wavelengths. LXe experiments detect the emitted 178 nm light, where Hamamatsu photo-multiplier tube technology today achieves a maximum of ∼35% quantum efficiency (in the R12699-406-M4), with dark noise rate around $0.2\,\mathrm{Hz\,cm^{-2}}$, after-pulsing around 2% and transit time spread (single photon timing resolution) of 5.9 ns (FWHM). Silicon photo-multiplier (SiPM) approach these performances with the current state-of-the-art being the FBK VUV-HD3 and Hamamatsu VUV4 MPPC [20]. The best quantum efficiency achieved in this technology at 178 nm is 20-25%, with the dark noise rate around $10\text{-}50\,\mathrm{Hz\,cm^{-2}}$ at LXe temperature dropping down by a factor of 10 at LAr temperature. For both solutions, the technology is front side illuminated Single Photon Avalanche Diode (FSI-SPAD) array with passive (resistive quenching). LAr emits around 128 nm and detectors typically employ large-area WLS thin films such that light can be detected at ∼400 nm where the state-of-the-art in FSI-SPAD QE is ∼45% at LAr temperature. WLS films adds significant complexity for large-area readouts, and thus improving QE at 128 nm is strongly motivated. In general, SiPMs offer lower cost, higher fill factor, and better radiopurity – thus improving their performances is highly attractive, particularly for instrumenting large readout areas.

The frontier of this research now is developing solutions for overcoming the twin VUV issues of high reflectivity (>50%) and very shallow (nm scale) absorption depth in silicon. Such solutions have been demonstrated in

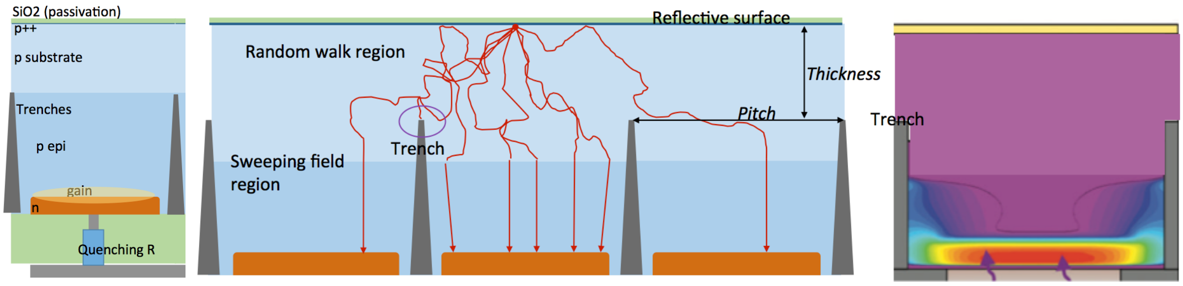

Figure 2: Left: scheme of back-side illuminated SPAD cell. Center: simulation of photo-electrons created in the array. Far right: simulated electric field in the cell.

charged coupled device (CCD) and other diodes but translating them to FSI-SPAD is difficult due to the presence of non-silicon features needed for operating the SPADs, therefore motivating the development of back-side illuminated (BSI) SPADs. Our aim is to pursue the development of a new generation of SPAD arrays, reaching ∼50% efficiency with dark noise rate comparable to or lower than PMTs. In addition, new PMT solutions doing away with the dynode chain for amplification will also be investigated.

Proposed Research: The methodology that we are proposing relies on 3 pillars: D1) the development of new solutions in partnership with SPAD manufacturers (e.g. FBK, Hamamatsu, Teledyne-e2V, Teledyne-DALSA) and PMT manufacturers (Hamamatsu, Abalone); D2) optimisation of integration strategies for the VUV that scale to m^2 of photo-coverage; and, D3) a suite of characterization tools at various institutes enabling rapid and precision characterization of the devices.

Optimised sensors for maximum QE efficiency in the VUV wavelength range R&D focusses on optimising (i) SPAD and SiPM designs; (ii) anti-reflective coatings for the VUV and non-normal incidence; and, (iii) surface passivation for the VUV, including coatings and passivation. The strategies we propose to develop include drawing on the surface treatment and coatings technology developments for BSI-CCDs which achieve >40% quantum efficiency at 178 nm as shown in processing [21, 22]. The lack of structure on the exposed back side of the device maximises efficiency because the structure-less surface is easy to process for an optimally shallow junction and anti-reflective coating, and, there is no loss of efficiency due to front structure. For the objective of minimising dark count rate and correlated noise, we would operate at relatively low gain and fabricate this SPAD with trenches between pixels going all the way through the epi to minimise cross-talk. A conceptual scheme with 3 cells is shown in Fig. 2 (center). Simulation of this scheme, with n on p SPAD, shows optimal performance with pixel pitch as small as feasible (likely 5 µm), and super-thin p-substrate (ideally <= 1 µm). Institutes collaborating on this deliverable work with industry leaders FBK, Frauenhofer, Hamamatsu, and Teledyne-e2v, and would request funding for wafer production runs and coatings/passivation technology splits to support this development.

Optimised integration for maximum QE in the VUV wavelength range Integration couples closely to the sensor development work. This R&D will develop strategies in collaboration with ongoing developments of custom SPAD/SiPM technologies at FBK, with the INFN-ARCADIA consortium, and with the Photon-to-Digital Converter (PDC) consortium who work with industry partner Teledyne-DALSA. 3D integration offers an attractive solution to achieve fast timing and manageable data rates. For large-area readouts, 2D integration of digital SiPMs is a cost-effective strategy that will be explored with VUV-optimised sensors. For rare event searches, BSI-SPAD integration has an added development challenge of achieving radiopure TSV bonding, but brings the potential advantage of up to 100% fill factor and an enhanced optical stack. Rapid feedback from qualification measurements early in the process is essential for integration R&D, for example qualifying SPAD arrays at the wafer level is necessary before packaging into detectors as the typical device yield ranges from 50% to 90%. The PDC instrumentation for wafer-level characterisation of SPAD reported in [23] will be available to us in probing early prototypes of BSI-SPADs without requiring the complete processing (back-side thinning and processing) by illuminating the sensor from the front but producing electrons deep in the silicon as if they had been generated by photons impinging onto the backside. Institutes collaborating on this deliverable work with industry leaders FBK, Frauenhofer, and Teledyne-DALSA, and would request funding for production runs and detector integration materials and services.

Operational characterisation facilities for sensors in the VUV wavelength range We propose to develop (i) detailed characterization setups for measuring photon detection efficiency; (ii) setups used to validate operation in liquid Argon and Xenon with particular attention to noise rates impacting SNR of single photon detection; and, (iii) underground setups used to validate operation in rare-event search experiments, both for liquid nobles (SoLAIRE) and water/liquid scintillator (BUTTON). We anticipate operating the characterisation facilities in a user-access model, as described in section 3.

Overall Goals: **T2.G1:** Sensor optimization **T2.G2:** Detector intergration optimisation **T2.G3:** Characterisation facilities for sensors in the VUV wavelength range

2.2.2 Task 2.2: Higher efficiency WLS/collection

The Task 2.2 leaders are C. Cuesta (CIEMAT), M. Kuźniak (AstroCeNT/NCAC PAS) and Justo Martín-Albo (IFIC) in collaboration with the institutes listed for the deliverables of T2.2 in table 4.

Scientific motivation and context: Next generation LAr (and potentially some LXe) DM experiments, neutrino and neutrinoless double beta decay experiments will face the challenge of efficiently wavelength shifting and collecting scintillation light, emitted in the vacuum ultraviolet (VUV), from very large detector volumes. This will entail: enhancing properties of wavelength shifting (WLS) materials, needed in order to convert VUV to visible, where typically photosensors are more effiecient. While the WLS needs are highest for the 128 nm scintillation light of Ar, there could still be benefits to the overall light collection efficiency for the 175 nm scintillation light of Xe. R&D on production and installation of highly efficient WLS layers and/or reflective liners on inner surfaces of detectors with the surface area of $\mathcal{O}(10\,\mathrm{m}^2)$ - $\mathcal{O}(1000\,\mathrm{m}^2)$; and cost-effective light collector or concentrator systems coupled to photosensors (SiPMs or PMTs) and integrated with the overall detector design. In the new technique of opaque liquid scintillators the light is confined to a few cm volume near its creation point extracted by a lattice of WLS fibers running through the scintillator. In all cases extensive testing of such WLS materials, WLS or WLS-reflector surfaces and more complex light collector/concentrator systems in representative conditions is required. WLS also find application in liquid scintillators, water Cherenkov and WbLS detectors, enhancing the overall light yield by increasing the effective detection efficiency to the near UV light, constrained due to physical (UV absorption in optical windows) or budgetary (limited coverage with photosensors) reasons. In all types of detectors WLS with tailored slow time constants are also applicable for background mitigation via pulse shape discrimination.

In LAr-based DUNE and ARGO enhancing the light yield would lower the energy threshold extending the sensitivity to the few-MeV and few-keV region, respectively, and improving the detector performance for triggering, timing, calorimetry and background rejection. This R&D poses several challenges: the scintillation light from LAr is emitted in VUV where most materials are not transparent/reflective; the large volume of detectors requires cost-effective photon collectors; and for DUNE, specifically, the integration of photon detectors with the LArTPC field cage and charge readouts. DUNE's photosensors are the so-called X-ARAPUCAs whose efficiency is 2-3% and R&D is required to optimize the X-ARAPUCAs design and increase its efficiency. In LXe, despite high reflectance of the PTFE sheets covering the internal walls, $\mathcal{O}(10\%)$ of scintillation photons could be detected in XLZD, impacting the sensitivity to low-mass WIMPs Previous efforts on WLS coatings revealed issues with poor adherence and solubility.

Proposed Research: Existing, or foreseeable, approaches to this challenge include work on better WLS/WLS-reflectors and development of more complex light collectors/concentrators.

Better scalable WLS and reflectors: Tasks include scaling up the TPB evaporation technology as well as more in depth studies of the reported issues with TPB stability in LXe and LAr, and ways to mitigate that issue (e.g. with protective coatings). Methods for embedding WLS in PTFE (or other polymers) include: PTFE/WLS mixture coating, mixing WLS with granular PTFE powder, and WLS diffusion into PTFE at elevated temperature. In parallel, intrinsically stable WLS polymeric films (e.g. polyethylene naphthalate, PEN), WLS-doped polymeric films and other novel candidate WLS (e.g. nanoparticles) will be further developed to better match the experimental requirements (higher efficiency, short re-emission time, radiopurity).

Optimized light collectors and concentrators: Strategies employed to improve light collection efficiency are detailed in section 2.3.4 of [24]. Light collectors and metalense-based light concentrators need identification and characterization of materials to increase photon collection. Particularly needed for the DUNE LArTPCs are: highly reflective/transmissive materials for the X-ARAPUCAs, highly reflective metals in the VUV for the detector components, and dichroic filters highly transparent to photons with wavelengths in the range between the VUV and a cut-off to wavelengths above it. In both contexts, cryogenic infrastructures for wavelength shifting efficiency and photon detection efficiency measurements and complete response characterization in representative conditions are needed, to provide data necessary for design optimization and simulations. This is challenging due to VUV excitation wavelengths and cryogenic conditions, and thus the existing of collaboration-wide access to such facilities as described in section 2.2.1 would accelerate developments across institutes.

In the case of the opaque liquid scintillator, we propose R&D on the fiber selection with high trapping efficiency and large attenuation length and optimization of the fiber coupling to the SiPM.

Overall Goals: **T2.G1** Better scalable WLS and reflectors **T2.G2** Optimized light collectors and concentrators

2.3 Work Package 3: Target Properties

Work Package 3 addresses **DRDT 2.3 - Improve the material properties of target and detector components in liquid detectors**. The objectives of Work Package 3 are to optimize target properties. The key tasks are:

- **Task 3.1:** Isotope loading and target properties of Water and Liquid Scintillator. This addresses the detailed understanding of light production and transport in these types of detectors and how liquid mixtures

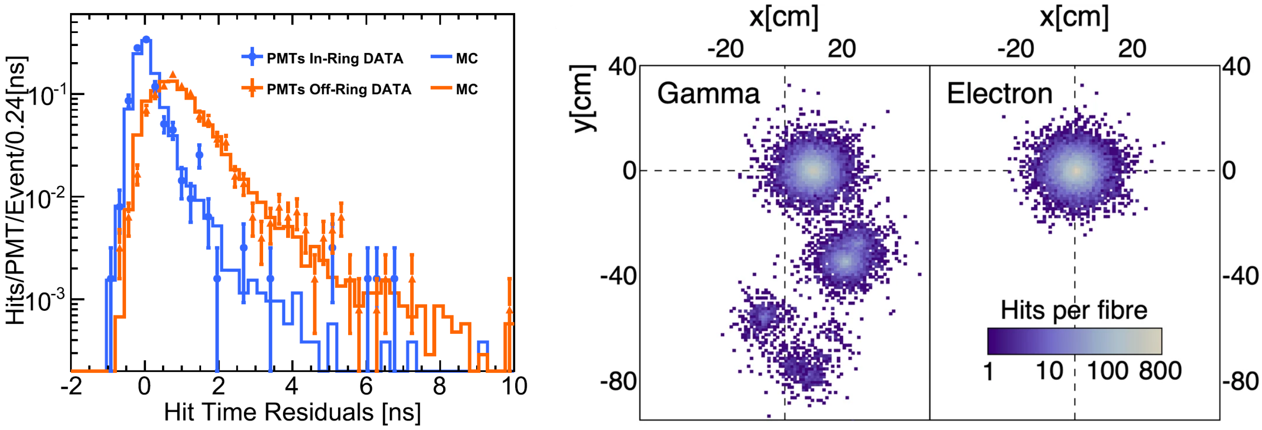

Figure 3: Left panel: Data to Monte-Carlo (MC) comparison of PMT hit-time residual distributions for PMTs inside and outside of a Cherenkov ring measured in 5% water-based liquid scintillator with the CHESS setup [25]. Reprinted from [26] under CC-BY license. Right panel: Simulation of a gamma (left) and electron (right) event with 2 MeV kinetic energy in an opaque scintillator. Optical fibres are arranged along the z-direction in a lattice of 1 cm pitch. While the electron shows a single energy deposition, the gamma deposits energy at several vertices through Compton-scattering. A positron (not shown) combines both patterns. Reprinted from [27] under CC-BY license.

can be manipulated to increase the target amount or to modify the light emission properties.

- **Task 3.2:** Noble Liquid target properties. This focuses on understanding of the microphysics of the charge and scintillation light produced in noble elements, as well as the transport of these signals in the medium. It also encompasses the study of dopants to modify the signal production and signal properties.

The initial deliverables and milestones of this Work Package are defined and mapped to the community's current involvements and further aspirations in table 5.

The participating institutes contributing to these deliverables are listed in table 6.

The estimated FTE and non-FTE resource required to carry out the planned R&D activities are summarized in tables 10 and 11 in section 7, respectively.

2.3.1 Task 3.1: Target properties and isotope loading of Water and Liquid Scintillator

The leaders of Task 3.1 are S. Schoppmann, H.Th.J. Steiger and M. Wurm, all from JGU Mainz, in collaboration with the institutions listed for the deliverables of T3.1 in table 6.

Scientific motivation and context: Water Cherenkov and organic liquid scintillator detectors are widely-used target materials for current-day and future large-scale neutrino experiments and substantial R&D has been performed to understand the target properties. Both liquids can be loaded with metals or noble gases to improve detection properties, e.g. neutron tagging, or widen the physics scope, e.g. isotope loading for neutrino-less double beta decay (NLDBD) searches.

However, continuous further development is required to adjust water and scintillator detectors for their use in future large-scale experiments. The next generation of long-baseline oscillation experiments requires improved energy reconstruction capabilities. NLDBD detectors aiming to reach sensitivity for normal-hierarchy neutrino masses require large isotope loading fractions and excellent particle ID. Moreover, both Gd-loaded water and scintillators are increasingly used as external vetoes for direct dark matter and feebly interacting particle (FIP) searches, requiring special adjustments to these new use-cases.

Proposed Research: European research groups are currently working on a large variety of different technical solutions to adjust water and organic targets to new scientific objectives, often in close cooperation with US and other international research groups. Many of these efforts are exploring possible detection techniques for the fourth Far Detector module in the US Long-Baseline Neutrino Facility (LBNF) program, a.k.a. the Deep Underground Neutrino Experiment (DUNE) Module of Opportunity, and its possible later use as a NLDBD experiment.

Target optimization and characterization Over the past years, several new lines of development have emerged in the scintillator sector [28]. The most prominent ones are hybrid detectors (either water-based [29–32] or slow liquid scintillators via low concentrations of primary fluors [33–37] or via intrinsically slow fluors [38, 39]) that aim at the simultaneous detection of Cherenkov and scintillation signals (cf. Fig. 3) in a target medium optimized for transparency (THEIA [40, 41], Borexino [42], SNO+ [43]), offering both directionality and additional means of background discrimination based on the Cherenkov/scintillation ratio. Another area of interest is improved position resolution, multi-site background discrimination and tracking capabilities [44] via fast liquid scintillator

Timeline of milestones and major deliverables						
Goals	**Deliverables**	**Milestones 2024**	**Milestones 2025**	**Milestones 2026**	**Milestones 2027-2029**	**Milestones >2030**
WP3: Target properties						
T3.1: Target properties and isotope loading of Water and Liquid Scintillator						
T3.1.G1: Optimization and full characterization of hybrid, opaque and novel scintillators	T3.1.G1.D1 Demonstration of hybrid scintillator (hLS) performance in several ton-scale experiments (2028)	- characterization of GdWbLS in ANNIE - completion of 30TBNL	- full light-yield slow LS for directionality - optical properties of Ca-loaded WbLS at 1T/30TBNL, EOS	- slow LS optimized for $\beta\beta$ metal loading	- characterization of slow LS in EOS with ν's from reactor/SNS	
	T3.1.G1.D2 Demonstration of opaque scintillator (oLS) performance in ton-scale setup (2028)	- topology reconstruction for positrons	- high light yield oLS suitable for high loading	- combination of hybrid and opaque techniques	- measurement of reactor ν's in AMOTech/CLOUD	
	T3.1.G1.D3 Publications on properties of novel target media and detector concepts (2027)	- optical properties of WbQDLS	- optimize ultrafast LS - optimize QDs for for WbQDLS	- characterize hydro-carbon target for TPCs - tungsten-loaded WbLS - scintillation of WbQDLS	- environmental effects of WbQDLS	
T3.1.G2: Achieve high isotope loading factors in water and scintillator	T3.1.G2.D1: Demonstration of > 0.1% Gadolinium loading in ton-scale setups (2026)	- achieve > 0.1% loading in water - GdWbLS (> 0.1%) demonstration in 30TBNL		- recovery of GdS from water/WbLS - demonstration in 30TBNL		
	T3.1.G2.D2: Demonstration of $\beta\beta$ isotope loading in scintillators on several per-cent level (2028)	- demonstrate > 0.3% Te loading in LS/WbLS	- demonstrate high-pressure Kr/Xe loading in slow LS - 10% Ca-loading in WbLS	- demonstrate 3% Te loading in LS/WbLS	- demonstrate high Te loading in LS/WbLS	
T3.2: Target properties of liquid nobles						
T3.2.G1: Understanding Microphysics of noble liquid (NL) response	T3.2.G1.D1: Measurement of the NL response to low energy recoils in the sub-keV (2028)	1. Monte-carlo campaign for the optimization of the system completed. 2. New optimized TPC constructed and equipped with photosensors. 3. Redesign and procurement of the new neutron spectrometer.	1. TPC commissioned and characterized. 2. Procurement of the neutron source/gun. 3. Integration and mounting of the global system at LNS.	1. Commissioning of the integrated system. 2. Data taking for low-energy recoils.	1. Data taking for single-electron background. 2. Ancillary calibrations, data analysis and finalization.	
	T3.2.G1.D2: Demonstration of directionality from bubble formation in superheated noble mixture (2027)	1. Commissioning of the detector and R&D technology for new cameras	1. R&D technology for new cameras and Data taking to establish techniques to measure directionality	1. Measurement with the optimized detector design.		
	T3.2.G1.D3: Design and commissioning of techniques for low-energy calibrations (2030)	1. Validation of ^{37}Ar source. 2. novel TOF detectors for O(10-100 keV) neutrons	1. Test new calibration sources (photoneutron) 2. Test of new neutron beams	1. Commissioning of low energy calibration detectors.		1. Commissioning for actual dark matter search detectors.
	T3.2.G1.D4: Publication of microphysical model of NL response (2027)	1. Nucleation efficiency revisited and MD modeling.	1. Validation of the nucleation model with calibration data. 2. MD simulations with NEST.	1. Extension of the NEST model from low to high energy regime.		
T3.2.G2: Characterizing and Modelling NL light emission and transport	T3.2.G2.D1: Measurement of the NL scintillation pulse shape as a function of dopants and or contaminants (2029)		1. Pulse Shape characterization of the scintillation response from the far to the near UV		1. Pulse Shape characterization of the scintillation response in the near IR	
	T3.2.G2.D2: Publication on characterization of the near IR emitted from Xe-LAr (2027)	1. Tests and construct charge-only readout.	1. Charge and light readout (IR+VUV)	1. Test in large scale TPC.		
	T3.2.G2.D3: Precise measurement of scattering and absorption lengths as a function of contaminant concentrations (2029)	1. Setup for Xe-doping assembled. Xe-loading established 2. Measure group velocity in LXe using existing, commissioned DPXe setup and muon detectors. 3. Study scattering and propagation in LXe	1. First measurements of Rayleigh scattering length (RSL) and refractive index in Xe-Ar mixture. 2. Optical time domain reflectometry (OTDR) measurements with ps laser pulses to determine refractive index and RSL.	1. RSL and refractive index measurements as a function of Xe-doping.	1. Consolidating findings from previous measurements and R&D studies. Refine measurement techniques for group velocity and Rayleigh Scattering length measurements. 2. Contribute to advancements in particle detection at the Xenoscope facility.	
	T3.2.G2.D4: Design new strategies for fast optical simulations (2026)	1. Establish mathematical model to minimize training of numerical approximated simulation models.	1. Identify and validate best performing paradigm to use GPUs for NL photon transport simulation.	1 Implement solutions in experiment code and standalone software.		
T3.2.G3: Characterizing Properties of Xe-Ar mixture	T3.2.G3.D1: Publication on characterization of thermodynamics of Xe-doped LAr (2026)	1. Phase diagram and solubility measurement				
	T3.2.G3.D2: Report on tests of the stability in time and uniformity in volume (2027)	1. Stability test with low concentrations (< ppm) of Xe		1. Stability test with high concentrations (a few %-level) of Xe		
	T3.2.G3.D3: Measurement of scintillation and ionization of Xe-LAr as a function of Xe concentration (2028)		1. Characterization of electronic recoil scintillation and ionization in LAr doped with <1% Xe 2. Characterize light response of different Xe doping levels in LAr using X-ARAPUCAs operating at CERN	1. Characterization of nuclear recoil scintillation and ionization in LAr doped with ≤1% Xe. 2. Bubble chamber Characterization of Xe-doped LAr concentration 3. Pulse Shape characterization of the scintillation response from the Far to the near UV for controlled amounts of Xe doping up to 100 ppm 4. Characterization of electronic recoil scintillation and ionization in LAr doped up to the maximum Xe solubility 5. Characterize light response of different Xe doping levels in LAr using X-ARAPUCAs operating at CERN	1. Pulse Shape characterization of the scintillation response in near IR or controlled amounts of Xe doping up to 100 ppm	

Table 5: Deliverables for Work Package 3. Acronyms used: LS - Liquid Scintillator; WbLS - Water-based LS; GdWbLS - gadolinium-loaded WbLS; ANNIE - 25t Cherenkov detector at FNAL/BNB; 1TBNL/30TBNL - BNL demonstrators with 1t/30t target mass; EOS - low energy demonstrator at UC Berkeley; SNS - Neutron spallation source in Oak Ridge; AMOTech/CLOUD - European project for reactor monitoring with oLS; QD - Quantum Dots; WbQDLS - QD-based WbLS; GdS - gadolinium sulfate; MD - Molecular Dynamics

Institute	**PI**	**T3.1**		**T3.2**		
Deliverable		**G1**	**G2**	**G1**	**G2**	**G3**
T3.1: Isotope loading and target properties of Water and Liquid Scintillator						
BNL	Yeh	×	×			
CERN	Ortega Ruiz	×				
HU Berlin	Lacker	×				
IJCLab	Cabrera Serra	×				
INFN Bologna	Selvi	×				
Liverpool	Coleman	×	×			
JGU Mainz	Schoppmann / Steiger / Wurm	×	×			
KC London	Katori	×				
Oxford	Biller	×	×			
Queen's	Chen	×	×			
RWTH Aachen	Roth	×				
UC Berkeley	Orebi Gann	×	×			
UC Davis	Svoboda	×	×			
UC Irvine	Ochoa-Ricoux	×				
T3.2: Noble Liquid target properties						
APC (France)	Franco			×		×
AstroCeNT (Poland)	Wada			×		×
Campinas University	Segreto			×		×
Canfranc (Spain)	Pesudo					×
CIEMAT	Gil-Botella					×
Colorado State U.	Mooney			×		
CTP (France)	Stringari			×		×
Edinburgh (UK)	Szelc				×	
FNAL	Zennamo			×	×	
Freiburg (Germany)	Kuger					
GOLD-IO-CSIC (Spain)	Larruquert					×
Granada (Spain)	Sanchez Lucas				×	×
GSSI (Italy)	Agnes			×		×
ICB (France)	J Simon			×		×
ICPJLab (France)	Wilson			×		×
IHEP (China)	Wang			×		×
INFN Cagliari	Bonivento			×		×
INFN LNS	Pandola			×		
INFN Milano	Zani				×	×
INFN Napoli	Fiorillo			×		×
INFN Torino	Rolo			×		×
LLNL	Xu					×
LPNHE (France)	Scotto-Lavina			×		×
JGU Mainz (Germany)	Oberlack					
Nikhef (Netherlands)	Decowski					
Princeton U.	Galbiati			×		×
Rice U.	Tunnell			×		
RPI	Brown			×		
Syracuse	Whittington					
U. Albany	Szydagis			×		
U. of Alberta	Piro			×		×
UC Berkeley	McKinsey			×		
UCDavis	Tripathi			×		
UCLA	Kamaha			×		
U. California - Riverside	Westerdale				×	×
U. of Zurich (Switzerland)	Baudis				×	

Table 6: Collaborating institutes on the deliverables of WP3: Target Properties. Deliverables are defined in table 5.

formulations which could greatly improve this discrimination, yielding vertex resolutions of just a few centimeters. On the opposite end of the spectrum, opaque scintillators [45] are designed to restrict the propagation distance of the photons before being read out by wavelength shifting fibers coupled to silicon photomultipliers (SiPMs) (LiquidO [27, 46]), promising superb vertex reconstruction (cf. Fig. 3). In addition, new wavelength shifters are explored to provide especially slow or fast scintillation or freely tunable emission spectra (quantum dots [47–50]). Beyond conventional photomultiplier tubes (PMTs), new kinds of photosensors (wavelength shifting optical modules (WOMs) [51], large area avalanche photodiodes (LAPPDs) [52, 53]) are investigated to maximize the benefit of the novel target properties. Efforts include the exploration of organic liquids as a target medium for time projection chamber (TPC) readout [54, 55].
In many cases, the production and especially the characterization of new (loaded) scintillator and water samples requires specific equipment and laboratory setups that cannot easily be maintained by the individual labs. The coordination between European groups will facilitate the shared use of laboratory setups to characterize light yield, fluorescence times and spectra as well as light absorption and scattering in bulk media. The inclusion of large-scale facilities at Brookhaven National Laboratory (BNL) permits for scintillator production and circulation tests on the scale of up several ten tons (1TBNL and 30TBNL, respectively). Finally, demonstrator detectors like ANNIE (FNAL [56]), EOS (Berkeley [57]), and AMOTech/CLOUD (Chooz [58]) permit the test of new targets in full-scale setups.

Target loading Several of these new technologies lend themselves to isotope loading at high concentration for NLDBD searches. Both water-based liquid scintillator and opaque scintillators are likely suitable for isotope loading beyond the current state of the art [45, 59, 60] and could achieve the several-per cent level, crucial to demonstrate that NLDBD experiments containing 10 tons of isotope or more are achievable (THEIA, JUNO-$\beta\beta$). Moreover, water with large loading factors of gadolinium ($\geq 0.1\%$) will provide efficient neutron tagging for future dark matter searches (DARWIN).

Overall Goals **T3.1.G1:** Optimization and full characterization of hybrid, opaque and novel scintillators); **T3.1.G2:** Achieve high isotope loading factors in water and scintillator.

2.3.2 Task 3.2: Noble Liquid target properties

The leaders of Task 3.2 are D. Franco from APC, A. Szelc from the University of Edinburgh, A. Zani from INFN Milano and Marie-Cécile Piro from the University of Alberta, in collaboration with the institutes listed for the deliverables of T3.2 in table 6.

Scientific motivation and context: Noble liquid technology has undergone impressive development in recent years in its applications to particle and astroparticle physics, as it can cover interactions with energies ranging from tens of eV to several GeV. The sub-keV regime represents a new frontier as it will extend the window of observation to light dark matter particles and astrophysics neutrinos via CEvNS (Coherent-elastic neutrino-nucleus scattering). Conversely, strategies to ascertain the directionality of low-energy particles will be essential for future massive detectors to discriminate between neutrino background and DM candidates. The potential of noble liquid technology will be further extended by doping liquid argon (LAr) with xenon. This increases both photon and ionization yields with respect to LAr, acts as a wavelength shifter extending the attenuation length of photons, and makes scintillation faster. The Xe-Ar mixture target is suitable for kiloton-scale neutrino experiments, thanks to the enhanced and more homogeneous light collection. It can also be applied in ton-scale experiments, such as for direct search of light dark matter particles, relying on the ionization signal only, and of $0\nu\beta\beta$ signals, by doping LAr with 10-20% of ^{136}Xe.

Proposed Research: To exploit the full potential of this technology, it is essential to understand and model the mechanisms underlying the response in scintillation and ionization, especially in the sub-keV region.

Understanding Microphysics of noble liquid (NL) response The measured signal in noble liquid detectors is formed through a series of complex processes including energy transfer by an impinging particle to atoms, formation of excited and ionized states and phonons, charge drift in the liquid and through the liquid surface (in double-phase detectors) and, electroluminescence. A better understanding of all these processes underlying the response in scintillation and ionization, especially in the sub-keV range, is essential for fully exploiting the technology potential. This challenge can be addressed through small-scale dedicated laboratory setups which also may be exposed to neutron/electron beam/sources, enabling the investigation of responses to low-energy recoils under controlled conditions. The work plan for this deliverable is described in table 5.

Characterizing and Modelling NL light emission and transport Once the NL energy response mechanisms are understood, it is necessary to understand the emission and propagation properties of scintillation and electroluminescence light. Key parameters such as absorption and Rayleigh scattering lengths, refractive indices and group velocity, are not precisely established yet. Precision application of scintillation light in future large-scale neutrino detectors necessitates the development of fast-simulation approximated models and GPU-based parallelization using the determined parameters.

Characterizing Properties of Xe-Ar mixture The primary challenge of implementing the Xe-Ar technology is its thermodynamics, which has not yet been fully assessed. The maximum Xe content in the Xe-Ar mixture is determined by the solubility limit of solid Xe in LAr, which can only be inferred from a precise knowledge of the Xe-Ar phase diagram. At the same time, the long-term stability of the mixture, in terms of spatial uniformity, must be demonstrated via experimental characterization of the emitted scintillation light pulses. This also implies that circulation of the liquid, required for LAr purification, needs continuous movement of the liquid to avoid stratification, along with possible localized Xe solidification. A detailed CFD simulation program is needed to understand the effects of scaling to a much larger volume on the circulation rate.

Overall Goals **T3.2.G1:** Understanding microphysics of noble liquid (NL) response ; **T3.2.G2:** Characterizing and Modelling NL light emission and transport; **T3.2.G3:** Characterizing Properties of Xe-Ar mixture.

2.4 Work Package 4: Scaling-up challenges

Work Package 4 addresses **DRDT 2.4 - Realise liquid detector technologies scalable for integration in large systems** as well as some of DRDT 2.3 - Improve the material properties of target and detector components in liquid detectors, focused on this topic at large scale. The objectives of Work Package 4 are to address scaling-up challenges. The key tasks are:

- **Task 4.1:** Radiopurity and background mitigation. This addresses the need for development in new and more sensitive assay methods, new material selection and cleaning protocols, and development of radiopure materials.
- **Task 4.2:** Detector and target procurement/production and purification. This addresses the needs to increase the productions and procurement of noble elements as well as the development of large-scale purification systems to further lower the presence of contaminants of all sorts.
- **Task 4.3:** Large-area readouts. This focuses on the needs for efficient readout methods to address very large number of channels as well as the need for dedicated mid- and large-scale facilities for the technology development.
- **Task 4.4:** Material properties. This address the need to push the understanding of material properties and material effects that will start to impact the very large-scale detectors. While it is an important topic, the community efforts at this time remain small and this task is currently not represented, but could be in the future.

There is overlap between the goals of T4.3 with DRD7 (liaison E. Gramellini). However, at this early stage, there are not specific tasks required from DRD7. Close collaboration in the future will be essential. The initial deliverables and milestones of this Work Package are defined and mapped to the community's current involvements and further aspirations in table 7.

The participating institutes contributing to these deliverables are listed in table 8.

The estimated FTE and non-FTE resource required to carry out the planned R&D activities are summarized in tables 10 and 11 in section 7, respectively.

2.4.1 Task 4.1: Radiopurity and background mitigation

The leaders of Task 4.1 are J. Dobson (King's College London) and R. Santorelli (CIEMAT), in collaboration with the institutes listed for the deliverables of T4.1 in table 8.

Scientific motivation and context: The mitigation and calculation of background signals in rare event search experiments are among the forefront challenges for the next generation of liquid detectors. Traces of radioactivity present in the materials used to construct the detector or in its surroundings can be the dominant background for rare event search experiments. Low-background detectors require extensive radio-purity assays, employing diverse techniques and utilizing facilities worldwide. Development of new and more sensitive assay methods is essential to ensure complete radiogenic characterization of the primordial radionuclide decay chain and the cosmogenic activation of the materials. Besides the bulk contamination, surface contamination of detector materials can be a significant source of background, primarily due to radon diffusion and plate-out of radon daughters. Exposure to environmental Rn during fabrication, assembly, and installation of the experiment can result in the accumulation of ^{210}Pb on surfaces. Due to its 22-year half-life, ^{210}Pb can act as a nearly constant source of radiation, along with its daughters ^{210}Bi and ^{210}Po, throughout the entire duration of an experiment. Moreover, alpha decays from ^{210}Po on the surfaces of the materials with high alpha-n cross sections can contribute to the neutron yield. The development of novel and effective strategies for material selection, as well as well-defined protocols for machining, storing, transporting, and assembling detector components, is necessary to mitigate the surface background.

		Timeline of milestones and major deliverables			
Goals	**Deliverables**	**Milestones 2024**	**Milestones 2025**	**Milestones 2026**	**Milestones 2027-2030**
WP4: Scaling-up Challenges					
T4.1: Radiopurity and background mitigation					
T4.1.G1: Radioassay techniques at required sensitivity for next generation of rare-event search experiments	T4.1.G1.D1 Measurement demonstrating $<5\,\mu$Bq sensitivity for warm/cold Rn emanation (2026)	Design and material selection for warm/cold Rn emanation at $<5\,\mu$Bq sensitivity	Portable gas Rn monitor constructed and tested	Rn emanation warm/cold sensitivity demonstrated at $<5\,\mu$Bq;	Throughput scale up for all techniques; Characterisation of stock materials and barrier methods for next-generation experiments.
	T4.1.G1.D2 Measurements demonstrating <20 ppq U/Th sensitivity with ICP-MS and HPGe to $<2\,\mu$Bq/kg (2026)	ICP-MS sample preparation protocols for key materials at <20 ppq U/Th	HPGe detector built and characterised	Demonstration rapid pre-screening using laser ablation ICP-MS to 10 ppt U/Th.	Throughput scale up for all techniques; Characterisation of stock materials and barrier methods for next-generation experiments.
T4.1.G2: Mitigation through material selection/treatment and clean manufacture	T4.1.G2.D1 Technical report on surface treatments and clean protocols to achieve few ng/cm^2 surface cleanliness levels (2026)	Evaluation of barrier materials and methods (electroplating, conventional)	Demonstration of dust removal using atmospheric plasma surface treatment	Protocols for dust removal surface treatments (chemical/electrochemical) demonstrated (few ng/cm^2); Barrier surface treatment of large scale detector components operational.	Demonstration of dust removal using vacuum plasma surface treatment
	T4.1.G2.D2 Prototype assay techniques to characterise few ng/cm^2 and $100\,\mu$Bq/m^2 contamination levels (2026)	Demonstration of ML-enabled optical and flurescence surface dust contamination to few ng/cm^2	Design and material selection for surface alpha-screening system (with industrial partners) with $100\,\mu$Bq/m^2 sensitivity	Facility for tests of surface contamination of large electrodes O(m^2); Barrier surface treatment of large scale detector components operational; Surface alpha-screening system operational with $100\,\mu$Bq/m^2 sensitivity	Demonstration of dust removal using vacuum plasma surface treatment
T4.1.G3: Development of novel materials for background suppression	T4.1.G3.D1 Report on performance and production at scale of novel veto materials (2026)	Development of low-background polymerization processes for passive shields and light guides; Design optimisation for Gd-PMMA system (maximum Gd-fraction, veto thickness)	Scale-up passive shield production; Materials screening/selection for high-radiopurity Gd-PMMA active shielding	Gd-PMMA scale-up via industrial transfer	
	T4.1.G3.D2 Prototype of Rn removal system based on microporous adsorbents (2026)	Synthesis of new microporous adsorbents for Rn capture in gas phase (Ar, Xe, N2)	New generation of microporous radon adsorbents characterised in Ar, Xe gas a function of T, P.	Design and construct Rn removal system based on microporous adsorbents	
T4.1.G4: Tools for the evaluation of backgrounds	T4.1.G4.D1 Public release of simulation and accounting tools (2026);	Implementation of generic highly shielded detector in GEANT4; Development of GPU-accelerated statistical inference tools; Improvement in accuracy of neutron yield calculations with uncertainties of 10% for most materials; Comparison between codes, models and datasets for cosmogenic and beam activation products; Development of material background accounting tool and data formats.	Development of techniques for high-stats simulations of highly shielded detectors (event biasing, bootstrapping, GPU/TPU accelerated); Release updated neutron yield library (SOURCE4) and paper; Toolkit for accurate simulation of cosmogenic production and activation of detector components and target materials	Improved (α-n) production cross-section measurements for key materials (e.g., argon); Report on design studies optimising active veto strategies vs fiducial trade off for 0vBB, DM.	
T4.2: Detector & Target Procurement/Production and Purification					
T4.2.G1: Scale-up mass production to O(100 tonne) active targets	T4.2.G1.D1: Massive purification/production facilities for (Md & Wb) LS/Wc (2026)	prototype: tonne-scale facility to exercise scale-up technology and requirement for metal-doped & water-based LS/Wc manufacture	facility capable of producing metal-doped & water-based LS/Wc to support 10s tons of prototype and deployment (i.e. 30TBNL, Eos, ANNIE, LiquidO, BUTTON100X)	Facility capable of >100-ton scale metal-doped & water-based LS/Wc manufacture for experimental deployment	
	T4.2.G1.D2: Massive (ktonne) xenon production: construction of pilot plant to extract xenon from air using PSA (2030)	report: R&D to extract xenon from air.	report: R&D pilot plant and production plant.	report: Perform R&D for pilot plant	detector: construct pilot plant
	T4.2.G1.D3: Prototype setup for radioactive sampling of UAr (2026)	Setup and commissioning a detector for the measurements of the residual contamination of 39Ar	Operation of the detector for 39Ar measurements for the Urania production	Report: design, setup and 0peration of a detector for 42Ar	
	T4.2.G1.D4: Construction of plants for UAr purification from contaminants (2030)	Urania and Aria construction	Urania and Aria run	Report: Design a Scale up system for Argo and DUNE MoO	Report: Find new UAr sources, finalise design of scale up plants
T4.2.G2: Improve Purification technologies to match the needs for O(100 tonne) active targets.	T4.2.G2.D1: Construction of nanofiltration systems for in-situ purification and production *for (Md & Wb) LS/Wc detector (2030)*	report: develop QA/QC procedures to guide manufacture process	Demonstrate the feasibility of nanofiltration for WbLS detector and inline purification technology for metal-doped LS/Wc at 10s of tons	A scale-up nanofiltration system for WbLS and an inline purification system for LS detectors at 100s-1000s of tons	Report: Tech-transfer and communicate with the commercial vendors to improve starting materials
	T4.2.G2.D2: Design and validation of xenon purification technologies for DARWIN/XLZD (2030)	report: demonstration of 85Kr and Rn suppression by online distillation in LZ and Xenon-nT		design and test of facilities for Kr and Rn removal technology for DARWIN/XLZD	design and test of a system for online Kr and Rn diagnostics for DARWIN/XLZD
	T4.2.G2.D3: Ar extreme purification 1) Construction of a system to measure electron lifetime and liquid argon purity in-situ using laser beams (2030) 2) Publication and countermeasures on identification of the residual isolated electron background of Darkside S2-only analyses with an ad-hoc experimental setup. (2026)	1) report: design a system to measure electron lifetime/liquid argon purity in-situ using a system of laser beams; 2) Detector: Assembly of a setup to study residual isolated electron study	1) Construction and installation of laser-based, programmable, calibration systems for the ProtoDUNE detectors at CERN; 2) Detector: Understand with the setup the sources of single electrons; development and verification of countermeasures (e.g filters, ...);	1) Characterization of ionization charge dependence with track length, and stability	1) Measurement of electron lifetime in ProtoDUNE-HD or VD with laser; report: Tuning of simulation model for ionisation charge with real calibration data in PD
T4.3: Large-area Readouts					
T4.3.G1: Development of mid-scale facilities for large-area readout assembly and characterization at cryogenic temperature	T4.3.G1.D1 Photodetector facility (2026)	Design of the photodetector facility	Construction and commissioning of the photodetector facility	First operation of the photodetector facility	
	T4.3.G1.D2 Upgraded TPC-testing facility (2026)	Upgrade of the TPC-testing facility	Commissioning and TPC construction for the TPC facility	First operation of the TPC-testing facility	
T4.3.G2: Large-scale digitization technologies	T4.3.G2.D1 Report on multi-PMT readout (2024)	Test of multi-PMTs readout at WC Test experiment at CERN			
	T4.3.G2.D2 Report on SiPM readout with cold electronics (2029)		Design of cold ADC and FPGA boards for scintillation light signal processing	Production of prototypes of cold ADC and FPGA boards for scintillation light signal processing	Testing of cold electronics for scintillation light signal processing
T4.3.G3: Large-scale joint integration tests	T4.3.G3.D1 Report on large scale photodetection in a field cage (2026)			Demonstration of large scale photodetection in a field cage at ProtoDUNE with charged particle beams	
	T4.3.G3.D2 Design of O(10 million) pixel readout (2029)				Design of pixel readout for O(10 million) channels
	T4.3.G3.D3 Report on operation of large fill-factor UV sensors. (2024)	Operation of 192 $6\times6\,\mathrm{mm}^2$ MPPCs in Xenoscope			

Table 7: Deliverables and milestones of WP4: Scaling-Up Challenges.

Institute	PI	T4.1				T4.2		T4.3		
Deliverable		**G1**	**G2**	**G3**	**G4**	**G1**	**G2**	**G1**	**G2**	**G3**
T4.1: Radiopurity and Background Mitigation										
Aix Marseille Univ, CNRS/IN2P3, CPPM	Busto	×	×							
CIEMAT	Cano/Santorelli				×					
Complutense University of Madrid	Fraile				×					
GSSI	Di Marco			×						
INFN Genova	Testera				×					
INFN LNL	Azzolini		×							
Jagiellonian University	Zuzel	×								
JGU Mainz	Oberlack/Deisting		×							
King's College London	Dobson	×	×		×					
LIP	Lindote				×					
LLNL	Pereverzev			×						
Padova University/INFN	Brugnera			×						
Polytechnic University of Catalonia	Tarifeño				×					
Roma Tre University/INFN	Salamanna			×						
STFC Boulby Underground Laboratory/BUGS	Scovell	×	×							
STFC RAL PPD	Van der Grinten	×								
University College London	Ghag/Saakyan/Waters	×			×					
University of Edinburgh	Murphy	×	×		×					
University of Sheffield	Kudryavtsev/Tovey	×	×		×					
University of Zaragoza	Sarsa		×							
T4.2: Detector & target procurement/production & purification										
Astrocent	Wada					×	×			
BNL	Yeh					×	×			
CIEMAT	Santorelli					×				
ICRR	Sekiya					×	×			
INFN Bologna	Selvi					×	×			
INFN Cagliari	Bonivento					×	×			
INFN MIlano	Lombardi					×	×			
INFN Napoli	Fiorillo					×	×			
JGU Mainz	Schoppmann/Steiger/Wurm					×	×			
Kavli IPMU	Vagins					×	×			
LIP Lisbon and Coimbra	Barros, Maneira						×			
LLNL, Yale, PNNL, SLAC	Heffner					×				
Max-Plank Institute	Buck					×	×			
Muenster	Weinheimer						×			
UC Davis	Svobado					×	×			
Zaragoza	Cebrian/Sarsa					×				
T4.3: Large-area Readouts										
CIEMAT	Crespo							×	×	×
Fermilab	Cavanna									×
LLR, OMEGA, ILANCE and CEA/IRFU	Buizza								×	
INFN Napoli	Fiorillo							×		×
University of Zürich	Baudis									×

Table 8: Collaborating institutes on the deliverables of TA4: Scaling Up. Deliverables are defined in table 7.

To accurately measure and interpret the signals of interest, it is crucial to understand and model all the background contributions in an experiment. Neutrons and gamma rays can contribute to background even from distant sources, making the precise calculation of the radiogenic neutron flux induced by alpha-n reactions and the cosmogenic gamma flux indispensable for future experiments. Accurate knowledge of (α,n) cross sections is crucial to determine the neutron flux induced by alpha particles in the target or in the materials surrounding the active volume. Furthermore, comprehensive simulations are necessary to model the transport of gamma rays from cosmogenic activation, considering the specific experimental setup and shielding configurations. Advanced simulation techniques, coupled with improved (α,n) cross-section data are imperative to understand, control, and reject these sources of background.

Proposed Research: Techniques employed include meticulous material selection to ensure the highest radiopurity, the utilization of radio-pure fabrication techniques, implementing measures to control radon exposure, and incorporating novel shielding strategies to minimize the impact of the external radiation.

Radioassay techniques at required sensitivity for next generation of rare-event search experiments Significant efforts are planned in the coming years to overcome the current limitations in the sensitivity of radio purity assays for materials required for the construction of the next generation of detectors. R&D activities encompass both achieving higher sensitivity in measuring bulk material contamination using traditional methods such as Inductively Coupled Plasma Mass Spectrometry (ICPMS) and High Purity Germanium (HPGe) detectors, as well as refining more recent methods required for scrutinizing the entire decay chain of ^{238}U and ^{232}Th (e.g., Po-extraction). The forthcoming generation of experiments will require achieving sensitivities of $\approx 1\,\mu\mathrm{Bq\,kg^{-1}}$ (for example for HPGe). This represents an improvement of at least an order of magnitude compared to the achievements thus far. Additionally, new ideas are being developed for the detailed measurement of surface contamination resulting from the plate-out of radon progeny, aiming to measure surface activity as low as approximately $10\,\mu\mathrm{Bq\,m^{-2}}$.

Mitigation through material selection/treatment and clean manufacture Radon mitigation needs significant efforts in terms of surface cleaning, as well as storage and transportation of materials. Moreover, the fabrication of materials for low-background experiments necessitates stringent control over all the manufacturing process. Addressing these challenges requires specialized protocols to maintain low background conditions, regular monitoring, and maintenance of surfaces to ensure long-term mitigation of radon contamination. A further crucial aspect is the development of cleaning, transportation, and manipulation protocols aimed at reducing the native surface contamination of materials used in low background experiments, such as copper, stainless-steel, acrylic. In addition to radiogenic surface backgrounds, other material induced background will be considered e.g. surface defects leading to the field emission in electrodes of dual phase TPCs, surface treatments or new materials to reduce surface-trapped electron dwelling time. R&D on various approaches is planned, ranging from chemical and electrochemical methods to atmospheric and vacuum plasma techniques. At the same time, it is mandatory to minimize the Rn contamination inside the detector, requiring characterization of the Rn emanation of materials as a function of temperature and pressure.

New tools/materials for the evaluation/suppression of backgrounds Neutrons are one of the main sources of background in rare-event search experiments. For the accurate calculation of radiogenic neutron production rates, it will be crucial to measure the (α,n) production cross-section in those materials relevant to the construction of low-background detectors for which experimental measurements are not available (e.g., argon). In parallel, significant research efforts are expected in the coming years to investigate innovative configurations of active veto technologies based on new materials for neutron background mitigation, e.g. R&D is currently ongoing aimed at producing a large amount (few tens of tons) of radiopure acrylic loaded with a gadolinium compound.

Overall Goals: **T4.1.G1:** Radioassay techniques at required sensitivity for next generation of rare-event search experiments; **T4.1.G2:** Mitigation through material selection/treatment and clean manufacture; **T4.1.G3:** Development of novel materials for background suppression; **T4.1.G4:** Tools for the evaluation of backgrounds.

2.4.2 Task 4.2: Detector & target procurement/production & purification

The Task 4.2 leaders are W.M.Bonivento (INFN Cagliari) and Minfang Yeh (BNL), in collaboration with the institutes listed for the deliverables of T4.2 in table 8.

Scientific motivation and context: A pure, many kiloton target of liquid scintillator has great sensitivity for sub-MeV neutrinos and other rare-event physics which often cannot be achieved by other detector mediums. While such detectors have high light yield, fast signals, and can be cost-effective, on some occasions large pure LS detectors might not be a viable choice due to no directional information, fluorescence quenching, and chemical safety. Some major R&D directions have emerged in recent years. Water-based Liquid Scintillator (WbLS) is a novel detection medium that delivers a hybrid event detection of particle interactions to combine the unique topology of Cherenkov light with the increased low-threshold scintillation light yield to improve energy and vertex resolution and obtain particle identification. As well, further detector enhancements, such as metal-doping, slow scintillation, dichroicon, and highly opaque, can be added on either LS or WbLS to extend their physics reaches

for next-generation physics experiments.
Cryogenic noble liquids, especially argon and xenon, are used for many applications such as target for dark matter searches (WArP, DarkSide-50, DarkSide-20k, DEAP3600, ARGO, ZEPLIN I/II/III, XENON10/100/1T/nT, XMASS, LUX, LZ, PandaX-I/II/4t/30t, DARWIN/XLZD), neutrino physics (ICARUS, MicroBoone, DUNE, EXO-200, nEXO), medical imaging and in veto systems (LEGEND-200, LEGEND-1000, DarkSide-20k). Over the past decade, purification technologies for LXe have reached part-per-quadrillion levels of key impurities, and production and purification technologies for argon extracted from underground have progressed from prototypes to demonstration at the 50 kg scale towards the production at the few 100-tonne-scale.

Proposed Research: for this proposal period, the activities planned are in the following main areas.

Scale-up mass production Several WbLS testbeds and LS experiments are now under development at numerous laboratories, in addition to research programs at several universities, worldwide. R&D required to progress this area includes establishing production and purification facilities supporting fundamental research and prototyping studies for proof of concept in different detector configurations, and to develop in-situ purification or circulation systems prolonging the detector lifetime by mitigating the colored quenching and radioactive background introduced from air ingression and material leaching.

For scaling-up noble liquid detectors, the proposed and in-preparation experiments are confronted with R&D challenges in procurement, storage and transport of large quantities of noble liquids. Ar dark matter searches and neutrino-less double beta decay experiments employing Ar veto detectors (i.e. LEGEND-1000) need to extract and purify 10-100 tonne quantities of underground argon, depleted of the ^{39}Ar isotope relative to atmospheric Ar. For Xe the availability of large quantities of the target material is at present a bit difficult commercially due to the international situation, but may return back to normal in few years from now; actions are being undertaken to develop alternative production methods including the development of new extraction method from air using PSA methods instead of cryogenic distillation.

Purification and Metrology For purification, the key challenges for liquid nobles are the need for understanding of the impurities leading to the production of single isolated electrons. These constitute an irreducible background in the ionisation-only ("S2-only") analyses that have leading sensitivity to light dark matter. For argon, the purification of the argon extracted underground, related to the facilities of Urania and Aria, is an enabling development to demonstrate the viability of kilotonne-scale future rare-event search detectors.

For QA/QC of target purification it is vital to develop a method to measure electron lifetime/cryogen purity in-situ at large detectors, within the active volume. Existing methods for large LAr detectors employ miniature TPCs located outside the active volume, that have the disadvantage of not measuring the region used for data analysis. Other methods use samples of cosmic ray data, that are less frequent in deep underground labs. Developments are proposed to use a system of laser beams for in-situ measurement, based on the system operated in MicroBooNE but with several improvements. The aim is to test this concept in the ProtoDUNE detectors at CERN in the next years to develop the operational and analysis details of this new method.

Overall Goals: **T4.2.G1:** Scale-up mass production to O(100 tonne) active targets; **T4.2.G2:** Improve Purification technologies to match the needs for O(100 tonne) active targets.

2.4.3 Task 4.3: Large-area readouts

The Task 4.3 leaders are J.I Crespo-Anadón (CIEMAT), G. Fiorillo (Università degli Studi Federico II/INFN Napoli) and I. Gil-Botella (CIEMAT), in collaboration with the institutes listed for the deliverables of T4.3 in table 8.

Scientific motivation and context: The scope of this Task covers the R&D on scalability of light and charge readout for current and future neutrino and dark matter experiments. All these liquid detectors plan to exploit scintillation or Cherenkov light signatures, which drives the need for an increase of photo-coverage to improve energy resolution and lower thresholds. The readout of the detectors will become challenging due to the increased number of readout channels and data volumes. In order to accomplish the scaling-up of the current detectors, mid-scale and large facilities will be necessary for assembling and testing the readout in protoyopes before the final scaling is pursued.

The state-of-the-art in scale-up of liquid argon (LAr) TPCs is represented by the ProtoDUNE detectors at the CERN Neutrino Platform and ICARUS at the Fermilab Short-Baseline Neutrino Program. These single phase detectors feature several hundreds of tons of LAr mass, and encompass readouts based on wire planes or perforated PCBs for the ionization charge, and PMTs or X-ARAPUCAs for the scintillation light. For the dual phase detectors, DarkSide-50 has reached the 50 kg scale and employs a PMT readout. A demonstrator for the DUNE Near Detector (ND-LAr 2×2, $0.75\,\mathrm{m} \times 0.75\,\mathrm{m} \times 1.6\,\mathrm{m}$) using pixelated charge readout and ArCLight (another light trap technology) is being tested at Fermilab. In addition to the previous TPCs, GERDA features a $64\,\mathrm{m}^3$ LAr veto read out by PMTs and SiPMs coupled to WLS fibers. Regarding the liquid xenon TPCs, the state of the art is the dual-phase $\sim$ 6 tons XENON-nT and LZ $\sim$ 7 tons experiments with PMT readout.

The state of the art of liquid scintillator detectors is represented by the recently concluded Borexino experiment (278 ton) and the upcoming JUNO experiment ($\sim$ 20 kton), both using PMTs as readout technology. For the water

Cherenkov detectors, it is Super-Kamiokande, holding 22.5 kton and using PMTs as well, and the community is preparing for the Hyper-Kamiokande detector that will be up to 8 times bigger, using high quantum efficiency PMTs for the light readout.

Proposed research: The need for accomplishing the assembly and characterization of readout units at the final scale before deployment drives the creation of dedicated facilities equipped with the cryogenic infrastructure, slow controls and DAQ services capable of handling the required scales. A complementary and parallel effort is required to address the large data volumes expected from these detectors by using readout electronics placed as close as possible to the sensors and digitizing the signal as far upstream as is feasible, in order to benefit from the higher signal-to-noise and multiplexing, which reduces the number of channels, simplifying the detector design and construction. Finally, there is a need for offering platforms for performing joint integration tests where all readout systems can be deployed simultaneously. A remarkable challenge is the extension of the photocoverage in the noble liquid TPCs. Since the cathode and field cage are subject to a very high voltage, any photodetector to be deployed on them must be electrically isolated, requiring power and signal transmission via non-conductive connections. The field cage structure will be slimmed down for new photodetectors to be embedded within the available space. A solution based on the use of power and signal over fiber systems will have to be tested on the large scale before it can be adopted.

Overall Goals: **T4.3.G1:** Development of mid-scale facilities for large-area readout assembly and characterization at cryogenic temperature; **T4.3.G2:** Large-scale digitization technologies; **T4.3.G3:** Large-scale joint integration tests.

3 Common test facilities and tools

Cross-cutting the R&D for liquid detectors, a pressing need for small, medium, and large-scale testing facilities emerges to facilitate the development of new detector prototypes and to explore the properties of media. A list of current and future, planned facilities identified in the Work Package sections of the proposal can be found in table 9. This list reflects the current plans of DRD2 community participants to the proposal development process. We expect this will coalesce and evolve into access-granting and eventually common facilities as the DRD2 collaboration develops. We anticipate eventually operating access-giving and common facilities in a user-access model, whereby host institutes make a fraction of the operation time available to external DRD2 collaborators, with the allocation of time to be done annually by an appointed board of the collaboration, following the successful RD model.

Infrastructure	**Location**	**Work Package . Task**	**Current/Future**
MMP Common Test Platform	SNS	1.1	Current
MMP Common Test Platform	CERN (potentially Neutrino Platform)	1.1	Future
ARIADNE	Liverpool	1.2	Current
NUXE	UCSD	1.2	Future
PANCAKE	Freiburg	1.2	Current
PIONEER	TRIUMF	2.1	Current
BUTTON	Boulby	2.1	Current
QE, noise vs. (λ, T)	CIEMAT, Liverpool, Napoli	2.1	Future
CLEAR	TRIUMF	2.1	Future
SOLAIRE	Boulby	2.1	Future
Materials characterisation	Nikhef	2.2	Future
WLS/light collection	Astrocent	2.2	Future
1TBNL, 30TBNL	BNL	3.1	Current
1TBNL, 30TBNL	BNL	3.1	Current
Xenoscope	Zurich	3.2	Current
WbLS Testbeds	various	4.2	Current
100 tonne-scale WbLS facility	TBD	4.2	Future
URANIA	Colorado	4.2	Current
ARIA	Sardinia	4.2	Current
Neutrino Platform	CERN	4.3	Current
WCTE	CERN	4.3	Current

Table 9: Facilities and Infrastructures, Current and Planned, engaging with liquid detectors R&D. For description, see the related Work Package section.

3.1 Small and Medium facilities

Several institutions such as universities and national institutes already possess unique and useful capabilities that we intend to integrate and share within our collaboration, and a number of small and medium-scale R&D facilities are proposed here (i.e. DRDT2.1.D3). This sharing of resources requires effective coordination, management, and a database system. To address this, we propose the establishment of a Network of Small Experimental Efforts (NoSEE), which will provide a collaborative platform for every aspect of DRD2.

The resources required for NoSEE are 2 FTEs, namely a resource manager and a deputy, as well as a website and database developer and maintainer. Each joining institution will provide a point of contact, a list of shared equipment, and an availability schedule.

User access proposals for use of NoSEE resources will be evaluated by the collaboration appointed board. Priority of use will be granted to the home institution up to a maximum of 80% use time annually. Proposals will be evaluated according to criteria of scientific excellence, timeliness and strategic value.

The suite of complementary setups will be a major asset to support the new technology development, and making access available will enable efficient, collaborative development across institutes with a range of skills and expertise.

3.2 Large facilities

As described in section 2.4.3, the need for accomplishing the assembly and characterization of readout units for liquid detectors at the final 10-100 m^2 scale before deployment drives the creation of dedicated facilities equipped with the cryogenic infrastructure, slow controls and DAQ services capable of handling the required scales. A complimentary and parallel effort is required to address the large data volumes expected from these detectors by using readout electronics placed as close as possible to the sensors and digitizing the signal as far upstream as is feasible, in order to benefit from the higher signal-to-noise and multiplexing, which reduces the number of channels. Finally, there is a need for platforms for performing joint integration tests where all readout systems can be deployed simultaneously.

This is currently available to the neutrino oscillation physics community at CERN in the ProtoDUNE cryostats. The availability of this facility to support the European neutrino community is an essential and invaluable infrastructure underpinning liquid argon detectors R&D over the coming years. Allocation of experiment time at this facility proceeds via CERN's established scientific review process, and we envision DRD2 collaboration projects presenting proposals to the CERN SPSC for beam time in the Neutrino Platform facility. Furthermore, the Water Cherenkov Test Experiment (WCTE) is currently in construction at CERN and is expected to operate in the East Area T9 beam line with low momentum particle fluxes (pions, muon, electrons,...). The WCTE is expected to act as a technology and physics demonstrator for Hyper-Kamiokande and its Intermediate Water Cherenkov Detector (IWCD) but could also run for new future Water Cherenkov projects (ESSnuSB) and represents a good opportunity for the DRD2 collaboration.

3.3 Common simulation tools

This research community, particularly those focused on rare event searches, will witness an increasing necessity for common software and simulation toolkits such as LArSoft, NEST, SaG4N, NeuCbot and WCSim in the coming years. These packages play an instrumental role for the R&D in simulating and reconstructing the detector response, calculating background levels, and evaluating the expected sensitivity of experiments. The rising demand for these common tools highlights the need for their continuous enhancement and development. This not only standardizes the software tools used across different R&D efforts but also enables the achievement of an unparalleled level of detail in simulation and detector response calculations.

Based on the current state-of-the-art simulations tools, it is clear that there are still examples of software that are targeted at specific Work Packages and applications (e.g. BxDecay0 is for low-energy and rare decays, GENIE is for GeV neutrino interactions, RAT for noble element light simulations...). In the early stages of the collaboration, each Work Package will ensure that the simulation tools meet the needs from the Work Packages. When needs are identified, small groups (e.g. Task Forces) will evaluate how best to move forward to further develop the simulation softwares. The ultimate goal will be to have a set of common, easily adaptable, simulation tools that can be used across all DRD2. Coordination between other DRDs (e.g. DRD1) will also be beneficial to adapt the simulation tools to wider audiences.

4 Partnerships (industrial, other research areas, other applications)

Partnerships with other DRDs are identified in the different sections above. Current examples of industrial partnerships and applications are listed for some Work Packages below.
T1.1: Instrumentation Frontier Scientific, Texas Instruments
T2.1: industry: FBK, Fraunhofer, Hamamatsu, Teledyne-DALSA, Teledyne-e2v; project partners: BUTTON, PDC; applications: remote forest fire sensing, LiDAR
T2.2: Photon Export, Saint Gobain, Kuraray
T4.1: industry : Mirion/Canberra, Agilent, Analytix, XIA
T4.2: industry : Carbosulcis, Polaris, SAES getters
T4.3: industry: CRIOTEC, DEMACO, Costruzioni Generali, CAEN

5 Networking and training

Regarding networking, there are currently some opportunities (conferences or workshops) for the liquid detector communities to exchange knowledge but those typically have some focus related to a science area or a specific Work Package. This new DRD collaboration will offer a new, highly needed and with the appropriate focus for stimulating and productive intellectual exchange. The whole collaboration would meet once a year but other targeted meetings would be organized leveraging existing conferences that have more specific focuses (e.g LIDINE). The Work Package conveners would ensure that the collaboration meeting organization stimulates exchanges across the different areas and have joint work package meetings.

For the training, the collaboration plans once again to leverage existing instrumentation schools by adding an area of teaching related to liquid detectors. Furthermore, within the context of the collaboration, sessions could be added to the collaboration meeting where younger scientists could attend teaching seminars given by a wide range of experts from the collaboration. The collaboration will follow closely the activities carried out by students and postdocs, provide a forum for them to present their work and offer networking opportunities within the collaboration.

6 Proposal for the collaboration structure

The collaboration governance will be initially modeled on the existing RD51 collaboration. The collaboration will be structured around four Work Packages led by conveners responsible for the coordination of the Work Package task activities. The collaboration may designate, if necessary, liaisons with other DRDs to coordinate possible common R&D activities. An illustration of the collaboration structure is shown in figure 5.

The ECFA DRD Steering Committee envisions there will be one “lightweight” Memorandum of Understanding (MoU) between all institutes and CERN for the formation of the collaboration covering topics like Intellectual Property and Common fund. Separately, the Committee envision one Annex per Work Package should be signed by funding agencies of the institutes involved in the respective work packages, specifying its activities and a nominal annual common fund contribution to enable user-access experiments (as described in section 3).

The collaboration will have an Institutional Board with one representative per institute signing the ”lightweight” MoU, that will elect a spokesperson(s) every two years. The spokesperson(s) will be responsible for communications with review bodies and funding agencies on behalf of the collaboration. The Institutional Board will appoint the Common Facilities board with representatives from all regions every (alternate) two years. The Financial Board will be composed of representatives from each country (either national PIs or their nominees), and hold responsibility for the common fund, and for preparing reports on collaboration finance to funding agencies and the Institute Board. The Institute Board will appoint committees as needed (i.e. Speakers Board, Editorial Board), and be responsible for organizing an annual collaboration meeting week.

6.1 Summary of current relations and synergies with other DRD Collaborations

For convenience, we summarize here the current relations and synergies with other DRD collaborations. We expect these to naturally evolve and adapt as the DRD2 collaboration is established. To facilitate this, DRD2 has liaisons responsible to interact with the relevant DRDs where there are identified synergies or overlaps. These are:

- Task 1.1: Pixels and Charge + Light Readouts – The DRD2 focus is primarily on deployment of readouts within liquid nobles. Cross-cutting topics include electronics development for these readouts, which is addressed within DRD7 (liaison E. Gramellini).

- Task 1.2: Amplification structures, charge to light conversion, and granular light readout of dual-phase detectors – similarly, cross-cutting topics include electronics development for these readouts, which is addressed within DRD7 (liaison E. Gramellini).

- Task 1.3: ion detection – by agreement with the DRD1 conveners, current efforts on DRD2-specific topics related to ion detection in gas are currently covered in DRD1 (liaison K. Mavrokoridis). Given promising potential, while this is not currently represented in the DRD2 proposal, this topic may evolve to be represented in DRD2 in the future.

- Task 2.1: Increased sensor quantum efficiency – by agreement with the DRD4 and 7 conveners, the DRD2 focus here is primarily on the sensor development for cryogenic detectors, whilst the DRD4 focus is on room-temperature detectors and the DRD7 focus is on the development of the front end electronics themselves. The areas where we envision close cross-collaboration are DRD7.4 on cryogenic ASICs (liaison J. Monroe) and DRD4.3 on integration developments (liaison F. Retiere).

- Task 2.3: improved sensors for liquid scintillators (LS)/Water – this topic covers developments that directly overlap with DRD4, as it targets visible light at room temperatures. By agreement with the DRD4 conveners,

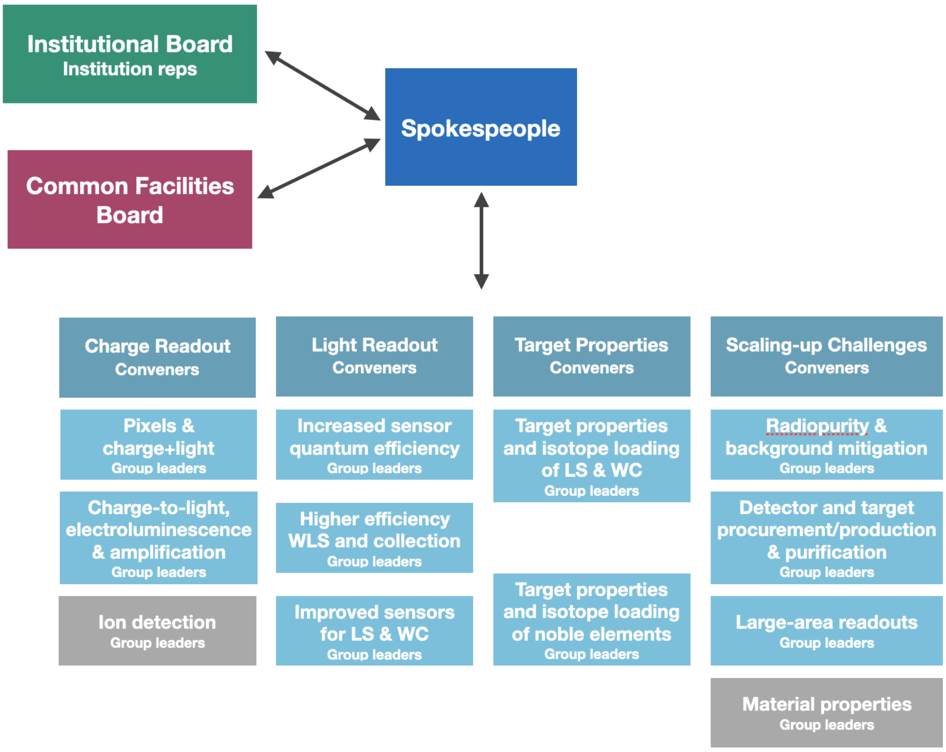

Figure 4: DRD2 Collaboration structure. The two gray boxes represents groups that are not yet formed but are anticipated in the future.

this topic is currently covered in DRD4. The task is listed here for the purpose of coordinating the efforts with DRD4 for the applications to Liquid Detectors (liaison: F. Retiere).

- Task 4.3: large-area readouts – there is overlap between the goals of Task 4.3 with DRD7 (liaison E. Gramellini). While at this early stage there are not specific division of tasks identified with DRD7, close collaboration in the future will be essential.

7 Resources

The estimated FTE required to carry out the planned R&D activities are summarized in table 10, together with the currently-funded FTE. The estimated non-FTE resource required to support these activities, including consumables, materials, equipment, and services, is summarized in table 11, together with the currently-funded resource. We expect these estimates to evolve and adapt as required, following the approval of the collaboration. In particular, in areas which are currently unfunded, but for which there is a strong interest, we expect establishing the collaboration will be an important underpinning step for collaborators to pursue the required increase in national resources.

Total FTE estimated to be required to deliver the outlined R&D programme	2024	2025	2026	2027-2029	>2030
Work Package 1: Charge Readout					
T1.1: Pixels and charge+light readouts	Available/Required FTE				
T1.1.G1 fC charge sensing pixel	9/16	9/16	9/16	9/16	-
T1.1.G2 Scaling pixel readout to O(100million) channels	6/12	6/12	6/12	6/12	-
T1.1.G3 Multimodal signals	6/15	6/15	6/15	6/15	-
T1.1 Total	21/43	21/43	21/43	21/43	-
T1.2: Electroluminescence, charge multiplication, and charge-to-light readouts	Available/Required FTE				
T1.2.G1 Granular S2 light readout	6/11.5	6/11.5	6/11.5	10/20.5	-
T1.2.G2 Charge amplification structures	7/13.5	7/13	6/12.5	15/39.5	-
T1.2.G3 Scalability at $\mathcal{O}(\mathrm{m}^2)$ and $\mathcal{O}(10\,\mathrm{m}^2)$	3/7	3/7.5	3/8	10/24	-
T1.2 Total	16/32	16/32	15/32	35/84	-
WP1: Total	**37/75**	**37/75**	**36/75**	**56/127**	-
Work Package 2: Light Readout					
T2.1: Increased Sensor QE	Available/Required FTE				
T2.1.G1 Sensor optimisation & characterization	4/9	4/9	4/9	4/9	-
T2.1.G2 Detector integration optimisation	5/9	5/9	5/9	5/9	-
T2.1.G3 Characterisation facilities for VUV	17/19	17/28	17/28	17/28	-
T2.1 Total	26/37	26/46	26/46	26/46	-
T2.2: WLS and increasing light collection	Available/Required FTE				
T2.2.G1 Better scalable WLS and reflectors	3.5/11	3.5/11	3.5/11	3/11	-
T2.2.G2 Optimized light collectors and concentrators	3.8/6.3	3.8/6.3	3.8/6.3	3.8/6.3	-
T2.2 Total	7.3/17.3	7.3/17.3	7.3/17.3	6.8/17.3	-
WP2: Total	**33.3/54.3**	**33.3/63.3**	**33.3/63.3**	**32.8/63.3**	-
Work Package 3: Target Properties					
T3.1: Microphysics, Light emission and transport and isotope loading for LS and WC detectors	Available/Required FTE				
T3.1.G1 Target optimization and characterization	23.5/30	23.5/30	23.5/30	23.5/30	-
T3.1.G2 Target loading	10/13	10/13	10/13	10/13	-
T3.1 Total	33.5/43	33.5/43	33.5/43	33.5/43	-
T3.2: Microphysics, Light emission and transport and isotope loading for Liquid Noble detectors	Available/Required FTE				
T3.2.G1 Understanding microphysics	0/8	0/12	0/9.5	0/1.5	-
T3.2.G2 Characterizing and modeling light emission and transport	6.7/7.2	6.7/9.2	0.5/5.35	0/5	-
T3.2.G3 Characterizing properties of Ar-Xe mixtures	0/7.75	0/11.45	0/11.35	0/2	-
T3.2 Total	6.7/22.95	6.7/32.65	0.5/26.2	0/8.5	-
WP3: Total	**40.2/65.95**	**40.2/75.65**	**34.0/69.2**	**33.5/51.5**	-
Work Package 4: Scaling up challenge					
T4.1: Radiopurity and background mitigation	Available/Required FTE				
T4.1.G1 Radioassay techniques at required sensitivity	0.5/8.6	0.5/11.6	0/11.6	0/3.6	-
T4.1.G2 Material selection and clean manufacture	5.3/9.3	5.3/11.3	5.3/10.3	1.3/2.8	-
T4.1.G3 Novel materials	1.7/6.7	1.7/6.7	1.7/6.7	0.7/4.7	-
T4.1.G4 Tool development	3.2/9.4	3/9.2	3/8.1	3/6.9	-
T4.1 Total	10.7/34	10.5/38.8	10/36.7	5/18	-
T4.2: Detector and Target procurement/production and Purification	Available/Required FTE				
T4.2.G1 Scale-up mass production & characterization	13/24	10/24	10/24	10/25	-
T4.2.G2 Purification technologies	10/24	10/24	10/24	10/25	-
T4.2 Total	23/48	20/48	20/48	20/50	-
T4.3: Large-area readout	Available/Required FTE				
T4.3.G1 Mid-scale facilities at cryogenic temperature	3.3/7.1	3.3/7.1	3.3/7.1	3.3/7.1	-
T4.3.G2 Large-scale digitization technologies	0.2/2.8	0.2/0.7	0.2/0.7	0.2/0.7	-
T4.3.G3 Large-scale joint integration tests	0.7/18.4	0.7/18.4	0.7/21.0	0/19.6	-
T4.3 Total	4.2/28.3	4.2/26.2	4.2/28.8	3.5/27.4	-
WP4: Total	**37.9/110.3**	**34.7/113**	**34.2/113.5**	**28.5/95.4**	-
DRD2 Total	**148.4/ 305.6**	**145.2/ 327.0**	**137.5/ 321.0**	**150.8/ 337.2**	-

Table 10: Summary of existing (available) and required (available + additional needed) FTE to carry out the planned R&D activities. Note that the fourth column (2027-2029) shows the numbers per year, so the total for the three-year period needs to be multiplied by 3.

Total non-FTE estimated to be required to deliver the outlined R&D programme	2024	2025	2026	2027-2029	>2030
Work Package 1: Charge Readout					
T1.1: Pixels and charge+light readouts	Available/Required Funding (kEUR)				
T1.1.G1 fC charge sensing pixel	235/415	235/415	235/415	235/415	-
T1.1.G2 Scaling pixel readout to O(100million) channels	150/300	150/300	150/500	150/500	-
T1.1.G3 Multimodal signals	150/300	150/350	150/350	150/400	-
T1.1 Total	535/1015	535/1065	535/1265	535/1315	-
T1.2: Electroluminescence, charge multiplication, and charge-to-light readouts	Available/Required Funding (kEUR)				
T1.2.G1 Granular S2 light readout	100/377	100/277	5/11	5/33	-
T1.2.G2 Charge amplification structures	70/148	70/183	50/108	50/144	-
T1.2.G3 Scalability at $\mathcal{O}(\mathrm{m}^2)$ and $\mathcal{O}(10\,\mathrm{m}^2)$	10/25	100/305	50/200	50/350	-
T1.2 Total	180/550	270/765	105/319	105/527	-
WP1: Total	**713 / 1565**	**805 /1830**	**640 / 1584**	**640 / 1842**	-
Work Package 2: Light Readout					
T2.1: Increased Sensor QE	Available/Required Funding (kEUR)				
T2.1.G1 Sensor optimisation & characterization	150/530	150/465	150/975	100/725	-
T2.1.G2 Detector integration optimisation	130/400	130/900	130/500	130/500	-
T2.1.G3 Characterisation facilities for VUV	400/1080	400/875	400/900	200/750	-
T2.1 Total	680/2010	680/2175	680/2375	430/1975	-
T2.2: WLS and increasing light collection	Available/Required Funding (kEUR)				
T2.2.G1 Better scalable WLS and reflectors	140/315	10/300	10/280	50/500	-
T2.2.G2 Optimized light collectors and concentrators	20/60	10/30	10/30	10/30	-
T2.2 Total	160/375	20/330	20/310	60/530	-
WP2: Total	**840/2385**	**700/2505**	**700/2685**	**490/2505**	-
Work Package 3: Target Properties					
T3.1: Microphysics, Light emission and transport and isotope loading for LS and WC detectors	Available/Required funding (kEUR)				
T3.1.G1 Target optimization and characterization	100/350	100/250	100/250	200/450	-
T3.1.G2 Target loading	50/150	50/300	50/250	100/600	-
T3.1 Total	150/500	150/550	150/500	300/1050	-
T3.2: Microphysics, Light emission and transport and isotope loading for Liquid Noble detectors	Available/Required funding (kEUR)				
T3.2.G1 Understanding microphysics	0/215	0/500	0/235	20	-
T3.2.G2 Characterizing and modeling light emission and transport	337/347	164/214	0/132	0/170	-
T3.2.G3 Characterizing properties of Ar-Xe mixtures	0/77	0/487	0/556	0/50	-
T3.2 Total	337 / 639	164/1201	0/923	0/240	-
WP3: Total	**487 / 1139**	**314 / 1751**	**150 / 1423**	**300 / 1290**	-
Work Package 4: Scaling up challenge					
T4.1: Radiopurity and background mitigation	Available/Required funding (kEUR)				
T4.1.G1 Radioassay techniques at required sensitivity	0/618	0/858	0/522	0/135	-
T4.1.G2 Material selection and clean manufacture	5/353	30/278	30/318	5/114	-
T4.1.G3 Novel materials	0/250	0/236	0/230	0/157.5	-
T4.1.G4 Tool development	0/102	0/84	0/78	0/75	-
T4.1 Total	5/1323	30/1456	30/1148	5/481.5	-
T4.2: Detector and Target procurement/production and Purification	Available/Required funding (kEUR)				
T4.2.G1 Scale-up mass production & characterization	50/240	50/240	0/240	0/300	-
T4.2.G2 Purification technologies	50/270	50/270	0/270	0/300	-
T4.2 Total	100/510	100/510	0/510	0/600	-
T4.3: Large-area readout	Available/Required funding (kEUR)				
T4.3.G1 Mid-scale facilities at cryogenic temperature	0/320	100/280	0/110	0/210	-
T4.3.G2 Large-scale digitization technologies	50/50	0/10	0/30	0/10	-
T4.3.G3 Large-scale joint integration tests	500/TBD	-	-	-	-
T4.3 Total	550/870	100/290	0/140	0/220	-
WP4: Total	**555/2703**	**130/ 2256**	**30/1798**	**5/1301.5**	-
DRD2 Total	**2595/7792**	**1949 / 8342**	**1520 / 7490**	**1435 / 6938.5**	-

Table 11: Summary of existing (available) and required (available + additional needed) non-FTE funding to carry out the planned R&D activities. Note that the fourth column (2027-2029) shows the numbers per year.

8 Summary

Overall, 114 institutions participated in the DRD2 proposal, with 51 written contributions submitted. Over 150 participants registered to the DRD2 Community Meeting (https://indico.cern.ch/event/1214404). The breakdown of the participating institutions by country and by WPs is shown below.

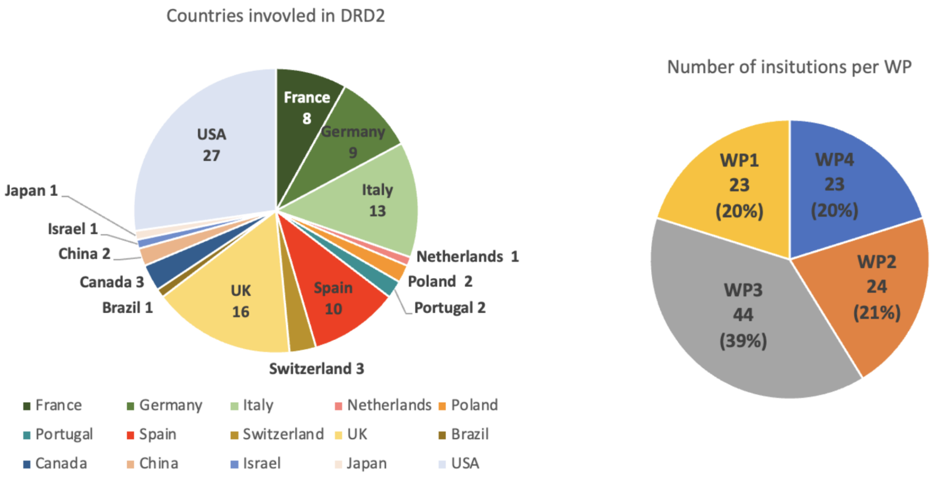

Figure 5: Distributions of participating institutions by country (left) and by WPs (right).

References

[1] D. Nygren and Y. Mei. 'Q-Pix: Pixel-scale Signal Capture for Kiloton Liquid Argon TPC Detectors: Time-to-Charge Waveform Capture, Local Clocks, Dynamic Networks' (Sept. 2018). arXiv: 1809.10213 [physics.ins-det].

[2] D. A. Dwyer et al. 'LArPix: Demonstration of low-power 3D pixelated charge readout for liquid argon time projection chambers'. *JINST* 13.10 (2018), P10007. DOI: 10.1088/1748-0221/13/10/P10007. arXiv: 1808.02969 [physics.ins-det].

[3] C. Adams et al. 'Enhancing neutrino event reconstruction with pixel-based 3D readout for liquid argon time projection chambers'. *JINST* 15.04 (2020), P04009. DOI: 10.1088/1748-0221/15/04/P04009. arXiv: 1912.10133 [physics.ins-det].

[4] M. Rooks et al. 'Development of a novel, windowless, amorphous selenium based photodetector for use in liquid noble detectors'. *Journal of Instrumentation* 18.01 (2023), P01029. DOI: 10.1088/1748-0221/18/01/P01029.

[5] S. K. Barman et al. 'Surface and Optoelectronic Properties of Ultrathin Trigonal Selenium: A Density Functional Theory Study with van der Waals Correction'. *Langmuir* 38.28 (2022), pp. 8485–8494. DOI: 10.1021/acs.langmuir.1c02935. arXiv: 2104.14455 [cond-mat.mtrl-sci].

[6] P. Agnes et al. 'DarkSide-50 532-day dark matter search with low-radioactivity argon'. *Phys. Rev. D* 98 (10 2018), p. 102006. DOI: 10.1103/PhysRevD.98.102006.

[7] E. Aprile et al. 'First Dark Matter Search with Nuclear Recoils from the XENONnT Experiment'. *Phys. Rev. Lett.* 131 (4 2023), p. 041003. DOI: 10.1103/PhysRevLett.131.041003.

[8] J. Aalbers et al. 'First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment'. *Phys. Rev. Lett.* 131 (4 2023), p. 041002. DOI: 10.1103/PhysRevLett.131.041002.

[9] The MicroBooNE Collaboration. 'MeV-scale Physics in MicroBooNE'. *MicroBooNE public note: MICROBOONE-NOTE-1076-PUB* (June 2020).

[10] A. Lowe et al. 'A Novel Manufacturing Process for Glass THGEMs and First Characterisation in an Optical Gaseous Argon TPC'. *Applied Sciences* 11.20 (2021). ISSN: 2076-3417. DOI: 10.3390/app11209450.

[11] V. Chepel et al. 'First results on FHM — a Floating Hole Multiplier'. *Journal of Instrumentation* 18.05 (2023), P05013. DOI: 10.1088/1748-0221/18/05/P05013.

[12] E Aprile et al. 'Measurements of proportional scintillation and electron multiplication in liquid xenon using thin wires'. *Journal of Instrumentation* 9.11 (2014), P11012. DOI: 10.1088/1748-0221/9/11/P11012.

[13] F. Kuger et al. 'Prospects of charge signal analyses in liquid xenon TPCs with proportional scintillation in the liquid phase'. *Journal of Instrumentation* 17.03 (2022), P03027. DOI: 10.1088/1748-0221/17/03/P03027.

[14] J. Qi et al. 'Low energy electronic recoils and single electron detection with a liquid Xenon proportional scintillation counter'. *JINST* 18.07 (2023), P07027. DOI: 10.1088/1748-0221/18/07/P07027. arXiv: 2301.12296 [physics.ins-det].

[15] E. Erdal et al. 'Bubble-assisted Liquid Hole Multipliers in LXe and LAr: towards "local dual-phase TPCs"'. *Journal of Instrumentation* 15.04 (2020), p. C04002. DOI: 10.1088/1748-0221/15/04/C04002.

[16] A. Roberts et al. 'First demonstration of 3D optical readout of a TPC using a single photon sensitive Timepix3 based camera'. *Journal of Instrumentation* 14.06 (2019), P06001. DOI: 10.1088/1748-0221/14/06/P06001.

[17] A. Lowe et al. 'ARIADNE+: Large scale demonstration of fast optical readout for dual-phase LArTPCs at the CERN Neutrino Platform' (2023). arXiv: 2301.02530 [physics.ins-det].

[18] A. Lowe et al. 'Optical Readout of the ARIADNE LArTPC Using a Timepix3-Based Camera'. *Instruments* 4.4 (2020). ISSN: 2410-390X. DOI: 10.3390/instruments4040035.

[19] K. Thieme. 'DARWIN – a next-generation liquid xenon observatory for dark matter and neutrino physics'. *PoS* ICRC2021 (2021), p. 548. DOI: 10.22323/1.395.0548.

[20] G. Y. R. F. e. a. Gallina G. 'Performance of novel VUV-sensitive Silicon Photo-Multipliers for nEXO'. *Eur. Phys. J. C* 82 (2022). DOI: 10.1140/epjc/s10052-022-11072-8.

[21] P. Jerram et al. 'Back-thinned CMOS sensor optimization'. *OPTO*. 2010.

[22] J. Heymes et al. 'Comparison of Back-thinned Detector Ultraviolet Quantum Efficiency for Two Commercially Available Passivation Treatments'. *IEEE NSS&MIC*. 2019.

[23] J. B. McLaughlin et al. 'Characterisation of SiPM Photon Emission in the Dark'. *Sensors* 21.17 (2021), p. 5947. DOI: 10.3390/s21175947. arXiv: 2107.13753 [physics.ins-det].

[24] E. D. R. R. P. Group. *The 2021 ECFA detector research and development roadmap*. Tech. rep. Geneva, 2020. DOI: 10.17181/CERN.XDPL.W2EX.

[25] J. Caravaca et al. 'Experiment to demonstrate separation of Cherenkov and scintillation signals'. *Phys. Rev. C* 95 (5 2017), p. 055801. DOI: 10.1103/PhysRevC.95.055801.

[26] J. Caravaca et al. 'Characterization of water-based liquid scintillator for Cherenkov and scintillation separation'. *The European Physical Journal C* 80.9 (2020). DOI: 10.1140/epjc/s10052-020-8418-4.

[27] A. Cabrera et al. 'Neutrino physics with an opaque detector'. *Communications Physics* 4.1 (2021). DOI: 10.1038/s42005-021-00763-5.

[28] S. Schoppmann. 'Review of Novel Approaches to Organic Liquid Scintillators in Neutrino Physics'. *Symmetry* 15.1 (2023), p. 11. DOI: 10.3390/sym15010011. arXiv: 2212.11341 [physics.ins-det].

[29] M. Yeh et al. 'A new water-based liquid scintillator and potential applications'. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 660.1 (2011), pp. 51–56. ISSN: 0168-9002. DOI: 10.1016/j.nima.2011.08.040.

[30] L. Bignell et al. 'Characterization and modeling of a Water-based Liquid Scintillator'. *Journal of Instrumentation* 10.12 (2015), P12009. DOI: 10.1088/1748-0221/10/12/P12009.

[31] D. R. Onken et al. 'Time response of water-based liquid scintillator from X-ray excitation'. *Materials Advances* 1.1 (2020), pp. 71–76. DOI: 10.1039/d0ma00055h.

[32] H. T. J. Steiger et al. 'Development, Characterization and Production of a novel Water-based Liquid Scintillator based on the Surfactant TRITON™X-100'. *Journal of Instrumentation* to be published (2023).

[33] C. Aberle et al. 'Measuring directionality in double-beta decay and neutrino interactions with kiloton-scale scintillation detectors'. *Journal of Instrumentation* 9.06 (2014), P06012. DOI: 10.1088/1748-0221/9/06/P06012.

[34] A. Elagin et al. 'Separating Double-Beta Decay Events from Solar Neutrino Interactions in a Kiloton-Scale Liquid Scintillator Detector By Fast Timing'. *Nucl. Instrum. Meth. A* 849 (2017), pp. 102–111. DOI: 10.1016/j.nima.2016.12.033.

[35] M. Li et al. 'Separation of scintillation and Cherenkov lights in linear alkyl benzene'. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 830 (2016), pp. 303–308. ISSN: 0168-9002. DOI: 10.1016/j.nima.2016.05.132.

[36] J. Gruszko et al. 'Detecting Cherenkov light from 1–2 MeV electrons in linear alkylbenzene'. *JINST* 14.02 (2019), P02005. DOI: 10.1088/1748-0221/14/02/P02005.

[37] Z. Guo et al. 'Slow liquid scintillator candidates for MeV-scale neutrino experiments'. *Astroparticle Physics* 109 (2019), pp. 33–40. ISSN: 0927-6505. DOI: 10.1016/j.astropartphys.2019.02.001.

[38] S. D. Biller, E. J. Leming and J. L. Paton. 'Slow fluors for effective separation of Cherenkov light in liquid scintillators'. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 972 (2020), p. 164106. DOI: 10.1016/j.nima.2020.164106.

[39] J. Dunger, E. J. Leming and S. D. Biller. 'Slow-fluor scintillator for low energy solar neutrinos and neutrinoless double beta decay'. *Physical Review D* 105.9 (2022). DOI: 10.1103/physrevd.105.092006.

[40] M. Askins et al. *The Physics and Nuclear Nonproliferation Goals of WATCHMAN: A WAter CHerenkov Monitor for ANtineutrinos*. 2015. DOI: 10.48550/ARXIV.1502.01132.

[41] M. Askins et al. 'THEIA: an advanced optical neutrino detector'. *Eur. Phys. J. C* 80.5 (2020), p. 416. DOI: 10.1140/epjc/s10052-020-7977-8.

[42] M. Agostini et al. 'First Directional Measurement of Sub-MeV Solar Neutrinos with Borexino'. *Phys. Rev. Lett.* 128 (9 2022), p. 091803. DOI: 10.1103/PhysRevLett.128.091803.

[43] J. Paton. *Event by Event Directional Reconstruction in the SNO+ Scintillator Phase*. 2022.

[44] J. Dunger and S. D. Biller. 'Multi-site event discrimination in large liquid scintillation detectors'. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 943 (2019), p. 162420. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2019.162420.

[45] C. Buck, B. Gramlich and S. Schoppmann. 'Novel opaque scintillator for neutrino detection'. *Journal of Instrumentation* 14.11 (2019), P11007–P11007. DOI: 10.1088/1748-0221/14/11/p11007.

[46] A. Cabrera. *LiquidO Opaque Neutrino Detection: New Results and Status*. 2022. DOI: 10.5281/zenodo.6697273.

[47] L Winslow and R Simpson. 'Characterizing quantum-dot-doped liquid scintillator for applications to neutrino detectors'. *Journal of Instrumentation* 7.07 (2012), P07010–P07010. DOI: 10.1088/1748-0221/7/07/p07010.

[48] C. Aberle et al. 'Optical properties of quantum-dot-doped liquid scintillators'. *Journal of Instrumentation* 8.10 (2013), P10015. DOI: 10.1088/1748-0221/8/10/P10015.

[49] E. Graham et al. 'Light yield of Perovskite nanocrystal-doped liquid scintillator'. *Journal of Instrumentation* 14.11 (2019), P11024–P11024. DOI: 10.1088/1748-0221/14/11/p11024.

[50] K. Dropiewski et al. 'Optical Properties of InAs Quantum Dots/GaAs Waveguides for Ultra-fast Scintillators'. *Journal of Luminescence* 220 (2020), p. 116952. ISSN: 0022-2313. DOI: 10.1016/j.jlumin.2019.116952.

[51] B. Bastian-Querner et al. 'The Wavelength-Shifting Optical Module'. *Sensors* 22.4 (2022). ISSN: 1424-8220. DOI: 10.3390/s22041385.

[52] A. V. Lyashenko et al. 'Performance of Large Area Picosecond Photo-Detectors (LAPPD™)'. *Nucl. Instrum. Meth. A* 958 (2020). Ed. by M. Krammer et al., p. 162834. DOI: 10.1016/j.nima.2019.162834.

[53] M. Minot et al. 'Large Area Picosecond Photodetector (LAPPD™) - Pilot production and development status'. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 936 (2019). Frontier Detectors for Frontier Physics: 14th Pisa Meeting on Advanced Detectors, pp. 527–531. ISSN: 0168-9002. DOI: 10.1016/j.nima.2018.11.137.

[54] J. V. Dawson and D. Kryn. 'Organic liquid TPCs for neutrino physics'. *Journal of Instrumentation* 9.07 (2014), P07002–P07002. DOI: 10.1088/1748-0221/9/07/p07002.

[55] T. Radermacher et al. *Liquid-organic time projection chamber for detecting low energy antineutrinos*. 2022. arXiv: 2203.01090 [physics.ins-det].

[56] I. Anghel et al. 'Letter of Intent: The Accelerator Neutrino Neutron Interaction Experiment (ANNIE)' (2015). DOI: 10.48550/arXiv.1504.01480.

[57] T. Anderson et al. 'Eos: conceptual design for a demonstrator of hybrid optical detector technology'. *Journal of Instrumentation* 18.02 (2023), P02009. DOI: 10.1088/1748-0221/18/02/P02009.

[58] A. Cabrera. 'The SuperChooz Experiment: Unveiling the Opportunity'. *CERN* EP Seminar (2022).

[59] Y. Gando et al. 'The nylon balloon for xenon loaded liquid scintillator in KamLAND-Zen 800 neutrinoless double-beta decay search experiment'. *Journal of Instrumentation* 16.08 (2021), P08023. DOI: 10.1088/1748-0221/16/08/p08023.

[60] D. Auty et al. 'A method to load tellurium in liquid scintillator for the study of neutrinoless double beta decay'. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 1051 (2023), p. 168204. ISSN: 0168-9002. DOI: https://doi.org/10.1016/j.nima.2023.168204.